**Hazard Resilient Pipeline Research Panel**

**Final Report**

**February 2024**

**Hazard Resilient Pipeline Research Panel Members**

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Masakatsu Miyajima, Kanazawa University, Professor Emeritus

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Table of Contents

## 1. Introduction

The Hazard Resilient Pipeline Research Panel (HRPRP) was organized as an international group of researchers from the USA and Japan. Annex 1 in this report presents the founding document that lays out the HRPRP formation and guidelines. The HRPRP worked for two years with the purpose of reducing the risks posed to buried pipelines by hazards and their relation to resilience and sustainability. They include all types of buried water pipelines (i.e., the research did not focus on any specific pipeline materials or connection methods). The expert panel took on the charge to advance the knowledge and understanding of hazard-resilient pipelines. A wide range of hazards are known to affect the performance of water systems. Buried pipeline behavior influences the ability of water systems to provide services to customers following a hazard strike. The more extensive the damage, the longer the repair times and duration of service losses. It is therefore important to consider the potential impact of hazards on pipeline performance as well as the response of water supply networks.

The number of disasters caused by natural hazards is increasing on an annual basis. Historically, hazards have been recognized to include earthquakes, landslides, subsidence, sinkholes, and land erosion. Climate change results in the increased intensity of many natural hazards that affect water systems. Some examples include drought, wildfires, hurricanes, extreme cold, extreme heat, thawing of permafrost, and intense flooding. The purpose of the HRPRP is to improve the understanding of the risks that natural hazards and some anthropogenic hazards pose to buried water pipelines and how they relate to resilience and sustainability.

The HRPRP defined hazard-resilient pipelines as *having an ability to recover from or adjust easily to the effects of hazards* (modified from Merriam-Webster, 2023). A practical application of this definition is to understand how hazard-resilient pipelines can accommodate the effects of hazards (forces and displacements) and easily be repaired. This definition should be taken in context of providing services, usually within a network, to meet societal needs. The time to recover is relative to the pipelines' purpose for meeting the serviceability needs of the users.

Outcomes from the HRPRP include:

- Summary documents and presentations on topics related to hazard resilient buried pipelines (Annex 2),
- Summary of discussions during meetings (Annex 3)
- Hazard matrix (Section 3)
- List of hazards, with definitions, commonly impacting buried pipelines (Annex 4)
- Proposal for implementing the use of hazard-resilient pipelines.

The HRPRP identified how different hazards have a common feature of imposing displacements and strains on pipelines through different mechanisms (i.e., thermal, ground displacement, etc.). Some hazards, like a wildfire, may impose other types of damage. As a result, the HRPRP concluded that resilient pipelines are beneficial for coping with the displacements and strains imposed by a wide range of events. The HRPRP developed a hazard matrix to list commonly experienced hazards in the USA and Japan and an associated process to address these hazards through resilient buried pipelines.

This report initiates the accomplishment of the HRPRP objective to provide information for use in the water sector to improve systems using hazard-resilient pipelines. The plan is to follow up on this report by presenting the key findings and results to the water sector profession.

Following this introduction, an overview of the HRPRP activities is provided. Then the hazard matrix is summarized along with guidance on how it may be used. Conclusions are presented, which include recommendations on how to utilize hazard-resilient pipelines to improve water networks.

## 2. Overview

The HRPRP met four times. Two meetings were online, and two meetings were in person, one in the USA and one in Japan. The meeting minutes are provided in Annex 3. Presentations and discussions during each meeting had themes focusing on improving the understanding of hazard-resilient pipelines as follows:

- Overview of resilient infrastructure
- Understanding risks
- Available and upcoming technologies
- Resilient systems, guidelines, and standards
- Application of the hazard matrix

Each presentation is provided in Annex 2. Summary papers were also prepared on critical topics, which are also presented in Annex 2. The topics are as follows:

1. Lifeline Earthquake Engineering: Legacy and Lessons Learned
2. Resilience of Water Pipelines and Facilities against Hazards such as Earthquakes and Heavy Rains
3. Understanding Risks/Pipeline Damage Geohazards, Man-Made Land and Ground Monitoring
4. Ground and Pipeline Failures in Balboa Blvd. (1994 Northridge): Suspected Mechanisms of Liquefaction & Cyclic Softening, and Predictive Capabilities
5. Water Outage and Fire Fighting Water
6. Pipeline Damage and Assessment for Hazards
7. Recent Studies for Enhancement of Resilient Water Supply System
8. Initiatives at the Center for Smart Infrastructure
9. Pipeline Rebuild, Design and Installation of Hazard-Resilient Pipelines
10. Example of Pipeline Failure based on Hazard Impact Matrix and Latest Seismic Design and Construction Guideline for Water Facilities in Japan
11. Hazard Resilient Design in USA and Examples of Pipeline Failures based on Hazard Impact Matrix
12. SimCenter Tools for Response and Recovery: Future for Lifelines
13. Pipeline damage: Case, physical and numerical studies; Experimental study of the countermeasure on pipeline uplift due to liquefaction; Numerical analysis of floatation characteristics of buried pipelines due to liquefaction and countermeasure

The second meeting, which was in person at the University of California Berkeley, had several guests who participated by presenting and discussing the needs and uses of hazard-resilient pipelines. The presentations identify the wide range of topics surrounding the main topic of hazard-resilient pipelines.

The HRPRP discussions revealed the need to itemize the primary hazards of concern and how they may damage buried pipelines. The primary hazards of concern are limited to natural hazards and some anthropogenic hazards (i.e., those leading to ground subsidence and from construction-related activities). Further, it was identified that clear definitions of the hazards are necessary for proper communication. The HRPRP concluded that resilient pipelines are beneficial for coping with the ground deformation and strains imposed on them by a wide range of hazards. However, the specific types of movements and forces imposed on buried pipelines should be evaluated for each hazard-resilient system. Being resilient to one hazard does not necessarily mean a buried pipeline is resilient to other hazards. The following process helps to identify the need for and application of hazard-resilient pipeline systems:

1. Recognize the hazards of concern. These are the hazards that may threaten buried pipelines in a particular supply, transmission, or service area.
2. Identify the exposure of buried pipelines to various hazards by showing where they coincide on local and regional maps.
3. Understand the potential effects of hazards on buried pipelines:
    a. Assess the potential strains and associated forces the ground may impose on buried pipelines.
    b. Investigate individual pipelines exposed to the hazards and their cumulative effect on the water supply within the total area of exposure (i.e., potential extent of damage to individual pipelines and total number and level of damage to the network).
    c. If possible, identify the probability or likelihood of damage to pipelines.
4. Characterize the potential service disruptions to customers/users (e.g., ability to deliver water, meet quality regulations, the quantity, and fire service) and the consequences to social and economic activity.
5. Select the pipelines critical to providing continuous services.
6. Plan, design, and construct using hazard-resilient pipelines. This includes the installation of new as well as the replacement of existing ones.

A pipeline may be continuous, segmented, or hybrid (Wham and Davis, 2019) and includes all joints, valves, and fittings (i.e., tee, ell, couplings, reducers, etc.). The joints, valves and fittings are commonly the weak points in the pipeline system requiring special consideration in item 5 in the above process to ensure the pipeline can perform resiliently.

## 3. Hazard Matrix for Buried Pipelines

Table 1 presents a hazard matrix for Buried Pipelines. The matrix was developed to help implement the process outlined in Section 2 (referred to herein as 'the process'). Expert judgement is used in all phases of the process. In the far-left column, the matrix lists hazards of concern. This column supports item 1 in the process. Each hazard is defined in Annex 4 with references from recognized authorities. The second column identifies the types and causes of ground deformation and other potential strains and forces imposed on buried pipelines.

The next five columns (columns three to seven) identify the types and likelihood of impacts the hazard may impose on a buried pipeline. Column eight identifies the likelihood of concurrent impacts on multiple pipelines. These columns support item 3 in the process.

The next three columns estimate the likelihood of water delivery, fire flow, quantity, or quality service disruptions (Davis, 2014) to one or more customers. These columns support item 4 in the process.

The X, XX, and XXX symbols in the matrix identify the likelihood of an impact and service disruption and are indicators of a probability qualification. This probability is contingent upon an actual hazard (e.g., given a hazard, one can identify its likelihood with respect to buried pipelines and service disruption).

The last column estimates the service disruption consequence to social and economic activities, given the hazard, using low (L), medium (M), and high (H) probability qualifications. This column supports item 4 in the process. The consequence increases with potential impacts to multiple pipelines. It is estimated using the likelihood of multiple pipes and greatest likelihood of service disruption (e.g., given a hazard, one can expect service disruption consequences).

Risk cannot be assessed directly from the hazard matrix. Risk is estimated from the probability of a hazard resulting in service disruption. In general, risk cannot be estimated using only the matrix, since the probability of a given hazard changes by location. However, if the relative probability of each hazard occurrence at a specific location can be identified using low (L), medium (M), or high (H), then the relative risks can be estimated by combining these qualifications with the consequence qualifications in the hazard matrix.

The matrix can help to identify the potential causes of pipeline damage and service disruption. It also helps to assess the potential consequences of pipeline and the water system damage as well as the disruption of the social and economic activities of water system customers. The information helps guide water system pipeline owners to identify, prioritize, and plan for the use of hazard-resilient pipelines.

To enhance the use of the process and the matrix, the HRPRP encourages future activities to include:

1. The development of maps covering the significant hazards, and
2. The evaluation of pipeline material and connection performance for the ground deformation and pipeline strain caused by hazards.

Hazard maps can identify the potential movement and strains that affect buried pipelines, and thus support item 2 in the process. System owners can use such maps to identify where hazard-resilient pipelines should be installed to improve system resilience against the hazards.

**Table 1. Hazard Matrix for Buried Pipelines.**

| Hazard | | Impact Likelihood | | | | | | Likelihood of Service Disruption To: | | | Service Disruption Consequence |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | On Pipeline Structure | | | | | | | Water Quality | | |
| | Ground deformation or *pipeline strains and forces* | Slip-out | Breakage /Collapse | Scratch/ Corrosion | Strength Reduction Heat/Chem., Fatigue/Creep | Uplift or Settlement | Concurrent on Multiple Pipelines | Water Delivery, Fire Flow, Quantity | (Water quality) Leaching | (Water quality) Odor, Taste, Chromaticity, Turbidity | |
| Earthquake | TGD (Shaking) | XX | XX | XX | XX | XX | XXX | XX | | XX | M-H |
| | PGD (Landslide, etc.) | XXX | XXX | XX | XX | XXX | XXX | XXX | | XX | H |
| | Fault | XXX | XXX | XX | XX | XXX | XX | XXX | | XX | H |
| | Liquefaction | XX | XX | XX | XX | XXX | XXX | XXX | | XX | H |
| Landslide | PGD | XXX | XXX | XX | | XXX | X | XXX | | | L-M |
| Erosion | PGD | XX | XX | XX | | X | X | XX | | | L-M |
| Subsidence | PGD | XX | XX | XX | | XXX | XX | XXX | | | M |
| Heavy rain | PGD (Landslide, etc.) | XXX | XXX | XX | | XXX | X | XXX | | | L-M |
| | Erosion | XX | XX | XX | | XX | X | XX | | | L-M |
| Hurricane | PGD (Landslide, etc.) | XXX | XXX | XX | | XXX | X | XXX | | | L-M |
| | Erosion | XX | XX | XX | | XX | X | XX | | | L-M |
| | *Strong wind (e.g., uprooting trees)* | X | X | | | | | X | | | L |
| Flooding | PGD (Erosion) | XX | XX | XX | | XX | XX | XX | | X | M |
| | *Impact force by water & driftage* | XX | XX | XX | | | XX | XX | | | M |
| Tsunami | PGD (Erosion) | XX | XX | XX | | X | XX | XX | | X | M |
| | *Impact force by water & driftage* | XX | XX | XX | | | XX | XX | | | M |
| Volcanic Activity | TGD (Shaking) | XX | XX | XX | XX | XX | XX | XX | | XX | M |
| | PGD (Landslide, heave, etc.) | XXX | XXX | XX | XX | XXX | XX | XXX | | XX | M-H |
| | *Thermal strain from heat* | | XX | | XX | | XX | XX | XX | | M |
| Sinkhole | PGD | XXX | XXX | X | | XXX | X | XXX | | | L-M |
| Expansive soil | PGD | XX | XX | X | | XX | XX | XX | | | M |
| Drought | PGD (Subsidence) | X | XX | | | XX | XX | XX | | | M |
| | PGD (Soil shrinkage) | X | XX | | | XX | XX | XX | | | M |
| Wildfire | *Thermal strain from heat* | | | | XX | | XX | XX | XX | XX | M |
| Temperature Change | *Thermal strain from heat* | | X | | | | XX | XX | | | M |
| (Includes freeze-thaw cycle and permafrost thaw) | *Thermal strain from cold* | | XX | | XX | | XX | XX | | | M |
| | PGD (Frost heave, Thaw subside) | X | XX | X | X | XX | XX | XX | | | M |
| | *Freeze bursting* | | XX | | | | XX | XX | | | M |
| Construction-Related | PGD | XX | XX | | | XXX | XX | XX | X | X | M |
| | Subsidence | XX | XX | | | XXX | XX | XX | X | X | M |

Hazard: Hazards which have a potential for significant impact to buried water pipelines, hazards are defined in Annex 4.
PGD: Permanent Ground Displacement
TGD: Transient Ground Displacement
XXX: Frequently happens, XX: Some times happens, X: Rarely happens
L; Low, M; Medium, H High

## 4. Conclusion and Proposal

### 4.1 Conclusion

Following two years of meetings, discussions, and special topic presentations from international experts, the HRPRP concludes that hazard-resilient pipelines can be used successfully to improve system resilience where hazards threaten the performance of buried pipelines. Consistent procedures should be implemented to identify the need for and implement the use of hazard-resilient pipelines. Additionally, further efforts should be focused on the (1) development of maps covering hazards where buried pipelines are installed, and (2) the evaluation of pipeline material and connection performance for ground deformation and strains caused by hazards.

Further, the HRPRP recommends the distribution of information for use by water agencies and industry professionals as described in the following subsection.

### 4.2 Proposal

A common feature among hazards is how they impose strains on buried pipelines through different mechanisms (e.g., thermal, ground displacement) that may lead to damage. Hazard-resilient pipelines are beneficial for coping with the strains imposed by a wide range of different events that may impact buried water pipelines located in any region.

When asked about the future of buried pipelines by the Japan Newspaper of Waterworks Industry, Professor Thomas D. O'Rourke, professor emeritus at Cornell University, stated "*One aspect is expansion of the application for earthquake-resistant pipelines. Japanese products, exemplified by the robustness of their joints, are not solely limited to their potential for protecting against the effects of earthquakes. As you know, in the U.S., earthquake damage concerns are greatest on the West Coast, and there is less risk in the Midwest and the East Coast regions where I reside. However, Japanese earthquake-resistant pipes, which can also demonstrate their resilience to other hazards like heavy rainfall, floods, and landslides, should be applied beyond just the West Coast and used to accommodate any type of ground movements that may occur. Another point is that recently, we have been conducting experiments related to pipeline rehabilitation incorporating hazard resilience, because we believe they are essential for prolonging the lifespan of the entire piping system.*" (Newspaper of Waterworks Industry, 2023)

The number of disasters continues to increase annually, many caused by climate change. The hazards causing these disasters can impact buried pipelines and disrupt water services. These hazards and their potential impacts on buried pipelines and the provision of water services have been compiled into a matrix shown in Figure 1. Hazard-resilient pipelines can be used to protect against the effects of multiple different hazards and preserve the distribution of water services. The following process is proposed to identify the need for and application of hazard-resilient pipeline systems.

1. Recognize the hazards of concern using the hazard matrix.
2. Identify the exposure of buried pipelines to the hazards of concern.
3. Understand the potential impacts of each hazard on buried pipelines.
4. Characterize the potential service disruptions to customers/users.
5. Select the pipelines critical to providing continuous services.
6. Plan, design, and construct using hazard-resilient pipelines*.

*Hazard-resilient pipelines, including their joints, valves, and fittings, can accommodate the effects of hazards and easily be repaired, such as hazard resilient ductile iron pipes.

## 5. References


Davis, C.A., 2014, "Water service categories, post-earthquake interaction, and restoration strategies," Earthquake Spectra, Vol. 30, No.4, pp.1487-1509.

Merriam Webster. 2023. "Resilience." https://www.merriam-webster.com/dictionary/resilience

Newspaper of Waterworks Industry, 2023, "Dialogue: Achievements and Significance Obtained through Collaboration among Japanese Academic Societies", No. 5627, June 15, 2023, in Japanese.

Wham, B. P. and C. A, Davis, 2019, "Buried Continuous and Hybrid-Segmented Pipes Subjected to Longitudinal Permanent Ground Deformation," ASCE, Journal of Pipeline Systems Engineering and Practice, Vol. 10, No. 4, DOI: 10.1061/(ASCE)PS.1949-1204.0000400. [ISSN 1949-1190].

**Annex 1**
**US-Japan Hazard Resilient Pipeline Research Panel (HRPRP)**
**Purpose and Overview**

Purpose: Improve the understanding of hazard impacts on water systems, including all types of buried water pipelines. Communicate pipeline resilience issues across international lines, document and study pipeline performances in disaster occurrences from a variety of pertinent natural hazards. Track emerging and altering natural hazards resulting from climate change and the effect of increased intensity and frequency which affect pipeline performances and lead to an increasing number of disasters.

Objectives: Provide information for use in the water sector to improve their systems through use of hazard resilient pipelines.

Charge: Advance the knowledge, understanding, and importance for using hazard resilient pipelines. The focus is primarily on water system pipelines.

Background: A wide range of natural hazards are known to have capability to affect the performance of water systems and specifically buried water pipelines. The performance of buried pipelines directly impacts the ability of water systems to provide services to customers following a hazard strike. Damaged pipelines result in loss of service provision. The greater and more extensive damages result in longer repair times and duration of service losses. The number of disasters is increasing on an annual basis. Climate change is also resulting in increased intensity and types of natural hazards impacting water infrastructure systems. Some examples include drought, wildfires, hurricanes, extreme freeze, extreme heat, thawing permafrost, and rapid onset and intense flooding along with their cascading effects. These are in addition to the hazards which historically were most understood to impact buried pipelines including earthquake, landslides, differential settlement, sinkholes, and land erosion; some of which are intensified by climate change impacts. The purpose of the HRPRP is to improve the understanding of the risks that hazards pose to buried water pipelines and how they relate to resilience and sustainability. To do this, the HRPRP needs to track the emergence and changing nature of hazards and communities which use buried pipelines. The changing nature of communities, their water systems and hazard intensities affect how buried pipelines may perform and how these impacts affect the way water systems can provide services to customers.

Research Panel Members: The HRPRP members will include a nearly equal number of people from the United States and Japan in the academic sector. Four or five people from each country are proposed as shown in Figure 1. The panel members are to have experience and understanding of buried pipelines and geotechnical engineering founded with an understanding geohazards. The HRPRP members from both countries will be organized by a single chairperson. Craig Davis will serve as the founding chairperson and Nagahisa Hirayama will serve as the founding co-chair.

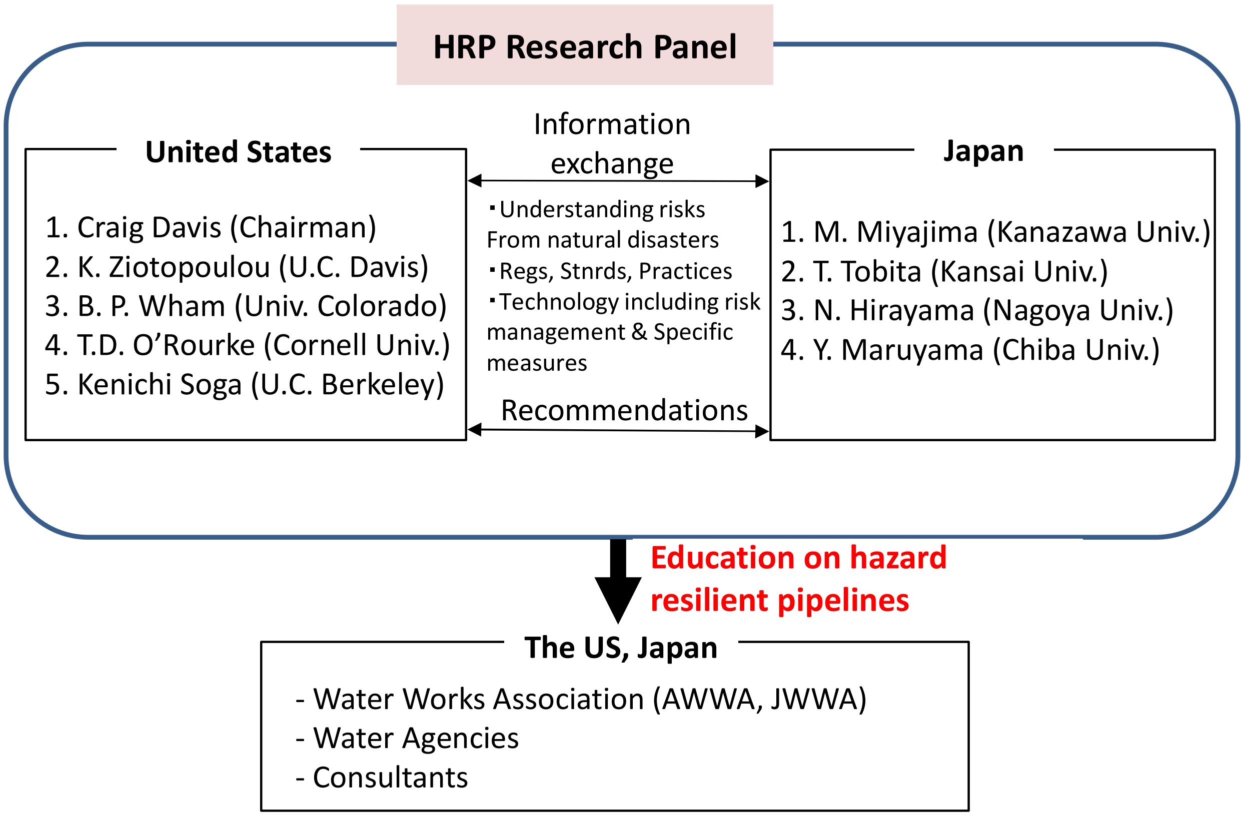


**Figure A1-1. The US-Japan Hazard Resilient Pipeline Research Panel.**

HRPRP Activities: The HRPRP will initially conduct meetings on-line approximately twice a year. The purpose of these meetings will be to exchange information on the performance of pipelines and recovery of water systems in disasters and other associated research results. The information will not be limited to individual research but also to reviewing the research of others related to the meeting topic. Keywords will be provided for each meeting. The information exchange will also include regulations, standards, practices related to buried pipeline resilient performance, and risk management. The activities could potentially lead to joint investigations and collaborative research, including experiments, to document buried pipeline performances in response to natural hazards and how these pipeline performances affected the delivery of water. Investigations and experiments are to be fact-based supported by evidence. Activities may also include follow-on international research to understand the observations.

The exchanges are intended to provide a common understanding of issues affecting the performance of buried pipelines in each country and potentially around the world. From the common understandings, recommendations can be made on specific measures on how to improve the resilient performance of buried pipelines and the systems they are used within relative their hazard exposure.

In relation to the HRPRP purpose, objectives, and charge, the activities will also include writing summary documents and public presentations to share and advance the knowledge about hazard resilient pipelines. Documents may include conference and journal papers, summary reports made available to the public and similar. Presentations are to be given to public forms and water agencies and may include workshops, conferences, webinars and individual presentations to selected organizations. Activities should also be oriented toward educating water-related organizations including the American Water Works Association, Japan Water Works Association, American Society of Civil Engineers, Japan Society of Civil Engineers, public and private water agencies, the Water Research Foundation, Japan Water Research Center, and consultants.

HRPRP Meetings: Meetings may be held on-line or in-person, with an attempt to have at least 1 in-person meeting per year. Meeting agendas will target aspects of the HRPRP purpose, objectives and charge. On-line meetings will be held in the evenings for the US (3 or 5pm Pacific) and mornings for Japan (8 or 9am Japan). Meeting durations may be 1.5 to 3 hours depending on the topics. Meetings will be held approximately every 6 months thereafter (targeting 2 meetings per year). The kick-off meeting was held remotely on November 23, 2021. The first technical meeting was held remotely on April 12, 2022. The second technical meeting was held in person at the University of California Berkeley on November 8, 2022. The third technical meeting was held remotely on April 25, 2023. The fourth and final meeting was held in person at Nagoya University on November 7, 2023.

HRPRP Member Compensation: Research members will be compensated for a limited time spent to prepare for and attend meetings. The compensation for meetings will be provided from a research fund managed by Nagoya University in Japan. Compensation for other activities will be determined on a case-by-case basis depending on resources available.

Definition: *a hazard resilient pipeline has an ability to recover from or adjust easily to the effects of hazards* (modified from Merriam-Webster). This definition must be taken in context of the pipelines intended purpose to convey water as a conduit within a larger system to provide services to meet societal needs. So, the time to recover is relative to the pipelines' purpose within a larger system and its importance to meeting the serviceability needs of the users.

**Annex 2**

**Presentations and Technical Papers**

**Annex 2 Table of Contents**

**Thomas D. O'Rourke, Presentation, Cornell University, Professor Emeritus**
**"Lifeline Earthquake Engineering: Legacy & Lessons Learned"**

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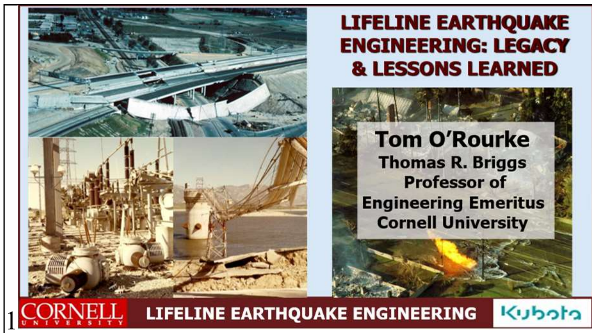


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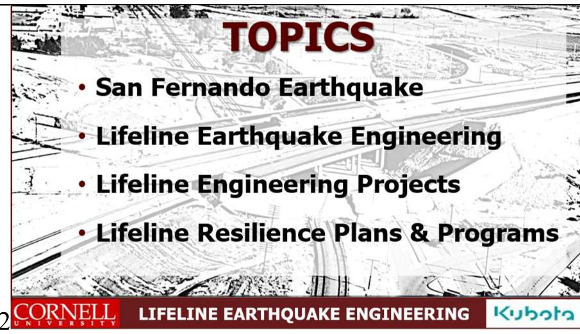


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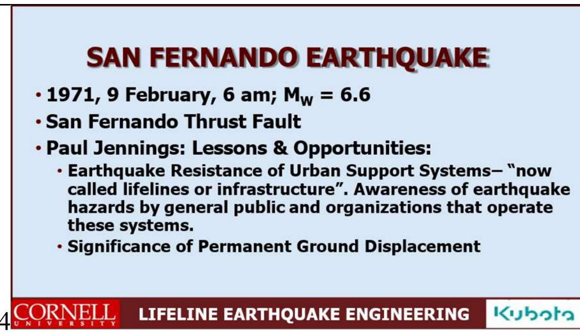


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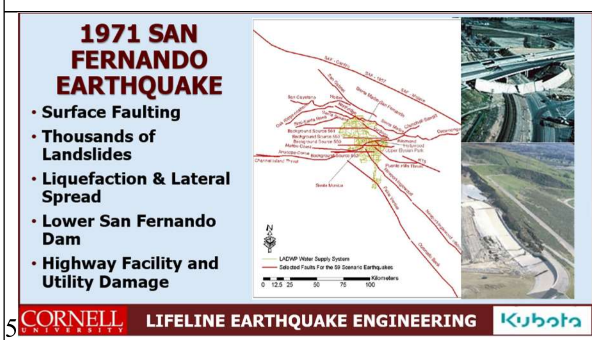


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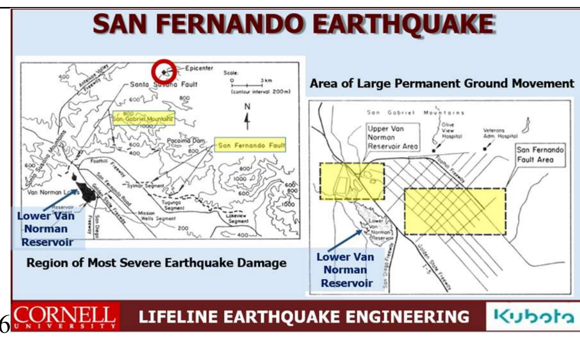


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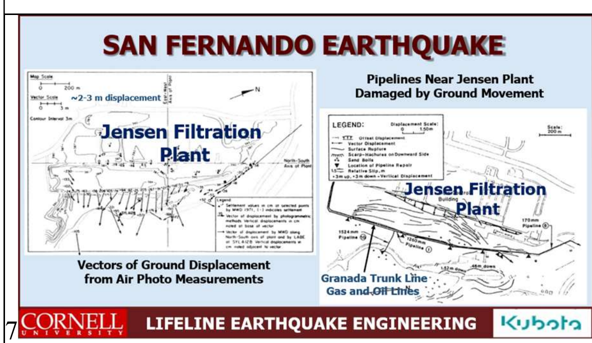


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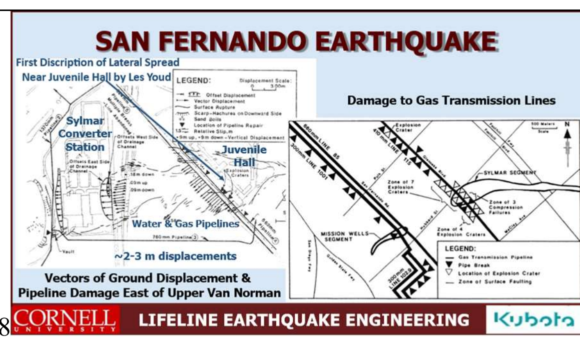

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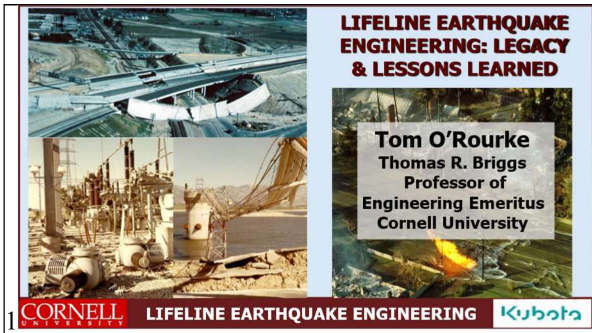
LIFELINE EARTHQUAKE ENGINEERING: LEGACY & LESSONS LEARNED
Tom O'Rourke
Thomas R. Briggs
Professor of
Engineering Emeritus
Cornell University
CORNELL UNIVERSITY
LIFELINE EARTHQUAKE ENGINEERING
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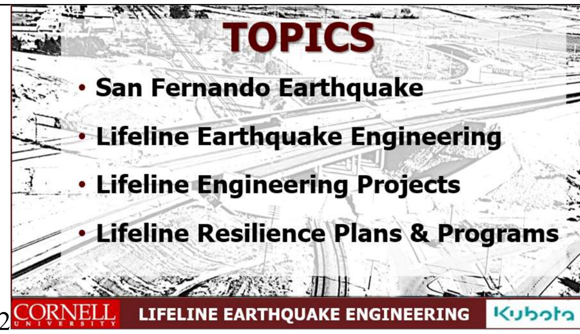
TOPICS
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• Lifeline Earthquake Engineering
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• Lifeline Resilience Plans & Programs
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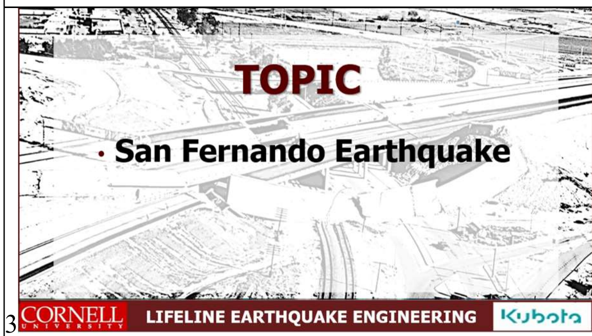
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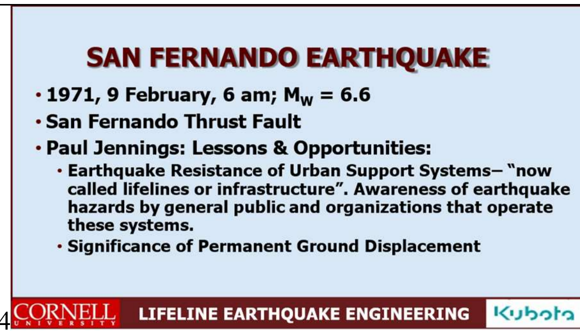
SAN FERNANDO EARTHQUAKE
• 1971, 9 February, 6 am; $M_W$ = 6.6
• San Fernando Thrust Fault
• Paul Jennings: Lessons & Opportunities:
• Earthquake Resistance of Urban Support Systems– "now called lifelines or infrastructure". Awareness of earthquake hazards by general public and organizations that operate these systems.
• Significance of Permanent Ground Displacement
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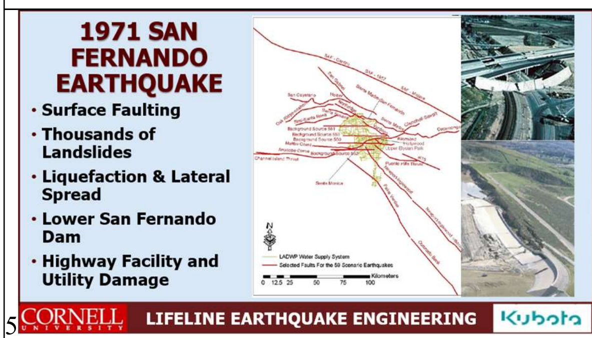
1971 SAN FERNANDO EARTHQUAKE
• Surface Faulting
• Thousands of Landslides
• Liquefaction & Lateral Spread
• Lower San Fernando Dam
• Highway Facility and Utility Damage
LADWP Water Supply System
Selected Faults For the 50 Scenario Earthquakes
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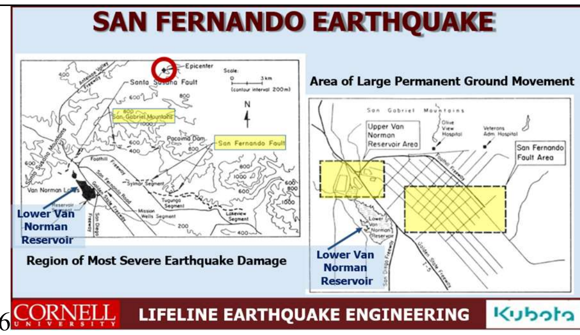
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Pacoima Dam
Lower Van Norman Reservoir
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Area of Large Permanent Ground Movement
San Gabriel Mountains
Upper Van Norman Reservoir Area
Olive View Hospital
Veterans Adm. Hospital
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Lower Van Norman Reservoir
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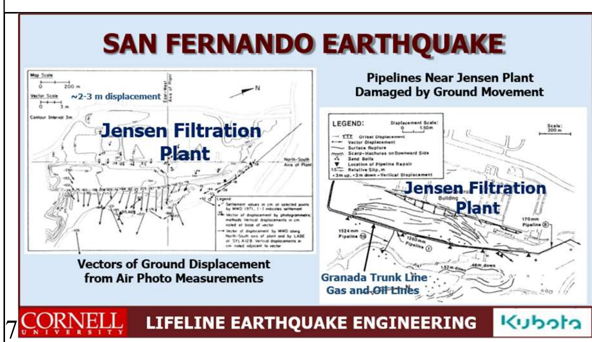
SAN FERNANDO EARTHQUAKE
~2-3 m displacement
Jensen Filtration Plant
Vectors of Ground Displacement from Air Photo Measurements
Pipelines Near Jensen Plant Damaged by Ground Movement
LEGEND:
Jensen Filtration Plant
Granada Trunk Line Gas and Oil Lines
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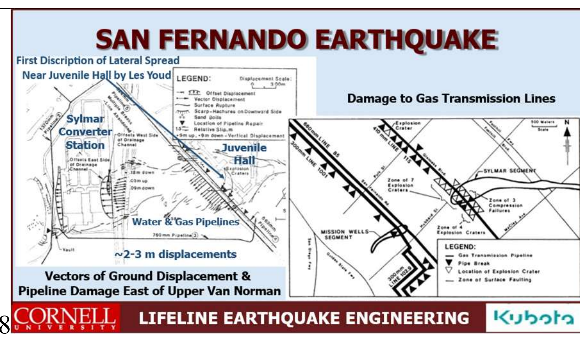
Kubota

8

SAN FERNANDO EARTHQUAKE
First Discription of Lateral Spread Near Juvenile Hall by Les Youd
LEGEND:
Sylmar Converter Station
Juvenile Hall
Water & Gas Pipelines
~2-3 m displacements
Vectors of Ground Displacement & Pipeline Damage East of Upper Van Norman
Damage to Gas Transmission Lines
SYLMAR SEGMENT
MISSION WELLS SEGMENT
LEGEND:
Gas Transmission Pipeline
Pipe Break
Location of Explosion Crater
Zone of Surface Faulting
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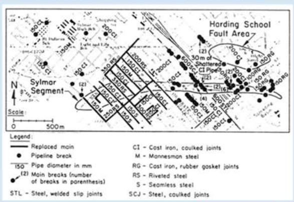
9

## SAN FERNANDO EARTHQUAKE


Damage to Gas Distribution Pipelines Near Sylmar Segment of San Fernando Fault

Damage to Water Distribution Pipelines Near Sylmar Segment of San Fernando Fault

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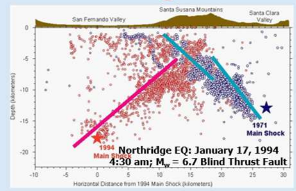
10

## 1994 NORTHRIDGE EARTHQUAKE

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11

## TOPIC

- Lifeline Earthquake Engineering

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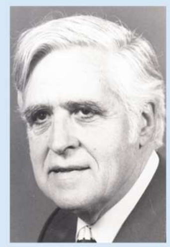
12

## C. MARTIN DUKE

- UCLA Professor 1947-1980
- President of Earthquake Engineering Research Institute (EERI) 1970 - 1973
- Led EERI Learning from Earthquakes for San Fernando Earthquake
- Originator of Lifeline Earthquake Engineering
- C. Martin Duke Lifeline Earthquake Engineering Award (since 1990)
- Le Val Lund Practice Award for Lifeline Risk Reduction (since 2014)



C. Martin Duke (1917 – 1988)
UCLA Professor 1947-1980

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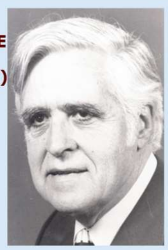
13

## ASCE TECHNICAL COUNCIL ON LIFELINE EARTHQUAKE ENGINEERING (TCLEE)

Founded 1975

Initial Committees:

- Seismic Criteria & Risk
- Gas & Liquid Fuels
- Transportation
- Water & Sewage
- Electrical Power & Communications



C. Martin Duke (1917 – 1988)
First Chair TCLEE (1974)

## LIFELINE EARTHQUAKE ENGINEERING

- Electric Power
- Gas & Liquid Fuels
- Telecommunications
- Transportation
- Water & Sewage
- (Flood Protection)

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14

## TECHNICAL COUNCIL ON LIFELINE EARTHQUAKE ENGINEERING (TCLEE)

- **Purpose: advance the state-of-the-art and practice of lifeline engineering for earthquakes, hurricanes and other extreme events**
- **Main goal: earthquakes, but increasingly multi-hazard**
- **Nine technical committees**
- **Monograph series, guidelines, and TCLEE reports**
- **As of 2014, 38 TCLEE Monograph Series reports**
- **Formally incorporated into ASCE Infrastructure Resilience Division (IRD) in 2014**

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15

## ASCE INFRASTRUCTURE RESILIENCE DIVISION

- **Formally instituted 2014**

### INFRASTRUCTURE RESILIENCE DIVISION

**Executive Committee**

- Civil Infrastructure & Lifeline Systems
- Disaster Response & Recovery
- Emerging Technolgies
- Risk & Resilience Measurements
- Social Science, Policy Economics, Education

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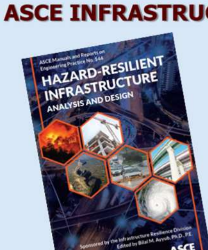
16

## ASCE INFRASTRUCTURE RESILIENCE DIVISION




Guidelines for Practice 2022

Lifeline Conference 2022

Blast Protection of Buildings 2021

Sustainable Infrastructure 2021

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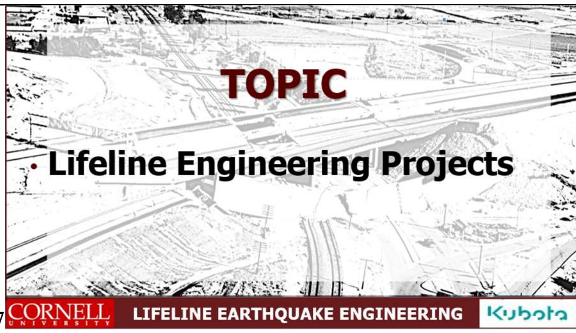
17
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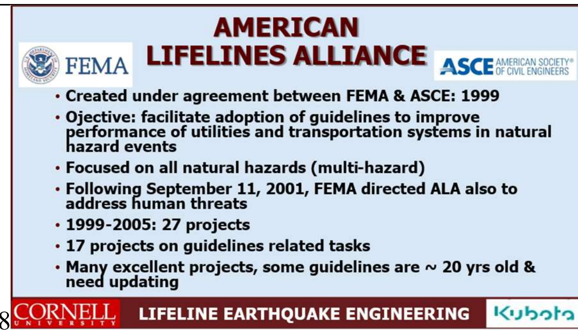


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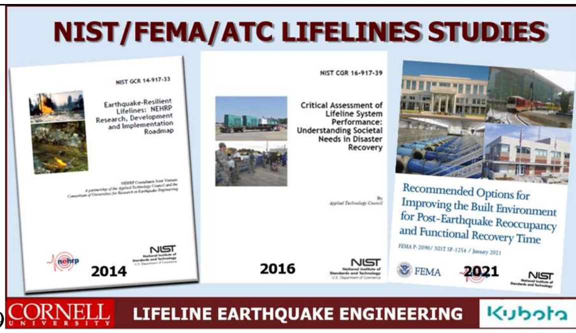


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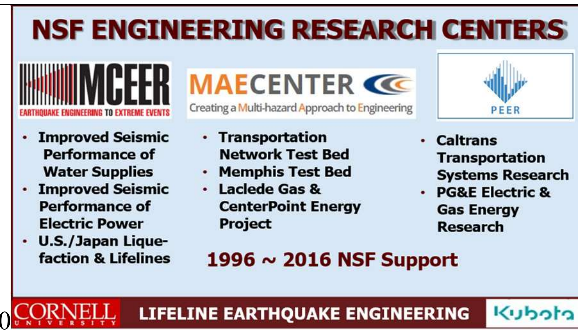


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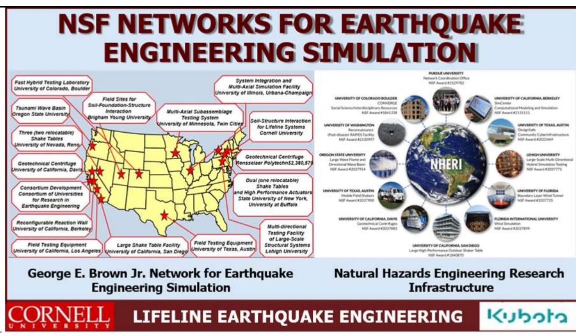


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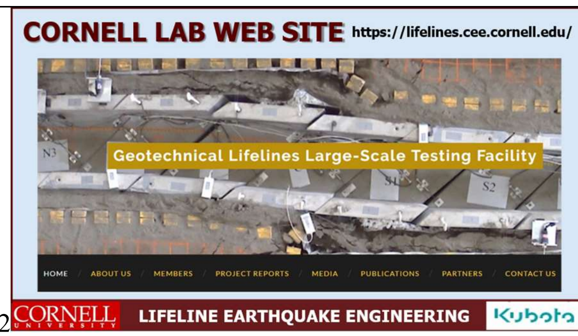


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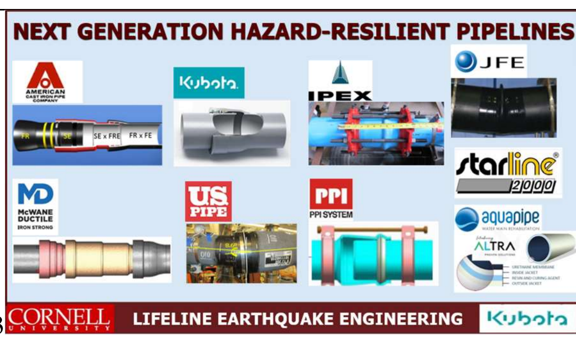


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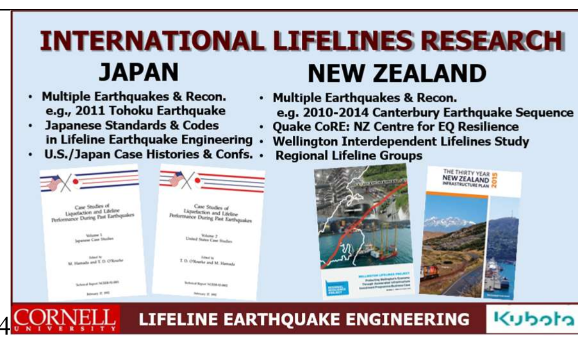

25

## TOPIC

- Lifeline Resilience Plans & Programs

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26

## LOS ANGELES RESILIENCE


- Strengthen Buildings
  - Soft story/non-ductile concrete
- Fortify Water System
  - Fire protection, resilient water pipelines
- Enhance Telecommunications

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27

## SOUTHERN CALIFORNIA WATER SUPPLY


70% Imported Water:

- California Aqueduct
- Los Angeles Aqueducts
- Colorado River Aqueduct

30% Ground Water

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28

## SEISMIC RESILIENT WATER SUPPLY TASK FORCE

- CA Aqueduct (CA DWR)
  - 49 billion $m^3$/yr
  - Faulting Rupture >25 places
- LA Aqueducts (LADWP)
  - 390 million $m^3$/yr
  - Elizabeth Tunnel
- Colorado River Aqueduct (MWD)
  - 900 million $m^3$/yr
  - Multiple fault ruptures & > 1 m uplift
  - San Gorgonio Pass

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29

## EARTHQUAKE SAFETY AND EMERGENCY RESPONSE BOND

2010 EARTHQUAKE SAFETY AND EMERGENCY RESPONSE BOND

| Projects and Programs | Cost (millions) |
|---|---|
| AWSS Core Facilities | $35.0 |
| Critical Firefighting Facilities and Infrastructure | 134.3 |
| Public Safety Building | 243.0 |
| Total | $412.3 |

| | |
|---|---|
| Neighborhood Fire Stations | $65.1 M |
| Firefighting Cisterns | $36.6 M |
| Firefighting Pipes and Tunnels | $32.6 M |
| Total CFFI | $134.3 M |

| ESER 2014 projects and programs | Budget (millions) |
|---|---|
| Neighborhood Firehouses | $85 |
| Emergency Firefighting Water System | $55 |
| District Police Stations and Infrastructure | $30 |
| Motorcycle Police and Crime Lab | $165 |
| Medical Examiner Facility | $65 |
| Total | $400 million |

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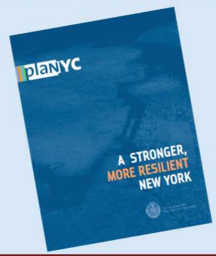
30

## NEW YORK CITY RESILIENCE PLAN




- Authorized by Mayor Bloomberg
- Hurricane Sandy Effects
- Science of Coastal Flooding
- Engineering Options
- Community Plan by Neighborhoods

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31

## WATER UTILITY COLABORATIONS

**Water System Seismic Studies**

- Los Angeles Dept. Water & Power
- East Bay Municipal Utility District
- San Fancisco Public Utilities
- San Diego County Water Authority
- Portland Water Bureau
- Seattle Public Utilities
- Greater Vancouver Metro Water District
- Willamette Water Supply Program

**Water Supply & Academic Partnerships**

- Los Angeles Depart. of Water & Power
- East Bay Municipal Utility District
- San Francisco Public Utilities

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32

## WILD FIRES

Camp Fire in Paradise, CA, 2018

Marshall Fire near Boulder, CO, 2021

PG&E Bankrupcy: $13.5 Billion Payout to Fire VictimTrust

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33

EVOLUTION OF POLICY
SEPTEMBER 11
• Protection of Critical Infrastructure
Hurricane Katrina
• Resilient Communities
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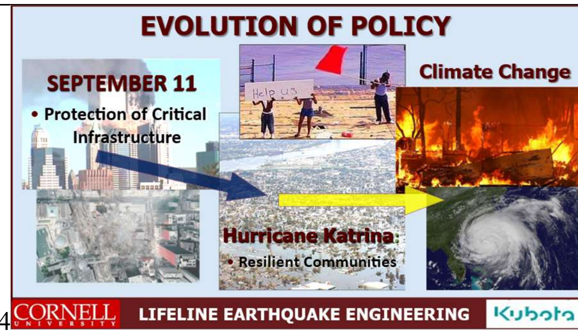
34

EVOLUTION OF POLICY
SEPTEMBER 11
• Protection of Critical Infrastructure
Climate Change
Hurricane Katrina
• Resilient Communities
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Kubota

**Masakatsu Miyajima, Presentation, Kanazawa University, Professor Emeritus**
**"Resilience of Water Pipelines and Facilities Against Natural Hazards such as Earthquakes and Heavy Rains"**

Resilience of water pipelines and facilities against natural hazards such as earthquakes and heavy rains

Kanazawa University
Masakatsu Miyajima

1

Contents

- Natural Hazards in Japan
- Damage to Water Supply Utilities due to Natural Hazards in Japan
  - ✓ Heavy Rain in July 2018
  - ✓ The 2018 Hokkaido Iburi-Tobu Earthquake
- Lessons Learned from Hazard Cases for Resilience

2

Contents

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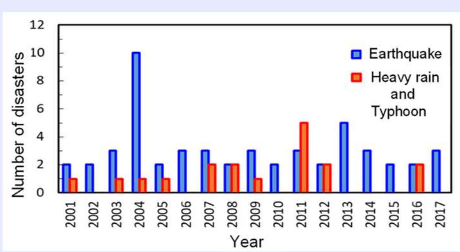
3

Natural hazards in Japan

- The Japanese archipelago is formed by four plates, and seismic activity and volcanic activity are active.
- There are many steep terrains, and the river flow is short and rapid.
- Located in the Asian monsoon region, torrential rains often occur during the rainy season and typhoons.
- Land use is dense, with cities and agricultural lands adjacent to rivers, coasts and volcanoes.

4

Natural hazards in Japan




Number of disasters
that water outage was occurred at more than 10,000 households.
(FY2001- 2017)

5

Natural hazards in Japan (2003-)

| Date | Type | hazard Name |
|---|---|---|
| 2022.3 | Earthquake | 2022 Fukushima earthquake |
| 2021.7 | Heavy rain/ Landslide | Atami landslide |
| 2021.2 | Earthquake | 2021 Fukushima earthquake |
| 2020.7 | Heavy rain | 2020 Kyushu floods |
| 2019.9 | Typhoon/ Wind disasters | Typhoon Faxai (2019), Typhoon Hagibis (2019) |
| 2019.8 | Heavy rain | 2019 Kyushu floods |
| 2018.9 | Earthquake | 2018 Hokkaido Iburi-Tobu earthquake |
| 2018 | Extreme heat | 2018 Extreme heat |
| 2018.7 | Heavy rain | 2018 July heavy rain |
| 2018.6 | Earthquake | 2018 Osaka earthquake |
| 2017.7 | Heavy rain | 2017 Northern Kyushu floods |
| 2016.4 | Earthquake | 2016 Kumamoto earthquakes |
| 2015.9 | Heavy rain/Levee failure | 2015 Kanto-Tohoku flood |
| 2014.9 | Volcanic eruption | 2014 Mount Ontake eruption |
| 2014.8 | Heavy rain/ Landslide | 2014 Hiroshima landslides |
| 2013.10 | Typhoon/ Landslide | Typhoon Wipha (2013) |
| 2011.9 | Typhoon/ Landslide | Typhoon Talas (2011) |
| 2011.3 | Earthquake/Tsunami | 2011 Tōhoku earthquake and tsunami |
| 2005.3 | Earthquake | 2005 Fukuoka earthquake |
| 2004.10 | Earthquake | 2004 Chūetsu earthquake |
| 2003.9 | Earthquake/Tsunami | 2003 Tokachi-oki earthquake |

6

7

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- Natural Hazards in Japan
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8

## Heavy Rain Disaster in July 2018

Number of casualties : 221
Number of serious injuries : 68
Number of minor injuries : 319

Totally collapsed houses : 6,296
Partially collapsed houses : 14,829

Inundation above floor level: 8,937
Inundation under floor level: 20,507

Special warning (Heavy rain) was issued in 11 prefectures

(Source: Fire and Disaster Management Agency Disaster Report)

8

9

## Damage to Water Supply facility

- Number of affected prefectures: 18
- Number of affected municipalities: 75
- Total number of water outage: 263,381 households
- 8,074 households have not been restored

as of 13:00 in 2 nd of August, 2018

9

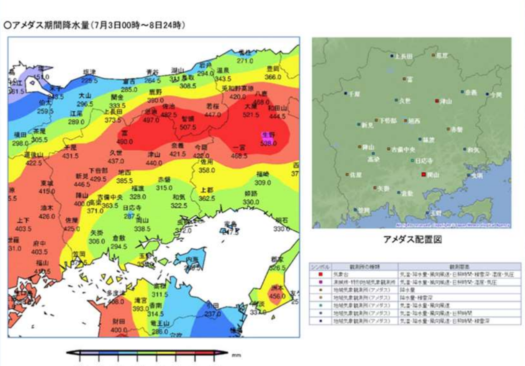
10

## Situation in Mabi-cho, Kurashiki-City, Okayama Prefecture

10

11

## Amount of precipitation of 5 days in the area of struck

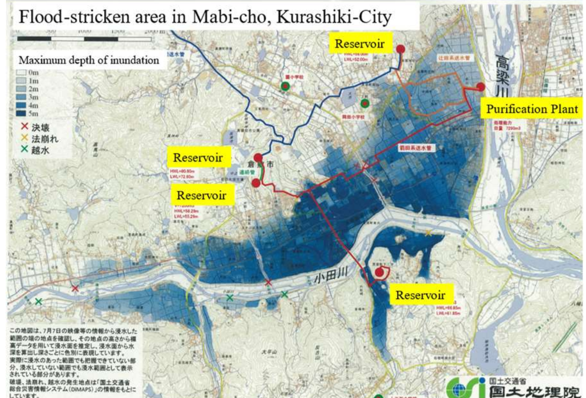



11

(Source: Quick Weather Report for Okayama Prefecture: Okayama Local Meteorological Observatory, 2018.7.10)

12

## Flood-stricken area in Mabi-cho, Kurashiki-City

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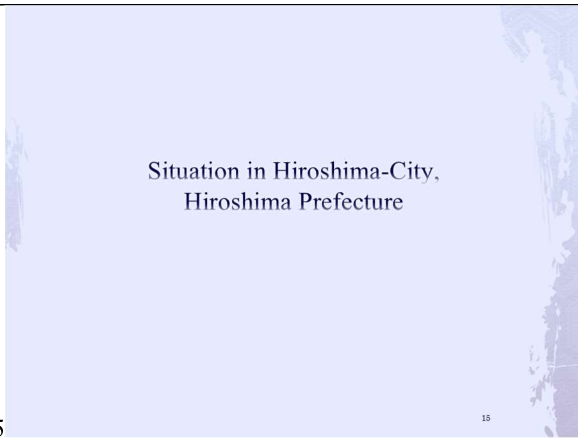
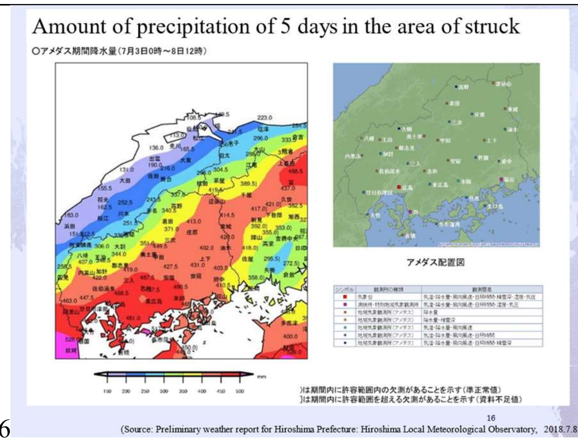
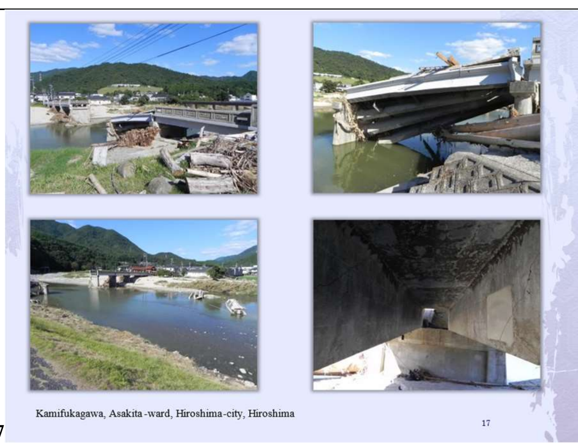
(provided by Kurashiki City Waterworks Bureau)

13 


14 


15 


16 


17 


18 

19


Yano, Aki-ward, Hiroshima-city

19

20


Yasuura Town, Kure-city

20

21

## Contents

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22

## Overview of Earthquake

Date : 2018.9.6 3:07AM(Local Time)
Epicenter : Hokkaido Iburi-Tobu Region
(N42.7° , E142.0° )
Depth of Focus : 37km
Magnitude : $M_{JMA}$ : 6.7, $M_W$ : 6.6


Maximum PGA : 1,796cm/s/s (K -Net Oiwake)
Maximum JMA SI : 7
(AtsumaTown, KiK-net Oiwake)

23

## Summary of Damage

Number of casualties : 41
Number of serious injuries : 18
Number of minor injuries : 731

Totally collapsed houses : 409
Partially collapsed houses : 1,262

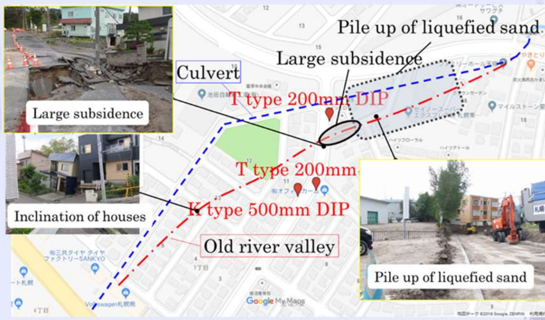
24

## Outline of Damage to Lifelines

- Blackout : 2.95 million households (All of Hokkaido)
  Maximum length: about one month
- Water service disruption: 68,000 households
  Maximum length: 34 days

| | Number of water suspension (Household) | Duration of water suspension(day) |
|---|---|---|
| Sapporo city | 15,991 | 7 |
| Abira town | 3,593 | 24 |
| Atsuma town | 1,944 | 34 |
| Hidaka town | 1,530 | 11 |
| Mukawa town | 1,031 | 7 |

## Liquefied Ground Displacement




25

## Liquefied Ground Displacement

26

## Liquefied Ground Displacement


27

## Damage of Sapporo City Waterworks Bureau

- Damage to facility : None
- Damage to pipelines : 32 (As of 9.12, provisional)

| | | |
|---|---|---|
| Pipes | | : 13 |
| | Φ 75 | : 1 (water supply pipe) |
| | Φ 100 | : 7 |
| | Φ 200 | : 4 |
| | Φ 500 | : 1 (Inlet Pipe) |
| Air valves | | : 18 |
| Fire hydrant | | : 1 |

28

## Slope failure in Atsuma

29

## Tomisato Purification Plant (Atsuma)

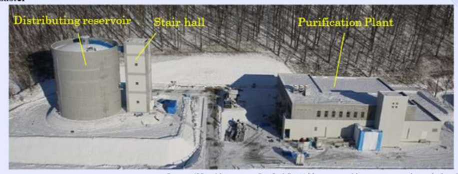
30

## Damage to purification plant by landslide


31

## Damage to purification plant by landslide

Pre-disaster



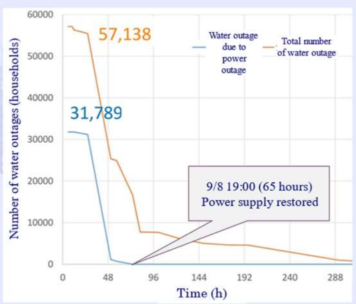

Source：Maruhironozawa Co., Ltd (http://www.maruhiro-nozawagumi.com/sekou.html)

Post-disaster

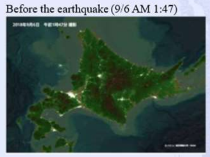

Source:Geospatial Information Authority ofJapan (https://saigai.gsi.go.jp/1/H30_09quake/0906atsumagawa/photo/qv/0072.jpg)

32

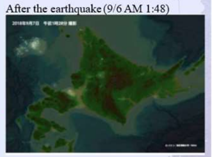
## Water outage due to widespread blackout




Before the earthquake (9/6 AM 1:47)



After the earthquake (9/6 AM 1:48)



PASCO CORPORATION, Tokyo University of Information Sciences, NASA

33

## Characteristics of the Hokkaido Iburi-Tobu Earthquake

- The damage to buildings was minor compared with other earthquakes with a seismic intensity of 7.
- Geotechnical disasters (Flow of liquefied ground and slope failure) caused by volcanic ash soil were remarkable.
- The blackout had a significant impact on social activities.
- Damage to water purification plants (Atsuma, Abira) caused prolonged water outage.

34

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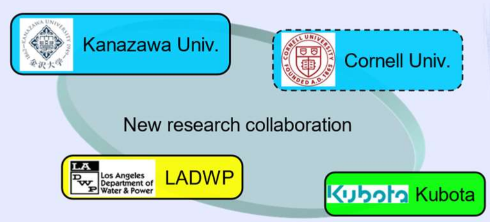
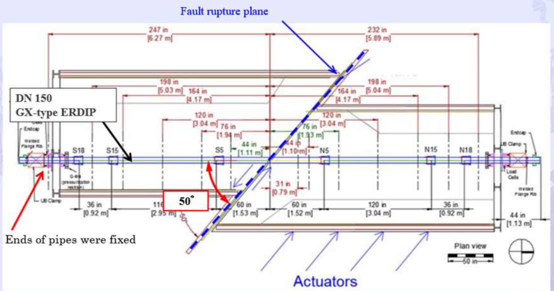
35

## Joint research on design method of pipeline crossing fault with HRDIP




36

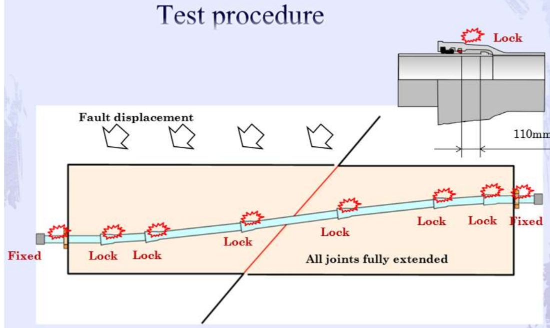
## Large scale split-box test set-up




① Pressurized with water to approximately 550 kPa (80 psi)
② Moved one of the two boxes using the actuators

37

## Test procedure




Testing under the extreme conditions.

38

## Test box after the test

39

## Specimens after the test

- No leakage immediately occurred even though the fault displacement exceeded 1.1m.
- When the fault displacement was 1.13m, the end of the spigot of joint S5 passed the rubber gasket and leakage occurred.


Each joints are deflected and HRDIP pipeline absorb the fault displacement.

40

## Joint deflection tests of DN2600mm (104”) HRDIP for pipeline design crossing fault

Before the test

After the test ( **4.93°** )

41

## Joint deflection tests of DN2600mm (104”) HRDIP for pipeline design crossing fault

42

43

## Lessons for resilience

- We must consider not only the strengthening of individual pipelines and facilities, but also the strengthening of the system.
- Toughening of the pipeline does not contribute to the strengthening of the system unless the strengthening of the water purification plant is assumed.
- The connection with other lifelines (especially electricity) is also important for strengthening the system.
- It was verified that the earthquake-resistant ductile iron pipe demonstrated the performance even in heavy rain sediment hazard, and that it is a hazard resistant pipe (HRDIP).

44

# Resilience of Water Pipeline and Facilities against Natural Hazards such as Earthquakes and Heavy Rains

**Masakatsu Miyajima**[1]

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## ABSTRACT

This report focuses on the resilience of water pipelines and facilities against geo-hazards induced by earthquakes and heavy rains. First, I introduce a situation of natural hazards in Japan in recent years. Next, the damage is explained to water supply facilities and pipelines induced by geo-hazards in Japan in recent years, such as the heavy rain disaster in July 2018 and the 2018 Hokkaido Iburi-tobu Earthquake. Finally, the joint research project on the design method of pipeline crossing fault between US and Japan is introduced.

## INTRODUCTION

Japan is one of the world's most prone country to natural disasters due to the following conditions. The Japanese archipelago is formed by four plates, such that there is a lot of seismic and volcanic activity. There are many steep terrains, and the river flows are short and rapid. Located in the Asian monsoon region, torrential rains often occur during the rainy season and typhoons. Land use is dense, with cities and agricultural lands adjacent to rivers, coasts, and volcanoes. Therefore, it suffers natural disasters almost every year.

First, I introduce a situation of natural hazards in Japan in recent years. Table 1 lists natural hazards occurred in Japan from 2003 to 2022. Japan is affected almost every year not only by earthquakes and tsunamis but also by typhoon- or heavy rain-induced landslides. Figure 1 shows the number of natural disasters when water outage occurred at more than 10,000 households in Japan from FY2001 to FY2017. According to this figure, large scale water outage occurred in the case of not only the earthquakes but also heavy rains and typhoons.

This report presents and explains the damages to water supply facilities and pipelines induced by geo-hazards in Japan in recent years, such as the heavy rain disaster in July 2018 and the 2018 Hokkaido Iburi-tobu Earthquake.

**Table 1. Natural hazards in Japan between 2003 and 2022.**

| Date | Type | hazard Name |
|---|---|---|
| 2022.3 | Earthquake | 2022 Fukushima earthquake |
| 2021.7 | Heavy rain/ Landslide | Atami landslide |
| 2021.2 | Earthquake | 2021 Fukushima earthquake |
| 2020.7 | Heavy rain | 2020 Kyushu floods |
| 2019.9 | Typhoon/ Wind disasters | Typhoon Faxai (2019), Typhoon Hagibis (2019) |
| 2019.8 | Heavy rain | 2019 Kyushu floods |
| 2018.9 | Earthquake | 2018 Hokkaido Iburi-Tobu earthquake |
| 2018 | Extreme heat | 2018 Extreme heat |
| 2018.7 | Heavy rain | 2018 July heavy rain |
| 2018.6 | Earthquake | 2018 Osaka earthquake |
| 2017.7 | Heavy rain | 2017 Northern Kyushu floods |
| 2016.4 | Earthquake | 2016 Kumamoto earthquakes |
| 2015.9 | Heavy rain/Levee failure | 2015 Kanto-Tohoku flood |
| 2014.9 | Volcanic eruption | 2014 Mount Ontake eruption |
| 2014.8 | Heavy rain/ Landslide | 2014 Hiroshima landslides |
| 2013.10 | Typhoon/ Landslide | Typhoon Wipha (2013) |
| 2011.9 | Typhoon/ Landslide | Typhoon Talas (2011) |
| 2011.3 | Earthquake/Tsunami | 2011 Tōhoku earthquake and tsunami |
| 2005.3 | Earthquake | 2005 Fukuoka earthquake |
| 2004.10 | Earthquake | 2004 Chūetsu earthquake |
| 2003.9 | Earthquake/Tsunami | 2003 Tokachi-oki earthquake |

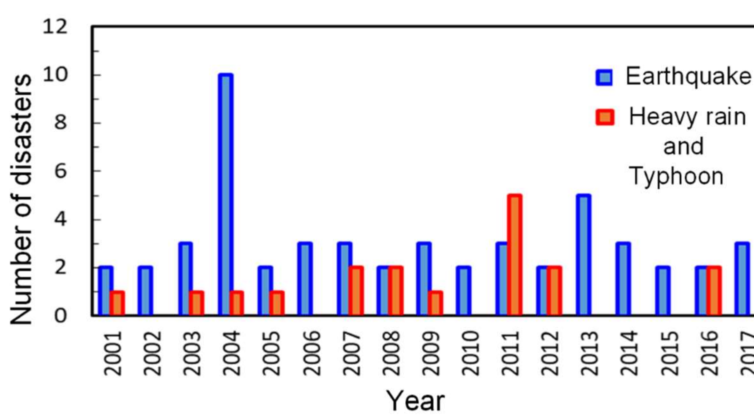



**Figure 1. Number of disasters when water outage occurred at more than 10,000 households. (FY2001- 2017)**

# DAMAGE TO WATER SUPPLY UTILITIES DUE TO HEAVY RAIN IN JULY 2018

The heavy rain disaster in July 2018 caused 221 casualties and 68 serious injuries. During this disaster, a total 6,296 houses collapsed fully and 14,829 houses partially collapsed. The water supply facilities and pipelines were also affected in 18 prefectural governments and 75 municipalities. The damage to water supply facilities and pipelines is discussed in what follows.

The situation in Mabi-cho, Kurashiki city, Okayama prefecture is as follows. Photo 1 shows the Maki water purification plant facility. The power was cut off at the time of flooding, so although most of the equipment was submerged in water, there was no fatal damage such as short circuits due to electrical leakage. Most of the electronic equipment was restored by washing with water or cleaning solution, and pumps, etc. were also washed with water, and coil parts were restored by the overhaul inspection.

Next, the situation in Aki word, Hiroshima city, Hiroshima prefecture is explained. Photo 2 shows the Kobo bridge in Aki wardy.  On the right bank side of the bridge is the Hatagakita No. 1 pump station of the Hiroshima city waterworks bureau, and a pressure feed pipe from the station was attached to the bridge. Although the bridge had fallen, the water were still functioning without leaks, and the water was still running at that time. The pipe had earthquake-resistant pipe fittings.

Photos 3 and 4 illustrate a mudslide site in Yano, Aki Ward. The riverbank at the water's edge was gouged out and caved in and buried pipes were exposed. Sling belts and single pipes are used to support hanging pipes for gas pipes and sewage pipes, but nothing is done  for water pipes, so the effectiveness of earthquake-resistant pipe fittings was clearly shown.

**Photo 1.  Maki purification plant**

**Photo 2. Kobo bridge**

**Photo 3. Mudslide site in Yano**

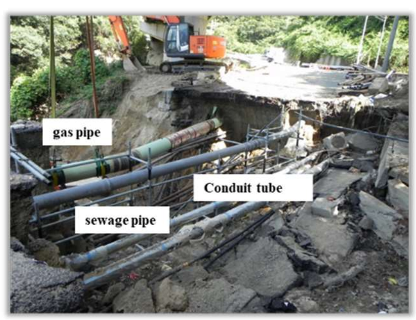



**Photo 4.  Gas, sewage, and water pipelines**

## DAMAGE TO WATER SUPPLY UTILITIES DUE TO THE 2018 HOKKAIDO IBURI-TOBU EARTHQUAKE

The 2018 Hokkaido Iburi-tobu Earthquake caused 41 casualties and 18 serious injuries. In this disaster, 409 houses totally collapsed were and partially collapse houses were 1,262. Blackout happened at 2.95 million households, that is, all of Hokkaido. Water outage occurred at 68,000 households just after the earthquake. Many slope failures occurred at the mountain area around the epicenter and liquefied ground flow happened at Sapporo city. The damage to water supply utilities induced by these geo-hazards is introduced. Table 2 lists the maximum number of households that experienced water service disruption and the duration of this disruption. The recovery of water service required 34 days for the town of Atsuma and 24 days for the town of Abira. Water service was restored to some towns near the epicenter within a week.

**Table 2. Water Service Disruption Duration.**

| | Number of water suspension (Household) | Duration of water suspension(day) |
|---|---|---|
| Sapporo city | 15,991 | 7 |
| Abira town | 3,593 | 24 |
| Atsuma town | 1,944 | 34 |
| Hidaka town | 1,530 | 11 |
| Mukawa town | 1,031 | 7 |

Table 3 lists information on pipe length, number of damage locations, and damage rate in the waterworks bureaus near the affected area during this earthquake. The drinking water supply pipe length for Sapporo city is 6,049.7km. Twelve pipe damage locations occurred along this pipe length, therefore,the damage rate was 0.002 cases/km. The damage rate of Kumamoto city in the 2016 Kumamoto Earthquake was 0.08 cases/km and 0.07cases/km for Sendai city in the 2011 Tohoku Earthquake. Therefore, the damage rate in Sapporo city was very small in comparison to the cities of Kumamoto and Sendai.

Extensive liquefied ground flow occurred in locations in the town of Satozuka, Kiyota ward, and Sapporo city. Figure 2 shows locations of pipe damage and ground deformation on a map of the town of Satozuka. Two water leaks happened in T-type ductile iron pipe with 200mm diameter and one water leak occurred in K type ductile iron pipe with 500mm diameter. Photos 5 and 6 show damage to 500 mm- and 200 mm- pipes, respectively. The 500 mm-diameter pipe is buried between the Hiraoka pumping station and the Satozuka service reservoir. The pump stopped when the earthquake happened because the water volume at the Satozuka service reservoir was adequate, thus it was observed that large water leak may not have occurred immediately after the earthquake. Since the water level of the service reservoir decreased after the earthquake, the pump was started, pumping water to the service reservoir. It is from this reservoir where the large water leak occurred.

**Table 3. Damage rates in Sapporo City and additional towns in the stricken area.**

| | Number of damage (cases) | Piping length (km) | Damage rate (cases/km) |
|---|---|---|---|
| Sapporo city | 12 | 6049.724 | 0.002 |
| Abira town | 29 | 211.412 | 0.137 |
| Atsuma town | 141 | 179.124 | 0.787 |
| Mukawa town | 20 | 177.689 | 0.113 |
| Hidaka town | 15 | 308.706 | 0.049 |

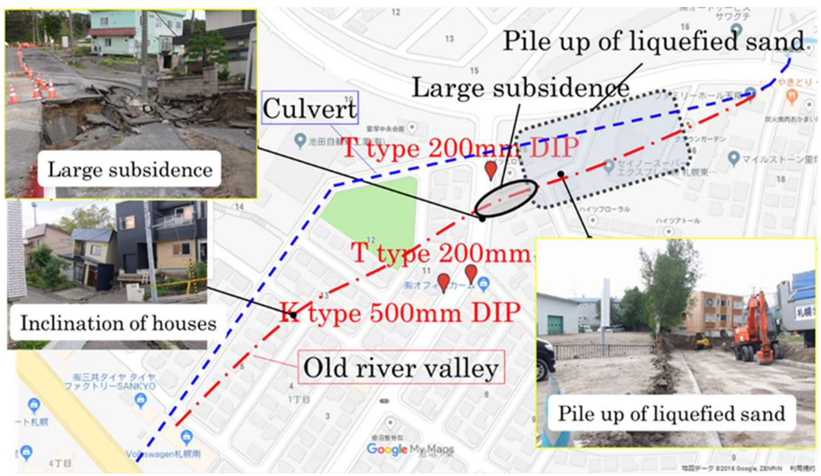



**Figure 2. Locations of pipe damage locations and ground deformation on a map of Satozuka Town.**


**Photo 5. Damage to 500 mm-diameter pipe.**


**Photo 6. Damage to 200 mm-diameter pipe.**

The Tomisato water purification plant and service reservoir were built at an upper stream of the Atsuma river in 2018. Water supply began one month before the earthquake. Severe damage was caused by an extensive landslide that occurred in slopes behind the plant, stopping service. Photo 7 shows the Tomisato water purification plant and service reservoir before the earthquake (Maruhironozawa Co., Ltd., 2018). The Tomisato water purification plant consists of an aplite level two and three-story building. The service reservoir has four levels. The first level is located underground, the second level is raw water reservoir, the third level is a machine room, and the fourth level is the service reservoir. Photo 8 shows the Tomisato water purification plant and service reservoir after the earthquake (Geographical Survey Institute, 2018). Landslide debris reached the roof of the purification plant but damage was limited to a failure of the outer wall and a deposition of soils. However, a stairway for the service reservoir was overturned and displaced by the landslide. The pipelines between the purification plant and service reservoir were also displaced, causing the purification plant and service reservoir to lose function completely. The Shinmachi water purification plant that was used before start of the Tomisato purification plant restarted after the earthquake to provide water.


**Photo 7. Tomisato purification plant and service reservoir before the earthquake. (Maruhironozawa Co., Ltd., 2018)**

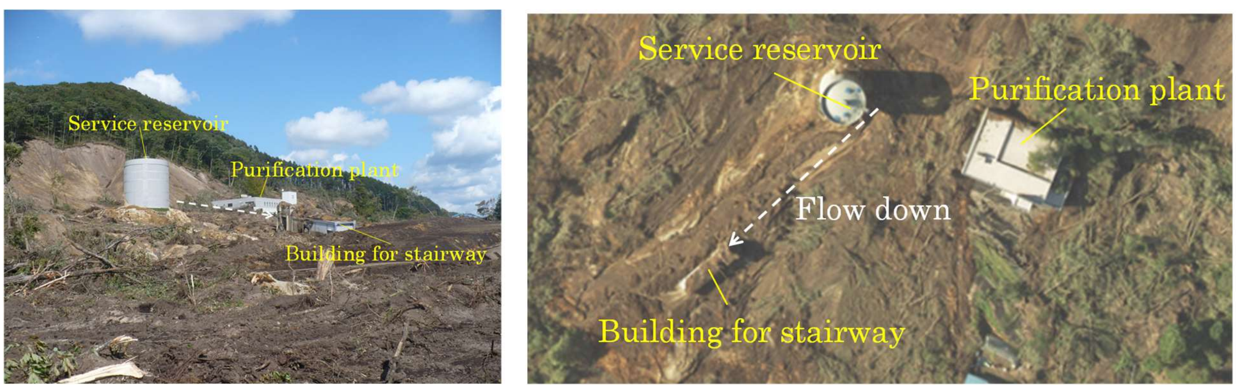



**Photo 8. Tomisato purification plant and service reservoir after the earthquake. (Geographical Survey Institute, 2018)**

## JOINT RESEARCH ON DESIGN METHOD OF PIPELINE CROSSING FAULT WITH HRDIP

The joint research project on design method of pipeline crossing fault between US and Japan is introduced at last. The US side is Cornell University and LADWP (Los Angeles Department of Water and Power) and the Japan side is Kanazawa University and Kubota Co. Ltd.

Figure 3 shows the plan view of a large-scale split-box. The pipes are 150 mm GX-type ERDIP, pressurized with water to about 550 kPa (80 psi), and then move the movable side box with actuators. The number of joint is 6 and the joints were assembled with compressed state. Design performance limit of joint extension is 110 mm. Fault crossing angle is 50 degrees. For example, when fault displacement is 1 m, the axial extension is 640 mm. We conducted under the severe condition as fault displacement exceeds the sum of joint extension of 660 mm and the ends of pipes were fixed to the split-box in order to pull the pipeline with all joint fully extended.

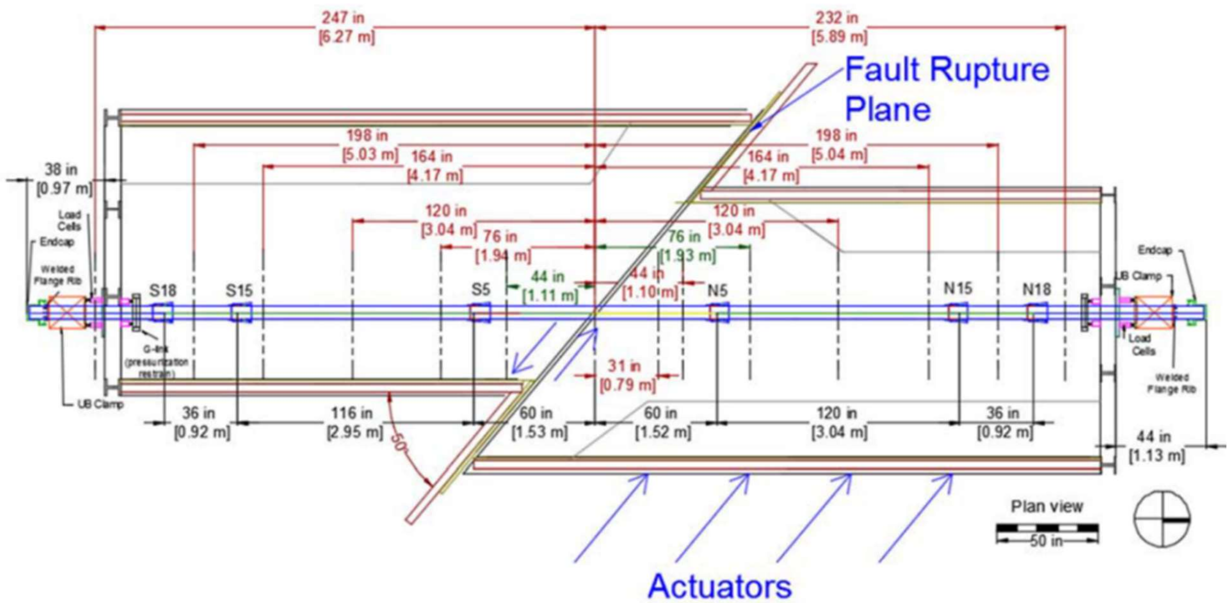



**Figure 3. Large scale split-box and test set up**

Figure 4 shows an outline of a test procedure. First, one of the two boxes was moved by 1.0 m using an actuator to simulate a fault displacement. At this time, all the joints in the boxes were fully extended. Second, one of the two boxes was moved and we observed the pipeline behavior. Actually, the chain structure pipeline can absorb larger displacement because of pulling next joint, but we fixed the ends of pipes to the split-box in order to pull the pipeline with all joint fully extended.

Photo 9 is the test specimen after the test. The behavior of the chain structure pipeline was observed such that the joints were extended and deflected following the fault displacement. No leakage immediately occurred even though the fault displacement exceeded 1.1m. When the fault displacement was 1.13m, the end of the spigot of joint S5 passed the rubber gasket and leakage occurred.

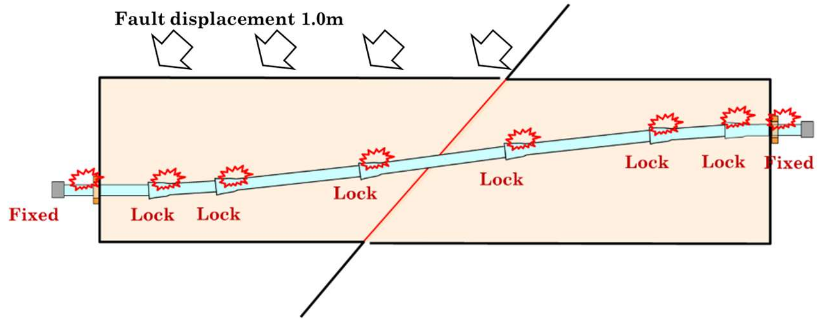



**Figure 4. Outline of the test procedure**


**Photo 9. Test specimen after the test**

## CONCLUSIONS

This report provides a summary of the resilience of water pipeline and facilities against natural hazards such as earthquakes and heavy rains. The summarized findings are:

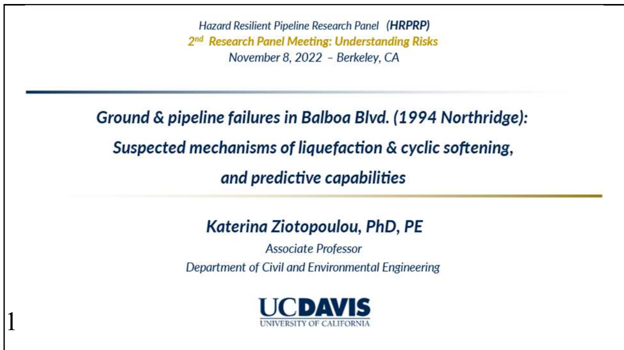
1) Large scale water outage recently occurred in case of not only the earthquakes but also heavy rains and typhoons in Japan.
2) The use of earthquake-resistant pipe fittings in a potentially landslide-prone area in Hiroshima Prefecture allowed the water pipes to withstand significant ground movement.
3) It was verified that the earthquake-resistant ductile iron pipe demonstrated the performance even in heavy rain sediment hazard, and that it is a hazard resistant pipe.
4) The Tomisato water purification plant suffered severe damage due to an extensive landslide that occurred uphill of the plant during the 2018 Hokkaido Iburi-tobu Earthquake. Strengthening of the pipeline does not contribute to the strengthening of the system unless the strengthening of the water purification plant is also assumed.
5) Joint Japan-US research has shown that the earthquake-resistant ductile iron pipes perform well in fault-crossing pipelines.

## REFERENCES

Geographical Survey Institute (2018), https://saigai.gsi.go.jp/1/H30_09quake/0906atsumagawa/photo/qv/0072.jpg (last visit: 30 July 2019)

Maruhironozawa Co., Ltd. (2018), http://www.maruhiro-nozawagumi.com/sekou.html (last visit: 30 Dec. 2018)

**Katerina Ziotopoulou, Presentation, University of California, Davis, Associate Professor Ground & Pipeline Failures in Balboa Blvd. (1994 Northridge): Suspected Mechanisms of Liquefaction & Cyclic Softening, and Predictive Ccapabilities**

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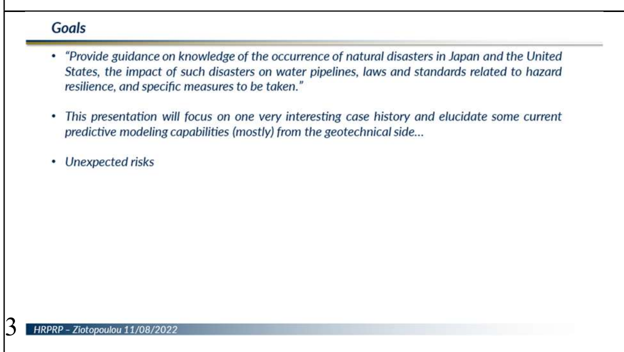


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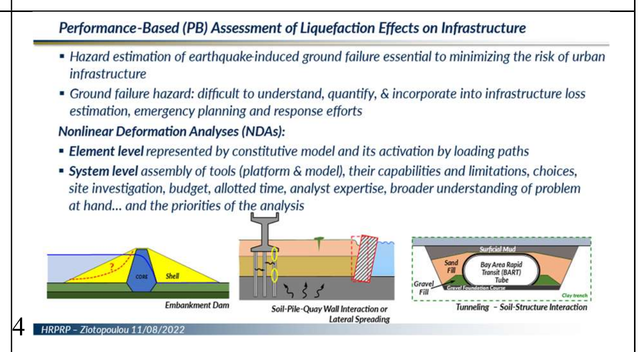


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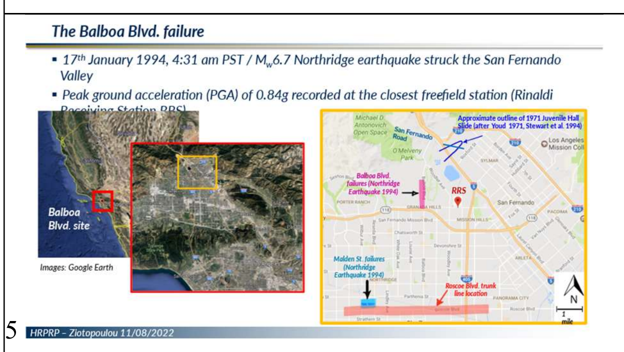


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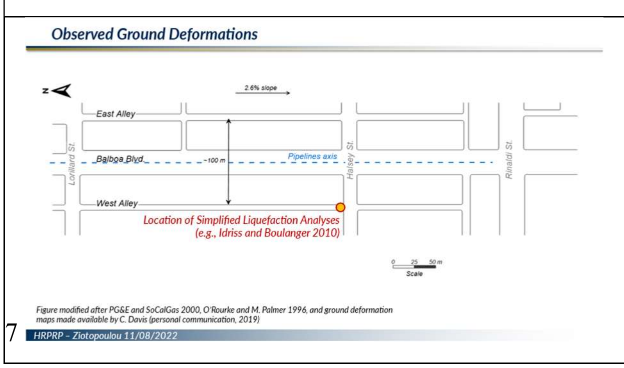


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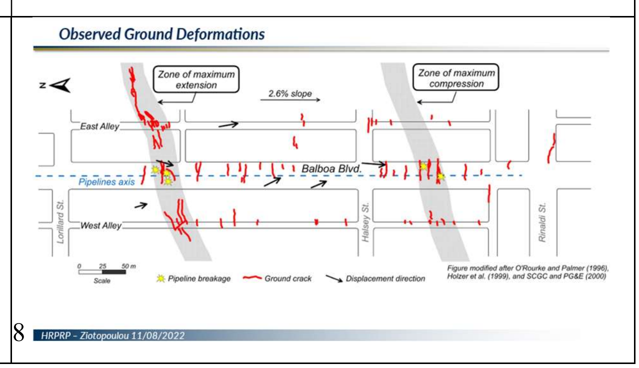


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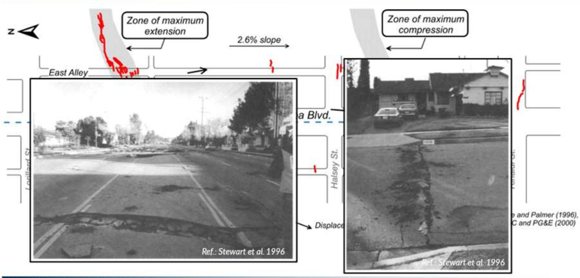
## Observed Ground Deformations



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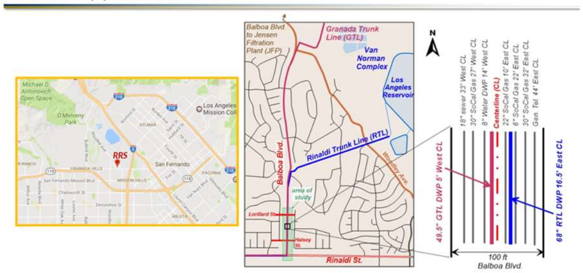
## Pipelines

O'Rourke and Palmer 1994
O'Rourke and O'Rourke 1995
and Los Angeles Department of Water and Power

11

## Area and pipelines of interest

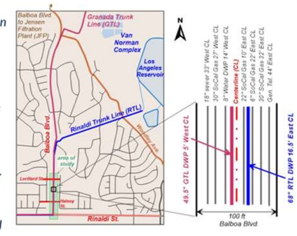





12

## Granada Trunk Line: GTL

- GTL constructed in 1956 to provide domestic water & fire protection to zones of higher elevation on the western side of the San Fernando Valley
- 125.7 cm (49 ½ inch) OD, 0.638 cm (0.25 inch) thick, ASTM A-283 grade C welded steel, high pressure
- Burial depth ~1-1.2 m (3-4 ft) bgl to top of pipe - varies along its length
- Bell and spigot slip joint connections with fillet welds around the outside perimeter.
- Some joint connections used unrestrained Dresser couplings to accommodate small axial & vertical post construction movements
- Inside lined with cement mortar / outside covered with a coal tar enamel undercoat overlain by cement mortar coating

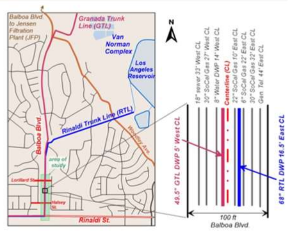




13

## Rinaldi Trunk Line: RTL

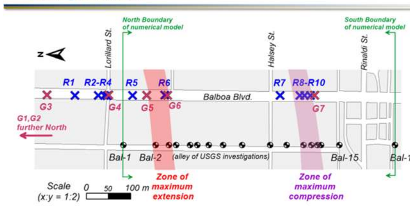
- Constructed in Balboa Blvd. in 1978: link between water supply from the VNC to the West Valley Feeder No. 1 pipeline located in Rinaldi St.
- 172.7 cm (68 inch) OD, 0.953 cm (0.375 inch) thick, ASTM A-283 grade C or D welded steel, high pressure
- Burial depth to top of pipe is mostly about 1.52 m (5 ft) bgl – varies along its length
- Bell and spigot slip joint connections with fillet welds around the outside perimeter.
- Inside lined with 1.27 cm (0.5 inch) cement mortar / outside covered with cement mortar coating





14

## Damage locations

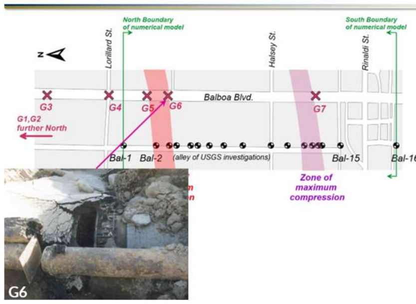



- GTL suffered a total of 7 breaks of various sizes
- Greatest damage at locations G6 & G7



15

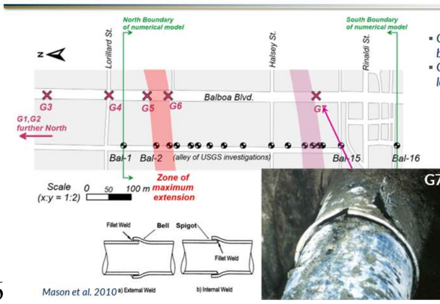
## GTL Damage locations




- GTL suffered a total of 7 breaks of various sizes
- Greatest damage at locations G6 & G7

16

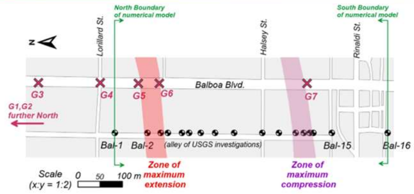
## GTL Damage locations




- GTL suffered a total of 7 breaks of various sizes
- Greatest damage at locations G6 & G7

Mason et al. 2010

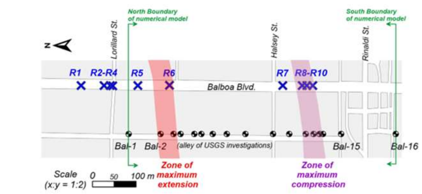
## GTL Damage locations




- GTL suffered a total of 7 breaks of various sizes
- Greatest damage at locations G6 & G7
- 4 additional damages (locations G2 to G5), occurred on the GTL within 409 m of G6 & 400 m of the north boundary of the head scarp

17

## RTL Damage locations




- RTL suffered a total of 6 breaks of various sizes
- @R5, R7, R9 and R10: distress noted during interior inspections
- Greatest damage locations R6 & R8
- 4 additional damages, (R1 to R4), all from tensile strains, occurred on the RTL within 174 m of R6 & 154 m of the head scarp

18 

## Possible mechanisms contributing to ground deformation (& thus pipeline damages)

- **Liquefaction** (Stewart et al. 1996, Holzer et al. 1999, Idriss & Boulanger 2010, Boulanger & Idriss 2015)
- **Cyclic softening** of lean clays (Holzer et al. 1999, Stewart et al. 1996)
- **Seismic compaction** of unsaturated surficial sediments (Day 1996, and others)
- **Co-seismic displacement** caused by secondary faulting (Cruikshank et al. 1996, Johnson et al. 1996, Stewart et al. 1996)

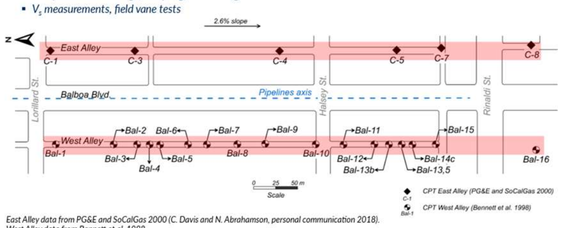
19 

## Site Characterization

20

## Field Investigations

- 2 geotechnical campaigns (West and East alley)
- CPT paired with borings, sampling, and testing
- $V_s$ measurements, field vane tests




East Alley data from PG&E and SoCalGas 2000 (C. Davis and N. Abrahamson, personal communication 2018).
West Alley data from Bennett et al. 1998.

21 

## Field Investigations

- 2 geotechnical campaigns (West and East alley)
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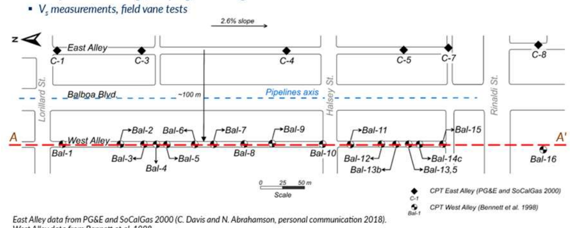
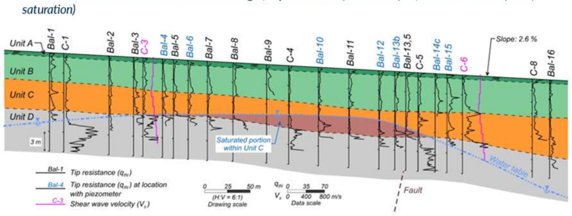



East Alley data from PG&E and SoCalGas 2000 (C. Davis and N. Abrahamson, personal communication 2018).
West Alley data from Bennett et al. 1998.

22 

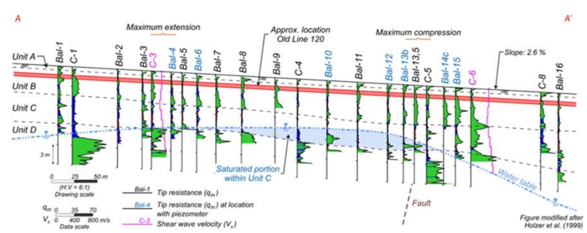
## Subsurface Conditions

Water table best estimate based on monitoring of 7 piezometers (18 months) & field observations (color, saturation)




23 

## Subsurface Conditions

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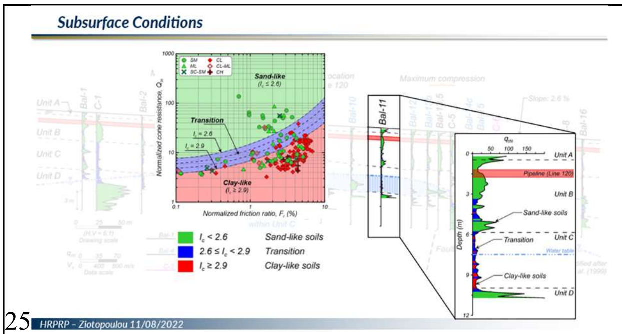

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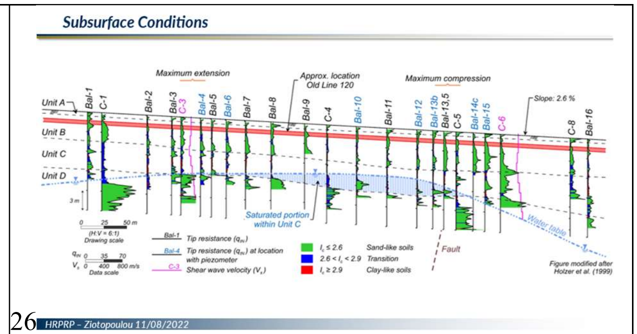

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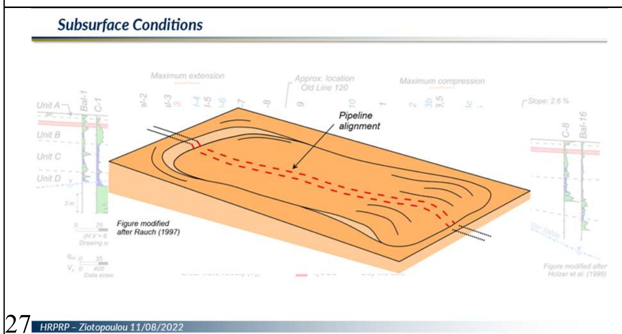

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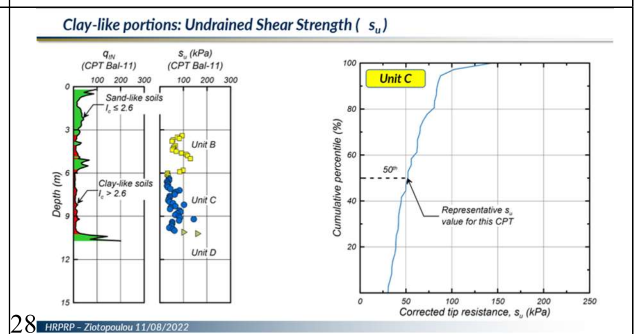

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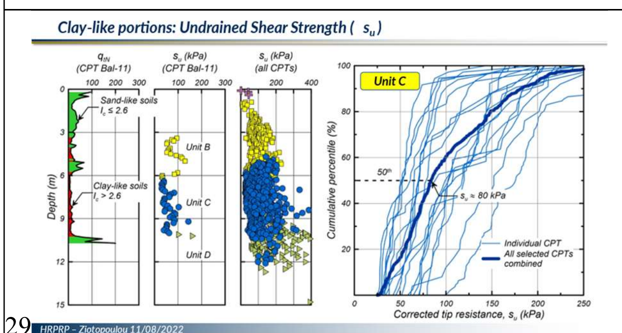

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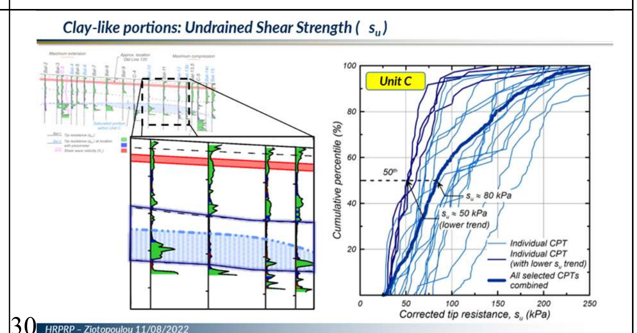

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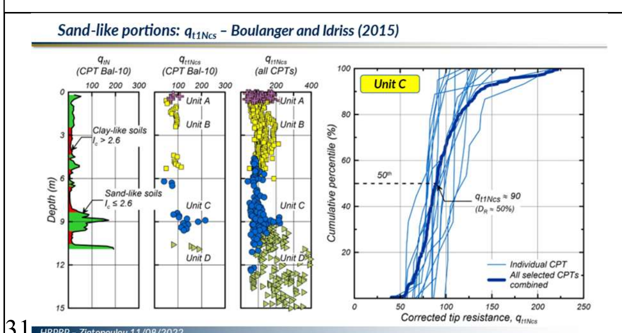

31

## Nonlinear Deformation Analyses

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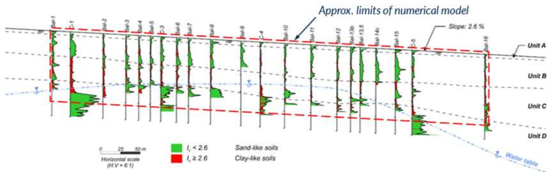
33

## Numerical Model

- $I_c$ cut-off = 2.6
- Units A, B, D: sand -like soils
- Unit C: heterogeneous interbedded sand -like and clay-like soils

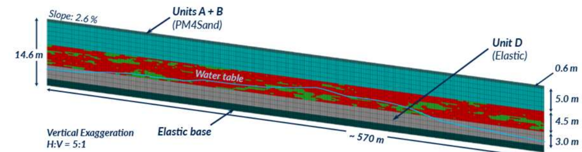





34

## Numerical Model

- 2D nonlinear deformation analyses (NDAs)
  - FLAC 8.1 (Itasca 2019)
  - Total of approx. 18,000 zones; 10,000 zones in Unit C (25 cm thick x 1 m wide)
- Stratigraphic realizations of heterogeneous deposits conditioned on CPT data given $I_c$ cut-off
  - Transition probability (= likelihood of transitioning from one category to another) geostatistics (T-PROGS – Carle 1999)



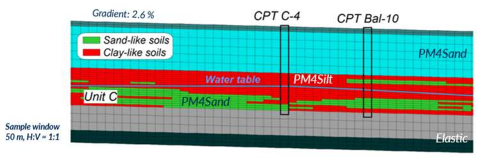



35

## Numerical model

Unit C

- 2D stratigraphic models conditioned on CPT data
- Sand-like soils: PM4Sand v3.1 constitutive model
- Clay-like soils: PM4Silt v1.0 constitutive model





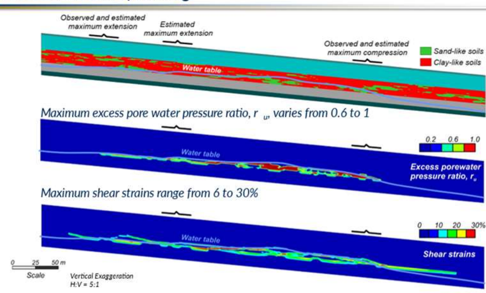

36

## NDA Results

- Is there any benefit in performing 2D NDAs using PM4Sand & PM4Silt with stochastic realizations of the alluvial sediments for the 1994 $M_w$6.7 Northridge earthquake at Balboa Blvd.?
- As reasonable as our choices have been, they all carry uncertainty. Where does it (not)/matter?
- Could we have predicted something similar with 1D LVIs?
- Could our results justify the pipeline damages?

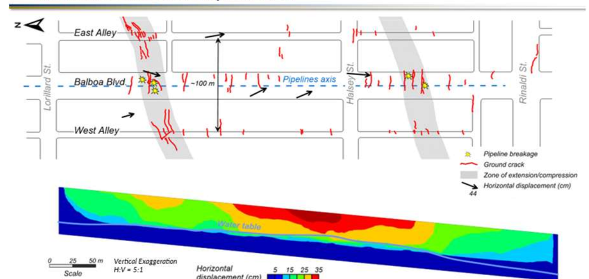
37

## NDA results: end of shaking




38

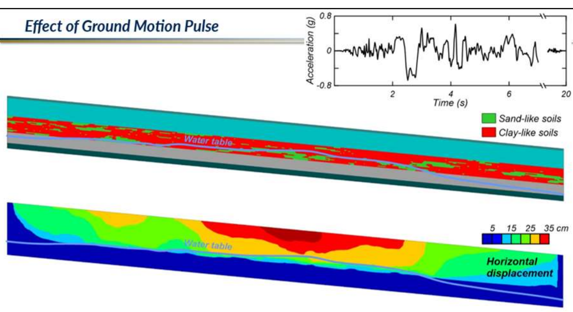
## NDA Results: Horizontal Displacements






39

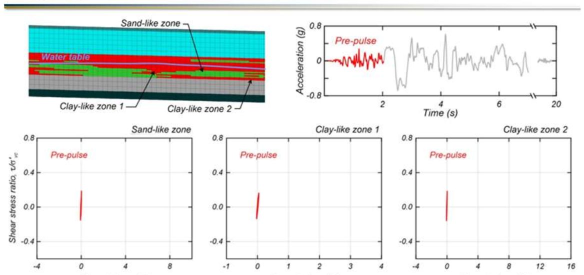
## Effect of Ground Motion Pulse



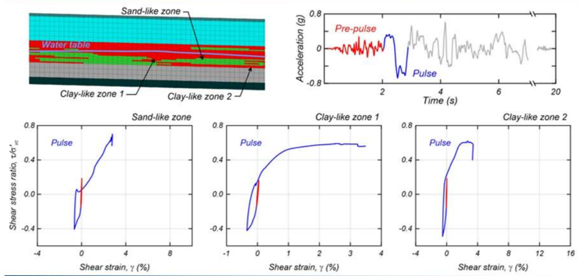



40

## Effect of Ground Motion Pulse

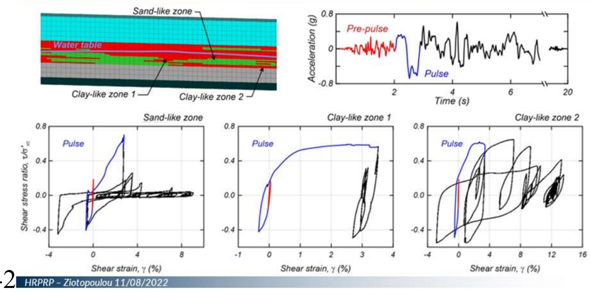


### Effect of Ground Motion Pulse




41 HRPRP – Ziotopoulou 11/08/2022

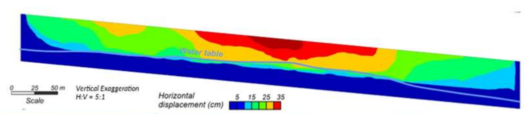
### Effect of Ground Motion Pulse




42 HRPRP – Ziotopoulou 11/08/2022

### NDA Results: (Overall) Horizontal Displacements

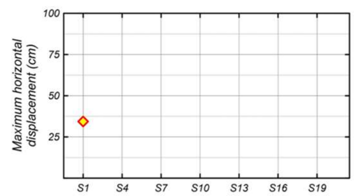
- 1 stratigraphic realization (S1)
- 1 $I_c$ cut-off ($I_c$ = 2.6)




43 HRPRP – Ziotopoulou 11/08/2022

### Effect of Stratigraphic Models

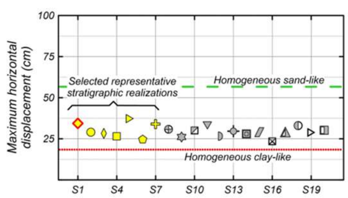
- 1 stratigraphic realization (S1)
- 1 $I_c$ cut-off ($I_c$ = 2.6)




44 HRPRP – Ziotopoulou 11/08/2022

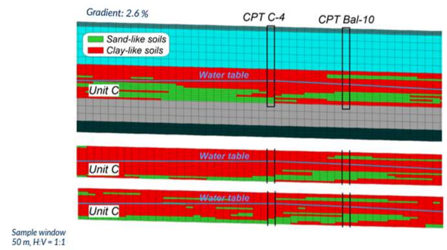
### Effect of Stratigraphic Models

- 20 stratigraphic realizations (S1 – S20)
- 1 $I_c$ cut-off ($I_c$ = 2.6)



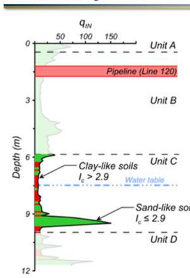

45 HRPRP – Ziotopoulou 11/08/2022

### Effect of $I_c$ cut-off

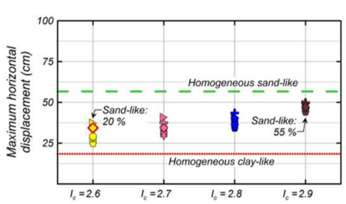



46 HRPRP – Ziotopoulou 11/08/2022

### Effect of $I_c$ cut-off

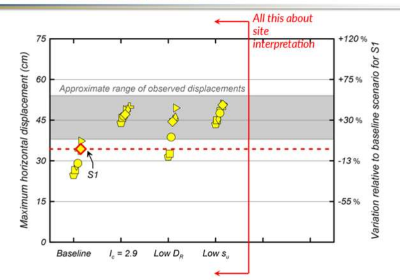



- 7 stratigraphic models (S1 to S7)
- 4 $I_c$ cutoffs ($I_c$ = 2.6 to 2.9)




47 HRPRP – Ziotopoulou 11/08/2022

### Summary: Maximum Horizontal Displacements




48 HRPRP – Ziotopoulou 11/08/2022

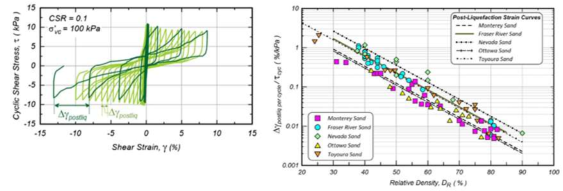
### Exploring a Calibration Priority Decision

- *To achieve a representative CRR, e.g., Boulanger and Idriss 2015*
- *To capture post-liquefaction shear strain accumulation rates* (Tasiopoulou et al. 2019, Humire and Ziotopoulou 2022)



### PM4Sand Calibration

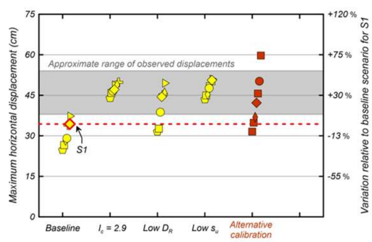
- *Post-liquefaction shear strain accumulation rate*




Ref.: Tasiopoulou et al. (2019)
Expanded by Humire and Ziotopoulou 2022



### PM4Sand calibration – Maximum horizontal displacements






### Observations Part 1

- *Is there any benefit in performing 2D NDAs using advanced constitutive models with stochastic realizations of the alluvial sediments?*
  - *Displacements of 30-70 cm were obtained with calibrations based on the SPT/CPT data; these are reasonably consistent with the average measured displacements.*
  - *The average 50 cm indicates that the combination of these analysis methods & engineering procedures can envelop the observations quite well.*
  - *The NDA results indicate that both sand -like (**liquefaction**) and clay-like (**cyclic softening**) soils contributed to ground deformation at Balboa Blvd.*
  - *It is challenging to pick up the complexity of this site and the role of the sands and clays without looking at it in greater detail.*

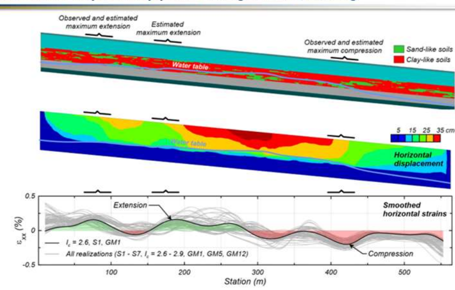


### Observations Part 1

- *As reasonable as our choices have been, they all carry uncertainty. Where does it (not)/matter?*
  - *Soil's heterogeneity leads to significant variability, up to about 40% in the estimated maximum displacements for the baseline case.*
  - *The estimated maximum horizontal displacements vary from 30 to 60 cm when accounting for calibrating the PM4Sand model based on triggering liquefaction and the rate of strain accumulation. These displacements are higher than those obtained from a triggering-based calibration and represent an upper bound for the Balboa Blvd. site.*
  - ***Considering the variability of the shear strength of the material dominating the failure mechanism in combination with the soil's stratigraphy is <u>critical</u>.*** *Here, it was the sand-like soil's $D_R$.*



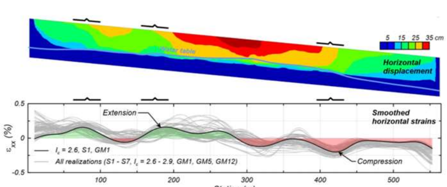
### NDA results compared to pipeline damages: end of shaking






### Comparison of observed and expected damages: End of shaking

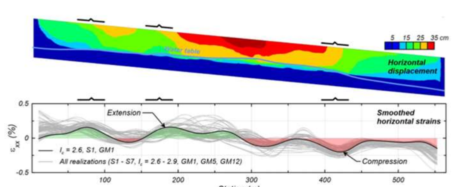
- *Analysis results in terms of ground movement observations compared to the post-earthquake observations & pipeline damages recorded*
- *Smoothed peak horizontal strains estimated at end of shaking @ depth of 1.35 m*






### Comparison of observed and expected damages: End of shaking

- *Comparison of the field observations & the numerical deformations indicates that the largest tensile & compression failures are **overall consistent with ground failure locations***
- *An analysis of the <u>timing</u> of strains should resolve where the cracks initiated (two locations of peak extension strains)*



57

## Comparison of observed and expected damages: Peak during shaking

| Damage | Joint and Failure Type | Smoothed Peak Strain (%) - Analysis |
|---|---|---|
| G5 | WBS, Tension | +0.10% |
| G6 | MC, Tension | +0.23% |
| G7 | WBS, Compression | -0.10% |
| R5 | WBS, Mortar failure | +0.1 - 0.2% |
| R6 | WJ, Tension | +0.25% |
| R7 | WJ, Mortar failure | -0.14% |
| R8 | WJ, Compression | -0.05% |
| R9 | WBS, Mortar failure | -0.05% |
| R10 | WBS, Mortar failure | -0.07% |

- *Smoothed peak strains during shaking at 1.35 m below the ground surface for the baseline analysis*
- *Only damages within BVP / numerical model*
- *Reasonable agreement within broader uncertainty*

WBS = welded bell and spigot ; MC = mechanical coupling ; WJ: welded joint



58

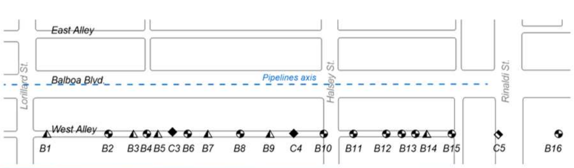
## 1D Liquefaction Vulnerability Indices
### (e.g. Lateral Displacement Index)

Tokimatsu and Asaka 1998, Zhang et al. 2004

$$LDI = \int_0^{z_{max}} \gamma_{max} dz$$

59

## LDI values (meters)



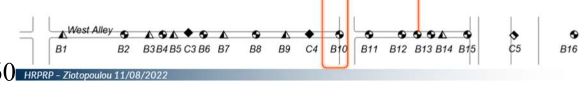



60

## LDI values (meters)

- *Conclusion: an LVI would have simply shown that there is a potentially big problem... but the LVI **would have to be obtained at the right location**.*

| $I_c$ | B1 | B2 | B3 | B4 | B5 | C3 | B6 | B7 | B8 | B9 | C4 | B10 | B11 | B12 | B13a | B13b | B14 | B15 | C5 | B16 | average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.6** | 0 | 0 | 0 | 0.05 | 0 | 0.02 | 0.05 | 0.04 | 0.06 | 0 | 0.00 | 0.26 | 0 | 0.11 | 0.21 | 0.25 | 0 | 0 | 0.07 | 0 | ***0.06*** |
| **2.7** | 0 | 0 | 0 | 0.17 | 0 | 0.14 | 0.05 | 0.04 | 0.11 | 0 | 0.04 | 0.56 | 0 | 0.11 | 0.21 | 0.42 | 0 | 0 | 0.07 | 0 | ***0.10*** |
| **2.8** | 0 | 0 | 0 | 0.17 | 0 | 0.18 | 0.15 | 0.04 | 0.17 | 0 | 0.22 | 0.75 | 0 | 0.11 | 0.40 | 0.71 | 0 | 0 | 0.07 | 0 | ***0.17*** |
| **2.9** | 0 | 0 | 0 | 0.17 | 0 | 0.23 | 0.21 | 0.11 | 0.23 | 0 | 0.58 | 1.12 | 0.55 | 0.26 | 0.70 | 0.97 | 0 | 0 | 0.22 | 0 | ***0.27*** |






61

## Observations Part 2

- *Re-evaluation of the Balboa Blvd. lateral spreading case history: 1) nonlinear deformation analyses & 2) comparison of recorded pipeline failures and simulated strains.*
- *Overall match of global deformation pattern (mobilized block) and individual damage locations indicates that, despite the uncertainties, this approach can be used to evaluate this case history.*
- *No explicit modeling of soil-pile interaction & no ability of continuum approach to capture ground cracking; modeled area smaller than failure area.*
- *Pipeline evaluations have shown that damage observed in buried components does not always coincide with final peak ground displacement & strains. **Maximum and minimum transient strains** need to be further investigated in order to explore what led to failures at specific locations.*
- *Further work to: 1) evaluate the sensitivity of the answers to the extent of the modeled area, 2) focus on the locations of cement mortar damage & explore their correlation with ground strains, 3) investigate timing of strains & their extraction from the numerical model, 4) Malden St and Roscoe Blvd.*
- *Evaluation of pipeline damages could narrow down some of the parameters, but still challenging because of many interacting & spatially varying parameters. Such complexities are trivially encountered in engineering practice and should be considered in the development of design criteria for pipelines in ground movement -prone areas.*



62

## Questions are welcome.

Thank you for your interest.

63

## References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# HRPRP Topic Summary:
# Ground and pipeline failures in Balboa Blvd. (1994 Northridge): Suspected mechanisms of liquefaction & cyclic softening, and predictive capabilities

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## ABSTRACT

The ground and pipeline failures observed in the San Fernando Valley and Balboa Blvd. in particular, during the 1994 $M_W$ 6.7 Northridge earthquake, yielded an unprecedented amount of case history data. This paper summarizes the site of interest and the deformations observed as well as the hypotheses behind the failure mechanisms. The seismic performance of the Balboa Boulevard is examined through nonlinear deformation analyses (NDAs) in FLAC with advanced constitutive models representing the soil units of interest. The numerical simulations predicted ground deformation patterns consistent with field observations. The results were also compared against the pipeline damage data and were interpreted to provide a second order validation by essentially reconciling soil deformation, pipeline failure, and numerical data. This study suggests that advanced numerical modeling can yield reliable hazard estimations of earthquake-induced ground failure which are essential to minimizing the damage risk of urban infrastructure.

## INTRODUCTION

The US-Japan Hazard Resilient Pipeline Research Panel (US-JP HRPRP) was formed to broadly improve the understanding of hazard impacts on all types of buried water pipelines and through that advance the resilience of water systems. This is being achieved through discussing and dissecting the multitude of components behind these issues as well as bringing up emerging challenges like those resulting from climate change. One of the more specific goals of the US-JP HRPRP is to "[…] *provide guidance on the knowledge of the occurrence of natural disasters in Japan and the United States, the impact of such disasters on water pipelines, laws and standards related to hazard resilience, and specific measures to be taken*." This goal can be served by presenting and discussing well-documented case histories and leveraging them to assess the capabilities and limitations of today's engineering procedures and tools. This is poised to establish the state of the art and practice such that future needs and goals can be better informed.

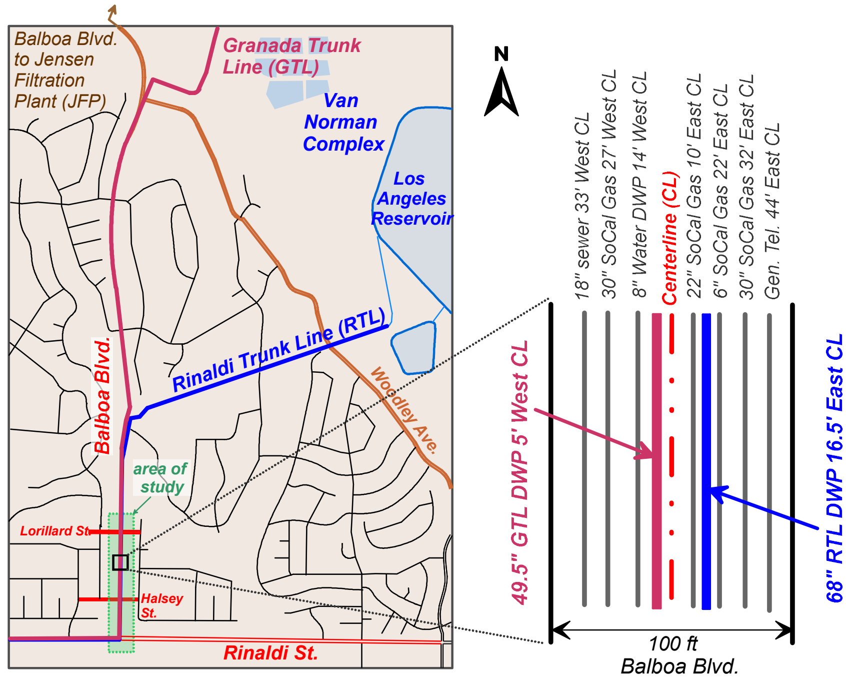


**Figure 1. Broader area of interest in the San Fernando Valley. The detail illustrates pipelines under Balboa Blvd., their external diameters, and their location with respect to the centerline of the boulevard.**

The hazard estimation of earthquake-induced ground failure is essential for understanding and minimizing the risk of urban infrastructure. Ground failure hazard, however, remains difficult to understand, quantify, and incorporate into infrastructure loss estimation, emergency planning and response efforts. For geographically distributed systems, such as lifelines that are intimately related to their surrounding ground, the challenges implications are amplified.

The $M_W$ 6.7 Northridge earthquake occurred on January 17, 1994, at 4:31 a.m. and was generated by an unknown blind thrust fault (Bardet and Davis 1996). Along with the 1971 San Fernando earthquake, the 1994 Northridge earthquake resulted in some of the most extensive damage to a U.S. water supply system since the 1906 San Francisco earthquake (Sano et al. 1999b). Balboa Boulevard is a north-south oriented street (Figure 1) with a mild gradient (2.6%) located at the northern end of the San Fernando Valley. This site coincided with the direction of the earthquake fault rupture propagation, and thus experienced directivity effects that contributed to ground deformations (Stewart et al. 1996). Ground deformations damaged water and gas pipelines and led to the formation of craters and the ignition of fires. Figure 1 shows the Balboa Blvd. alignment and Granada and Rinaldi trunk lines (GTL and RTL) water pipelines which are of focus in this study. The primary area of study is located near the bottom of Figure 1. The inset is an enlargement across a portion of Balboa Blvd. within the study area showing Balboa Blvd. as a major utility corridor containing nine subsurface conduits.

The aims of this paper and its supporting work (Pretell et al. 2021, Ziotopoulou et al. 2022, Pretell et al. 2022) are to (i) revisit this seminal case history and reevaluate it by employing state-of-the-art tools and engineering procedures, (ii) investigate the failure mechanism leading to ground deformations at Balboa Boulevard, (iii) evaluate the accuracy of the adopted analysis methods, engineering procedures, and state-of-the-art tools towards reasonably estimating horizontal ground displacements and through those the pipeline failures, (iv) identify key factors and parameters contributing to earthquake-induced ground deformations at this site, and (v) establish a baseline for future investigations. This paper presents a summary of the site investigation, recorded ground and pipeline failures, the scope and sensitivities of the numerical investigation, and conclusions drawn from the comparison between numerical results and case history recordings.

## SITE CONDITIONS AND FAILURES

### Geotechnical Site Characterization

The geotechnical characterization is based on two investigation campaigns carried out along two parallel alleys separated about 50 m (Figure 2a). Along the west alley, the United States Geological Survey conducted 17 cone penetration tests (CPTs), 13 of which paired with borings, most with continuous sampling followed by laboratory testing (Bennett et al. 1998, Holzer et al. 1999). Along the east alley, geotechnical investigations were conducted by request of the Southern California Gas Company and the Pacific Gas and Electric Company (SCGC and PG&E 2000), including six CPTs (two seismic CPTs), paired to five borings with sampling and laboratory testing. The geotechnical conditions were evaluated by interpretating the geology , boring logs, and laboratory data first and then selecting, processing, and interpretating the CPTs.

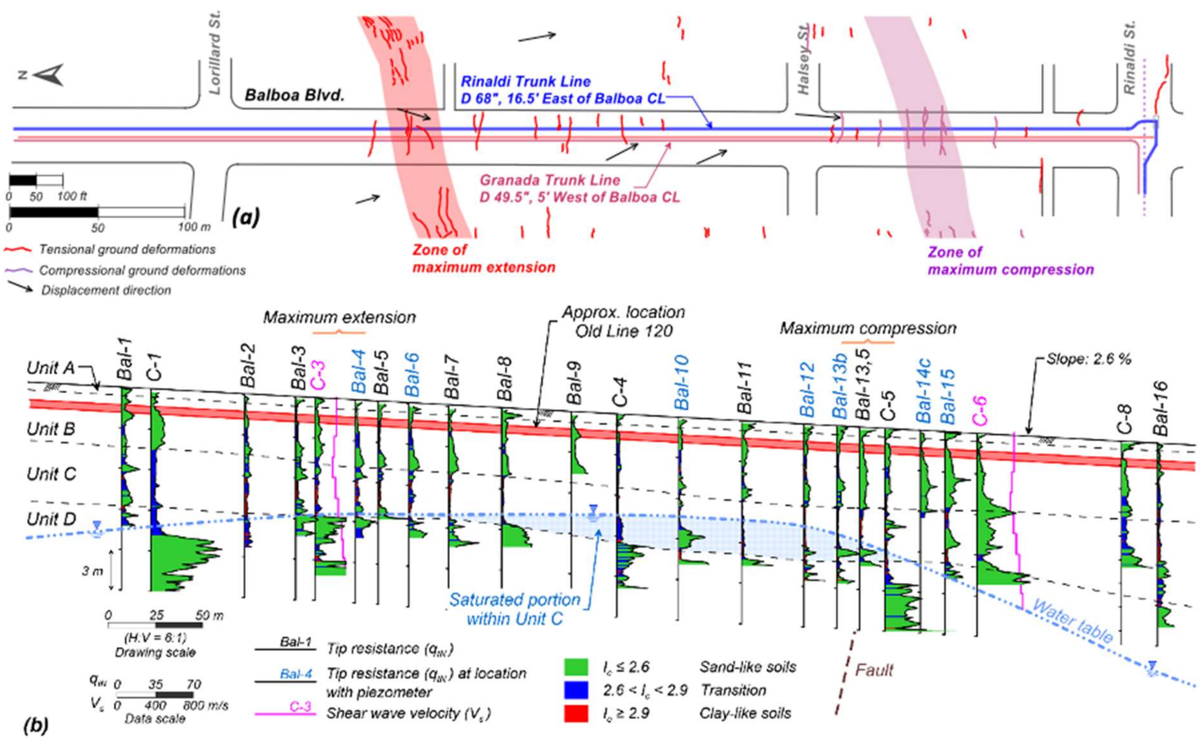


**Figure 1. Balboa Boulevard site: (a) Plan view of observed damages after the earthquake,; and (b) cross section along the west alley showing main features of the subsurface conditions (after Pretell et al. 2021). Note that the x-axes of the two figures are not aligned.**

Balboa Boulevard is underlain by four geologic units (Holzer et al. 1999) presented in Figure 2b. Unit A is a less than 1 m-thick layer of fill, reworked sandy silt, and lean clay with sand. Unit B is a 5 m-thick layer of sheet flood and debris flow deposits. Unit C, identified as the critical layer leading to ground deformations (Holzer et al. 1999, Pretell et al. 2021), is a 4.5 m-thick heterogeneous fluvial deposit of sand-like and clay-like soils. Unit D is part of an older and stronger formation. The groundwater table location at the time of event was inferred by Holzer et al. (1999) based on the monitoring of piezometers, and site-specific observations supported by common regional conditions, as described by Pretell et al. (2021). Sandy soils within Unit C are predominantly classified as SM, with smaller content of ML, SC-SM, and SC, according to the Unified Soil Classification System (USCS). The clayey soils are predominantly classified as CL, with minor content of CL-ML, and CH. Plasticity index (PI) of sand-like and clay-like soils range from 2 to 24, and 2 to 31, respectively. Measurements from two CPT-boring pairs (C-6, C-8) are incompatible with the overall site conditions and their data disregarded (Pretell et al. 2021). Soils in Unit C are distinguished based on their expected behavior, determined through the Soil Behavior Type Index (SBT), $I_c$ (Robertson and Write 1998, Zhang et al. 2002). Soils with $I_c$ lower than 2.6 are considered sand-like soils, and clay-like soils otherwise. Pretell et al. (2021), based on the available data, determined that an $I_c$ of 2.9 is a reasonable site-specific cutoff. Engineering parameters pertinent to each soil category are also estimated based on CPT data.

**Ground Deformations**

A peak ground acceleration (PGA) of 0.87g was recorded at the closest free-field station (Rinaldi Receiving Station, RRS), in the 228° component (Bardet and Davis, 1996). Significant ground movements in the broader area were the result of tectonic movement (e.g., Sano et al. 1999a) and local PGDs due mostly to liquefaction-induced deformations. The latter were responsible for lifeline damages while the strains due to the tectonic movements were negligible, with horizontal and uplift displacements of about 20 and 30 cm respectively distributed over large distances (Davis and Bardet, 1996; Sano et al. 1999b). Figure 2 shows zones of extension and compression (Hecker et al. 1995) observed after the earthquake, about 300 m apart in the north-south direction, within a larger damaged area spanning roughly 600 m in length and width. No typical evidence of liquefaction such as sand boils was found. Several authors have reported magnitudes of the visible ground deformation patterns in and surrounding Balboa Blvd. The Los Angeles Bureau of Engineering (LABE 1995) estimated displacements of 45 cm in the extensional zone, while Holzer et al. (1999) determined overall displacements of 50 cm at both the extensional and compressional zones based on street centerline surveys. Hecker et al. (1995) found approximate displacements of 33 to 54 cm in extension, and 27 to 42 cm in compression, based on the measurement of cumulative crack openings. Aerial photographs indicated values ranging from 48 to 90 cm. Hecker et al. (1995) indicated that vertical displacements after the earthquake were generally small (a few centimeters) with localized vertical offsets along cracks up to about 25 cm. Vertical displacements tended to be downward near the zone of extension and upward near the compression zone, consistent with a sliding mass failure mechanism (Stewart et al. 1996, SCGC and PG&E 2000).

**Pipeline Damages and Displacements**

Ground deformation at Balboa Blvd. caused the breakage of two water trunk lines, one gas transmission pipeline, and one gas distribution pipeline (e.g., O'Rourke and Palmer 1994), the subsequent formation of ground craters, and the ignition of fire. Cracks and displacement vectors in Figure 2 show an overall south-southeast ground movement orientation.

**Granada Trunk Line (GTL)**

The GTL was constructed in 1956 to provide domestic water and fire protection to zones of higher elevation on the western side of the San Fernando Valley in Los Angeles, CA. The GTL originates on the Van Norman Complex (VNC), in the northern San Fernando Valley, passes along the Jensen Filtration Plant (JFP) within a utility corridor, and extends down the boulevard (Figure 1). The GTL is a 125.7 cm outside diameter, 0.638 cm thick, ASTM A-283 grade C welded steel, high pressure, major supply buried pipeline owned and operated by the Los Angeles Department of Water and Power (LADWP). The burial depth is about 1-1.2 m below ground surface to top of pipe but varies along its length. The connections were primarily made with bell and spigot slip joints and fillet welds around the outside perimeter. Some joint connections used unrestrained Dresser couplings to accommodate small axial and vertical post-construction movements. The pipe is lined with cement mortar inside. The pipe is covered with a coal tar enamel undercoat outside, overlain with a 2.54 cm cement mortar coating. The design static head elevation is 457 m.

Ziotopoulou et al. (2021) summarized the failures of the Granada and Rinaldi trunklines along with the type of movement causing damage in tension or compression and the descriptions of pipe repairs. The GTL suffered a total of seven breaks of various sizes in Balboa Blvd. identified as locations G1 to G7 (Figure 3). Furthermore, the 55 cm diameter Old Line 120 steel natural gas pipeline in front of the GTL separated about 25 cm according to O'Rourke and O'Rourke (1995). These researchers reported that the GTL and Old Line 120 each experienced about 25 cm of shortening in the compression zone. The GTL shortening occurred at G7 just south of the toe scarp shown in Figure 3 resulted from the welded bell and spigot pipe joint buckling and telescoping into the pipeline. The telescoping caused a longitudinal tear in the shell.

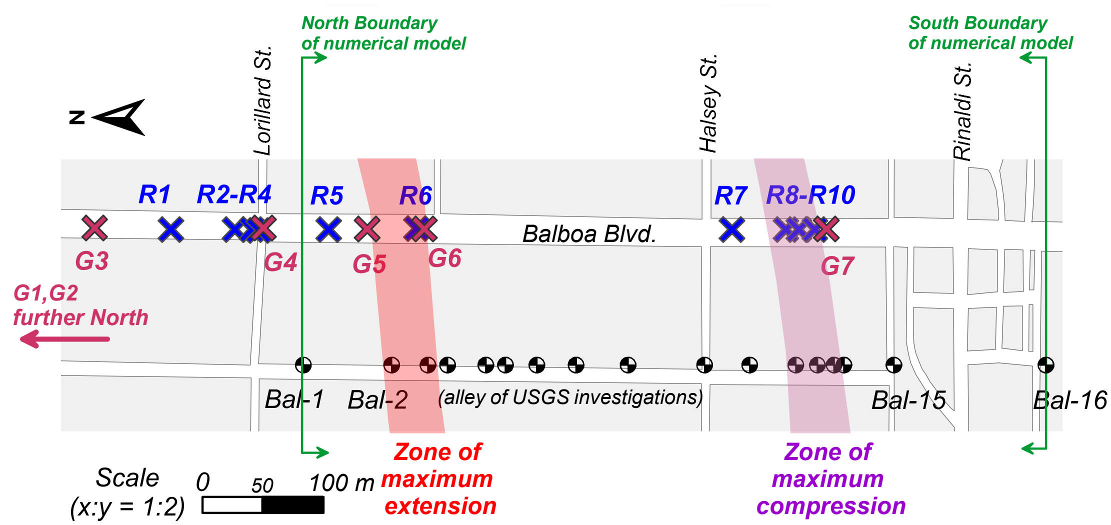


**Figure 3. Location of damages along GTL and RTL. Damages G1 and G2 are further north and not shown in the figure. The locations of the USGS CPT investigations (Bennett et al. 1998) are shown for reference together with the north and south boundaries of the nonlinear deformation analyses considered later in the paper.**

**Rinaldi Trunk Line (RTL)**

The RTL was constructed in Balboa Blvd. in 1978 as a link between water supply from the VNC to the Metropolitan Water District of Southern California's (MWDSC) West Valley Feeder No. 1

pipeline located in Rinaldi St. The LADWP leased the West Valley Feeder No. 1 in Rinaldi St. to provide domestic water and fire protection to lower elevations on the north and west side of the San Fernando Valley in Los Angeles. The RTL in Balboa Blvd. is a 172.7 cm outside diameter, 0.953 cm thick, ASTM A-283 grade C or D welded steel, high pressure, major supply buried pipeline owned and operated by the LADWP. The burial depth to top of pipe is mostly about 1.52 m below ground surface but varies along its length. The connections were primarily made with bell and spigot slip joints and fillet welds around the outside perimeter. The inside of the pipe is lined with 1.27 cm cement mortar. The outside of the pipe is covered with a 2.54 cm cement mortar coating. The design static head elevation is 386 m.

The RTL suffered a total of six breaks of various sizes identified as locations R1 to R4, R6 and R8 (Figure 3) in Balboa Blvd. (also summarized in Ziotopoulou et al. (2021)). The greatest damage occurred at locations R6 and R8 from the large block ground movements that caused similar failures in the GTL. After aligning the information of the head and foot scarps (zones of maximum extension and compression respectively) with the damage locations, R6 lies right inside the head scarp and R5 about 35 m north of the head scarp's north margin. Four additional damages, locations R1 to R4, all from tensile strains, occurred within 174 m of R6 and 154 m of the head scarp respectively. R8 occurred within the toe of block slide while the three distress locations (R7, R9, R10) ranged from above, within, and just below the toe.

## NONLINEAR DEFORMATION ANALYSES

The Balboa Boulevard's seismic performance was investigated using nonlinear deformation analyses (NDAs) and extensive findings were described by Pretell et al. (2021). The Balboa Boulevard numerical model was implemented in the commercial finite difference software FLAC (Itasca 2016). Figure 3 identifies the north and south boundaries of the Balboa Blvd. numerical model which spanned the distance of field subsurface investigations. The model consisted of a 566 m long 2.6% gradient slope of rectangular 1 m-wide quadrilateral zones of variable thickness, selected depending on the soil unit. Zones within Units A, B, C, and D had thicknesses of 0.3, 1.0, 0.25, and 1.0 m, respectively. The thinner zones within Unit C were intended to better capture the spatial variability of soils. These dimensions were consistent with recommendations by Kuhlemeyer and Lysmer (1973) for an accurate propagation of waves within the frequency range of interest. The model had a total of 17,546 zones, 10,188 of which were within Unit C.

The spatial variability of sand- and clay-like soils within Unit C was captured using CPT-conditioned stochastic stratigraphic models. These models honored (1) the volume proportion of sand- to clay-like soils within Unit C; and (2) locations where either sand- or clay-like soils were identified. The PM4Sand constitutive model (Boulanger and Ziotopoulou 2017) was used to model the behavior of sand-like soils (Units A, B, and pockets within of C), while the PM4Silt constitutive model (Boulanger and Ziotopoulou 2018) was used for clay-like soils (dominant within Unit C). Details of the constitutive model calibrations can be found in Pretell et al. (2021). The free-field ground motion recorded closest to Balboa Blvd. was at the RRS, located 2.2 km to the east, which 228° component has a peak ground acceleration (PGA) of 0.87g and a peak ground velocity (PGV) of 1.48 m/s.

Initially, twenty stratigraphic realizations by Pretell et al. (2021) were used to revisit observed and estimated pipeline displacements of this case history. The baseline model considered an $I_c$ index of 2.6as a cut-off between sand- and clay-like soils, and one ground motion. Pretell et al. (2022), extended this work by investigating variations of the baseline cases. Those sensitivity analyses investigated the effects of different plausible scenarios identified based on: (1) variability within the available data; and (2) expected variability of parameters that lack the data to support it. Scenarios in (1) accounted for the spatial variability of sand-like and clay-like soils, the $I_c$ cutoff, the input ground motions, and the $D_R$ and $s_{u,cs,eq}$. Scenarios in (2) accounted for the groundwater table depth, the surface gradient, and $V_S$.

**Results: Ground Deformations**

Results were obtained in terms of contour plots of excess pore pressure ratios, shear strains, displacements, and axial strains along the burial depth of the pipelines (e.g., Figure 4). Results from the baseline analysis shown in Figure 4 identify final permanent displacements ranging up to 40 cm but this number was found to be sensitive to parametric variations and never more than 75 cm with an overall average of 50 cm. Results are extensively reported by Pretell et al. (2021 and 2022) and Ziotopoulou et al. (2022). The results obtained with the analysis methods suggested liquefaction of sand-like soils together with cyclic softening and shear failure of clay-like soils as the failure mechanism leading to ground deformations at Balboa Blvd. (Pretell et al. 2021). Figure 5 illustrates an example of how soils behaved at the element level. It was also demonstrated that simplified methods would be either severely underpredicting or overpredicting the response of this site and would be incapable of shedding light on the failure mechanism. Overall, the use of finite difference solutions combined with transitional probability geostatistics and advanced constitutive models was found to be appropriate for the problem at hand.

The analysis results in terms of ground movement observations were compared to the post-earthquake observations and the pipeline damages recorded. Deformations were tracked as peak during shaking as well as final ones at the end of shaking but future work will examine strains as a function of time. Ziotopoulou et al. (2022) presented approximate pipe repair locations and the smoothed peak horizontal strains estimated during shaking at a depth of 1.35 m for the baseline

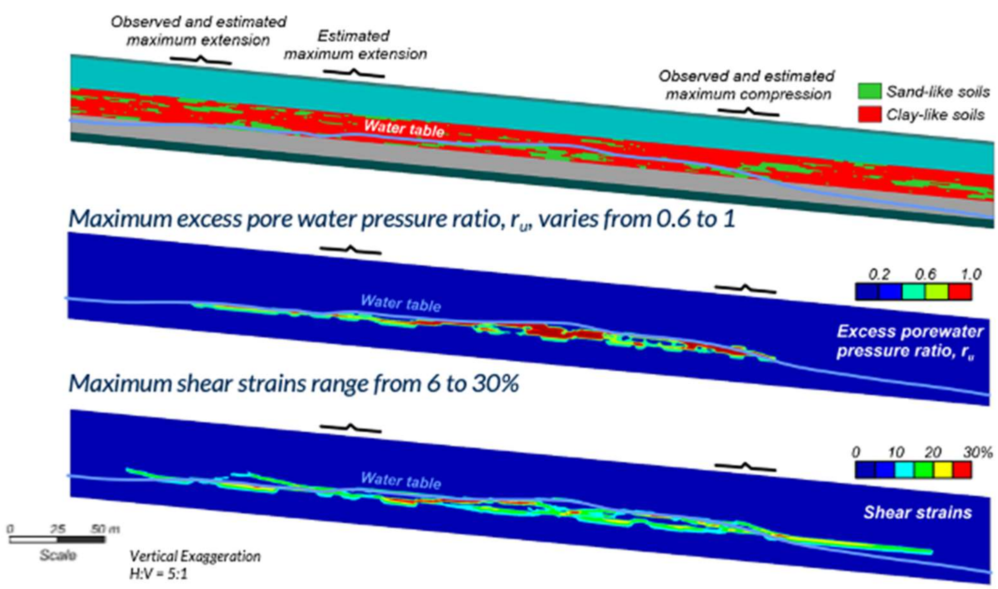


**Figure 4. (top) NDA domain illustrating one stratigraphic realization, (middle) contour plot of maximum excess pore pressure ratio in the saturated soils, (bottom) maximum shear strains throughout shaking (note that simulation is not capable of showing cracks).**

analysis. The depth was chosen as representative of the buried pipelines of interest and it was found that the conclusions are not affected by this choice. Figure 6 shows in solid lines the smoothed horizontal strains at ground surface at the end of shaking for multiple realizations and analyses along the length of the cross-section of Figure 4. The results from the numerical analyses cannot be utilized to directly obtain ground cracks but the extensional strains provide some indications with regards to the expected patterns and the extent to which the observed damages occurred at locations where the calculated strains reached largest values. In this context, there were two locations of peak extension strains shown in Figure 6 with only the first one (to the North) agreeing with the observed ground cracks of Figures 1 and 2. Future work will investigate the timing of transient strains such that this agreement can be further resolved and it can be checked whether the northern extension strains were the first leading to the cracks and the mobilization of the sliding block. The depth of block sliding was about 9.5 to 10 m corresponding to all units A, B, and C sliding on top of D along the liquefied and softened portions of the saturated Unit C and overall agrees with the observations of the extent of the movement.

## Results: Strains and Pipeline Failures

A comparison of the field observations of pipeline damage and the deformations obtained from the numerical simulations (Ziotopoulou et al. 2022) indicated that the largest tensile and compression failures were overall consistent with ground failure locations although a future analysis of the timing of strains should resolve where the cracks initiated. Unfortunately, a comparison cannot be performed for the damage locations north of the intersection of Lorillard and Balboa (R1 to R4, G3 and G4) since those are outside of the NDA bounds that were determined to cover the area with known subsurface data (Pretell et al. 2021). It needs to be noted that damage observed in buried components does not always coincide with the final peak ground displacement

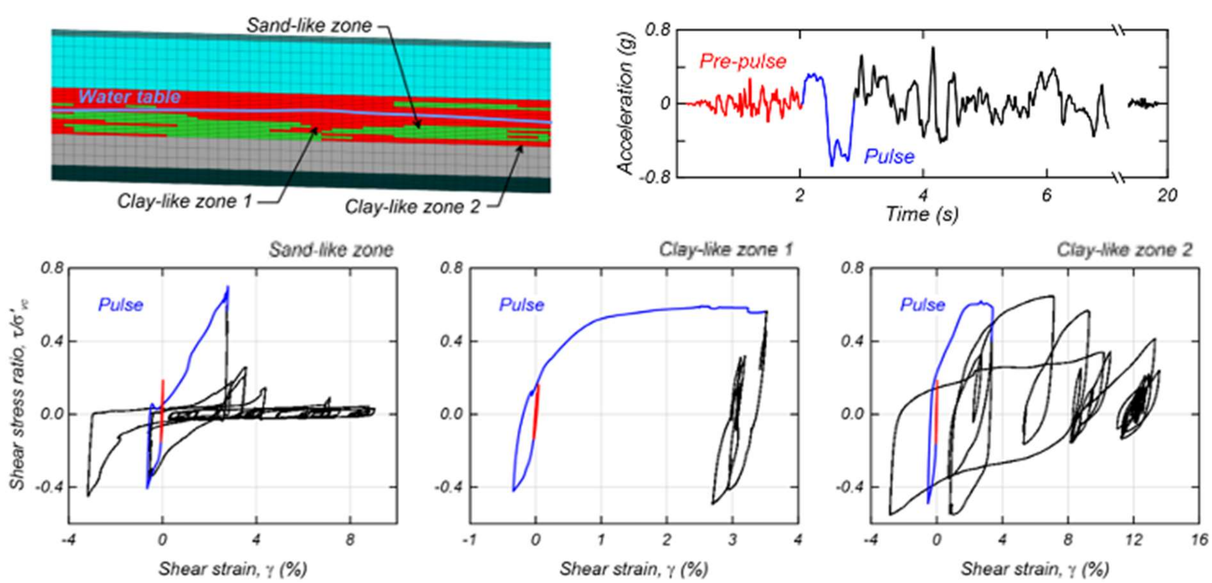


**Figure 5. Stress-strain loops at three different locations within the saturated portion of the site (indicated in the upper left image). Timing of large strain accumulation shows that it took place during the directivity pulse and that both the sands and the clays suffered large deformations.**

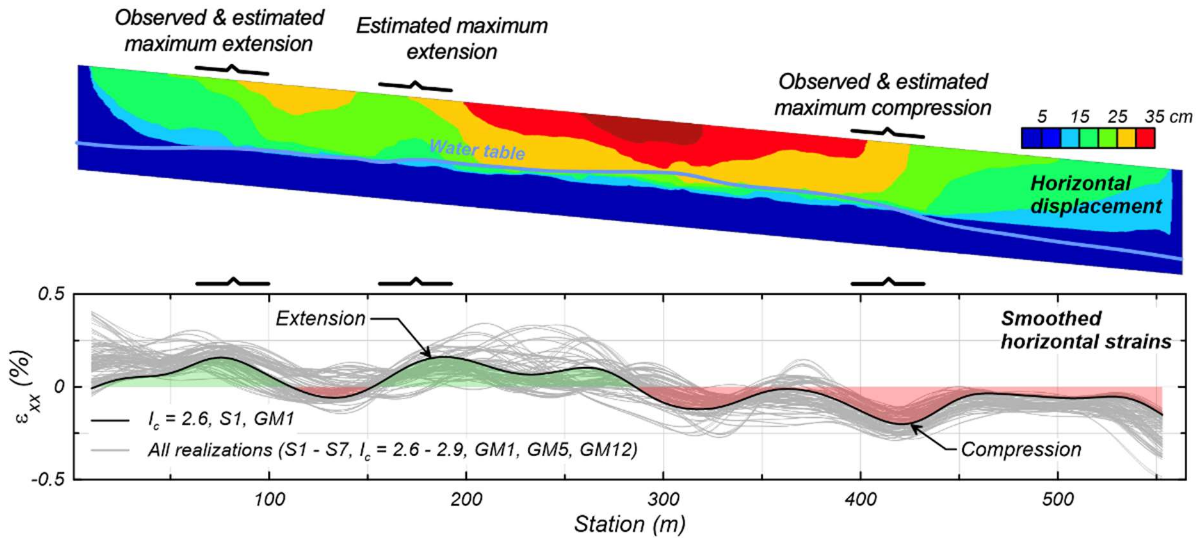


**Figure 6. (top) horizontal displacements; and (bottom) smoothed horizontal strains ($\varepsilon_{xx}$) along the surface from a range of parametric analyses.** ***Note: $\varepsilon_{xx}$ values were recorded at the top two grid points of the numerical models*** **(from Pretell et al. 2021).**

and strains (e.g., Davis 1999). As such, the maximum and minimum transient strains also need to be further investigated in order to explore what lead to failures at specific locations.

## CONCLUSIONS

The Balboa Blvd. lateral spreading case history during the 1994 Northridge earthquake was revisited. Two-dimensional nonlinear deformation analyses (NDAs) were performed using advanced constitutive models with stochastic realizations of the underlying alluvial sediments. The displacements obtained with calibrations based on the SPT/CPT data were reasonably consistent with the average measured displacements. The average displacement of 50 cm indicates that the combination of these analysis methods and engineering procedures can envelop the observations quite well. The NDA results indicated that both sand-like (liquefaction) and clay-like (cyclic softening) soils contributed to ground deformation at Balboa Blvd. It is definitely challenging to pick up the complexity of this site and the role of the sands and clays without looking at it in greater detail (e.g., with simplified methods).

The overall match of global deformation pattern (mobilized block) and individual damage locations indicates that, despite the uncertainties, the approach used can be used to evaluate this case history. There was however no explicit modeling of soil-pile interaction and the continuum model used did not have an ability to capture ground cracking. In addition, the modeled area was smaller than the failure area. The comparison of recorded pipeline failures and simulated strains showed an encouraging agreement, but one needs to keep in mind that damage observed in buried components does not always coincide with final peak ground displacement and strains. Maximum and minimum transient strains need to be further investigated in order to explore what led to failures at specific locations. Further work is also required to evaluate the sensitivity of the answers to the extent of the modeled area as well as to investigate the timing of strains and their extraction from the numerical model. The evaluation of pipeline damages should be able to narrow down some of the parameters, but one needs to consider the challenges because of the many interacting and spatially varying parameters. Such complexities are trivially encountered in engineering practice and should be considered in the development of design criteria for pipelines in ground movement-prone areas.

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**Tetsuo Tobita, Presentation, Kansai University, Professor**
**Understanding Risks/Pipeline Damage: Geohazards, Man-Made Land, and Ground Monitoring**

THINK × ACT 関西大学 KANSAI UNIVERSITY

Hazard Resilient Pipe Research Panel ( HRPRP) workshop
Nov. 9, 2022@UC Berkeley Richmond field station

## Understanding risks/Pipeline damage

Geohazards, Man-made land and ground monitoring

Tetsuo Tobita
Kansai University, Osaka, Japan

1

Hazards to pipelines
1) Liquefiable ground
2) Slopes
3) Embankments and manmade land
4) Seismic faults
5) Surface microtopography
6) Adjacent structure
7) Tsunami/High tide
8) Aging

2011 Tohoku

2018 Osaka

2

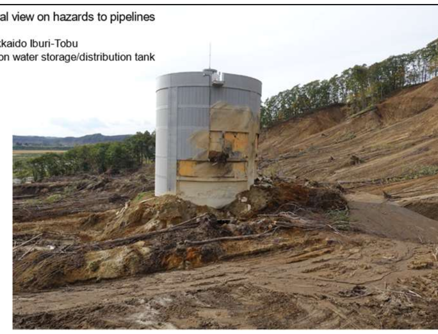
Contents

1. General view on hazards to pipelines
2. Lessons learned from major damage on WTP due to liquefaction
3. Lessons learned from major damage on WTP due to landslide
4. Summary for Understanding risks/Pipeline damage

3

1. General view on hazards to pipelines

2018 Hokkaido Iburi-Tobu
Damage on water storage/distribution tank



4

2004 Niigata-ken Chuetsu

5

2003 Tokachi-oki

6

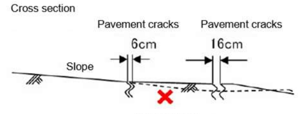

Ground surface of damaged pipe location
(D150DIP, leakage from joints: Higashi Matsushima, Miyagi pref.)

JWWA (2012)

7

D150 DIP Leakage from joints

Cross section

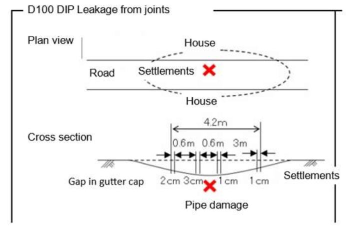



JWWA (2012)

8


Ground surface of damaged pipe location
(D100DIP, leakage from joints: Nankodai, Sendai, Miyagi pref.)

9 JWWA (2012)




10 JWWA (2012)

Each damage looks minor but once accumulated cause large impact on society.

These damages are one of our targets as a HRPRP.

Ground may have been moving or strained far before shaking.

Challenge is to monitor and detect these subtleties.

11

Distribution of pipeline damage, pipe type and cut and filled land ( Nankodai, Sendai, Miyagi pref.)

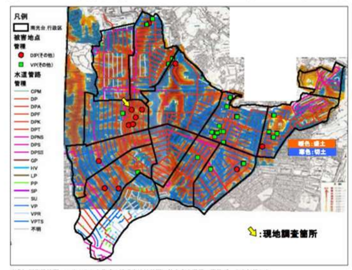



図 2.1.7 管路被害と切盛土の分布(南光台)

12 JWWA (2012)

Distribution of pipeline damage, pipe type and cut and filled land ( Midorigaoka, Sendai, Miyagi pref.)

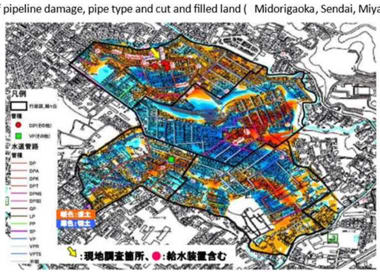



図 2.1.10 管路被害と切盛土の分布(仙台市太白区緑ヶ丘)

13 JWWA (2012)

Distribution of pipeline damage, pipe type and cut and filled land ( Sakuragaoka, Sendai, Miyagi pref.)

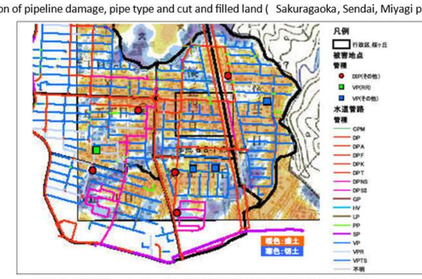
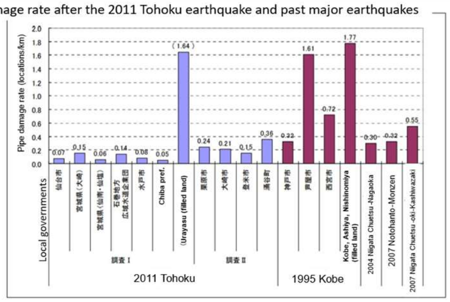



図 2.1.12 管路被害地点と切盛土の分布(仙台市青葉区桜ヶ丘)

14 JWWA (2012)

Pipe damage rate after the 2011 Tohoku earthquake and past major earthquakes




15 JWWA (2012)

16 http://urayasu-shinsai-archive.city.urayasu.lg.jp/infolib/cont/mst/G0000002UR/000/099/000099248.pdf

17


写真 1.2-4 公園、耐震性貯水槽、下水道施設等の被害

http://urayasu-shinsai-archive.city.urayasu.lg.jp/infolib/cont/mst/G0000002UR/000/099/000099248.pdf

18

Damaged and non-damaged pipes in Urayasu after 2011 Tohoku earthquake

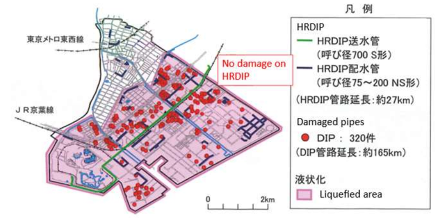



図1.4.6 DIP被害地点とHRDIPの埋設位置[13)]
【2011年東北地方太平洋沖地震 浦安市】

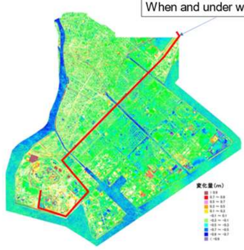
Ave. damage ratio on pipes in Urayasu: 1.64 /km (c.f. 1.77/km in Nishinomiya Kobe eq.)

Miyajima and Toshima (2022)

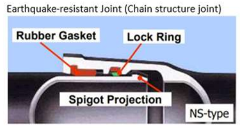
19

Change of elevation in Urayasu before and after 2011 Tohoku earthquake
LIDAR image

HRDIPs had no damage but joints might be pushed or stretched.
When and under what conditions should they be replaced?



Earthquake-resistant Joint (Chain structure joint)




Davis (2013)

Urayasu city HP

20

2. Lessons learned from major damage on WTP by liquefaction

Wanigawa water treatment plant after 2011 Tohoku earthquake



写真 10.5-1 鰐川浄水場 （2011 年 3 月 12 日時点、Google earth より衛星写真を引用）

Kuwata and Katagiri (2011)

21

**1st earthquake strike to 10 minutes later**


Iwatsubo, et al. (2022)

22

**2nd earthquake strike to 10 minutes later**

**3rd earthquake strike to 10 minutes later**


Iwatsubo, et al. (2022)

23

Event time sequence

| Time (epicenter, intensity) | Situation |
|---|---|
| 14:46 (Sanriku Coast, 6L) | 1st earthquake strike: A malfunction of the special high-voltage switchboard caused temporary power failure in the WTP's electrical installations. Power was restored manually, but operation of the WTP stopped due to frequent instrument errors. |
| 15:00 | Ground deformation, sand boiling, and uplift of the utility tunnel caused by liquefaction was observed at the site. However, it was still possible to walk from the administration building to the water distribution pumping station and extra high voltage substation. |
| 15:02–15:07 | An emergency alarm sounded for the floor drainage pumps of the utility tunnel. |
| 15:06 (Sanriku Coast, 3) | 2nd earthquake strike |
| 15:15 (Ibaraki Coast, 5) | 3rd earthquake strike: This was the largest perceived strike. Progressive ground deformation, sand boiling, and uplift of the utility tunnel occurred, making vehicle access impossible. |
| 15:27 | The floor drainage pump of the utility tunnel was recovered, but an abnormal water level was detected. It was presumed that inflow of groundwater and sediments from the joints due to the uplift of the utility tunnel occurred after the first earthquake strike (14:46), followed by the second strike (15:06) and third strike (15:15). |
| 17:00 | After the third earthquake strike (15:15), a tsunami warning was issued. Operators were temporarily evacuated, and returned to the WTP at approximately 17:00. At this time, serious ground deformation due to liquefaction and lateral flow occurred as well as a large amount of sand boiling from the joints of the utility tunnel and submergence of equipment. Thus, attempts to restart the recovery operation were abandoned. |
| Next day or later | Uplift of the utility tunnel was presumed to have continued after the next day (March 12), as rupture of the electrical cables and chemical dosing pipeline installed at the joints occurred during the restoration period. This may have been because of the ground deformation caused by the aftershocks and the load reduction due to the removal of sediment that flowed into the utility tunnel. |

After Iwatsubo, et al (2022)

24

写真 10.5-2 上水施設側の共同溝の浮上

写真 10.5-3 撤去された管路 DIP(T 形)

写真 10.5-4 ポンプ室前の地盤沈下

写真 10.5-5 管理棟（配水池）周辺の路面沈下

Kuwata and Katagiri (2011)

25

写真 10.5-8　取水ポンプ棟の管路取り合い部

写真 10.5-9　取り合い部の継手の漏水

Kuwata and Katagiri (2022)

26

Wanigawa WTP

Took one month for temporal operation

Took one year for full operation

Unexpected scenarios for the damage and recovery process

1. Multiple large after shocks caused gradual damage on facilities/pipelines
2. Power outage made quick damage assessment difficult.
3. Electrical cables and chemical dosing pipeline in the utility tunnel were cut during recovery operation, because removal of sands in the tunnel unloaded the weight on it causing its displacement.
4. Clean up of sands intruded into facility caused additional delay.
5. Backfill material l iquefied during recovery construction.
6. Operating staffs were not expecting damage due to liquefaction.
7. Staff members had to evacuate for every Tsunami warning.

After Iwatsubo, et al (2022)

27

3. Lessons learned from major damage on WTP by landslide

One month later after opening the plant, the earthquake hit.

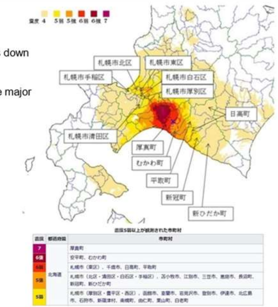
写真9　配水池の被災状況（断熱材の露出）

28

2018 Hokkaido Iburi-Tobu Earthquake

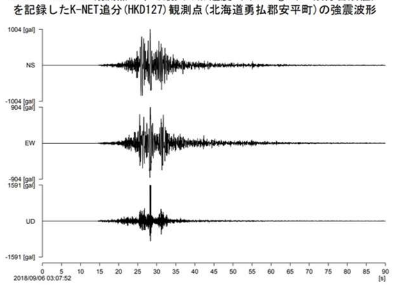
Electrical power in the Entire Hokkaido was down for the first time.

A small hydraulic power plant re-ignited the major thermal plants.




JMA (2018)

29




https://www.static.jishin.go.jp/resource/monthly/2018/20180906_iburi_2.pdf

30

Google map

31

GSI (2019)

32

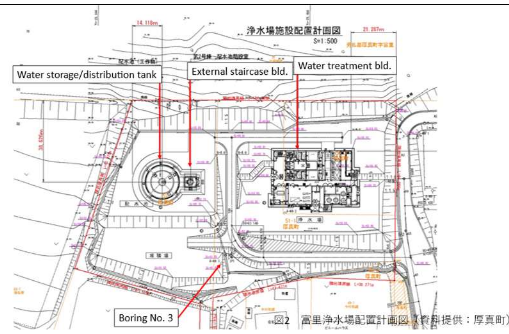



図2　富里浄水場配置計画図（資料提供：厚真町）

33


GSI (2019)

34

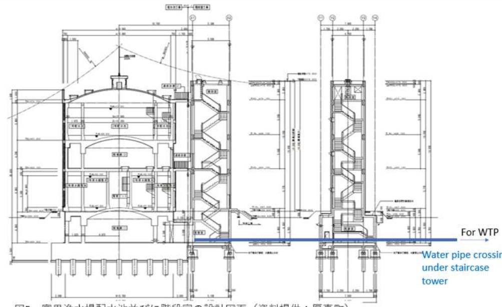



図5 富里浄水場配水池並びに階段室の設計図面（資料提供：厚真町）

35

36

写真10 配水池配管廊の階段室側開口部，基礎杭（長さ約4.5m）が流入している（写真右奥）

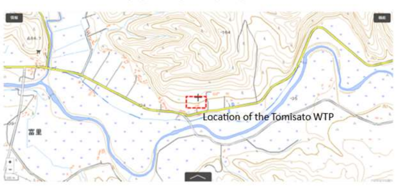
37

38

Such a landslide was totally unexpected because,,,,

39

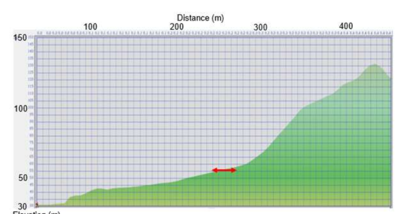
The site was only gently sloping.




(a) 厚真町富里周辺地形図，点線枠は富里浄水場のおおよその位置(国土地理院，2018)

GSI (2018)

40




Slope angle: Approx. 7 Deg. (1 : 8)

Elevation map Sugimoto (2002)

Before construction

Google Map

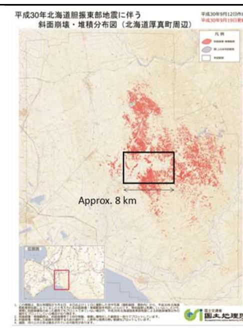
41

Cause of the landslide was not strong shaking!

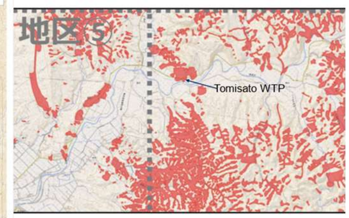
42

but soil!

43




Landslide area 13.4 km$^2$ in a single earthquake is a record.




44

Boring No. 3 (Tomisato WTP)

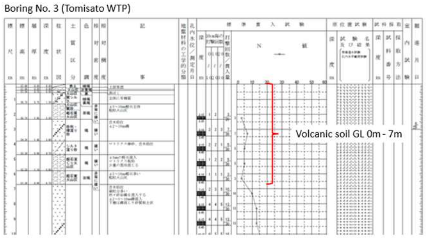



図4　富里浄水場構内における標準貫入試験地盤柱状図（ボーリングNo. 3）
（資料提供：厚真町）

45


**Fig. 11.** Tephra layers produced by post-caldera volcanoes of Shikotsu volcano and Eniwa and Tarumai volcanoes (Fig. 1; Stop 1). En-a is a pumice-fall deposit (20 ka) that was derived from Eniwa volcano and was the most voluminous tephra of the post-caldera eruptions. The activity of Tarumai volcano began at ca. 9 ka, and repeated Plinian eruptions with pyroclastic flows occurred. Three tephra layers of the volcano, Ta-c (2.5 ka), Ta-b (AD1667), and Ta-a (AD1739), are recognized at the outcrop. Activity at Eniwa and Tarumai volcanoes has continued to the present day.

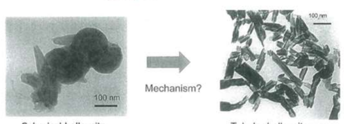
中川他(2018)

46

Geologists knew, but did not tell.

Mechanism of morphological transformation from spherical to tubular halloysite during weathering of vitreous materials

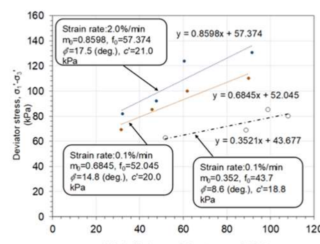
"During weathering of vitreous materials halloysite transforms in shape from spheres to tubes with the advancement of weathering or deposition age" (*e.g.*, Textbook of T. Sudo, 1974).




井上厚行　千葉大学教授
集中講義資料

47

Triaxial test results of weathered volcanic soil taken from Shirakawa, Fukushima Pref.
Results show normal clay behavior.




After Kawahara (2015), Kawahara et al. (2016), Tobita et al. (2015)

48

49

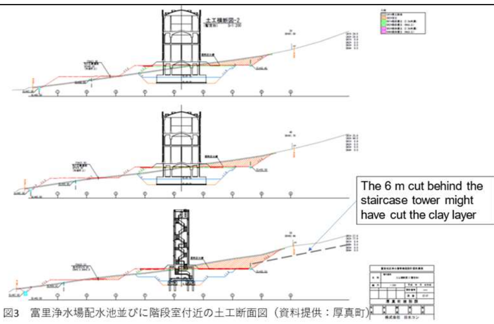



図3　富里浄水場配水池並びに階段室付近の土工断面図（資料提供：厚真町）

50


51

In-situ simple direct shear test!

Easily muddied

52

Thickness of the weathered pumice is only about 10 cm.

Easily overlooked in a soil profile if it is unknown.

53

Tomisato WTP

Took long time to repair

Old facility was temporally rebooted after two weeks.

Took 34 days for repairments of leakage of distribution pipes in Atsuma town.

Unexpected scenarios for the damage and recovery process

1. Repair works for distribution pipes were hindered due to lack of sufficient amount of water in pipelines (pipes could not be filled with water).
2. The site was on a gentle slope (<20 deg.), and construction near a gentle slope is not prohibited by the law.
3. Only local civil engineers and geologists knew weathered volcanic soil is troublesome.
4. Damage on access road made transport of construction machinery difficult.
5. Restoration of WTP affects whole recovery process in a town.

After Iwatsubo, et al (2022)

54

An updated Water Works Guideline, Japan Water Works Association (JWWA). 2022. "Seismic Design Criteria and Guidelines for Water Supply Facilities," emphasize to incorporate, in a design phase, the concept of "Anti-catastrophe" to minimize damage even in the events that exceeds predetermined design threshold.

Examples of anti-catastrophe:

- Important structures should be placed in a site away from possible hazards.
- Strong pipes (e.g., hazard resilient pipes) should be used.
- Number of joints should be reduced.
- WTP facility should be compactly constructed.
- Ground deformation should be analyzed as precisely as possible.

After Iwatsubo, et al (2022)

55

Summary for Understanding risks/Pipeline damage

- Hazardous conditions against pipelines are almost known.
- Development of advanced monitoring technics for detection of subtlety of ground deformation/water leakage for pinpoint retrofit
- Timing of replacement of HRDIP is another issue.
- Two lessons (liquefaction and slope) are introduced.
- Concept of "Anti-catastrophe" should be implemented explicitly in the design process.

56

Design examples focusing on liquefaction countermeasures

| | |
|---|---|
| Design condition | The facilities are located near a river. |
| | A weak earthquake (e.g., intensity 5) may result in damage or destruction based on past earthquake cases. |
| Damage scenario | The earthquake causes damage to the entire WTP, including body of the concrete structures, pipelines, equipment, and ground. |
| | The aftershocks of earthquakes cause progressive ground damage over time, leading to increased total damage. |
| Example of countermeasures | Critical structures should be placed in locations away from rivers. |
| | Ground improvement materials should be used for backfilling after the construction of underground structures. |
| | A non liquefaction layer above the formation in which liquefaction is expected should be ensured. |
| | Strong materials should be used for pipelines and piles. |
| | The number of structural joints should be reduced, and joints should not be used in the water tank. |
| | Joint trenches should not be used, and pipes and cables should be buried directly using expandable and flexible materials. |

After Iwatsubo, et al (2022)

Design examples focusing on landslide countermeasures

| | |
|---|---|
| Design condition | The site is located near a gentle slope in the upper part of a volcanic ash clay layer.<br>The target facility is the key WTP with a treatment capacity of several hundred thousand $m^3$/day. |
| Damage scenario | Landslides occur widely mainly on gentle slopes, affecting the entire site.<br>Because a backup water supply is difficult for a large WTP, partial operation by emergency restoration is required. |
| Example of countermeasures | To place the structure away from a slope, facilities should be compactly designed.<br>To make the facility compact, several facilities should be designed as integrated structures.<br>Connecting pipes should be laid on foundations that are integral to the structure.<br>The recoverability is increased by not adopting structural joints in the water tank.<br>Concrete water tanks should be carefully designed to avoid cracks.<br>Ground deformation should be accurately simulated by dynamic response analysis using a structure-soil interaction model. |

57

After Iwatsubo, et al (2022)

# Understanding risks/Pipeline damage: Geohazards

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## INTRODUCTION

Lessons learned from the past major earthquakes have demonstrated that buried pipeline facilities are vulnerable not only to ground shaking but also to ground movements. Once many pipelines for suppling drinking water, sewage water, and gases, which are called lifelines, are damaged during an earthquake, effects on human society are tremendous. Shortage of firefighting water may be the one of the priority issues just after the event. Then, shortage of water used in hospitals are critical. For most of the citizens, daily water shortage is unbearable. Shortage of drinking water can be prolonged for several months if major trunk lines are damaged.

Past field investigations have revealed the causes of pipeline damage as listed below:

1) Liquefiable ground
2) Slopes
3) Embankments and manmade land
4) Seismic faults
5) Surface microtopography
6) Adjacent structure
7) Tsunami/High tide (Fig. 1(a))
8) Aging (Fig. 1(b))

(a) (b)

**Figure 1. (a) Foundation of a tank swept away by tsunami after 2011 Tohoku earthquake, (b) Damaged ductile iron pipe after 2018 Osaka Hokubu, Japan, earthquake**

In what follows, firstly, general view on hazards to pipelines is given. Then, discussions are made on lessons learned from major damage on water treatment plant (hereafter abbreviated as WTP) in Japan due to liquefaction and landslide. Finally summary on understanding risks on pipeline damage is given.

## GENERAL VIEW ON HAZARDS TO PIPELINES

In major earthquakes, large ground deformation associated with sloping ground or liquefaction may occur and pipelines buried in such a ground suffer severe damages. Figure 2 shows pipe damage rate (damage location/km) in the past 5 large earthquakes in Japan (JWWA, 2012). In this figure, the damage rate in reclaimed land (Urayasu and Kobe,Ashiya, Nishinomiya) is significantly high. One of the causes is that the ground condition in a reclaimed land with shallow ground water table is typically soft and seismic waves tend to be amplified to the surface. Another cause may be the lack of compaction of soil in a pipeline trench. Other issues may be particular to Urayasu and Kobe, those cities are highly populated so the pipelines are densely distributed. In Fig. 3, the rate of Ashiya city is high (1.61 locations/km) this may be because highly damaged area is a slightly hilly residential area developed by cut and fill to make the flat site. It was reported that many houses on the valley fill embankment suffered damages (Kamai and Syuzui, 2002). As shown later, this type of damage has also been reported in Sendai, Miyagi Pref. in the 2011 Tohoku earthquake.

For example, Fig. 3(a) shows large ground deformation caused by the failure of a retaining wall located at downstream, which had been constructed to form a flatland by valley fill embankment for residential land. In Fig. 3(a), many pipes, for drinking water and sewage, can be seen. Another example in Fig. 3(b) shows an uplift of a manhole. Apparently damage is not only to the manhole itself, but also to pipes connected to it. Thus, in the repair work, the trench along the sewage pipe has to be dig out and a pipeline has to be placed with a tiny angle so that the sewage water can flow by the gravity. Those are examples easily recognizable by visiting the site after major earthquakes.

Another type of damage may be severer to buried pipelines, which is minor if one looks at one by one but is severer considering numbers of locations and difficulty for detection. Figure 4(a) shows a ground surface of a damaged pipe location after 2011 Tohoku, Japan, earthquake. The damage to pipes was illustrated as shown in Fig. 4(b). Another example is shown in Fig. 5(a) and its mechanism is seen in Fig. 5(b). Although both of the damages are quite minor compared with the ones shown in Fig. 3(a) and Fig. 3(b), once accumulated they may cause huge impact on society. Detection of leakage may take days to a week or more because ground surface deformation is usually minor and difficult to pin-point the damage location. Moreover, if the upstream facility, such as a WTP, is damaged and unable to supply water to pipelines, detection of leakage becomes impossible. In that case, priority will be put on the reconstruction of the WTP.

Typical locations where such a minor damages can occur have been known from the past earthquakes. Figure 6 identifies distribution of damages on the pipeline network with pipe type and cut and valley fill embankment at Nankodai, Sendai, Miyagi Pref. after the 2011 Tohoku, Japan, earthquake (JWWA 2012). Close look at Fig. 6 reveals that most of the damage is concentrated at the boundary between the cut and fill, where the strength characteristics of the ground may abruptly change. It is also reported that many houses on top of the fill have been suffered minor to major damages due to ground deformation.

Figure 7 shows location of damaged and non-damaged pipelines in Urayasu, Chiba Pref. after the 2011 Tohoku, Japan, earthquake. It is reported that the earthquake resistant pipes (here it is shown with a green sections.) have no damage even in a heavily liquefied ground. Such pipelines had a special feature on their joints as shown in Fig. 8 and is called the "Earthquake (or Hazard) Resilient Pipe." As shown, the lock ring and spigot projection keep the joints from separation under large ground deformation. This mechanism also gives flexibility in a train of pipes so that it can deform along with the ground deformation.

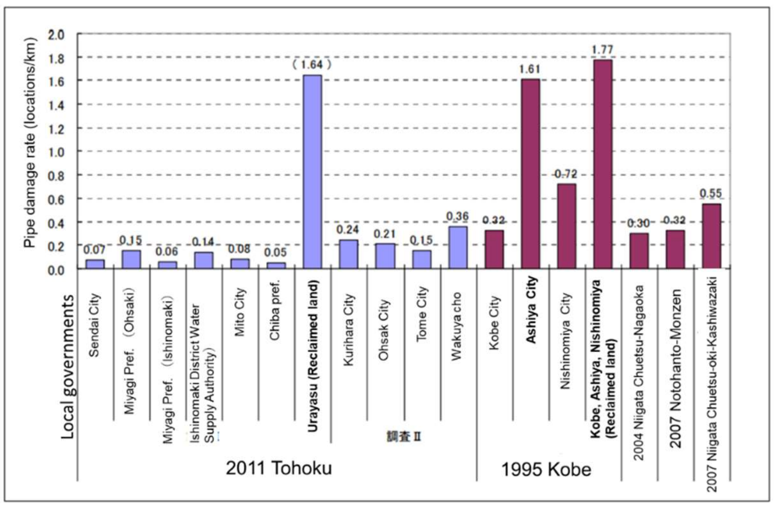
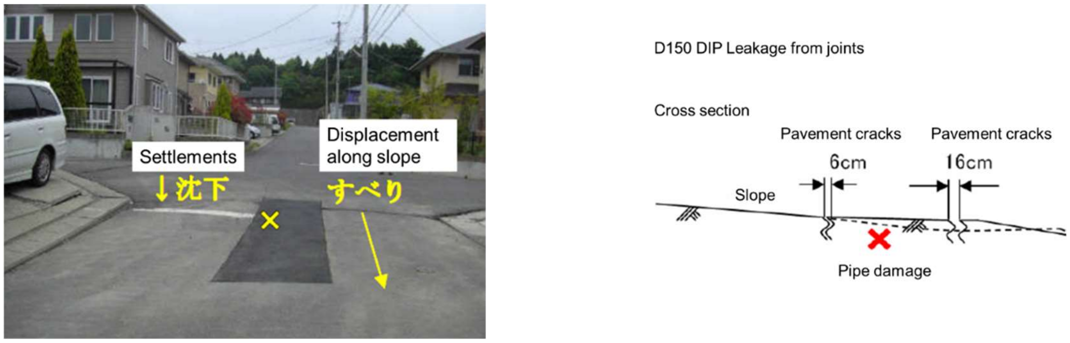



**Figure 2. Pipe damage rate obtained from the past 5 Japanese earthquake (JWWA 2012).**

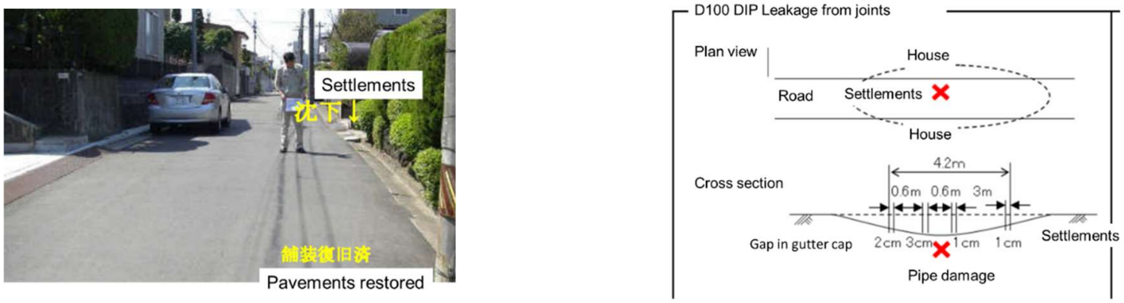
**(a)** **(b)**

**Figure 3. (a) Collapse of valley fill embankment after 2004 Niigata-ken Chuetsu, Japan, earthquake. (b) Manhole uplift after 2003 Tokachi-oki, Japan, earthquake.**



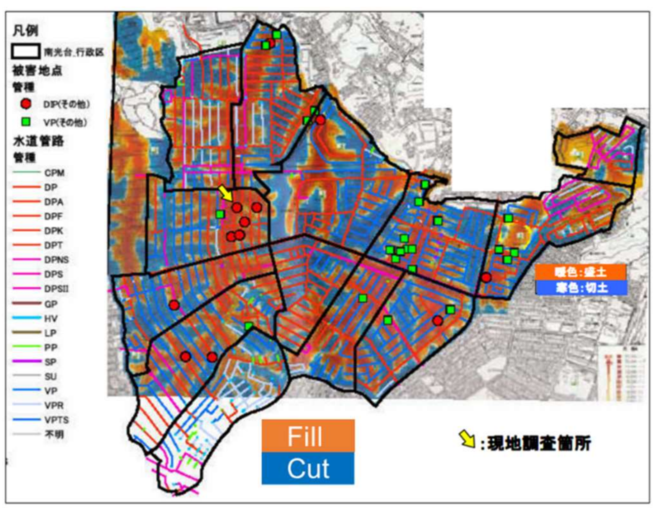

(a) (b)

**Figure 4. Example 1 of location of a pipe damage: (a) Paved road after repair works and (b) illustrated cross section of the site (JWWA 2012).**




(b) (b)

**Figure 5. Example 2 of location of a pipe damage: (a) Paved road after repair works and (b) illustrated cross section of the site (JWWA 2012)**




出典）㈱復建技術コンサルタント作成の造成宅地地盤図に仙台市水道局の提供データを加筆した。

図 2. 1. 7 管路被害と切盛土の分布（南光台）

**Figure 6. Distribution of pipeline damage, pipe type and cut and filled land (Nankodai, Sendai, Miyagi pref.) (JWWA 2012)**

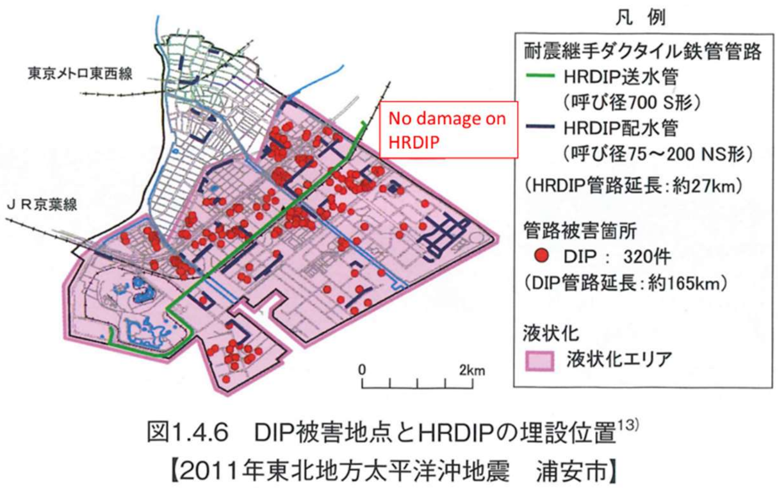



**Figure 7. Damaged and non-damaged pipes in Urayasu after 2011 Tohoku earthquake (Miyajima and Toshima 2022)**

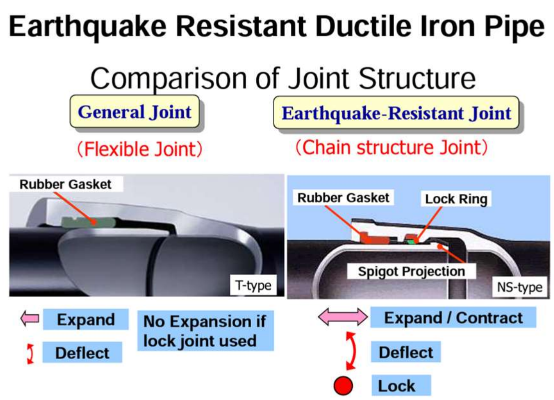



**Figure 8. Comparison of joint structure of ductile iron pipe (Davis 2013)**

## LESSONS LEARNED FROM DAMAGE ON WATER TREATMENT PLANT DUE TO LIQUEFACTION

After the 2011 Tohoku, Japan, earthquake, the Wanigawa WTP in Ibaragi Pref. (Fig. 9) suffered major damage due to liquefaction and was shutdown for one month until temporary restoration, and it took nearly one year for full recovery. The plant was constructed in 1982 and is located on Holocene ground near the Kita-Ura (lake). Figure 10 shows a time sequence of the photography of the plant 10 min after the main shock, and 1$^{st}$ and 2$^{nd}$ aftershocks. As shown, sand and water are ejected from the ground and as time goes by the ground settlements become prominent. Although the settlement of the utility conduits seem to be minor in the figure, it is reported that liquefied sand intruded to the conduits from the joints. Iwatsubo et al. (2023) conducted interview survey to the staffs of the plant and drew unexpected scenarios for the damage and recovery process as follows;

a. Multiple large after shocks caused gradual damage on facilities/pipelines.

b. Power outage made quick damage assessment difficult.
c. Electrical cables and chemical dosing pipeline in the utility tunnel were cut during recovery operation, because removal of sands in the tunnel unloaded the weight on it causing its displacement.
d. Clean up of sands intruded into facility caused additional delay.
e. Backfill material liquefied during recovery construction.
f. Operating staffs were not expecting damage due to liquefaction.
g. Staff members had to evacuate for every Tsunami warning.

In the restoration works, complex pipeline damages in the WTP as shown in Fig. 11 are manifested. Figure shows that deformation of single pipe may cause deformation of other pipes in the jungle of pipelines in a WTP.


写真 10.5-1　鰐川浄水場　（2011 年 3 月 12 日時点，Google earth より衛星写真を引用）

**Figure 9. Wanigawa water treatment plant after 2011 Tohoku earthquake (Kuwata and Katagiri, 2011)**


**Figure 10. (Contd.)**


**Figure 10. Time sequence of damage at Wanigawa WTP, Ibaraki Pref. after the main shock of the 2011 Tohoku earthquake (Iwatsubo et al. 2023).**

写真 10.5-8　取水ポンプ棟の管路取り合い部　　写真 10.5-9　取り合い部の継手の漏水

(a)　　(b)

**Figure 11. Complex pipeline damage at Wanigawa WTP, Ibaraki Pref. after the main shock of the 2011 Tohoku earthquake (Kuwata and Katagiri, 2022)**

## LESSONS LEARNED FROM DAMAGE ON WATER TREATMENT PLANT DUE TO LANDSLIDE

The Tomisato WTP, Atsuma-town, Hokkaido, Japan was severely damaged due to landslide occurred during the 2018 Hokkaido Iburi-Tobu, Japan, earthquake. The earthquake caused the landslide of volcanic layers of the ground in the largest area in recorded history of Japan. The WTP had been newly opened just two weeks before the earthquake. The damage was so serious that the pipeline connection between the water storage tank and the treatment facility was completely lost (Figs. 12 - 14). With this, the Atsuma-town decided urgently to use old facility and it was rebooted after two weeks. It took 34 days for repairments of leakage of distribution pipes in Atsuma town.

Lessons learned from this case as unexpected scenarios for the damage and recovery process are as follows (Iwatsubo et al. 2023);

a. Repair works for distribution pipes were hindered due to lack of sufficient amount of water in pipelines (pipes could not be filled with water).
b. The site was on a gentle slope (< 20 deg.), and construction near a gentle slope is not prohibited by the law (Fig. 15).
c. Only local civil engineers and geologists knew weathered volcanic soil is troublesome.
d. Damage on access road made transport of construction machinery difficult.
e. Restoration of WTP affects whole recovery process in a town.

**Figure 12. Damaged water storage tank at Tomisato WTP, Atsuma-town, Hokkaido after the 2018 Hokkaido Iburi-Tobu earthquake.**


**(a)** **(b)**

**Figure 13. Tomisato WTP (a) before (GSI 2002) and (b) after the 2018 Hokkaido Iburi-Tobu earthquake (after GSI 2022).**

**(a)** **(b)**

**Figure 14. Broken connection pipelines at Tomisato WTP.**

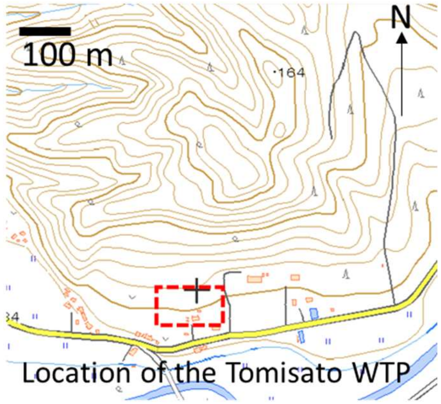



**Figure 15. Topographic map near Tomisato WTP (GSI 2022).**

## ANTI-CATASTROPHE CONCEPT FOR DAMAGE MINIMIZATION

An updated Water Works Guideline, Japan Water Works Association (JWWA) 2022, "Seismic Design Criteria and Guidelines for Water Supply Facilities," emphasizes to incorporate, in a design phase, the concept of "Anti-catastrophe" to minimize damage even in the events that exceeds predetermined design threshold. Iwatsubo et al. (2023) listed examples of anti-catastrophe measures:

a. Important structures should be placed in a site away from possible hazards.
b. Strong pipes (e.g., hazard resilient pipes) should be used.
c. Number of joints should be reduced.
d. WTP facility should be compactly constructed.
e. Ground deformation should be analyzed as precisely as possible.

Considerations listed above may have been already considered in a current design phase by designers. However, it may not be necessarily realized in practice. The anti-catastrophe concept enforces it in reality.

## CONCLUSIONS

Two particular lessons learned from the past large earthquakes are introduced. One is the damage to a WTP due to liquefaction, and the other is due to the earthquake-induced landslide of volcanic ground. Although hazardous conditions against pipelines are known from the lessons gathered from the past large earthquakes, it is very difficult to pin point the location of the damage on pipelines where only minor ground deformation occurred. Also it is fundamentally difficult to know exactly the level of the ground deformation under an earthquake at a site. Results of interview survey to staffs infer that it might have been difficult to anticipate such a large scale damage to the WTP. The important lesson here is to design pipelines and WTP that shall not catastrophically fail. Thus the concept of "Anti-catastrophe" is proposed and implemented to the updated Water Works Guideline, 2022, "Seismic Design Criteria and Guidelines for Water Supply Facilities." In addition to the above mentioned issues, development of advanced monitoring technics for detection of a subtle ground deformation/water leakage is strongly needed. Also, in the near future, a method to know the timing of replacement of HRDIP shall be implemented in the maintenance process.

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Miyajima, M., and Toshima, T. (2023) *Earthquake Engineering for Water Pipelines*, Suido Sangyo Shinbunsya, pp. 194.

Davis C. A. (2013) *Los Angles pilot project using Japanese earthquake resistant joint ductile iron pipe*, Presented to California-Nevada Section American Water Works Association < chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://ca-nv-awwa.org//canv/downloads/sessions/04/Session04_1630_Davis_Castruita.pdf> (Feb. 7 2023).

**Brad P. Wham, Presentation, University of Colorado Boulder, Associate Professor**
**Recent Advancements in Seismic Pipeline Performance Classification & Future Research Opportunities**

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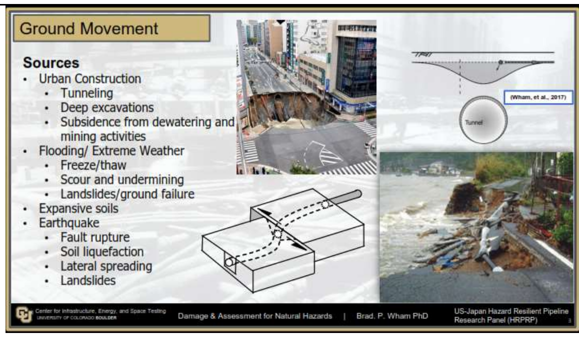


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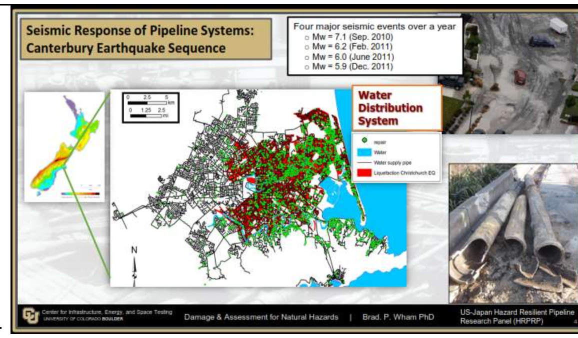


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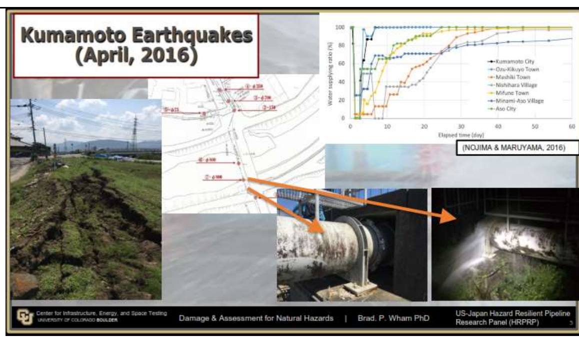


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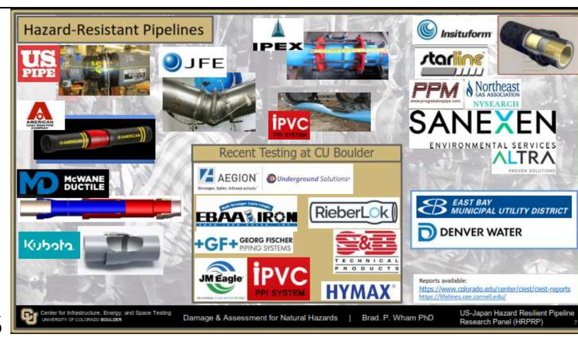


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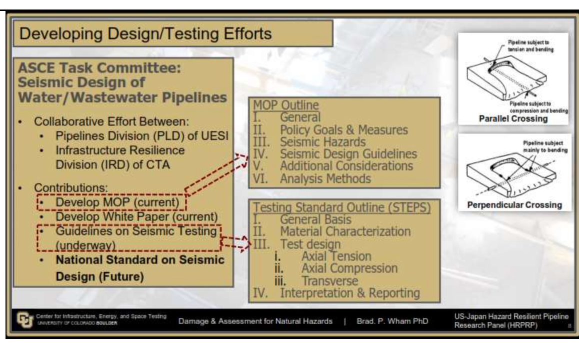


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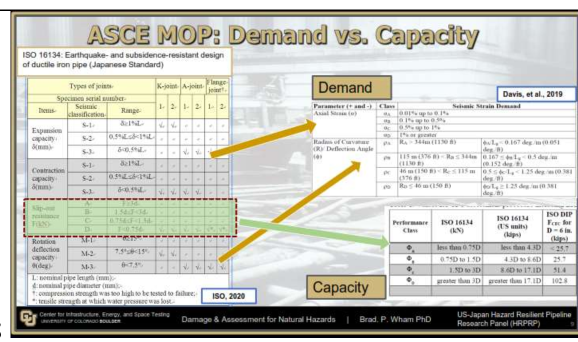

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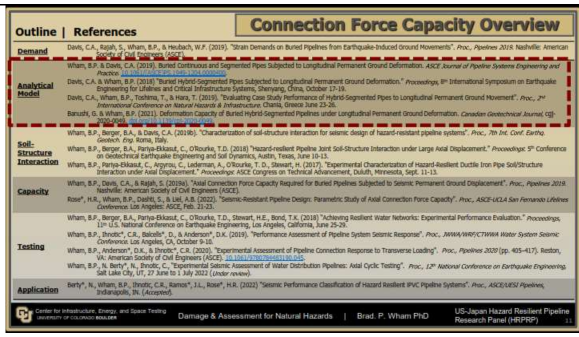


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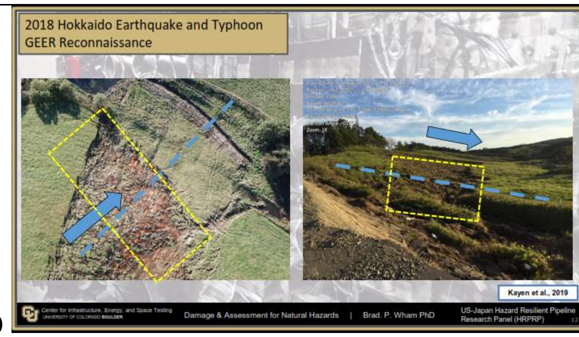


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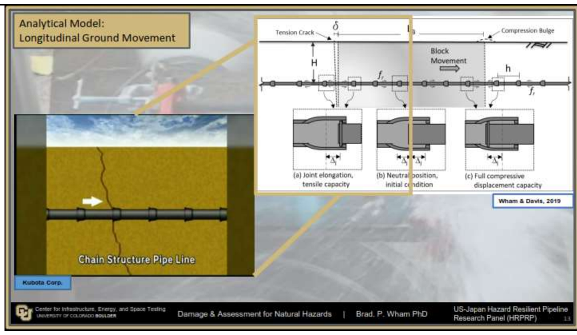


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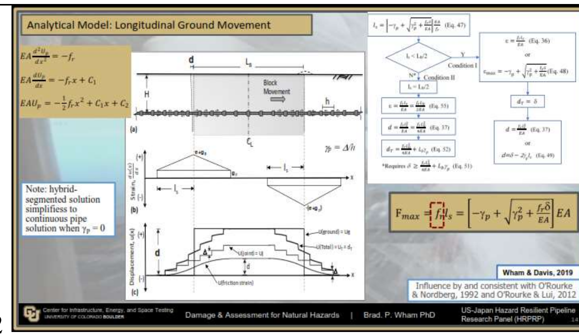


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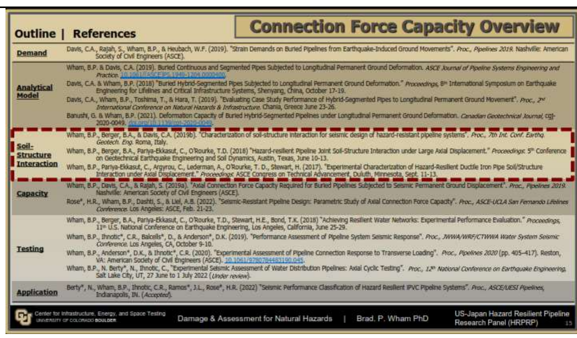


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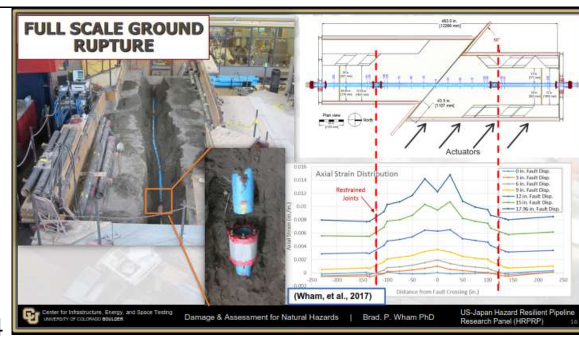


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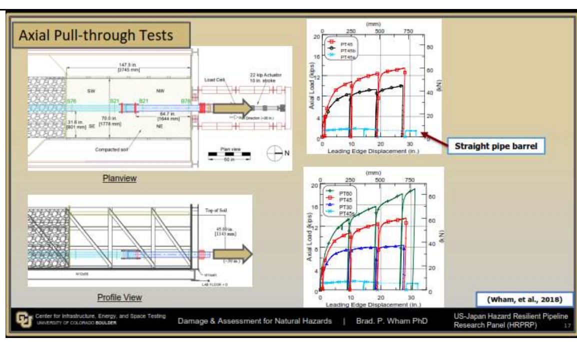


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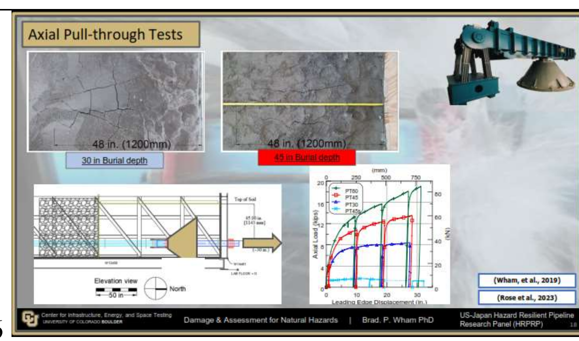

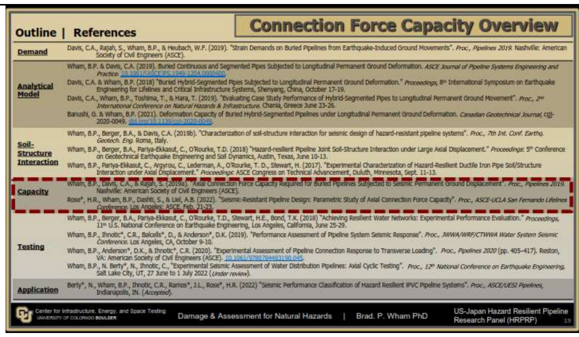


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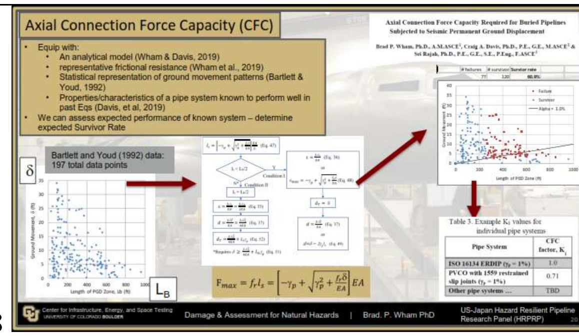


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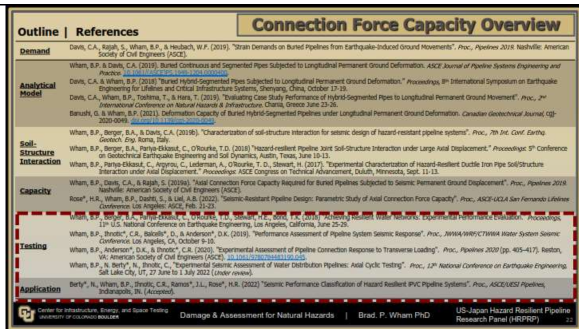


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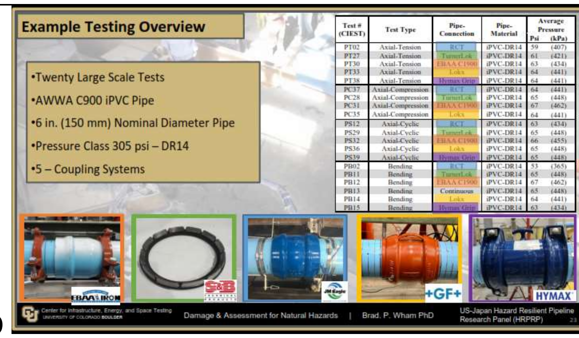


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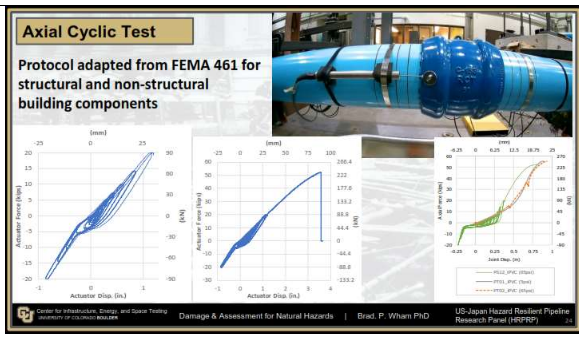


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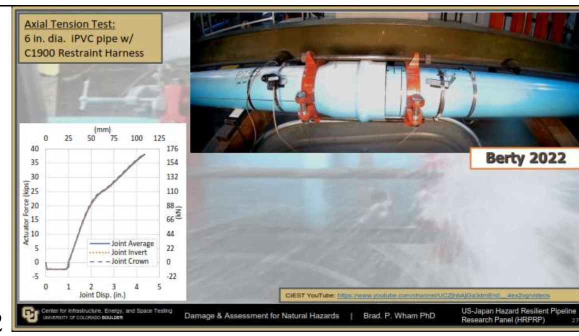


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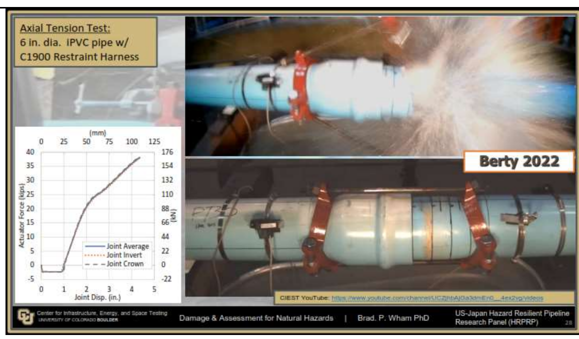


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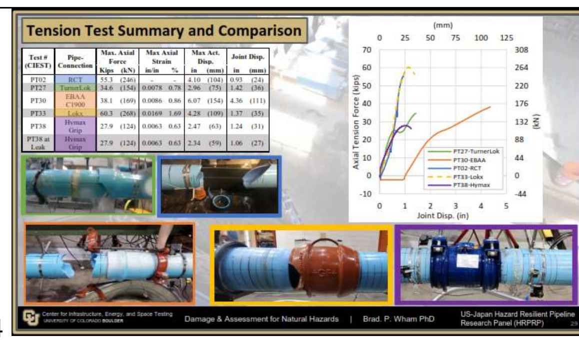


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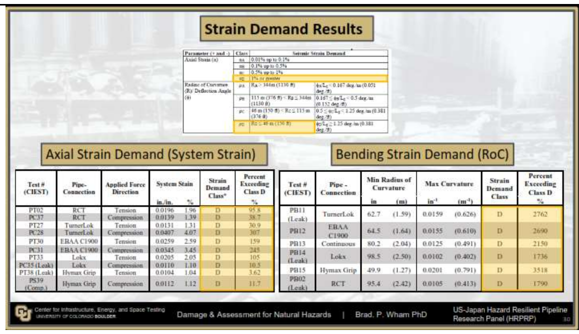

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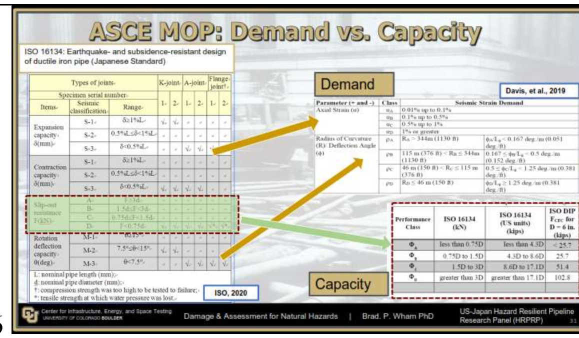

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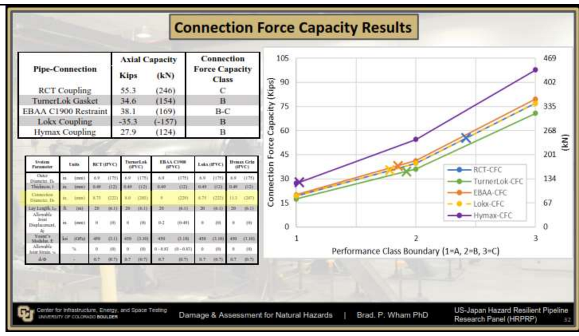

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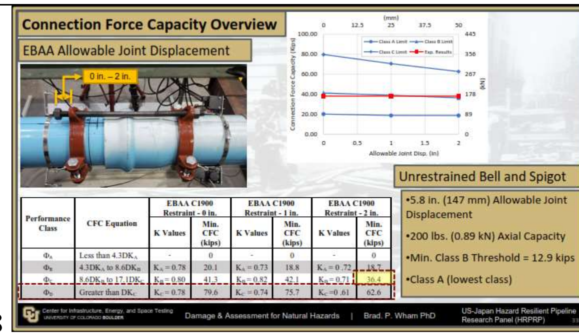

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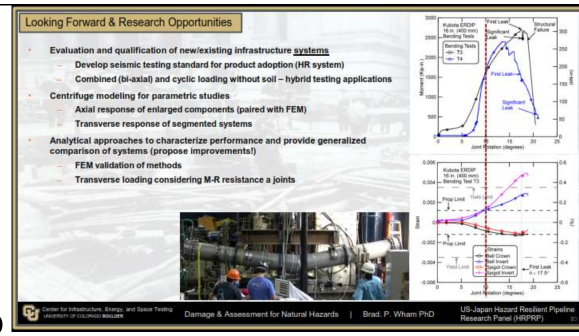

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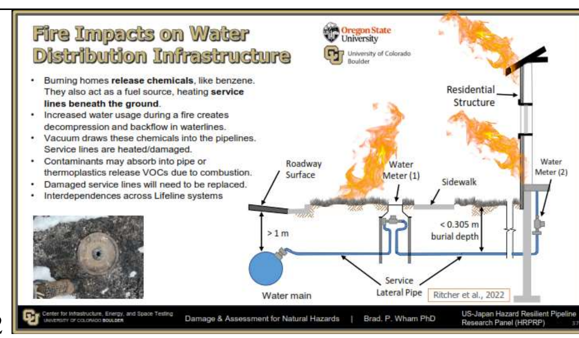

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Thank You!
Students & Colleagues:
Cory Ihnotic
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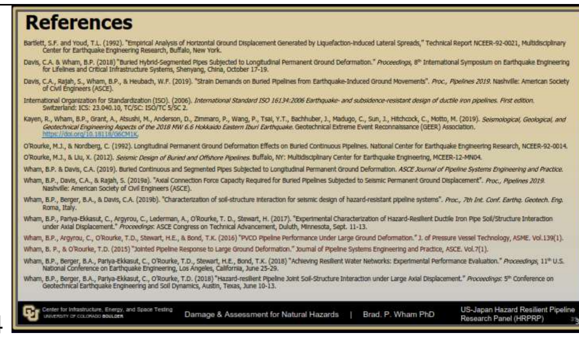
34 
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# Recent Advancements in Seismic Pipeline Performance Classification & Future Research Opportunities

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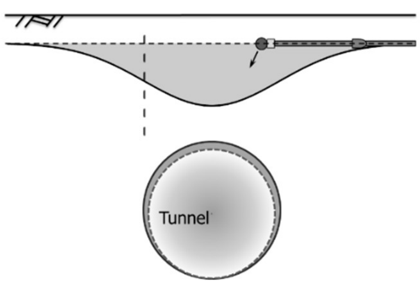
## ABSTRACT

Underground pipeline distribution systems are susceptible to damage when exposed to large ground motions produced by earthquake-induced fault rupture, landslides, and other significant seismic deformations. As technological advancements improve water distribution systems' ability to accommodate significant ground deformations, municipalities and pipeline designers need a systematic method to define and classify the seismic response and capacity of existing and developing pipeline systems. Currently, ISO 16134 is the only design standard that includes a seismic performance classification for pipelines. However, ISO 16134 only considers the axial capacity or Connection Force Capacity (CFC) of Earthquake-Resistant Ductile Iron Pipe (ERDIP) pipe and does not consider other commonly used pipeline materials. Recent work has expanded on ISO's performance classification to include other common pipeline materials so that systems can be systematically compared. The paper summarizes recent advances in providing a framework for how various systems can be assessed for seismic response, ultimately supporting ongoing development of ASCE's Manual of Practice on Seismic Design of Water and Wastewater Pipelines. Finally, future research needs an opportunities related to these developments are noted.

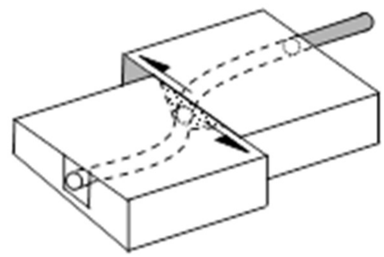
## INTRODUCTION

Many sources of ground movement may be imposed on buried infrastructure. Sources of ground movement include: Urban Construction (including, tunneling, deep excavations, subsidence from dewatering and mining activities), Flooding/ Extreme Weather (including freeze/thaw, scour and undermining, landslides/ground failure), expansive soils, and, of course, earthquake (e.g., fault rupture, soil liquefaction, lateral spreading, landslides). Figure 1 provides examples of several ground deformation modes. Figure 1(a) provides an example of construction activity that can cause pipeline deformation (Wham et al., 2016) while Figure 1(c), a sinkhole spanned a five-lane street stretching 30m (98ft) wide and 15m deep in Fukuoka, Japan, is an example of ground failure that can result from damaged (i.e., leaking) underground pipelines and further damage adjacent infrastructure systems. As the climate changes, Figure 1(d) shows an example of how coastal erosion from Typhoon can impact buried infrastructure and an example of a hazard-resilient pipeline system (i.e., ductile iron pipe with locking joints) can accommodate such challenges and continue to provide water supply.

Seismic events can be particularly damaging to buried systems, especially in regions prone to landsliding and liquefaction. The 2010-2011 Canterbury Earthquake sequence provides an unfortunate example of seismic impacts on pipeline systems where some 2000 pipeline repairs were required along approximately 2000 km of water distribution system. Figure 2(a) shows the water distribution pipeline system in Christchurch overlaid by areas of severe liquefaction in red. The green dots represent locations of pipeline repairs, which are largely correlated with the location of liquefaction, suggesting that pipeline damage was caused by permanent ground movements caused by liquefied soils. Figure 2(b) shows vectors of horizontal ground strain derived by LiDAR measurements taken before and after the event, demonstrating the direction, magnitude, and potential orientation of ground movement relative pipeline alignment (Toprak et al., 2018). Depending on the orientation of ground movement, pipelines may experience primary axial tension, axial compression, bending, or, for oblique crossings, a combination of the forementioned.




(a) tunnel induced settlement

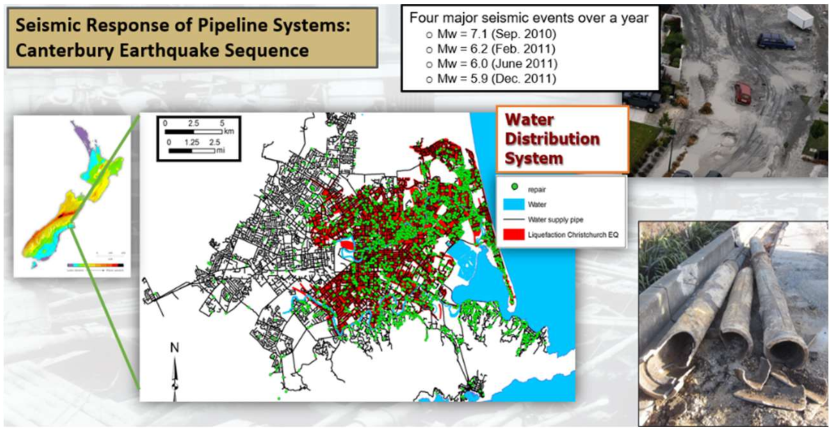


(b) fault rupture

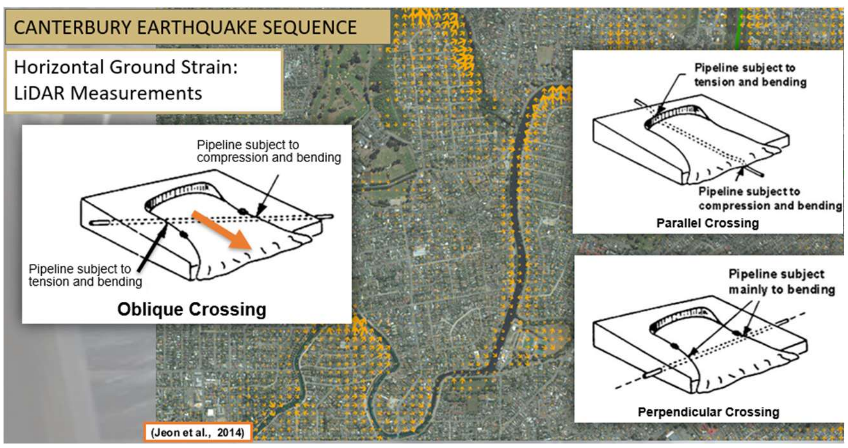
(c) sink hole (Japan)

(d) coastal erosion (Japan)

**Figure 1. Examples of ground deformation damaging pipelines**




(a)




(b)

**Figure 2. Canterbury Earthquake Sequence (a) liquified regions overlaid by pipeline damage and (b) ground strain measurements from LiDAR data**

Another example of ground deformation impacts on pipelines occurred during the 2016 Kumamoto, Japan earthquake. The earthquake series, which were focused outside of Kumamoto City located on the southern island of Kyushu, resulted in 450,000 people without water service initially and some 50,000 people without water 10 days after the event (Nojima & Maruyama, 2016). One site of particular interest was a lateral spread event, adjacent to parallel pipeline and traffic bridges crossing a tributary of the Midorikawa River at the east Kumamoto City limits (Wham et al., 2017) (Figure 3). Significant ground cracking was seen in the field to the northwest of the bridges (Kayen et al., 2016). The 800-mm steel pipeline carries emergency water supply to 57,000 people from reservoir tanks located in the agricultural field to the south over the river to populated residential districts. The pipe was equipped with slip joints to account for expansion/contraction (typical range of ±50 mm) near both the north and south abutments. During the event, leakage occurred at the slip joint close to the south abutment. Observations suggest leakage occurred due to over insertion of the joint, an indication that the banks of the river displaced as a result of the April 14 foreshock. It is likely a component capable of larger compressive displacements, or greater compressive force capacity may have survived the imposed deformation and continued uninterrupted conveyance of emergency water supply across the river.

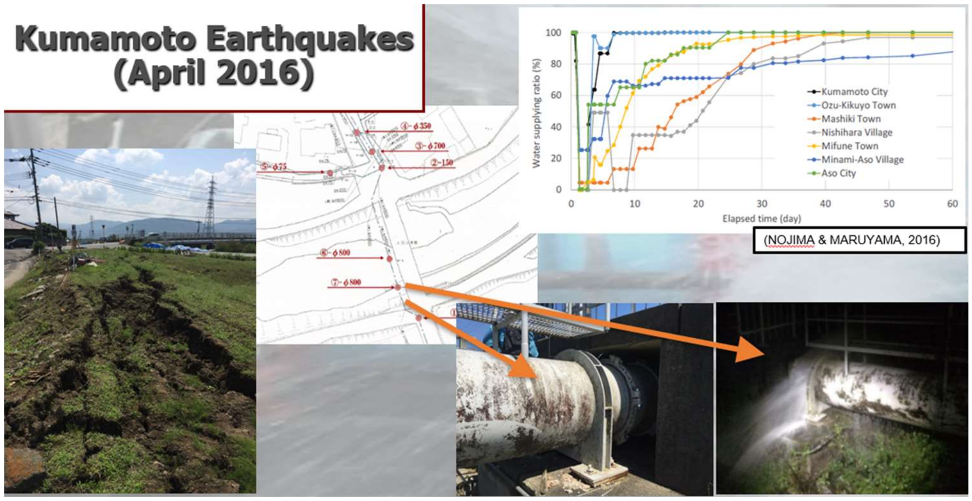



**Figure 3. Steel pipeline damage as a result of the Kumamoto, Japan earthquakes**

## DEVELOPING SEISMIC DESIGN GUIDELINES IN THE USA

Despite the significant damages to underground distribution systems being reported in past seismic events, industry standards have remained largely unchanged with little consideration for seismic design criteria. Current acceptance standards primarily pertain to hydrostatic loading produced by internal pressure and material testing, such as ASTM D1599 (2018) hydrostatic burst testing and ASTM D638 (2014) tensile strength testing (AWWA, 2007). However, experimental testing has shown that pipeline systems subjected to external loading representative of earthquake-induced ground deformations can fail at axial stresses far less than those developed during hydrostatic burst testing (Ihnotic, 2019).

The only current industry design standard pertaining to the seismic design of buried pipeline systems is ISO16134: Earthquake- and subsidence-resistant design of ductile iron pipelines (International Organization for Standardization (ISO), 2020) (Table 1). ISO16134 provides performance classes for the slip-out resistance, also more broadly referred to as the Connection Force Capacity (CFC), based on the nominal pipe diameter, D. While ISO provides recommended performance classes for pipelines of various diameters, the classification system only considers Earthquake Resilient Ductile Iron Pipe (ERDIP) systems and does not consider other materials, connection types, or geotechnical inputs such as burial depth or backfill conditions.

**Table 1. ISO 16134 Performance Class Values (Tables 3 and 4)**

| Parameter | Class | Component performance |
|---|---|---|
| Expansion/contraction performance | S-1 | ±1 % of $L$ or more |
| | S-2 | ±0,5 % to less than ±1 % of $L$ |
| | S-3 | Less than ±0,5 % of $L$ |

| Parameter | Class | Component performance |
|---|---|---|
| Slip-out resistance | A | 3 $d$ kN or more |
| | B | 1,5 $d$ kN to less than 3 $d$ kN |
| | C | 0,75 $d$ kN to less than 1,5 $d$ kN |
| | D | Less than 0,75 $d$ kN |
| Joint deflection angle | M-1 | $\theta_a$ or more |
| | M-2 | $\theta_a/2$ to less than $\theta_a$ |
| | M-3 | Less than $\theta_a/2$ |

**Key**

$L$ the component length, in millimetres (mm)

$d$ the nominal diameter of pipe, in millimetres (mm)

$\theta_a$ the joint deflection angle as shown in Table 4, in degrees (°)

| Nominal diameter $d$ | 80 to 400 | 450 to 1 000 | 1 100 to 1 500 | 1 600 to 2 200 | 2 400 to 2 600 |
|---|---|---|---|---|---|
| Joint deflection angle $\theta_a$ | 8° | 7° | 5°30′ | 4° | 3°30′ |
| (Ref) Pipe length[a] | 6 m | 6 m | 6 m | 5 m | 4 m |

[a] Ductile iron pipe is available in shorter lengths and, where needed, can be cut during installation to achieve greater pipeline deflection over shorter pipeline lengths.

The pipelines division of the Utility Engineering and Surveying Institute (UESI) is currently developing a Manual of Practice (MOP) designed to provide guidance to engineers when working in regions with varying levels of seismic risk. Current developing seismic design guidelines within the MOP consider three metrics for pipeline assessment. The first two are associated with seismic demand and were proposed by Davis et al. (2019): (1) axial strain demand, and (2) transverse strain demand, as shown in Table 2. The classification values are associated with ground strains, and define the amount of ground movement a system would need to withstand to be classified into a particular system.

**Table 2. Seismic Demand Levels Proposed by Davis et al. (2019)**

| Parameter (+ and -) | Class | Seismic Strain Demand | |
|---|---|---|---|
| Axial Strain (α) | $\alpha_A$ | 0.01% up to 0.1% | |
| | $\alpha_B$ | 0.1% up to 0.5% | |
| | $\alpha_C$ | 0.5% up to 1% | |
| | $\alpha_D$ | 1% or greater | |
| Radius of Curvature (R)/ Deflection Angle (ϕ) | $\rho_A$ | $R_A$ > 344m (1130 ft) | $\phi_A/L_g < 0.167$ deg./m (0.051 deg./ft) |
| | $\rho_B$ | 115 m (376 ft) < $R_B \leq$ 344m (1130 ft) | $0.167 \leq \phi_B/L_g < 0.5$ deg./m (0.152 deg./ft) |
| | $\rho_C$ | 46 m (150 ft) < $R_C \leq$ 115 m (376 ft) | $0.5 \leq \phi_C/L_g < 1.25$ deg./m (0.381 deg./ft) |
| | $\rho_D$ | $R_D \leq$ 46 m (150 ft) | $\phi_D/L_g \geq 1.25$ deg./m (0.381 deg./ft) |

## CONNECTION FORCE CAPACITY

The third metric is (3) connection force capacity, which is akin to and expands upon the ISO's classification of "slip-out resistance" such that multiple pipeline systems with different material characteristics and connection types can be classified. This metric falls on the seismic capacity side of the equation and Table 3 provides an overview of the sequence of publications that have progressed this pipeline classification method.

**Table 3. Sequence of publication relevant to determining axial Connection Force Capacity for pipeline systems**

**Connection Force Capacity Overview**

| Outline | References |
|---|---|
| **Demand** | Davis, C.A., Rajah, S., Wham, B.P., & Heubach, W.F. (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements". *Proc., Pipelines 2019.* Nashville: American Society of Civil Engineers (ASCE). |
| **Analytical Model** | Wham, B.P. & Davis, C.A. (2019). Buried Continuous and Segmented Pipes Subjected to Longitudinal Permanent Ground Deformation. *ASCE Journal of Pipeline Systems Engineering and Practice.* 10.1061/(ASCE)PS.1949-1204.0000400.<br>Davis, C.A. & Wham, B.P. (2018) "Buried Hybrid-Segmented Pipes Subjected to Longitudinal Permanent Ground Deformation." *Proceedings,* 8th International Symposium on Earthquake Engineering for Lifelines and Critical Infrastructure Systems, Shenyang, China, October 17-19.<br>Davis, C.A., Wham, B.P., Toshima, T., & Hara, T. (2019). "Evaluating Case Study Performance of Hybrid-Segmented Pipes to Longitudinal Permanent Ground Movement". *Proc., 2nd International Conference on Natural Hazards & Infrastructure.* Chania, Greece June 23-26.<br>Banushi, G. & Wham, B.P. (2021). Deformation Capacity of Buried Hybrid-Segmented Pipelines under Longitudinal Permanent Ground Deformation. *Canadian Geotechnical Journal,* cgj-2020-0049. doi.org/10.1139/cgj-2020-0049. |
| **Soil-Structure Interaction** | Wham, B.P., Berger, B.A., & Davis, C.A. (2019b). "Characterization of soil-structure interaction for seismic design of hazard-resistant pipeline systems". *Proc., 7th Int. Conf. Earthq. Geotech. Eng.* Roma, Italy.<br>Wham, B.P., Berger, B.A., Pariya-Ekkasut, C., O'Rourke, T.D. (2018) "Hazard-resilient Pipeline Joint Soil-Structure Interaction under Large Axial Displacement." *Proceedings*: 5th Conference on Geotechnical Earthquake Engineering and Soil Dynamics, Austin, Texas, June 10-13.<br>Wham, B.P., Pariya-Ekkasut, C., Argyrou, C., Lederman, A., O'Rourke, T. D., Stewart, H. (2017). "Experimental Characterization of Hazard-Resilient Ductile Iron Pipe Soil/Structure Interaction under Axial Displacement." *Proceedings*: ASCE Congress on Technical Advancement, Duluth, Minnesota, Sept. 11-13. |
| **Capacity** | Wham, B.P., Davis, C.A., & Rajah, S. (2019a). "Axial Connection Force Capacity Required for Buried Pipelines Subjected to Seismic Permanent Ground Displacement". *Proc., Pipelines 2019.* Nashville: American Society of Civil Engineers (ASCE).<br>Rose*, H.R., Wham, B.P., Dashti, S., & Liel, A.B. (2022). "Seismic-Resistant Pipeline Design: Parametric Study of Axial Connection Force Capacity". *Proc., ASCE-UCLA San Fernando Lifelines Conference.* Los Angeles: ASCE, Feb. 21-23. |
| **Testing** | Wham, B.P., Berger, B.A., Pariya-Ekkasut, C., O'Rourke, T.D., Stewart, H.E., Bond, T.K. (2018) "Achieving Resilient Water Networks: Experimental Performance Evaluation." *Proceedings,* 11th U.S. National Conference on Earthquake Engineering, Los Angeles, California, June 25-29.<br>Wham, B.P., Ihnotic*, C.R., Balcells*, D., & Anderson*, D.K. (2019). "Performance Assessment of Pipeline System Seismic Response". *Proc., JWWA/WRF/CTWWA Water System Seismic Conference.* Los Angeles, CA, October 9-10.<br>Wham, B.P., Anderson*, D.K., & Ihnotic*, C.R. (2020). "Experimental Assessment of Pipeline Connection Response to Transverse Loading". *Proc., Pipelines 2020* (pp. 405–417). Reston, VA: American Society of Civil Engineers (ASCE). 10.1061/9780784483190.045.<br>Wham, B.P., N. Berty*, N., Ihnotic, C., "Experimental Seismic Assessment of Water Distribution Pipelines: Axial Cyclic Testing". *Proc., 12th National Conference on Earthquake Engineering,* Salt Lake City, UT, 27 June to 1 July 2022 (*Under review*). |
| **Application** | Berty*, N., Wham, B.P., Ihnotic, C.R., Ramos*, J.L., Rose*, H.R. (2022) "Seismic Performance Classification of Hazard Resilient iPVC Pipeline Systems". *Proc., ASCE/UESI Pipelines,* Indianapolis, IN. (*Accepted*). |

In summary, Wham & Davis, (2019) propose an analytical model to define the Connection Force Capacity of various pipeline systems (Figure 4). The model quantifies the axial demand on a pipeline system, as a function of frictional resistance along the system, by considering various geometric combinations of ground movements (i.e., block length and ground displacement), pipeline geometry, and various soil characteristics. Wham et al. (2019b) propose a multiplication factor K, defined by comparing the calculated CFC of ERDIP systems that have performed well during past earthquakes to a system of interest (SOI) under the same ground movements and soil characteristics (Figure 5). The K factor is used to define the system's performance classes in relation to ISO standards ($3DK_C$, $1.5DK_B$, and $0.75DK_A$).

While these developing standard guidelines seek to provide background on expected ground deformations seen in the field, few studies have implemented these methods to classify pipeline system responses through laboratory testing.

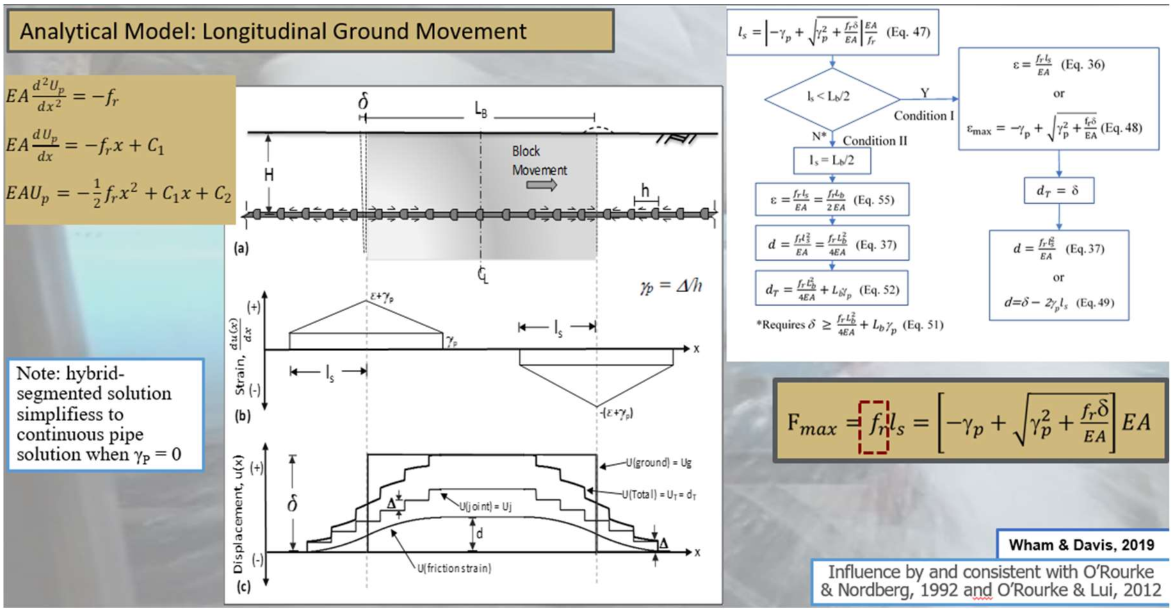



**Figure 4. Analytical model for longitudinal ground deformation proposed by Wham & Davis (2019)**

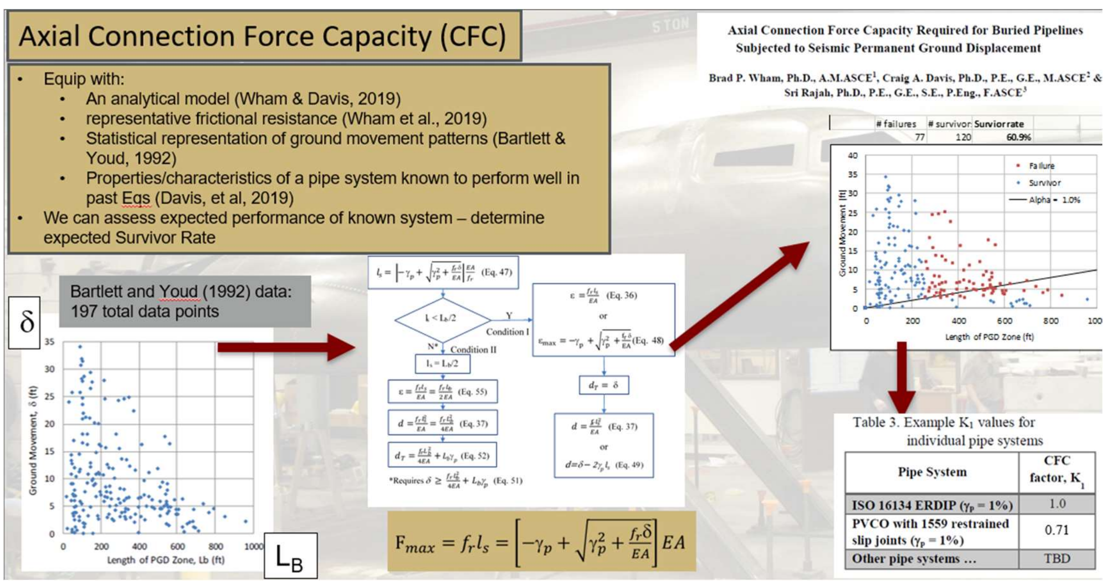



**Figure 5. Overview of method proposed for determining material independent CFC**

## EXPERIMENTAL SEISMIC ASSESSMENT

Testing methods are necessary to classify pipeline systems for seismic performance. Berty et al. (2022) report on a series of full-scale experiments identifying a pipeline's response to permanent ground displacements. The testing was performed on 6-in. (150-mm) diameter DR14 PVC pipe with various mechanically restrained joints (Berty, 2022). Figure 6 provides an overview of the various tests performed on five distinct coupling systems. The results focus on categorizing the axial and transverse response of each tested pipeline system into seismic performance classes.

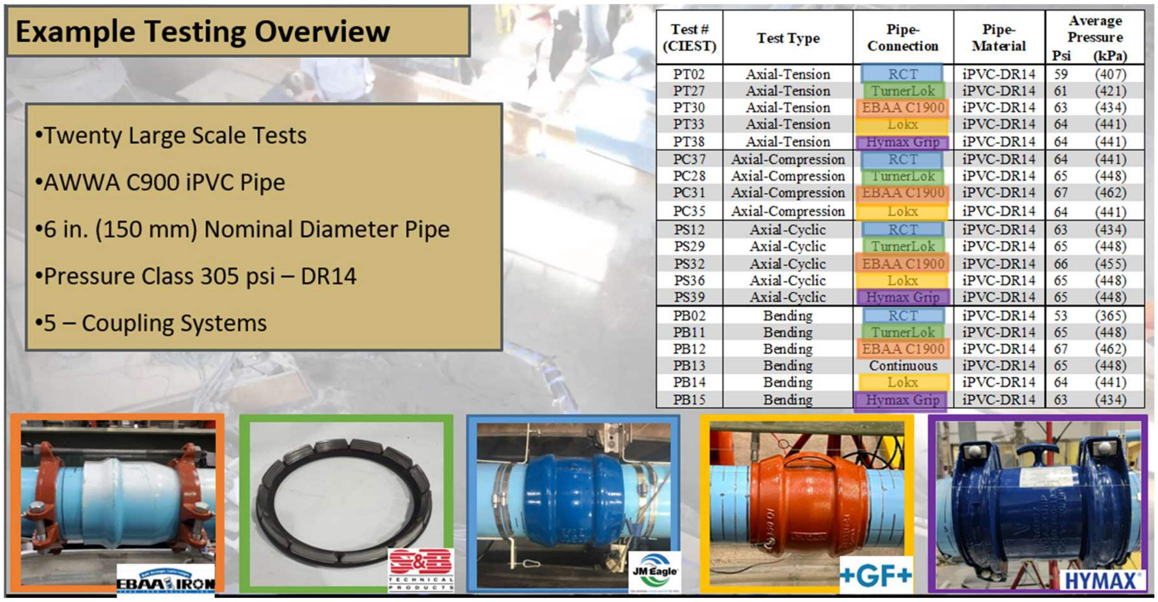



**Figure 6. Overview of PVC testing with various connection types**

Figure 7 shows example test results for axial tension test. The axial force vs. joint displacement plot is used to identify upper bound performance of each coupling system prior to serviceability failure (i.e., leakage) and ultimate failure. Examples of failure modes are also provided.

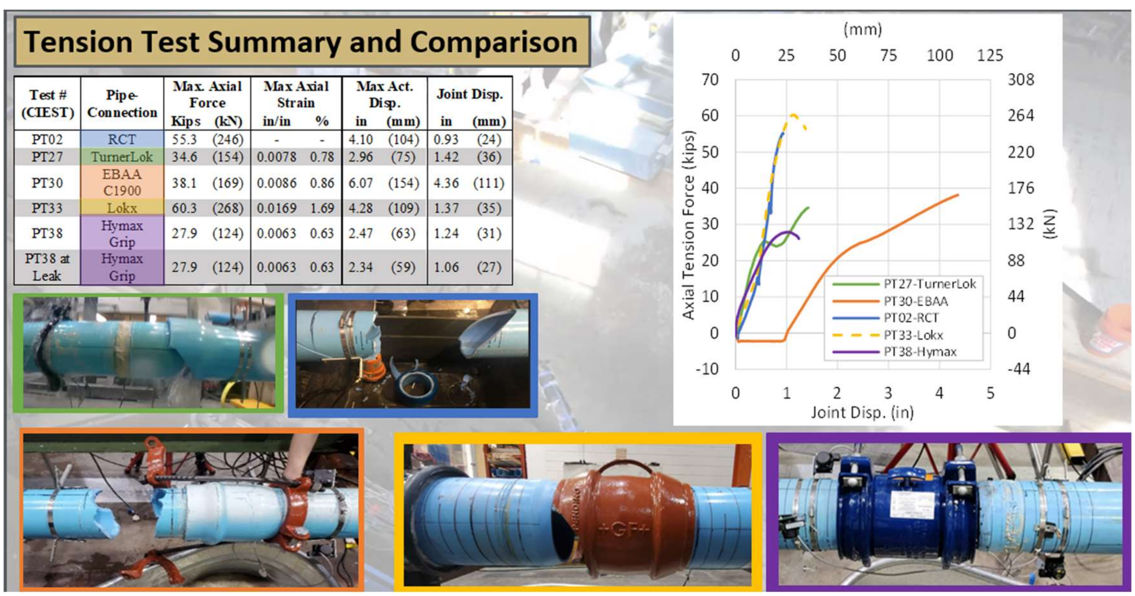
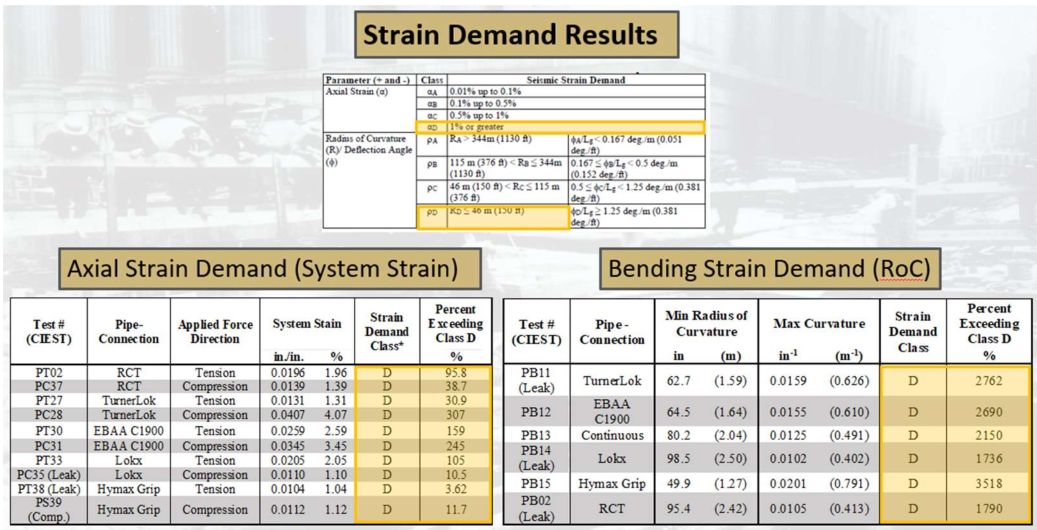



**Figure 7. Example of Seismic performance test on 6-in. pipe**

Figure 8 presents the strain demand class for each tested system in both tension and compression. Each test generated a system strain greater than the highest class threshold of 1% defined by Davis et al., (2019), placing each system in the highest seismic strain demand class of D. This suggests that the iPVC pipeline systems satisfy the strain demands to maintain integrity in field conditions when subjected to axial ground movements. The figure also shows that each system far exceeds the bending, or transverse, strain demand relative to Davis et al., 2019 classification levels.



Strain Demand Results

| Parameter (+ and -) | Class | Seismic Strain Demand | |
|---|---|---|---|
| Axial Strain ($\alpha$) | $\alpha_A$ | 0.01% up to 0.1% | |
| | $\alpha_B$ | 0.1% up to 0.5% | |
| | $\alpha_C$ | 0.5% up to 1% | |
| | $\alpha_D$ | 1% or greater | |
| Radius of Curvature (R)/ Deflection Angle ($\phi$) | $\rho_A$ | $R_A$ > 344m (1130 ft) | $\phi_A/L_g$ < 0.167 deg./m (0.051 deg./ft) |
| | $\rho_B$ | 115 m (376 ft) < $R_B$ ≤ 344m (1130 ft) | 0.167 ≤ $\phi_B/L_g$ < 0.5 deg./m (0.152 deg./ft) |
| | $\rho_C$ | 46 m (150 ft) < $R_C$ ≤ 115 m (376 ft) | 0.5 ≤ $\phi_C/L_g$ < 1.25 deg./m (0.381 deg./ft) |
| | $\rho_D$ | $R_D$ ≤ 46 m (150 ft) | $\phi_D/L_g$ ≥ 1.25 deg./m (0.381 deg./ft) |

Axial Strain Demand (System Strain)

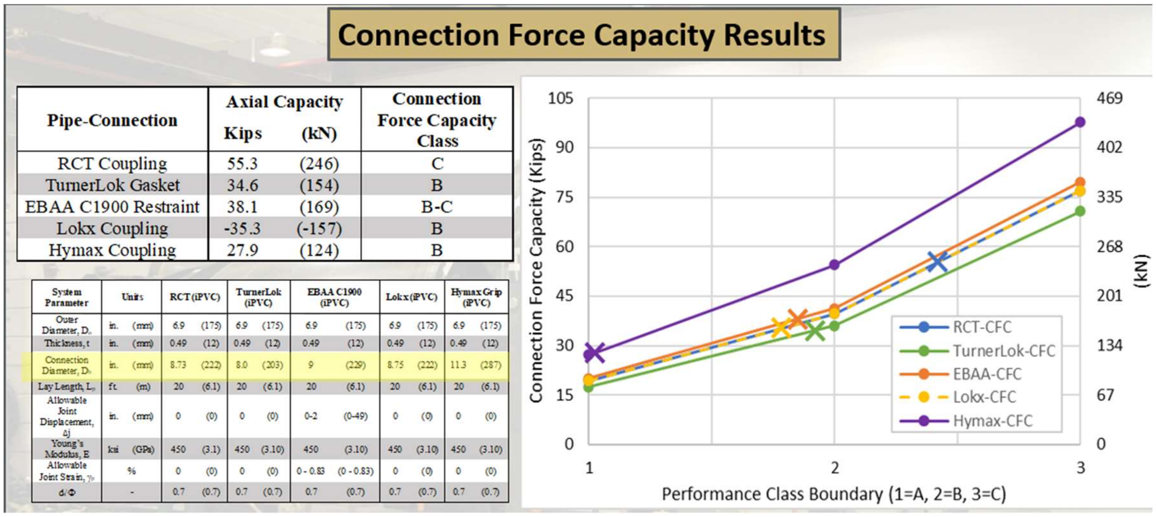
| Test # (CIEST) | Pipe-Connection | Applied Force Direction | System Stain | | Strain Demand Class* | Percent Exceeding Class D |
|---|---|---|---|---|---|---|
| | | | in./in. | % | | % |
| PT02 | RCT | Tension | 0.0196 | 1.96 | D | 95.8 |
| PC37 | RCT | Compression | 0.0139 | 1.39 | D | 38.7 |
| PT27 | TurnerLok | Tension | 0.0131 | 1.31 | D | 30.9 |
| PC28 | TurnerLok | Compression | 0.0407 | 4.07 | D | 307 |
| PT30 | EBAA C1900 | Tension | 0.0259 | 2.59 | D | 159 |
| PC31 | EBAA C1900 | Compression | 0.0345 | 3.45 | D | 245 |
| PT33 | Lokx | Tension | 0.0205 | 2.05 | D | 105 |
| PC35 (Leak) | Lokx | Compression | 0.0110 | 1.10 | D | 10.5 |
| PT38 (Leak) | Hymax Grip | Tension | 0.0104 | 1.04 | D | 3.62 |
| PS39 (Comp.) | Hymax Grip | Compression | 0.0112 | 1.12 | D | 11.7 |

Bending Strain Demand (RoC)

| Test # (CIEST) | Pipe-Connection | Min Radius of Curvature | | Max Curvature | | Strain Demand Class | Percent Exceeding Class D |
|---|---|---|---|---|---|---|---|
| | | in | (m) | $in^{-1}$ | ($m^{-1}$) | | % |
| PB11 (Leak) | TurnerLok | 62.7 | (1.59) | 0.0159 | (0.626) | D | 2762 |
| PB12 | EBAA C1900 | 64.5 | (1.64) | 0.0155 | (0.610) | D | 2690 |
| PB13 | Continuous | 80.2 | (2.04) | 0.0125 | (0.491) | D | 2150 |
| PB14 (Leak) | Lokx | 98.5 | (2.50) | 0.0102 | (0.402) | D | 1736 |
| PB15 | Hymax Grip | 49.9 | (1.27) | 0.0201 | (0.791) | D | 3518 |
| PB02 (Leak) | RCT | 95.4 | (2.42) | 0.0105 | (0.413) | D | 1790 |

**Figure 8. Strain demand classification of PVC pipeline systems**

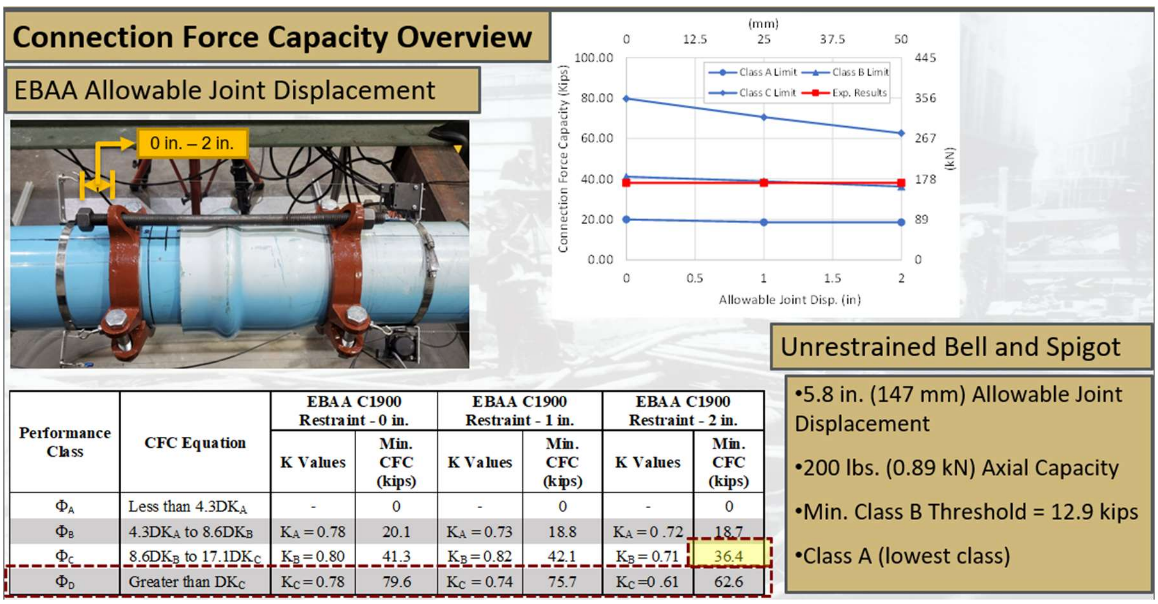
While each axial and transverse strain demand response for the testing exceeded the highest classification level, the connection force capacity results vary. Figure 9 provides the CFC class for each of the systems tested. All systems achieved a minimum classification of B following procedures previously outlines. Two systems reached class C, depending on the circumstances. The RCT test has the highest tested force capacity, which allowed it to exceed the class of others. The EBAA restraint, when allowing for greater than 2 in. of axial displacement before locking up the joint, was also able to achieve class C (Figure 10). If allowable axial displacement is 1 in. or less, the connection remains in the lower class B, demonstrating the importance of providing axial displacement capacity (this axial displacement capacity is why ERDIP is capable of accommodating large levels of ground movement). No coupling tested achieved the highest class, D.




| Pipe-Connection | Axial Capacity Kips | (kN) | Connection Force Capacity Class |
|---|---|---|---|
| RCT Coupling | 55.3 | (246) | C |
| TurnerLok Gasket | 34.6 | (154) | B |
| EBAA C1900 Restraint | 38.1 | (169) | B-C |
| Lokx Coupling | -35.3 | (-157) | B |
| Hymax Coupling | 27.9 | (124) | B |

| System Parameter | Units | | RCT (iPVC) | | TurnerLok (iPVC) | | EBAA C1900 (iPVC) | | Lokx (iPVC) | | Hymax Grip (iPVC) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Diameter, $D_o$ | in. | (mm) | 6.9 | (175) | 6.9 | (175) | 6.9 | (175) | 6.9 | (175) | 6.9 | (175) |
| Thickness, t | in. | (mm) | 0.49 | (12) | 0.49 | (12) | 0.49 | (12) | 0.49 | (12) | 0.49 | (12) |
| Connection Diameter, $D_b$ | in. | (mm) | 8.73 | (222) | 8.0 | (203) | 9 | (229) | 8.75 | (222) | 11.3 | (287) |
| Lay Length, $L_p$ | ft. | (m) | 20 | (6.1) | 20 | (6.1) | 20 | (6.1) | 20 | (6.1) | 20 | (6.1) |
| Allowable Joint Displacement, Δj | in. | (mm) | 0 | (0) | 0 | (0) | 0-2 | (0-49) | 0 | (0) | 0 | (0) |
| Young's Modulus, E | ksi | (GPa) | 450 | (3.1) | 450 | (3.10) | 450 | (3.10) | 450 | (3.10) | 450 | (3.10) |
| Allowable Joint Strain, $\gamma_p$ | % | | 0 | (0) | 0 | (0) | 0 - 0.83 | (0 - 0.83) | 0 | (0) | 0 | (0) |
| d/Φ | - | | 0.7 | (0.7) | 0.7 | (0.7) | 0.7 | (0.7) | 0.7 | (0.7) | 0.7 | (0.7) |

**Figure 9. Seismic connection force capacity classification for tested specimens**




| Performance Class | CFC Equation | EBAA C1900 Restraint - 0 in. K Values | Min. CFC (kips) | EBAA C1900 Restraint - 1 in. K Values | Min. CFC (kips) | EBAA C1900 Restraint - 2 in. K Values | Min. CFC (kips) |
|---|---|---|---|---|---|---|---|
| $\Phi_A$ | Less than $4.3DK_A$ | - | 0 | - | 0 | - | 0 |
| $\Phi_B$ | $4.3DK_A$ to $8.6DK_B$ | $K_A = 0.78$ | 20.1 | $K_A = 0.73$ | 18.8 | $K_A = 0.72$ | 18.7 |
| $\Phi_C$ | $8.6DK_B$ to $17.1DK_C$ | $K_B = 0.80$ | 41.3 | $K_B = 0.82$ | 42.1 | $K_B = 0.71$ | 36.4 |
| $\Phi_D$ | Greater than $DK_C$ | $K_C = 0.78$ | 79.6 | $K_C = 0.74$ | 75.7 | $K_C = 0.61$ | 62.6 |

**Figure 10. Example of Seismic performance test on 6-in. pipe**

## CONCLUSITONS & RESEARCH OPPORTUNITIES

This paper provides an overview of recent advancements in seismic design guidelines for water distribution pipelines. An overview of a method to classify various systems for seismic performance based on both strain demand and axial connection force capacity is discussed. Despite the advancements, several research needs exist to further seismic design practice and the resiliency of water distribution systems:

- Continued evaluation and qualification of new/existing infrastructure systems is needed to establish seismic capacity and encourage further advancements. A seismic testing standard, currently under development through ASCE, is needed to standardize methods and procedures.

- In addition to the primary loading tests outlined (i.e., axial and transverse bending), combined (bi-axial) testing is encouraged to better understand how systems respond to oblique crossings. Bi-axial testing would serve to identify primary ranges of combined loading under which various systems perform to the highest seismic capacity, and combinations of loading that may encourage design alterations or modifications (Ramos et al., 2024).
- While pipeline capacity in the axial direction is considered in both ISO and the developing MOP, both documents omit transverse or bending moment capacity. Currently, pipelines are prescribed an "allowable" deflection angle (across a joint) or radius of curvature along a pipe barrel. However, they do not take into account the moment capacity of the connection after the joint locks up and resists further motion. For smaller diameter pipelines and materials of lower modulus, this moment capacity is likely small relative to the demands imposed by ground movement. However, for large diameter pipelines, especially those of ferrous materials, taking into account the moment capacity of a joint is expected to significantly resist imposed soil displacements (Wham et al., 2019c). Consideration of joint moment-rotation capacity, following a procedure akin to CFC, is a valuable and needed research subject for further numerical analysis and experimental testing.
- To define the importance of moment-rotation response of pipeline joints and connections, centrifuge modeling is a valuable tool. Parametric studies of large diameter pipeline systems crossing faults, scaled down through the use of centrifugal acceleration, would be an inexpensive method to collect valuable data defining the soil-structure interactions associated with pipelines of varying transverse joint properties. Defining under what circumstances the moment capacity of the joint can resist ground movement (rather than the typical and conservative assumption that the pipeline moves with the ground) would serve as a basis for developing an analytical framework for introducing moment capacity into a seismic design classification system. Centrifuge testing would also inform numerical models that, once verified through reduced-scale experiments, could extrapolate results to other diameters and joint/connection configurations, aiding both pipeline design in the field and advancing product design.
- Earthquakes are not the only natural hazard that pipelines face. Climate changes impose additional challenges to our built environment. One example is the increasing impact of wildfire on infrastructure systems and resulting contamination that can cause long-term challenges (Fischer et al., 2022; Whelton et al., 2023). While researchers are striving to better understand where various types of contamination originate from, and how they migrate through a water distribution system (e.g., Ellsworth et al., 2020; Richter et al., 2022), conducting carefully designed fire susceptibility and contamination migration testing would aid water utilities in understanding how various pipe materials perform during and shortly following an urban wildfire scenario, and may help establish which materials are best suited for high wild fire risk regions.

## ACKNOWLEDGEMENTS

The author recognizes the excellent effort of University of Colorado students and staff that made the included experimental procedures successful. Specifically, Cory Ihnotic, Jessica Ramos, Hailey-Rae Rose, Nicholas Berty, David Balcells, Katherine O'Dell, Kent Polkinghorne, and John Hindman. Appreciation is extended to East Bay Municipal Utility Department and Denver Water for providing financial support, as well as PPI Pyungwha, JM Eagle, EBAA Iron, and S&B Technical Products for test specimens and research support.

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**Nagahisa Hirayama, Presentation, Nagoya University, Associate Professor**
**Water Outage and Fire Fighting Water**

NAGOYA UNIVERSITY

Water Outage and
Fire Fighting Water

2nd HRPRP Meeting
@UC Berkeley Richmond field station
2022.11.08

Nagahisa Hirayama

名古屋大学減災連携研究センター
Disaster Mitigation Research Center, NAGOYA UNIVERSITY

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## Water Outage in Natural Disaster

| | Impact | Number of Customers | Outage Duration |
|---|---|---|---|
| 1995 Kobe Earthquake | Mj7.3 | **1.3M** | 90 days |
| 2004 Niigata Earthquake | Mj6.8 | 130K | 30 days |
| 2004 NotoHanto Earthquake | Mj6.9 | 13K | 14 days |
| 2007 NiigataChuetsuoki Earthqauke | Mj6.8 | 59K | 20 days |
| 2009 Kyushu Hokubu Heavy Rain | rainfall: 129.5mm/h | 87K | 11 days |
| 2011 Tohoku Disaster | M9.0 | **2.3M** | 5 months |
| 2016 Kumamoto Earthquake | M7.3 | 446K | 100 days |
| 2018 Northern Osaka Pref. Earthquake | M6.1 | 94K | 2 days |
| 2018 West Japan Heavy Rain | rainfall: 82.4B | 264K | 30 days |
| 2018 Hokkaido Iburi Tobu Earthquake | Mj6.7 | 68K | 34 days |
| 2019 Typhoon No. 15 | Peak gust 57.5m/s | 139K | 17 days |

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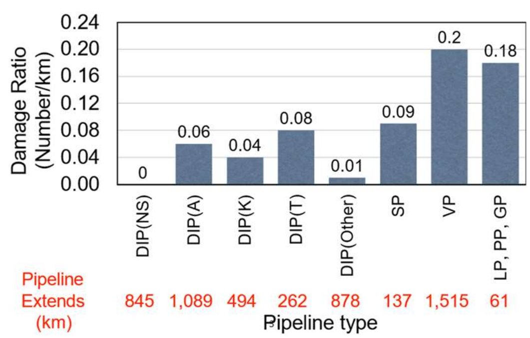
## Damage Ratio of Pipeline in City of Sendai

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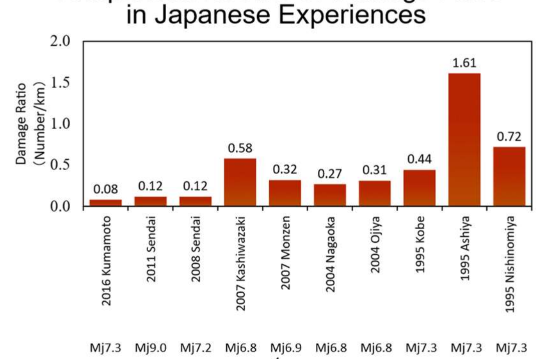
## Comparison Results of Damage Ratio in Japanese Experiences

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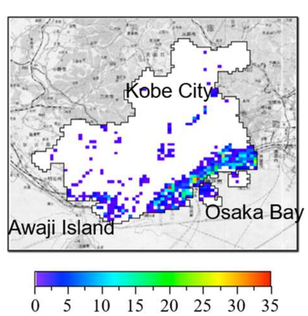
## Distribution Map of Damaged Pipes in Kobe

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## Water main, pipe break

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6

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## Damaged Pipes (Kobe City Waterworks Bureau)

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## Emergency Response to Water Outage

8 8

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## Temporary Water Station in Kobe City in 1995

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## Emergency Water Supply Station in Niigata

10 10

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## Emergency Water Supply by Tank Car

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## Number of Damaged Pipes and Duration of Water Outage

- Number of damaged pipes (damage estimation model) + emergency restoration process (number of engineers, external support) + duration of water interruption
- Seismic Vulnerability Assessment of Lifeline Networks
  - ✓ Hazard + Vulnerability + The extended length of pipelines

$$V = \frac{\sum_i\sum_j C_{d_i} C_{P_j} L_{ij}}{\sum_i\sum_j L_{ij}}$$ (Nojima, 2008)

- Correlation between restoration period and pipe damage ratio

$Day_{90} = 0.38 \cdot x_1^{0.86} \cdot x_2^{0.59}$ (Tsukamoto and et al., 2005)

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## Emergency water supply station

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## Disaster Community Training at KOBE primary school

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## 2018 West Japan Heavy Rain Disaster

15 ©Asahi, 2018

16

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## Damage to Water Treatment Plant in Ehime

16 ©後藤隆昭, 2018

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## Temporary Water Treatment Plant


17 ©後藤隆昭, 2018

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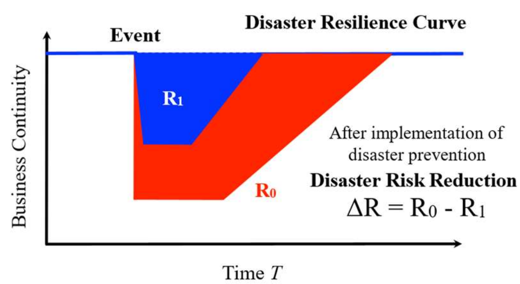
## Disaster Resilient in Water System

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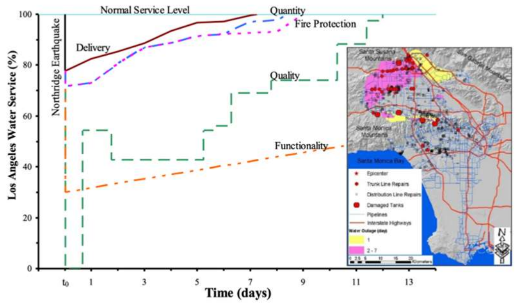
## 1994 NORTHRIDGE EARTHQUAKE L.A. WATER RESTORATIONS

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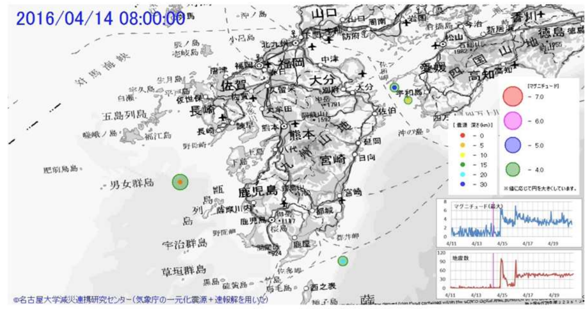
## 2016 Kumamoto earthquake




©Disaster Mitigation Research Center, Nagoya University, 2016

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## 1995 Kobe and 2016 Kumamoto earthquake

| | 2016 Kumamoto | 1995 Kobe |
|---|---|---|
| Fault Activity | Hinaku & Nutagawa | Nojima |
| Time & Date | April 16, 2016, 1:25 | January 17, 1995, 5:46 |
| Magnitude | Mj 7.3 | Mj 7.3 |
| Earthquake type | Intra-plate earthquake | Intra-plate earthquake |
| Death | 272【50】 | 6,434【5,500】 |
| Damaged municipal gov. | Kumamoto | Hyogo and Osaka |
| Damaged housing | 8,640 | 104,906 |
| Evacuation | 180K | 320K |
| Cause of death | relevant to the earthquake | crushing and/or suffocation by building collapse |
| Disaster debris | 3.02 millions ton | 14.50 millions ton |

21

©Kumamoto Pref., 2019, ©Hyogo Pref., 2008

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## 2016 Kumamoto Earthquake, Mashiki Town KiK-net Mashiki, Japanese Seismic Scale 7

22

©NIED, 2016

22

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## Damage to Water Facility in Nishihara, 2016 Kumamoto Earthquake

23

©Konaka, 2016

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## Damage to Water Facility in Nishihara, 2016 Kumamoto Earthquake


23

©Konaka, 2016

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## Pipeline Damage

25 ©Konaka, 2016

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## Damage to Wastewater & Drainage System due to Liquefaction


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## Water system in Kumamoto


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## Boil water advisory/notice/order

- ✓ a public health advisory or directive given by government or health authorities to consumers when a community's drinking water is, or could be, contaminated by pathogens.
- ✓ Under a boil-water advisory (BWA), the Centers for Disease Control and Prevention recommends that water be brought to a rolling boil for one minute before it is consumed in order to kill protozoa, bacteria and viruses.

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## Supply drinking water with limit intake notice in emergency

- ✓ Advisory of manager of water supply section, Ministry of Labour, health, and welfare on 31 March, 2016.
- ✓ Suspension of drinking water supply, water act 23
  - > harmful immediately
  - > directly affect to human body
- ✓ **CANNOT** meet water quality standard
- ✓ continue to supply drinking water with limit intake notice

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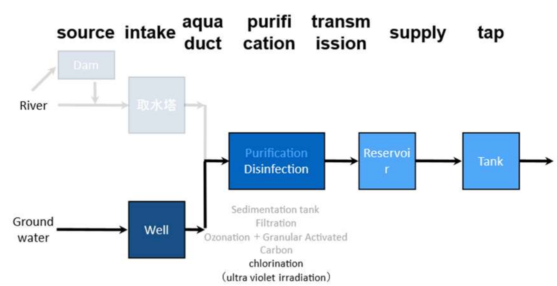
## Water system in Kumamoto region

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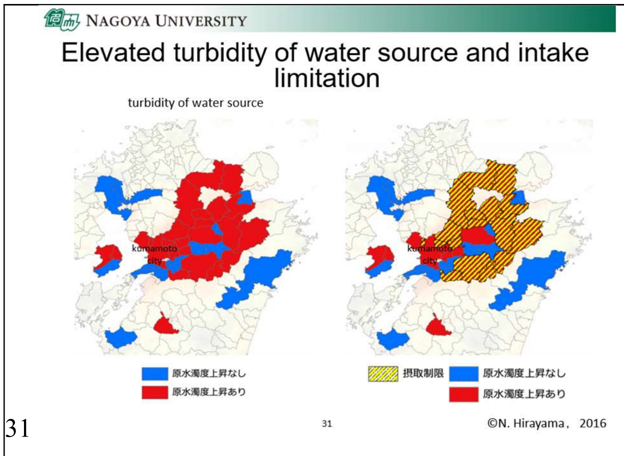


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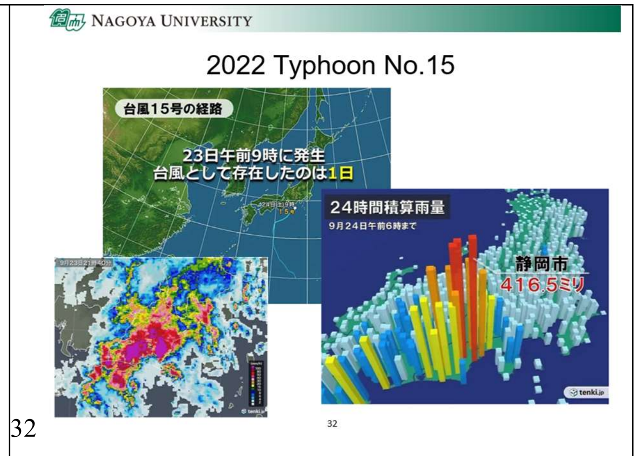


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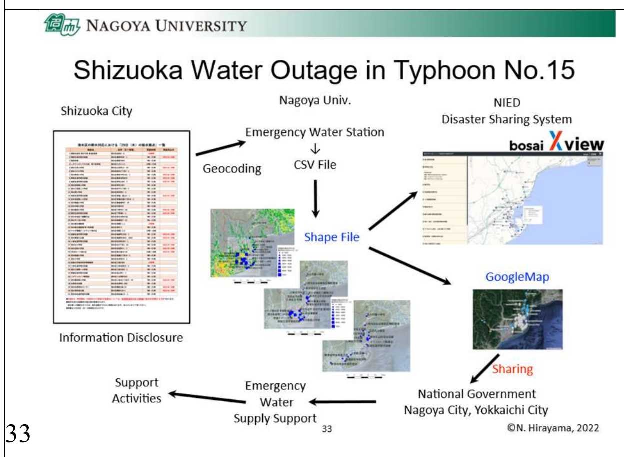


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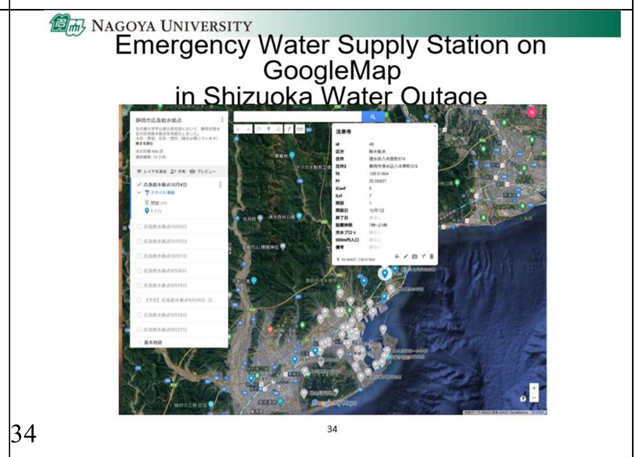


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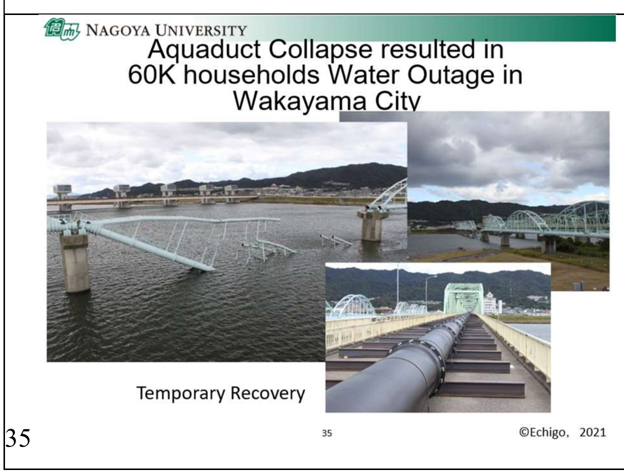


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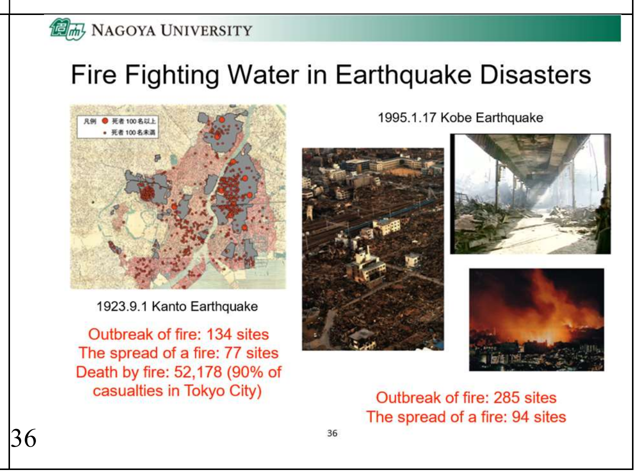


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## Fire and Pipe Break Balboa Boulevard

- 5 homes burned here
- 120 mobile homes burned
- 470 fires reported

37 37 ©Craig A., Davis, 2012

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38 38 ©DRI

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39 39 ©DRI

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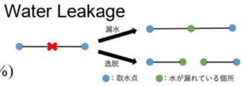
## Evaluation of Fire Protection in Emergency

- Water Distribution Analysis with Water Leakage
  - ✓ EPANET 2.0
  - ✓ Leakage (20%) or Deviation (80%)
  - ✓ Water Leak: $Q = C \times P^{\alpha}$, $C = 2.0 \times 10^{-3}$, $\alpha = 1.15$



- Evaluation Method
  - ✓ Fire Fighting Water: 3.0 m $^3$/min
  - ✓ When fire fighting water pull out of at a point as a fire hydrant, this hydrant is available in a case that the water pressure of all of the next points are positive.
  - ✓ Calculate the ratio of available fire hydrants

40 40

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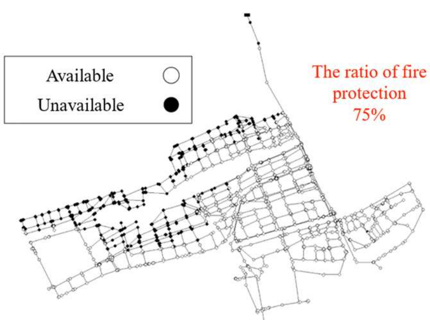
## A result of Fire Protection in Kobe Pipe Network

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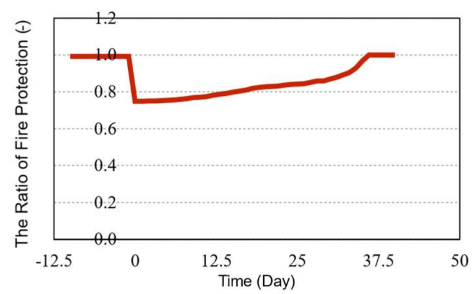
## Evaluation Result of Fire Protection by Disaster Resilience Curve

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## Depopulation Society in Japan

- Water Supply System
  - ✓ Adaptation, Aging pipeline network, Downsizing
- Fire Fighting System
  - ✓ Transition of fire fighting tactics, Technological innovation
- Fire Fighting Water
  - ✓ Dependence on water system
  - ✓ 40 m3, 1m3/min in 40 min, Pipe diameter over 150 mm
- Tradeoff between water and fire fighting

43

43

# Water Outage and Firefighting Water

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## ABSTRACT

In this paper, examples of damage to water supply systems during natural disasters in Japan will be described, and the importance of hazard resilience pipelines will be discussed. Then, the recent studies on the relationship between pipeline damage and water supply interruption damage are reviewed, and a resilient water supply system is discussed. The case of emergency water supply, as one of the disaster responses of water utilities in the aftermath of water supply disruptions, is described, and water quality management in emergency situations in Japan and United States is discussed. In addition, a case study of information sharing at emergency water supply stations after Typhoon No. 15 in 2022 will be presented. Finally, the necessity of securing water for firefighting during disasters is discussed, and the evaluation method of firefighting function by disaster resilience curves after disasters is outlined.

## INTRODUCTION

Water supply systems are indispensable lifelines for the lives of citizens and socioeconomic activities. To ensure a stable supply of water even in the event of a large-scale disaster, it is necessary to reduce damage to the water supply system itself through earthquake resistance and to realize a robust water supply system that can be quickly restored after a disaster (Ministry of Health, Labour and Welfare, 2013). However, as of the end of FY2019, the status of quake-resistant waterworks facilities remains low: 40.9% of water main are quake-resistant, 32.6% of water purification facilities are quake-resistant, and 58.6% of water distribution reservoirs are quake-resistant.

In this paper, examples of damage to water supply systems during natural disasters in Japan will be described. The recent studies on the relationship between pipeline damage and water supply interruption damage are reviewed. Thus, the case of emergency water supply activities as well as information sharing are described. And water quality management in emergency situations in Japan and United States is discussed. Finally, the necessity of securing water for firefighting during disasters is discussed, and the evaluation method of firefighting function by disaster resilience curves after disasters is outlined.

## WATER OUTAGE IN NATURAL DISASTER IN JAPAN

### Water Outage in Japan

In Japan, water supply systems have been damaged by natural disasters, resulting in water outages. In the case of earthquake disasters, 1.3 million people had their water supply interrupted for 90 days after 1995 Great Hanshin-Awaji Earthquake, 2.3 million people had their water supply interrupted for 5 months after 2011 Tohoku Disasters. And 264,000 people had their water supply cut off for 30 days after the 2018 West Japan Heavy Storm Disaster in the case of flood damage. The water supply interruption caused by natural disasters in Japan is shown in Table 1.

**Table 1. Water Outage in Natural Disasters in Japan**

| | Impact | Number of Customers | Outage Duration |
|---|---|---|---|
| 1995 Kobe Earthquake | Mj7.3 | **1.3M** | 90 days |
| 2004 Niigata Earthquake | Mj6.8 | 130K | 30 days |
| 2004 NotoHanto Earthquake | Mj6.9 | 13K | 14 days |
| 2007 NiigataChuetsuoki Earthqauke | Mj6.8 | 59K | 20 days |
| 2009 Kyushu Hokubu Heavy Rain | rainfall: 129.5mm/h | 87K | 11 days |
| 2011 Tohoku Disaster | M9.0 | **2.3M** | 5 months |
| 2016 Kumamoto Earthquake | M7.3 | 446K | 100 days |
| 2018 Northern Osaka Pref. Earthquake | M6.1 | 94K | 2 days |
| 2018 West Japan Heavy Rain | rainfall: 82.4B | 264K | 30 days |
| 2018 Hokkaido Iburi Tobu Earthquake | Mj6.7 | 68K | 34 days |
| 2019 Typhoon No. 15 | Peak gust 57.5m/s | 139K | 17 days |

During an earthquake, water supply could be cut off over a wide supply area due to damage to water pipelines. Figure 1 shows the ratio of water pipeline damage by pipe type in Sendai City after the 2011 Great East Japan Earthquake. Figure 2 shows strong-motion waveforms observed in Aoba Ward, Sendai City. The seismic intensity of the quake was just below 6 on the Japanese seismic scale, and the shaking lasted for about 170 seconds. The peak ground acceleration was 1808 cm/s$^2$ and the peak ground velocity was 83 cm/s.

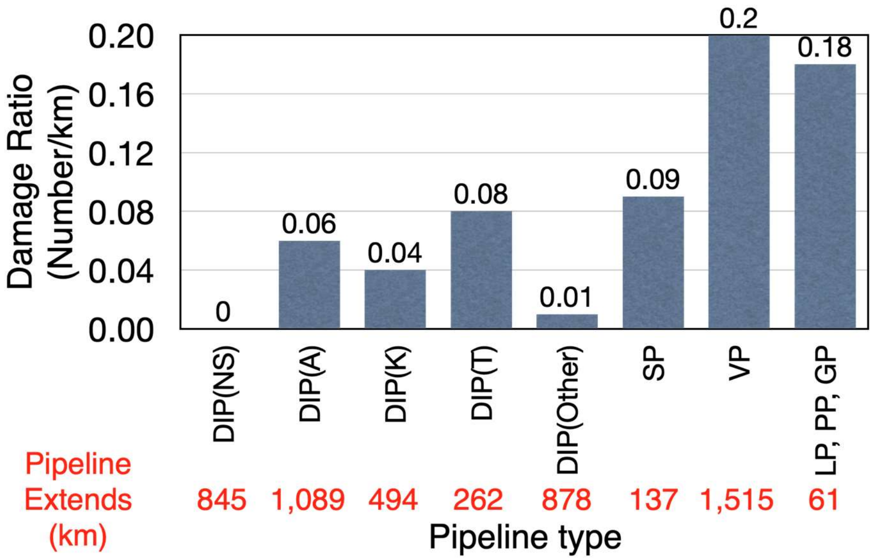


**Figure 1. Damage Ratio of Pipeline in City of Sendai in 2011.**

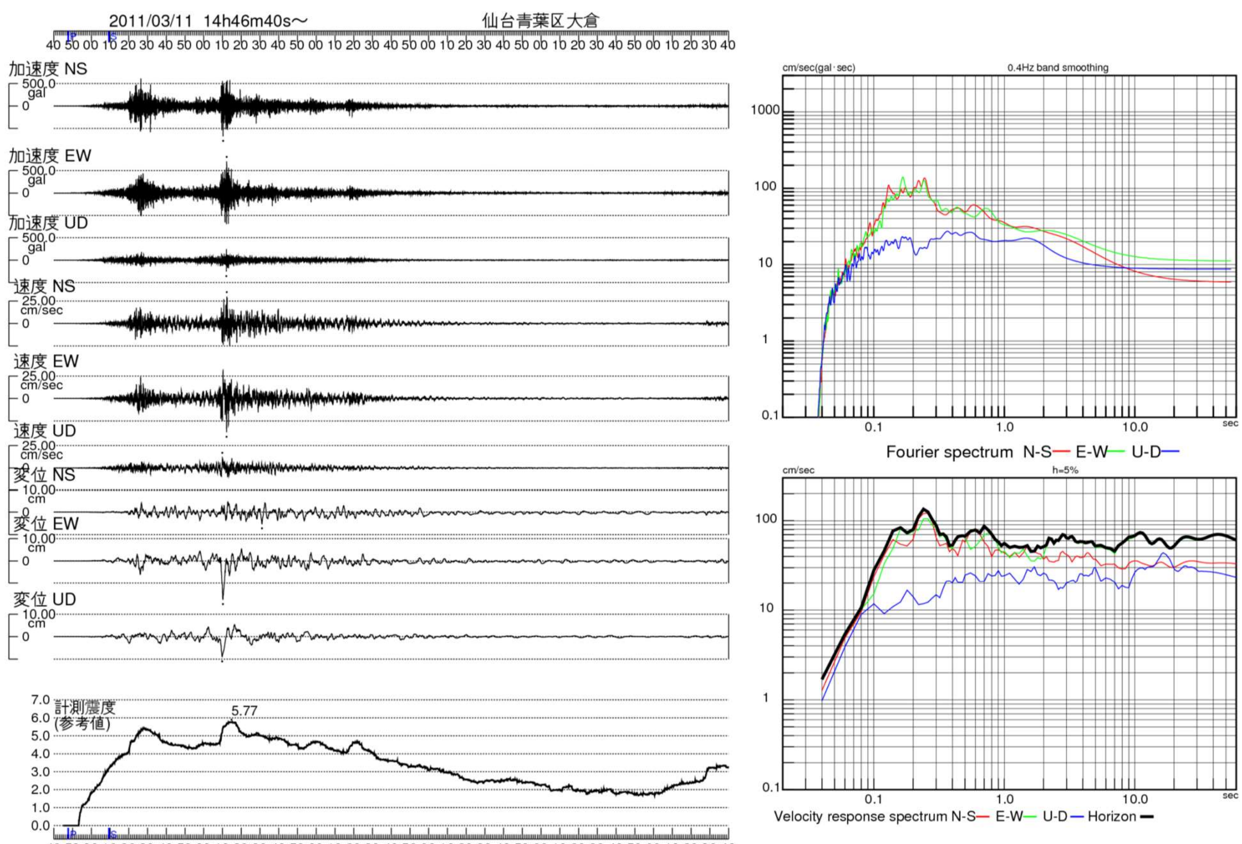


**Figure 2. Strong-motion Waveforms Observed in Aoba Ward, Sendai City (Japan Meteorological Agency, 2011).**

The change in the ratio of water pipeline damages due to recent earthquake is shown in Figure 3. In Japan, the earthquake resistance rate of water pipelines as of 2004 was 14% for main pipelines; by 2020, the rate of water pipelines will be 26.8% for main pipelines and 18.3% for all pipelines. It can be indicated that the increase in the earthquake resistance rate has reduced the ratio of damage to water pipelines in the event of recent earthquake disasters.

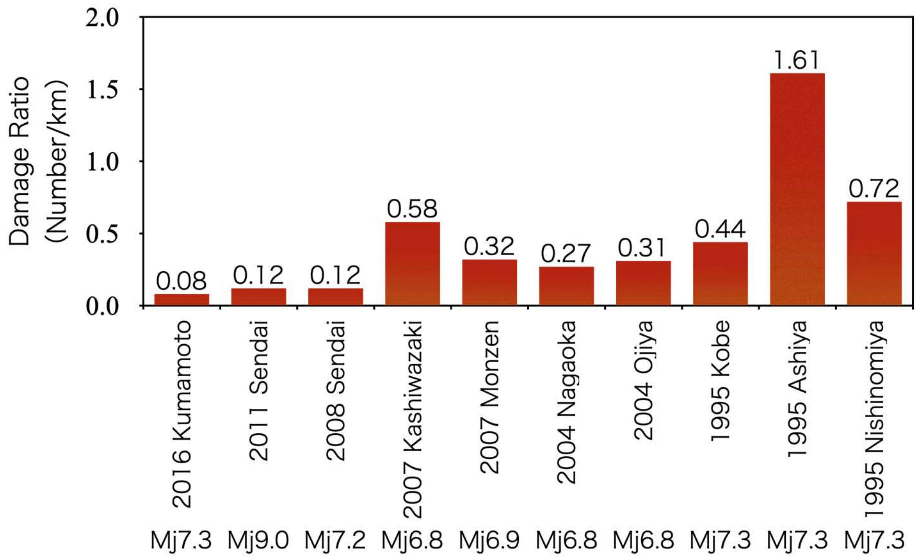


**Figure 3. Strong-motion Waveforms Observed in Aoba Ward, Sendai City (Japan Meteorological Agency, 2011).**

**Number of Damaged Pipes and Duration of Water Outage**

Many researchers have developed damage prediction models for water pipelines, making it possible to estimate the number of water pipeline damages during earthquakes. In addition, emergency restoration models that consider the number of engineers and outside support have been developed, making it possible to describe the emergency restoration process of water supply systems and to evaluate the impact on citizens, such as the duration of water outage during an earthquake.

Hirayama et al., (2015) developed the quantitative evaluation model for water distribution service in the restoration period with the damage estimation modeling for water distribution system and the emergency recovery operation model. This evaluation model could describe the recovery resilience curves of four water service categories: water delivery, quality, quantity, and opportunity loss of water. In this paper, a case study on applying the evaluation model to Kobe City water distribution system following the 1995 Kobe earthquake was conducted. Figure 4 illustrates the evaluation results of resilience curves of water service categories in the Tobu Center, Kobe Waterworks Bureau following the 1995 Kobe earthquake.

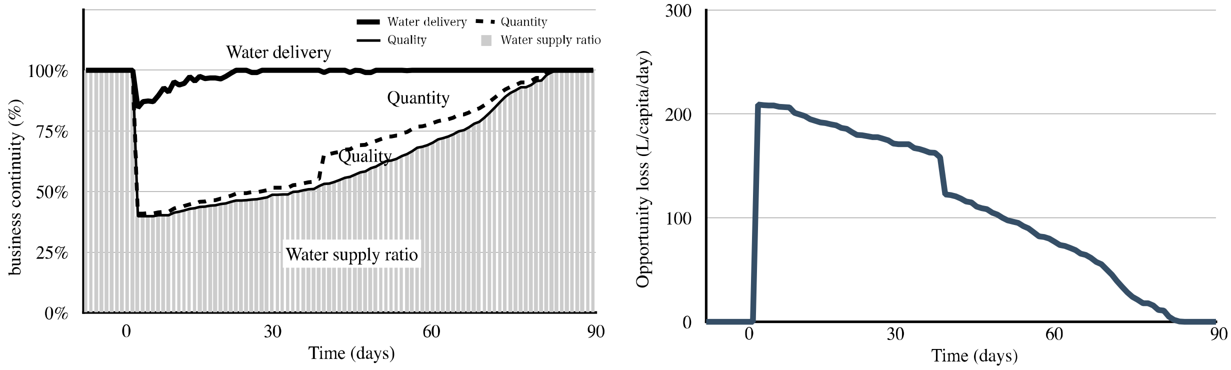


**Figure 4. Evaluation results of disaster resilience curves of water delivery, quantity, quality, and opportunity loss of water in Tobu center, Kobe city following the 1995 Kobe earthquake.**

Davis (2014) proposed five water service categories: Delivery, Quantity, Quality, Fire protection, Functionality. The results of 1994 Northridge Earthquake Los Angeles water restorations was shown in Figure 5.

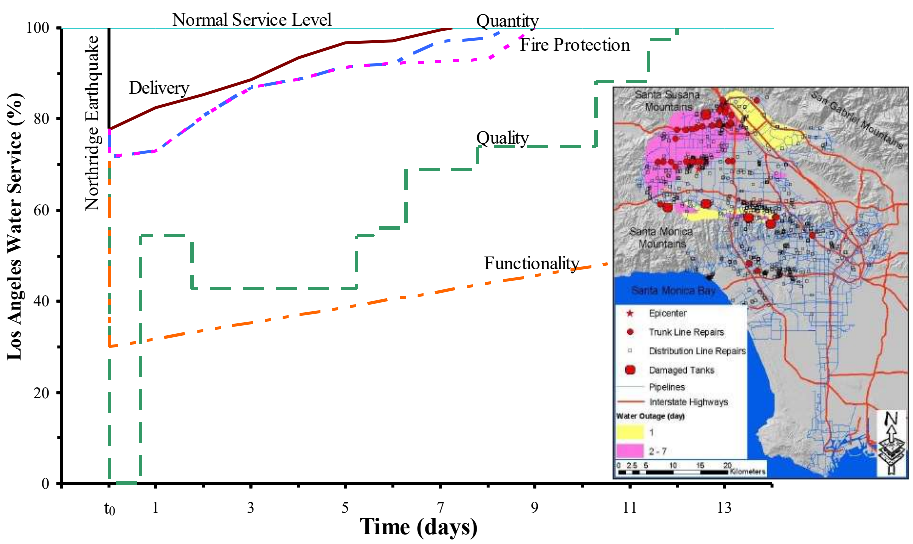


**Figure 5. 1994 Northridge Earthquake L.A. Water Restorations.**

Mathematical models for damage to pipelines and water outages have also been studied. Nojima (2008) developed the seismic vulnerability assessment of lifeline networks based on hazard, vulnerability of pipelines and the extended length of pipelines. Tsukamoto et al., (2005) have shown the correlation between restoration period and pipe damage ratio.

### Disaster Resilient in Water System

Davis (2014) proposed that opportunity loss of water is defined as the difference between the amount of water available in an emergency and the amount available during normal times, i.e., water which would have been available if the disaster had not occurred. In this study, we defined that opportunity loss is the difference between the amount of industrial manufacturer shipment during the restoration period and that during normal times based on the number of days which business entity cannot perform industrial activities by suspension of water supply caused by water pipe damage. The concept of the opportunity loss during emergency restoration period is shown in Figure 6.

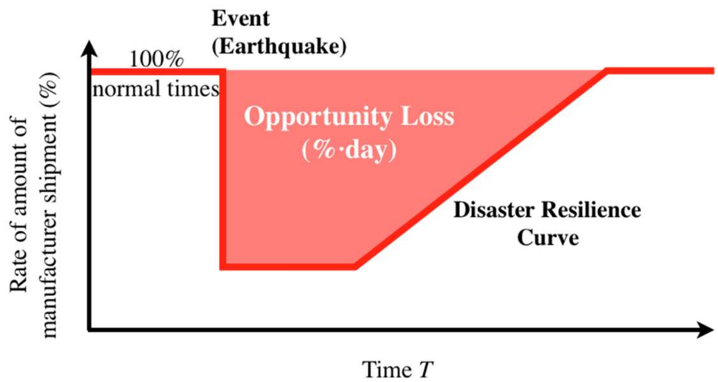


**Figure 6. The concept of the opportunity loss during emergency restoration period.**

## DRINKING WATER QUALITY MANAGEMENT IN EMERGENCY

### Boil Water Advisory/Notice/Order

In United States and European counties, a public health advisory or directive given by government or health authorities to consumers when a community's drinking water is, or could be, contaminated by pathogens. Under a boil-water advisory (BWA), the Centers for Disease Control and Prevention recommends that water be brought to a rolling boil for one minute before it is consumed to kill protozoa, bacteria, and viruses.

### Supply Drinking Water with Limit Intake Notice in Emergency

In May 2012, water outage was occurred in 5 cities and 360,000 households in Chiba prefecture due to the suspension of water intake following the detection of formaldehyde in the Tone River water system. This was the reason why the contamination of approximately 10.8 tons of highly concentrated hexamethylenetetramine in the wastewater from the plant. Article 23 of the Water Supply Law in Japan stipulates that water utilities must urgently shut off the water supply when the use of water may immediately endanger human life or affect the normal functioning of the human body. However, the water supply system in Japan was not designed to provide a boil water advisory system in the case of non-compliance with water quality standards. The concept of maintaining water supply with intake limitation in the event of a water quality incident was established in 2016. In the Kumamoto area, plentiful and purified groundwater from the Aso Mountains is used as the water source, and water supply is carried out only with disinfection treatment, without any purification treatment such as sedimentation tanks or filtration systems.

Therefore, after the 2016 Kumamoto earthquake, water utilities were forced to make a decision whether to shut down supply or continue water supply with intake limitation due to elevated turbidity. Figure 7 shows the responses by water utilities after 2016 Kumamoto Earthquake.

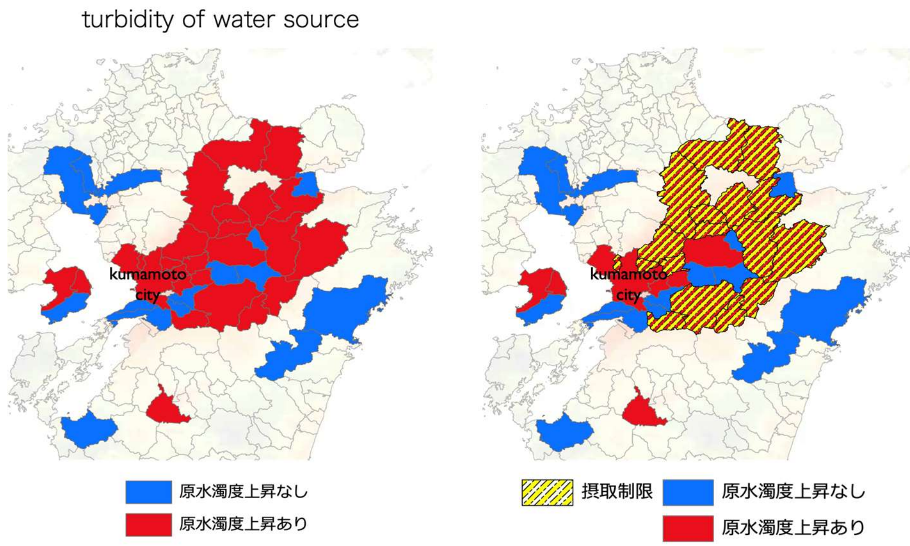


**Figure 7. Elevated Turbidity of Water Source and Intake Limitation after 2016 Kumamoto Earthquake.**

## INFORMATION ON EMERGENCY WATER SUPPLY

### Emergency Water Supply

In case of interruptions of water supply, emergency water supply activities by water utilities will continue to supply water to the affected customers. In Japan, water trucks and emergency water stations are operated during disasters (Figure 8).

**Figure 8. Emergency Water Supply Activities by Water Trucks and Emergency Water Supply Stations.**

Information disclosure to customers during disasters has been pointed out as an issue. Hirayama and Itoh (2017) revealed that information on water system in emergency with customers' controllability would result in to ensure reliability and trust to water utilities.

In Typhoon No.15 in 2022, water interruption for two weeks in Shimizu Ward, Shizuoka City was occurred due to damage to water intake facilities. Shizuoka City Water Supply and Sewerage Bureau conducted emergency water supply activities and provided information on emergency water supply stations to the public through its websites and other communication tools. However, the information provided was only a list of emergency water supply stations, which was not sufficient in terms of understandability. Therefore, information on emergency water supply stations was mapped not within the disaster area, but outside the disaster area, and shared with the BOSAI Cross view, which an information sharing system for disasters developed by NIED, as well as with the Ministry of Health, Labor and Welfare and supporting waterworks organizations using Google Maps. Figure 9 shows the outline of emergency water supply information sharing system, and the emergency water supply stations on Google Maps during Shizuoka Water Outage was shown in Figure 10.

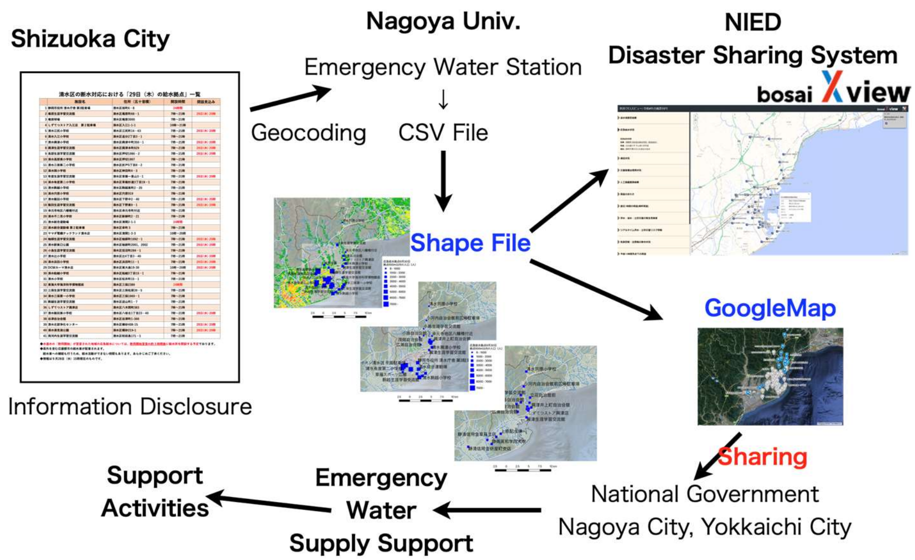


**Figure 9. Outline of Emergency Water Supply Information Sharing System.**

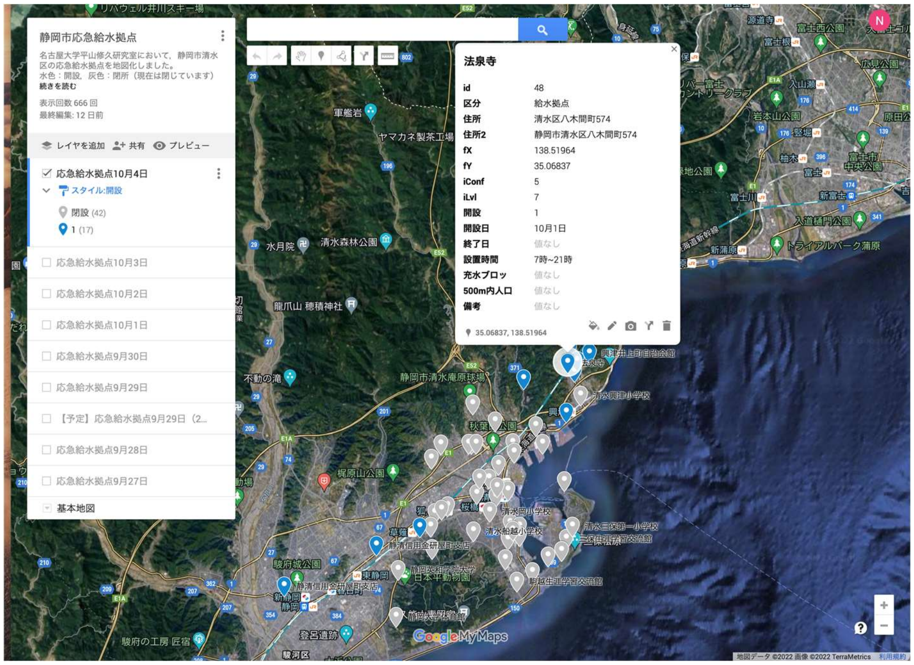


**Figure 10. Emergency Water Supply Stations on Google Maps during Shizuoka Water Outage.**

## FIRE FIGHTING WATER IN EMERGENCY DISASTERS

### Fire Fighting Water after Earthquakes

Ensuring water for firefighting during disasters is an important issue. One hundred years ago, in the Great Kanto Earthquake of 1923, fires broke out in 134 locations in Tokyo and spread to 77 locations, causing 90% of the city's victims to die in the fires.

In the 1995 Great Hanshin-Awaji Earthquake, fires broke out in 285 locations and spread to 94, resulting in 7,574 houses damaged. Of these, fires with a total loss area of 10,000 square meters or more were concentrated in Nagata Ward, Kobe City. At the time, most firefighting parties in the urban areas of Kobe were not equipped with portable power pumps, making it impossible for them to conduct firefighting activities on their own. Most of the hydrants were out of service due to the damage to the water supply network, and the firefighting teams searched for water in fire prevention tanks and school pools, but there was not enough water to fight the fires. In one case, seven fire trucks were linked together to transport water 4 kilometers from the Port of Kobe. In the 1994 Northridge earthquake in the U.S., fires also caused damage on Balboa Street and other streets.

### Evaluation of Fire Protection

Davis (2014) has proposed a method for evaluating fire protection in the event of a disaster. Tamai and Hirayama (2023) developed a method to evaluate restoration priorities as an emergency restoration strategy for water pipelines based on the local economic opportunity loss, population of water outage, and fire extinguishing capability. They conducted a pipe network analysis reflecting the damage, and evaluated firefighting function based on the water pressure distribution.

In their study, EPANET 2 (hereinafter referred to as EPANET) developed by the United States Environmental Protection Agency (USEPA) was used for pipe network analysis. When conducting pipe network analysis with damaged water pipes, it is necessary to set the damage condition of the water pipes. Damage to water pipelines caused by earthquakes can be divided into two types: pipe leaks from cracks caused by force applied to the pipes, and pipe deviation, in which a joint is dislodged by shaking. In EPANET, the pipe leakage and pipe deviation cannot be set directly on the pipe, and the leakage can be generated from the nodal point according to the water pressure. Therefore, two damage conditions are represented on the EPANET. Figure 12 shows a schematic diagram of the leakage and deviation in EPANET.

**Figure 11. Fire Spread Damage in Kobe City after 1995 Kobe Earthquake.**

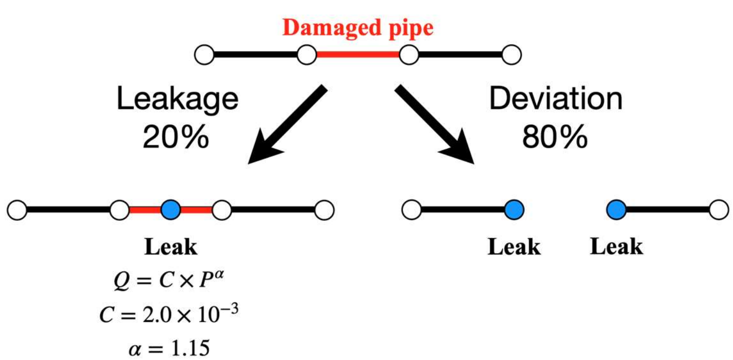


**Figure 12. Schematic diagram of the leakage and deviation in EPANET.**

The water intake point in this paper is the demand point in the pipe network analysis model. The percentage of water shutoffs in the 500-m grid mesh was defined as the ratio of the number of water intake points determined to be shutoffs to the total number of water intake points in the grid mesh. According to the Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communications (2002), the standards for fire extinguishing function are 0.25 MPa for outdoor hydrants and 0.2 MPa or higher for indoor hydrants. The percentage of water intake points with sufficient fire extinguishing capability in the entire target area was calculated.

Yamada et al., (2014) developed an evaluation method on the fire protection capacity of water distribution system from the viewpoint of business continuity. In addition, an evaluation model based on disaster resilience curve, which could describe disaster mitigation and resilience in water service, was developed. The fire protection capacity of the water distribution system in the emergency restoration period for the actual distribution network of the Kobe City was evaluated with the numerical evaluation model. Figure 13 shows the result of fire protection in Kobe pipe network after 1995 Kobe earthquake.


**Figure 13. Result of Fire Protection in Kobe Distribution Network after 1995 Kobe Earthquake.**

The evaluation target area is N City, Aichi Prefecture, and the water supply area of N City Waterworks and Sewerage Bureau. N City is the administrative and economic center of the Tokai region, which is expected to cause serious damage in the Nankai Trough Earthquake. It is the most important city of emergency response at the time. Figure 14 shows the recovery process of the percentage of water intake points with fire extinguishing functions. The recovery trend is like that of the population with water outages, with a rapid recovery at around the 15th day, followed by a gradual increase until restoration is completed.

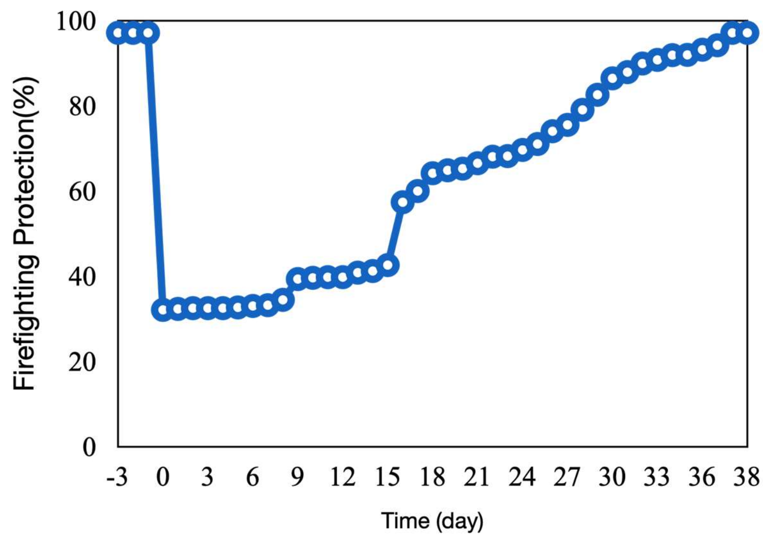


**Figure 14. Evaluation Result of Disaster Resilience Curve with Firefighting Function in A Case of N City.**

## CONCLUSION

In this paper, examples of damage to water supply systems during natural disasters in Japan will be described, and the importance of hazard resilience pipelines will be discussed. It can be indicated that the increase in the earthquake resistance rate has reduced the ratio of damage to water pipelines in the event of recent earthquake disasters. The recent studies on the relationship between pipeline damage and water supply interruption damage are reviewed, and a resilient water supply system is discussed.

The case of emergency water supply, as one of the disaster responses of water utilities in the aftermath of water supply disruptions, is described, and water quality management in emergency situations in Japan and United States is discussed. Also, it was pointed out that after the 2016 Kumamoto earthquake, water utilities were forced to decide whether to shut down supply or continue water supply with intake limitation due to elevated turbidity. In addition, a case study of information sharing at emergency water supply stations after Typhoon No. 15 in 2022 will be presented. Finally, the necessity of securing water for firefighting during disasters is discussed, and the evaluation method of firefighting function by disaster resilience curves after disasters is outlined.

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**Kenichi Soga, Presentation, University of California, Berkeley, Professor**
**"Resilient Infrastructure for Sustainability and Equity (RISE)"**


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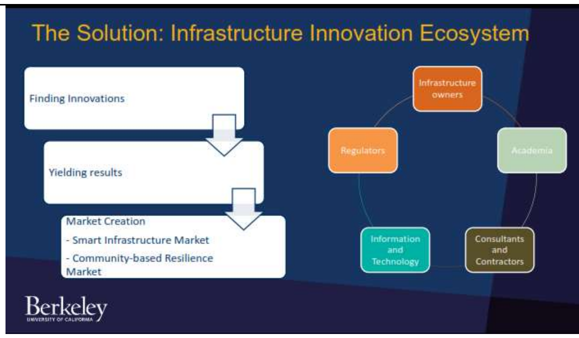


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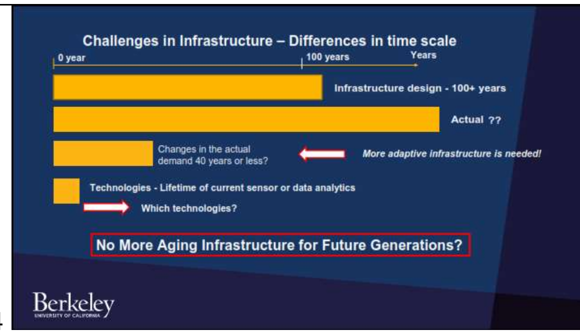


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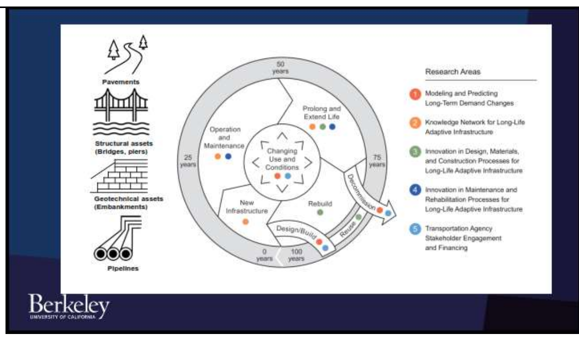


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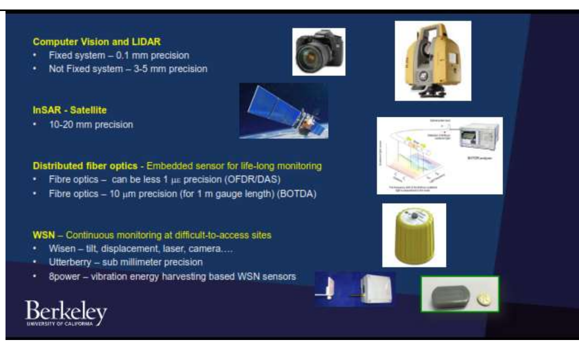


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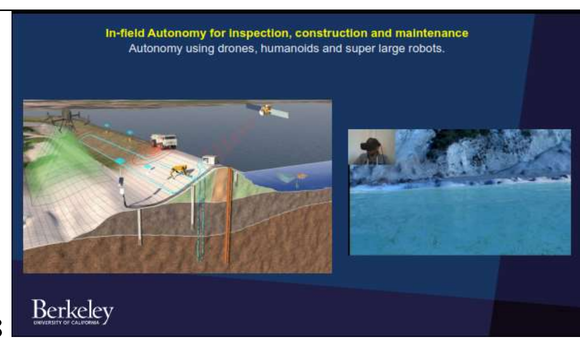


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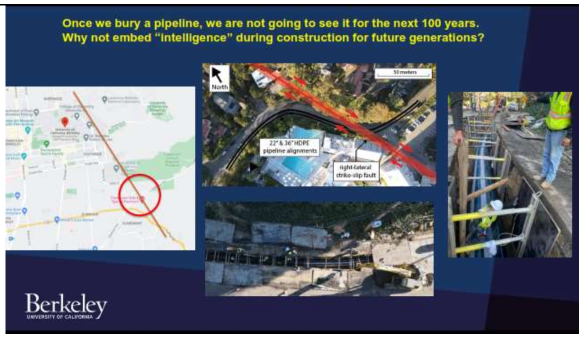


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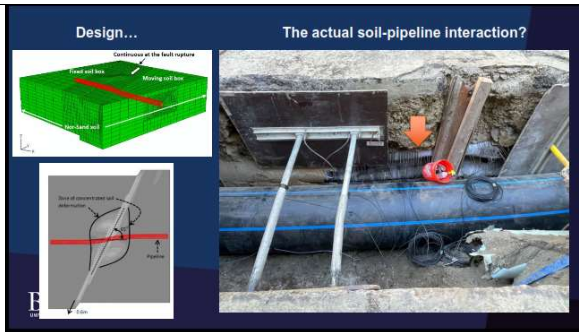


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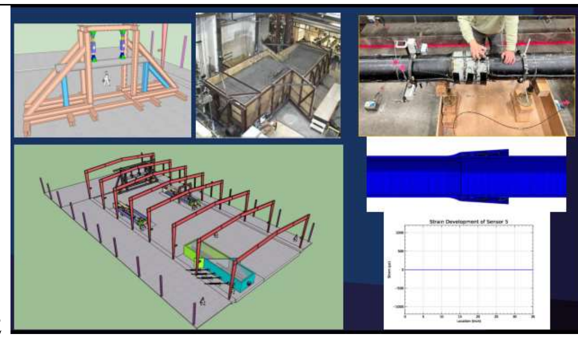


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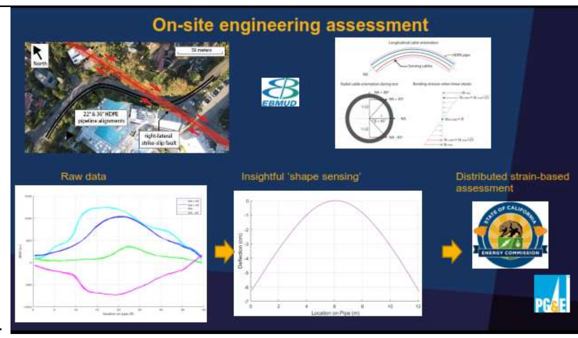


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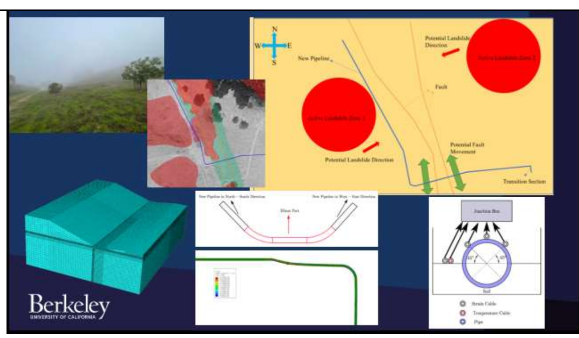


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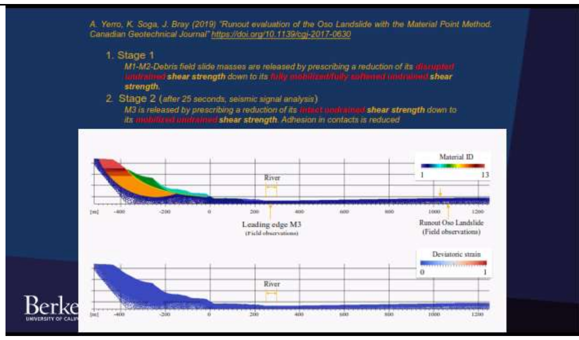


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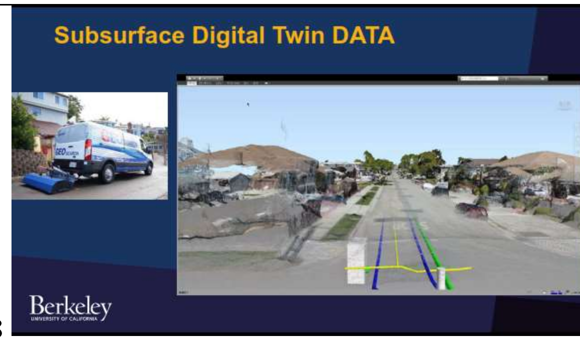


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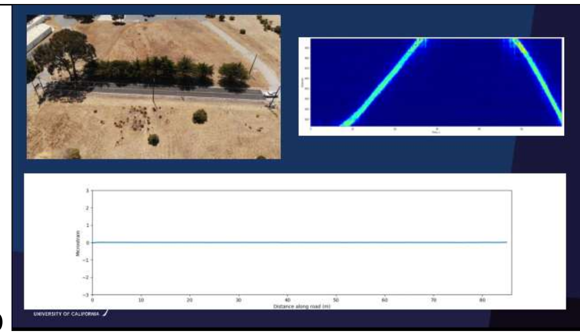


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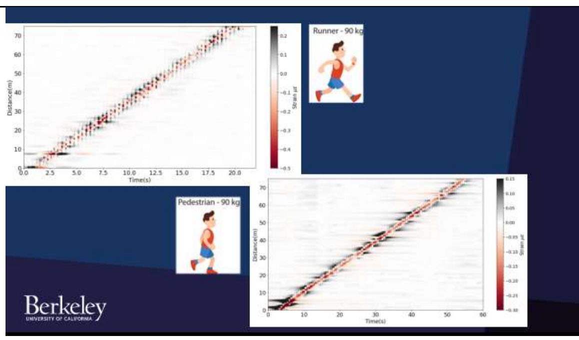


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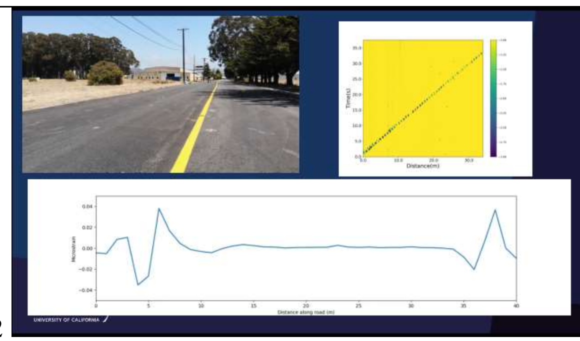


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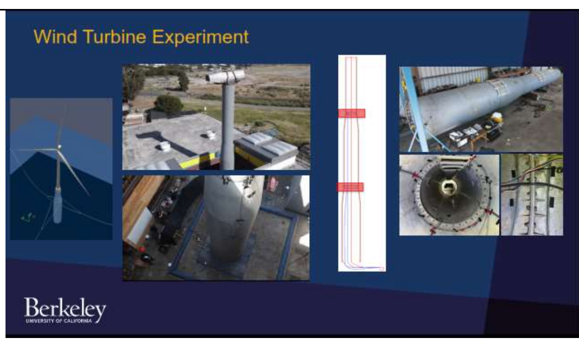


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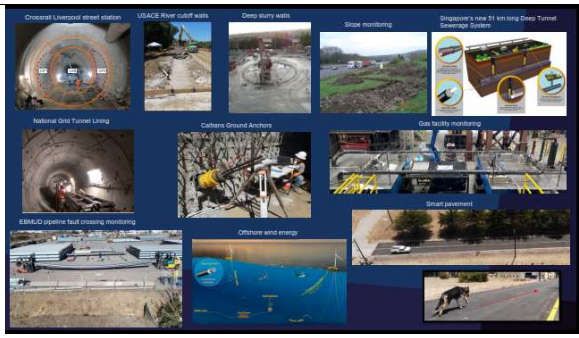


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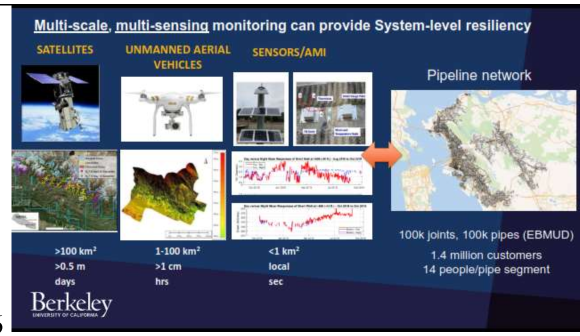


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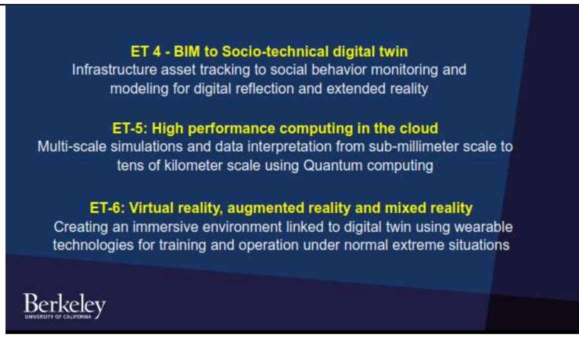


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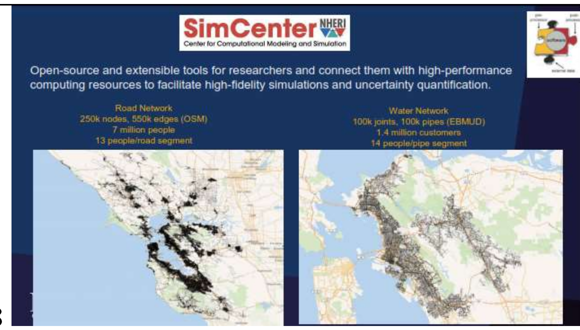


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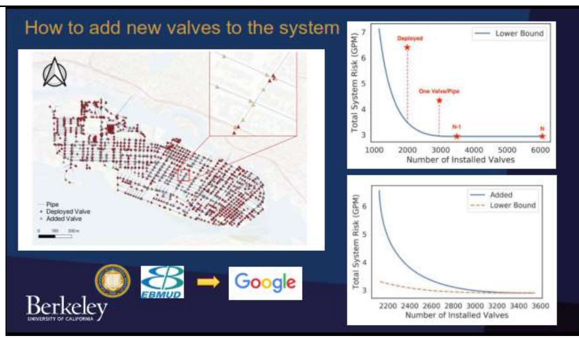


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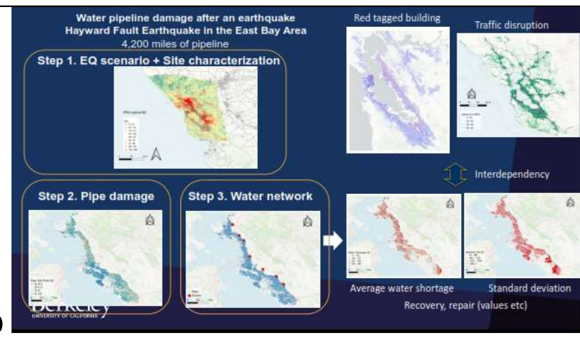


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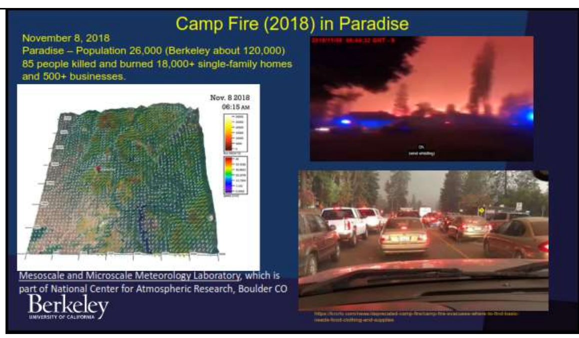


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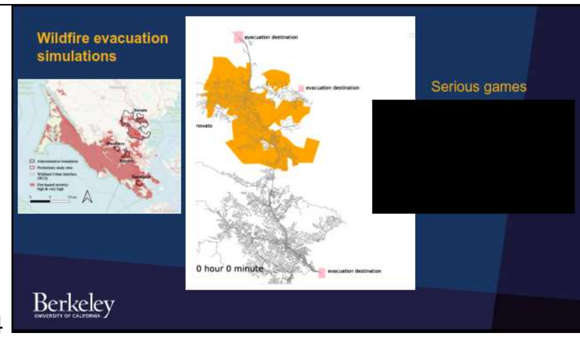


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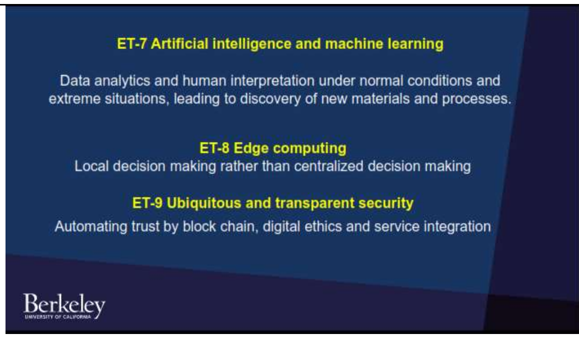


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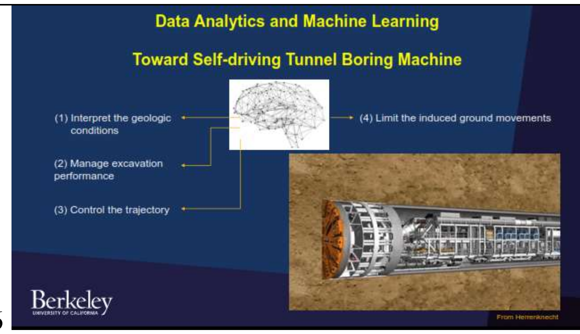


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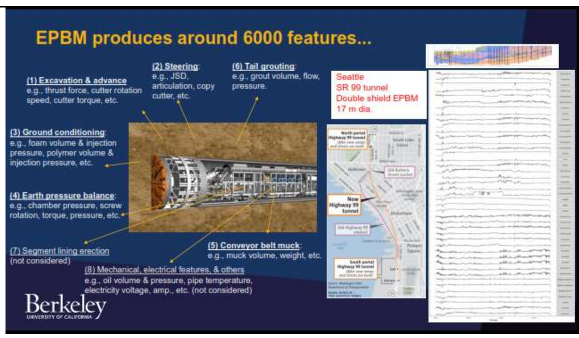


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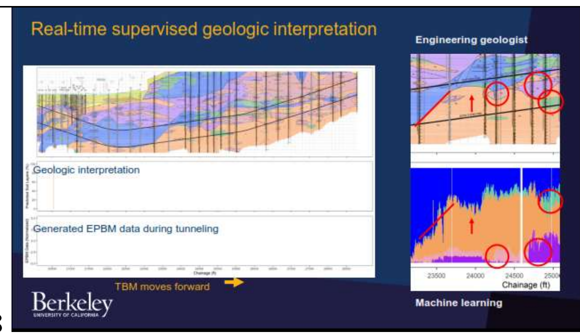


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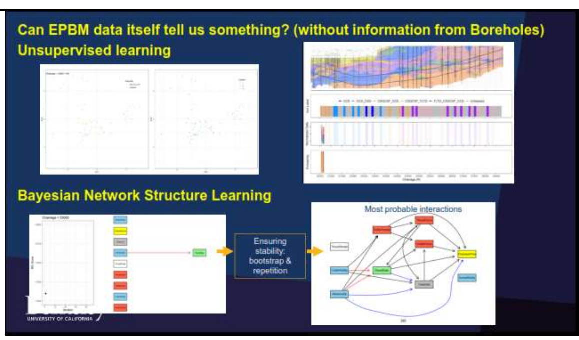


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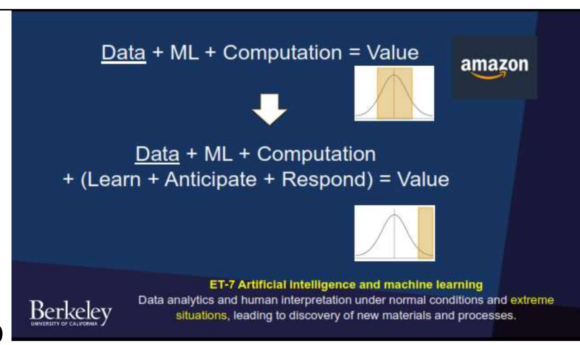

41


ET10: New materials
Zero or negative carbon, self-healing, sensing and adaptive
ET11: Renewable technologies
Energy generation and storages from micro-scale to mega-scale
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42


UC Berkeley and EBMUD Research Opportunities
• Dam Research
• Spillway subdrain performance
• Unlined spill dam performance
• Post-earthquake dam inspection criteria
• Large transmission line inspections and monitoring
• Wildfire modeling to inform vegetation management and improve response efforts
• Landslide modeling and impact on critical infrastructure
• Watershed modeling to improve runoff estimates
• AMI optimization
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43


District Sponsored Class – CE 112
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Berkeley
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# Berkeley Center for Smart Infrastructure

**Kenichi Soga[1], PhD, NAE, FREng, FASCE, FICE**

[1]The Donald H. McLaughlin Chair, Director of the Center for Smart Infrastructure, University of California, Berkeley

## INTRODUCTION

The Berkeley Center for Smart Infrastructure (CSI), which was established in 2022, is a partnership between infrastructure owners, academia, industry, and regulators to address the most pressing and challenging issues facing the infrastructure industry. CSI is addressing challenges with aging infrastructure, climate change, natural resources, and emergency and community preparedness by using a holistic socio-technical approach to provide resilient and sustainable networks through

- State of the art lab and field testing equipment,
- Smart sensors and robotics,
- Big data and machine learning, and
- Multi-scale computer modeling and simulation.

Led by the College of Engineering at the University of California at Berkeley (UCB), CSI is an interdisciplinary hub for infrastructure research and innovation with other UCB Programs and Centers. CSI works with future leaders in developing equitable, inclusive, interdisciplinary solutions and evaluating their integration with complex civil infrastructure, as well as the societal, institutional, and natural systems in which they are embedded.

CSI is leading innovation in infrastructure to co-develop new ways of thinking that incorporate systems integration, holistic analysis, and technology and analyzing data about how our infrastructure and the environment are used by utilities and communities. CSI is working closely with California water utilities to create a holistic collaboration environment in the areas of (a) Infrastructure maintenance, renewal, and replacement, (b) Water and wastewater systems operations, (c) Water Supply and natural resources, (d) Emergency/Community preparedness, and (e) Sustainability and resilience. The Center is part of a collaboration among members of the Civil and Environmental Engineering Department, Pacific Earthquake Engineering Research Center, Simcenter, Lawrence Berkeley National Laboratory, Berkeley Water Center, and Global Metropolitan studies. The specific issues addressed currently by CSI are described in the following sections.

## INFRASTRUCTURE REPLACMENT, RENEWAL, MAINTANANCE; SYSTEM OPERATIONS

The management of infrastructure is a critical aspect of modern society, and it requires constant attention and upkeep. The replacement, renewal, and maintenance of infrastructure are essential components in ensuring that our systems continue to operate smoothly. One of the significant challenges in this domain is the collection and utilization of data for better management and investment direction. To improve infrastructure management effectively, there is a need to capture, analyze and model data. CSI is developing better sensors and monitoring tools for data capture and management to track changes over time. In addition, a systems approach to infrastructure management is used to gain a holistic view of the various components. By doing so, we can ensure that we have the necessary information to make informed decisions and better manage our infrastructure.

CSI is identifying the data parameters needed to build out data sets, particularly for linear infrastructure such as pipelines. Additionally, a roadmap is developed to define what areas are ripe for analysis and/or modeling software to provide meaningful insights. Identifying correlations and actionable insights will better inform planning and recommendations around infrastructure management.

## CLIMATE CHANGE, SUSTAINABILITY & RESILIENCY

One of the most critical issues facing our planet today is climate change, which has increased the focus on sustainability and resiliency. Several areas of interest within this field at CSI include resilience of pipelines and tunnels, ensuring the safety and resiliency of dams, and the ability to adapt to and quantify the risk of climate change.

There is a significant need to prioritize adaptation measures to respond to climate change, including the performance of assets, carbon inventory, and quantifying resilience. CSI is conducting research to understand the reliability of the watershed/supply, considering that the impacts of climate change, sea level rise, snowpack, population, and water quality are crucial to inform decision-making around infrastructure investments.

CSI is also establishing key performance indicators and standardization for resilience, including defining what is meant by resilience and setting thresholds and expectations to restore a system. Redefining what century events look like based on the latest climate data is necessary. CSI is conducting research that illustrate the connection between climate change and reliability/ interdependencies.

Decision-making around sustainable infrastructure investments, such as the use of a scorecard, is another area that CSI is examining. This scorecard can be used in project prioritization and developing a business case, where there is a strong climate connection. Furthermore, identifying the optimal points of distribution where community engagement would be beneficial, particularly in the distribution system, is essential.

## EMERGENCY PREPAREDNESS AND CASCADING FAILURES

In the realm of emergency preparedness and cascading failures, there are several notable interest areas and gaps that require attention. One such area is emergency and community response, with a particular focus on preparedness in regard to dams. To address these issues, there is a need to develop a robust emergency response program that factors in interdependencies, hybrid teams, and to leverage data to make informed decisions. Additionally, understanding, visualizing, and simulating cascading failures and cascading recovery is crucial.

CSI is examining cascading failures and recovery, mapping out interdependencies, and emphasizing triggers for action/thresholds. This includes linking tools, identifying the interdependence of services/utilities, and securing their cooperation, as well as involving the community. To achieve these goals, CSI is developing a program that builds off a digital twin concept to support training, simulation, and planning.

Another critical area of CSI's focus is helping communities understand what is happening in wildfire and developing thresholds and triggers for action. This includes determining who and what response is necessary, such as when to make a decision on evacuation. CSI is developing a toolbox of solutions, including remote sensing solutions, that can be used for data collection and response around damage assessment and/or emergency situations. Addressing gaps in tools available may lead to sensor/tech development.

## WATER SUPPLY AND NATURAL RESOURCES

Water supply and natural resources are crucial factors that require attention. One of them is the mitigation of treated or potable water loss by using data and customer engagement tools, such as AMI data. To do so, it is essential to quantify and characterize leakage better. Additionally, traditional conservation measures need to be expanded and improved, and equity needs to be integrated into sustainability initiatives.

CSI is developing a tool to inform decision-making around sustainable infrastructure investments that can be used in project prioritization and developing the business case. This tool can help identify all the options for conservation at the end of the line, determine what is acceptable water loss, and what is the point of diminishing returns. It can also help integrate equity into the tool/model.

CSI is also investigating the case for "extreme decentralization," which involves looking at diminishing returns to advance the next scope of conservation. Addressing solids in the collection system and their impacts on infrastructure, such as other unintended consequences that the industry is worried about, is also part of this research area. Social scientists are leveraged to develop standardization for the industry to communicate and gain support for investments with external stakeholders. Collaboration with businesses can help identify investment and funding models, management of assets, and new service models. Building equity into decentralization and linking it to public policy can further accelerate projects, and developing standardization that enables adoption at scale for the industry is crucial.

## CLOSURE

Civil engineers face a major challenge of maintaining and upgrading existing infrastructure while also creating new infrastructure that meets society's needs. Existing infrastructure requires monitoring and remedial interventions when new infrastructure is created nearby, and the high cost of replacement often leads to a desire to extend the asset's life. Additionally, existing infrastructure is subjected to greater loads and usage than they were originally designed for.

Another challenge is developing response strategies when a catastrophic event occurs. Infrastructure systems face a multitude of hazards that must be assessed, communicated, and managed appropriately. Designing, constructing, and maintaining linear infrastructure systems such as power supply, buried pipelines, roads, and flood defense embankments are challenging because a break within one system can disrupt the whole system and lead to cascading failures of neighboring infrastructure systems.

In the past, engineering design philosophy has been rigid and based on demand predictions given at that time. Civil engineering structures are often fixed in space and time (e.g., 120-year design life) and provide independent services for transportation, energy supply, water, sewage, and communication without any appreciable linkage. Each of these elements is operated with different business models, is guided by different performance metrics, and deals with systems that involve different degrees of interconnectedness and time scales in terms of ageing and requirements for repair and maintenance.

To address these challenges, we need to better understand the performance of our infrastructure both during construction and throughout its design life. We must also understand how the infrastructure functions as a system. An effective use of existing and new smart monitoring systems with a better understanding of how infrastructure is used and systems interact would lead to the realization of resilient and adaptable infrastructure systems. The aim of CSI is to make a change in the infrastructure industry by providing innovative solutions to realize resilient and adaptable infrastructure systems with 'intelligence for life'.

CSI is developing and testing emerging technologies such as intelligent systems and networks, remote sensing and monitoring, and data analytics for decision-making. It houses a large-scale testing facility to develop intelligent water infrastructure system components and trial smart construction and maintenance methods using remote monitoring and robotics technologies. The center has a computer simulation and data analytics facility to examine the resiliency of water networks in terms of ageing, energy management, climate change, and cascading failures using the state-of-the-art big data and AI tools. The ultimate goal is to advance the development of sustainable, cost-effective, equitable, and resilient systems and communities through applied research and validation in real-world environments.

**Yoshihisa Maruyama, Presentation, Chiba University, Professor**
**“Understanding Risks and Technologies - Recent Studies for Enhancement of Resilient Water Supply System”**

## Understanding Risks and Technologies

## - Recent Studies for Enhancement of Resilient Water Supply System -


Yoshihisa Maruyama

Chiba University, Japan


1

1

### Contents

- Seismic fragility analysis of water distribution pipelines
- Restoration process of water supply systems
- Interdependence between power delivery and water supply system
- Road damage detection

2

2

### Introduction

The water supply system is an extremely important lifeline facility in modern society. Recent earthquakes in Japan occasionally caused severe damage to water distribution pipelines, and water supply was disrupted for weeks in the heavily affected area. The Kobe earthquake, which occurred on January 17, 1995 with a moment magnitude of 6.9, caused severe damage to water supply systems in Hyogo Prefecture. It took approximately 70 days for full restoration of water supply after the 1995 Kobe earthquake.

Based on the lessons after the Kobe earthquake, the important facilities for water supply systems were retrofitted against a large earthquake. In addition, the emergency response strategy was also planned among the water suppliers. However, the water supply was occasionally disrupted for several days or weeks because of recent large earthquakes.

2016 Kumamoto EQ.
DIP ϕ 200 mm

2011 Tohoku EQ.
SP ϕ 2400 mm

2011 Tohoku EQ.
SP ϕ 125 mm

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### 1995 Kobe Earthquake

Isoyama et al. (2000): Seismic damage estimation procedure for water supply pipelines

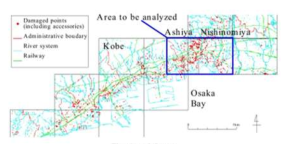
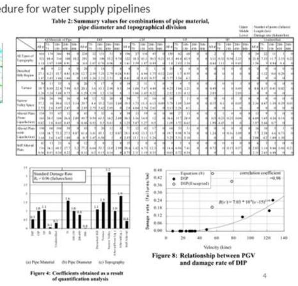



Figure 1: Analysis area




Estimation for damage rate (failures/km)

$$R_m(v) = C_p C_d C_g C_l R(v)$$

$C_p$: Correction coefficient for pipe material
$C_d$: Correction coefficient for diameter
$C_g$: Correction coefficient for soil condition
$C_l$: Correction coefficient for degree of liquefaction

4

4

### Fragility Function of Water Distribution Pipe

$$R_m(v) = C_p C_d C_g C_l R(v)$$

$$R(v) = 3.11 \times 10^{-3}(v - 15)^{1.30}$$

$C_p$: Correction coefficient for pipe material
$C_d$: Correction coefficient for diameter
$C_g$: Correction coefficient for soil condition
$C_l$: Correction coefficient for degree of liquefaction

**Table 2. Examples of correction coefficients for the fragility function of water distribution pipeline.**

| Pipe material | Correction coefficient ($C_p$) |
|---|---|
| DIP | 0.3 |
| VP | 1.0 |
| CIP | 1.0 |
| SP | 0.3 |
| ACP (asbestos cement pipe) | 1.2 |

| Diameter (mm) | Correction coefficient ($C_d$) |
|---|---|
| 50-80 | 2.0 |
| 100-150 | 1.0 |
| 200-250 | 0.4 |
| 300-450 | 0.2 |
| 500-900 | 0.1 |

| Liquefaction | Correction coefficient ($C_l$) |
|---|---|
| None liquefaction | 1.0 |
| Partial liquefaction | 2.0 |
| Total liquefaction | 2.4 |

| Zone | Japan engineering geomorphologic classification | Correction coefficient ($C_g$) |
|---|---|---|
| 1 | Mountain, Mountain footslope, Hill, Volcano, Volcano footslope, and Volcanic hill | 0.4 |
| 2 | Gravelly terrace, and Terrace covered with volcanic ashsoil | 0.8 |
| 3 | Valley bottom lowland, Alluvial fan, Back marsh, and Delta and coastal lowland | 1.0 |
| 4 | Natural levee, Abandoned river channel, Marine sand and gravel bars, and Sand dune | 2.5 |
| 5 | Filled land, Reclaimed land, and Water body | 5.0 |

Revised by Japan Water Research Center in 2013

5

5

### Fragility Function for Water Pipes in US

$$RR(V) = K_1 \cdot 0.00187 \cdot V$$ Shaking only

$RR$: repairs per 1000 of main pipe
$V$: peak ground velocity (inches/s)
$K_1$: modification factor

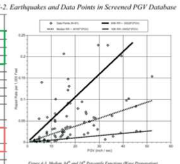
American Lifelines Alliance (2001)

| Earthquake | Data Points | Percentage |
|---|---|---|
| 1995 Hyogoken-nanbu (Kobe) | 9 | 11% |
| 1994 Northridge | 35 | 43% |
| 1989 Loma Prieta | 13 | 16% |
| 1971 San Fernando | 13 | 16% |
| Other Earthquakes (8) | 11 | 14% |
| **Total** | **81** | **100%** |

*Table 4-2. Earthquakes and Data Points in Screened PGV Database*

| Pipe Material | Joint Type | Soils | Diam. | $K_1$ |
|---|---|---|---|---|
| Cast iron | Cement | All | Small | 1.0 |
| Cast iron | Cement | Corrosive | Small | 1.4 |
| Cast iron | Cement | Non-corrosive | Small | 0.7 |
| Cast iron | Rubber gasket | All | Small | 0.8 |
| Welded steel | Lap - Arc welded | All | Small | 0.6 |
| Welded steel | Lap - Arc welded | Corrosive | Small | 0.9 |
| Welded steel | Lap - Arc welded | Non-corrosive | Small | 0.3 |
| Welded steel | Lap - Arc welded | All | Large | 0.15 |
| Welded steel | Rubber gasket | All | Small | 0.7 |
| Welded steel | Screwed | All | Small | 1.3 |
| Welded steel | Riveted | All | Small | 1.3 |
| Asbestos cement | Rubber gasket | All | Small | 0.5 |
| Asbestos cement | Cement | All | Small | 1.0 |
| Concrete w/Stl Cyl. | Lap - Arc Welded | All | Large | 0.7 |
| Concrete w/Stl Cyl. | Cement | All | Large | 1.0 |
| Concrete w/Stl Cyl. | Rubber Gasket | All | Large | 0.8 |
| PVC | Rubber gasket | All | Small | 0.5 |
| Ductile iron | Rubber gasket | All | Small | 0.5 |

*Table 4-5. Ground Shaking - Constants for Fragility Curve*



Large: Over 300 mm (12 inches)
Small: 100-300 mm (4-12 inches)

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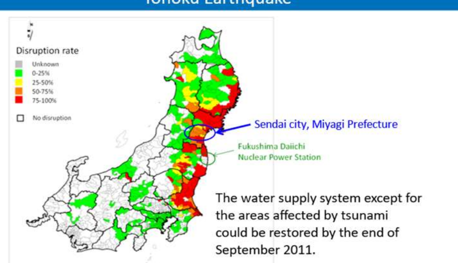
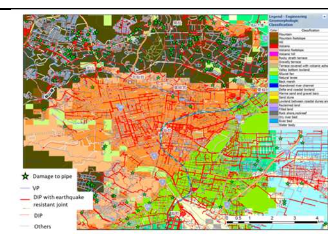
### Disruption Rate of Water Supply after the 2011 Off the Pacific Coast of Tohoku Earthquake



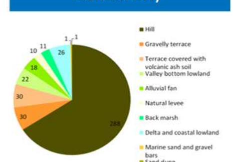

The water supply system except for the areas affected by tsunami could be restored by the end of September 2011.

Compiled by Japan Water Works Association (2011)

7




### Damage to Water Pipes in Sendai City




| Pipe material | Damage to pipe body | Loose of joint | Others | Total | Length (km) |
|---|---|---|---|---|---|
| DIP (Ductile cast iron pipe) *) | 27 | 84 | 6 | 117 | 2723.1 |
| VP (Polyvinyl chloride pipe) | 244 | 45 | 8 | 297 | 1514.5 |
| GP (Galvanized pipe) | 4 | 1 | 1 | 6 | 4.9 |
| SP (Steel pipe) | 1 | 4 | 7 | 12 | 137.3 |
| Others | 3 | 1 | 1 | 5 | 78.2 |
| Total | 279 | 135 | 23 | 437 | 4458.0 |

The locations of damage incidents are especially concentrated in the hilly areas.

8

## Example of Damage to Water Pipes in the Hilly Residential Area

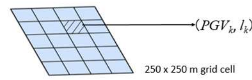

9

## Numerical Simulation to Evaluate the Correction Coefficient for Soil Condition

- **Input data**

$PGV_k$: Peak ground velocity at grid cell $k$

$l_k$: Pipe length at grid cell $k$




10

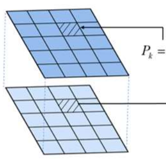
## Numerical Simulation to Evaluate the Correction Coefficient for Soil Condition

- **Assumption of damage ratio**

$P_k$: Damage ratio at grid cell $k$

$C$: Correction coefficient

$$P_k = 3.11\times10^{-3}(PGV_k - 15)^{1.30} \times C$$




Seismic vulnerability index

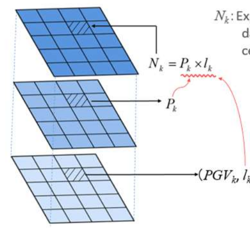
11

## Numerical Simulation to Evaluate the Correction Coefficient for Soil Condition

- **Expected number of damage incidents**

$N_k$: Expected number of damage incidents at grid cell $k$

$$N_k = P_k \times l_k$$



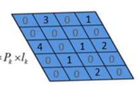

12

## Numerical Simulation to Evaluate the Correction Coefficient for Soil Condition

- **Generation of Poisson-distributed random variables**

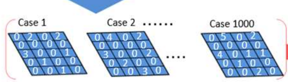
Poisson-distributed random variables are generated to simulate the number of pipe breakages for each 250 × 250 m grid cell.

$N_k = P_k \times l_k$



$$p(X = x_k) = (N_k)^{x_k} \cdot \exp(-N_k)/x_k! \quad (x_k = 0,1,2,\cdots)$$

$p(X=x_k)$: Probability mass function of $X$



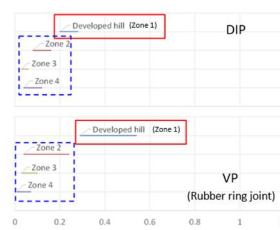

A total of 1,000 sets of Poisson-distributed random variables were generated for each grid cell.

The summation of the generated variables was calculated for each set, and the standard deviation of the sums was also obtained for each specific value of $C$.

13

## Numerical Simulation to Evaluate the Correction Coefficient for Soil Condition

$$R_m(v) = C_p C_d C_g C_l R(v)$$




$C_g$

Zone 1 — Small

Zone 2

Zone 3

Zone 4 — Large

The correction coefficient for developed hilly areas (Zone 1) were larger than those for other zones (Zone 2-4).

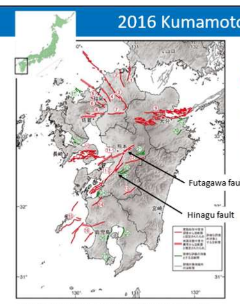
14

## Contents

- Seismic fragility analysis of water distribution pipelines
- Restoration process of water supply systems
- Interdependence between power delivery and water supply system
- Road damage detection

15

## 2016 Kumamoto Earthquake




http://www.jishin.go.jp/main/choukihyoka/kyushu.htm


16

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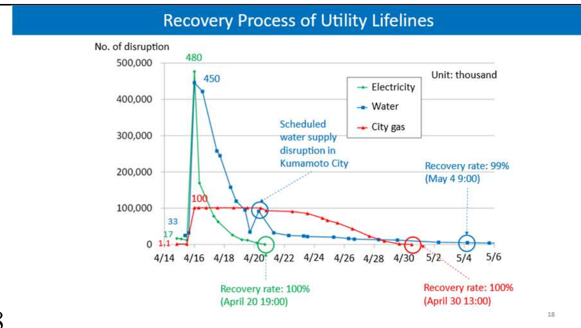


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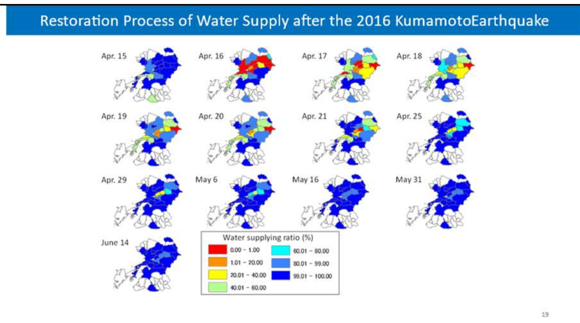


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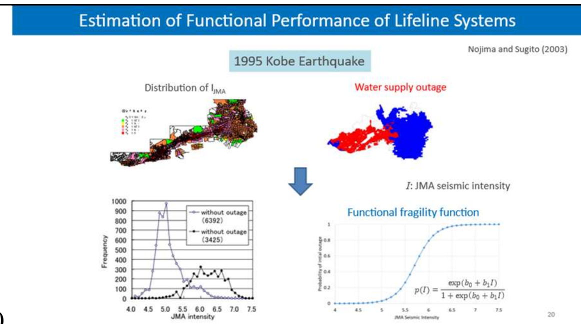


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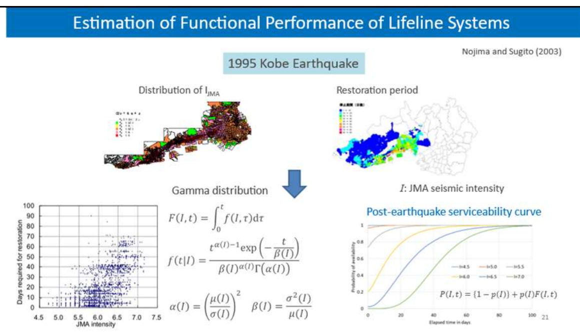


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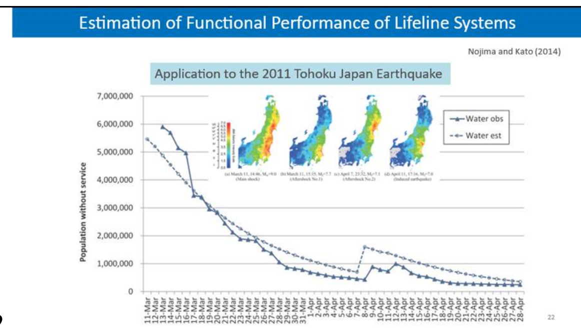


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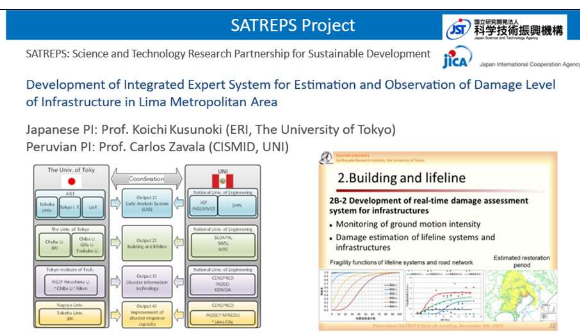
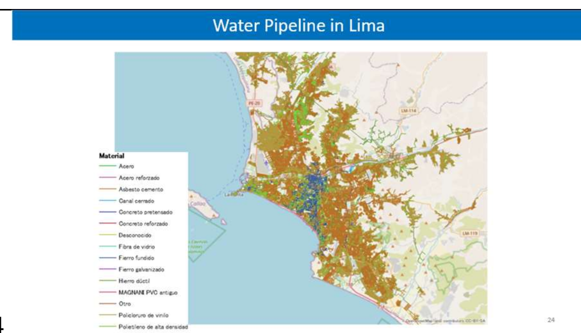
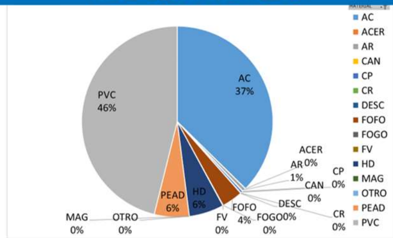



24


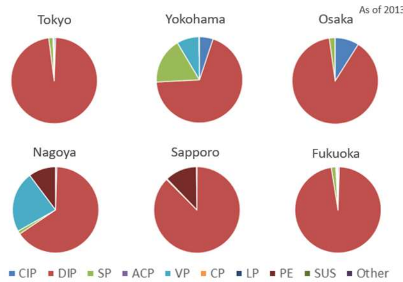
## Percentage of Pipe Material




Asbestos cement pipes (AC) and Polyvinyl chloride pipes (PVC) are mainly used. Ductile iron pipes (HD), High -density polyethylene pipes (PEAD), and Cast iron pipes (FOFO) are rarely used in Lima.

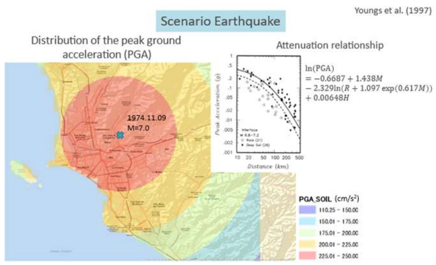
25

## Percentage of Pipe Material in Japan




26

## Simulation of Restoration Period




27

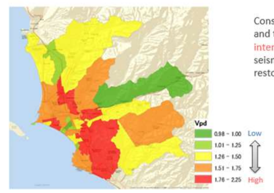
## Vulnerability Index of Water Pipeline

| Diameter (mm) | Cd |
|---|---|
| ~75 | 1.6 |
| 100 ~ 250 | 1.0 |
| 300 ~ 450 | 0.7 |
| 500 ~ 900 | 0.5 |
| 1000 ~ | 0.2 |

| Pipe material | Cp |
|---|---|
| DIP | 0.3 |
| CIP | 1.0 |
| VP | 1.0 |
| PE | 0.3 |
| ACP | 2.5 |

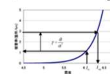
Vulnerability index

$$V_{pd} = \frac{\sum_i \sum_j C_{d_i} C_{p_j} L_{ij}}{\sum_i \sum_j L_{ij}}$$



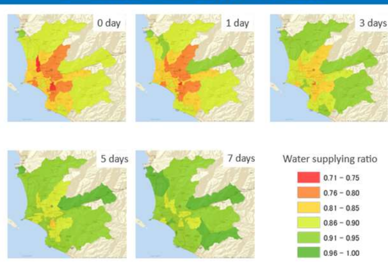

Considering the difference of $V_{pd}$ of Lima and that of Kobe (0.446), the seismic intensity is adjusted through the JMA seismic intensity to estimate the restoration period.

$$I_{eq} = I_0 + 0.647 \log_{10} \frac{V_{pd}}{0.446}$$



28

## Simulated Water Supplying Ratios



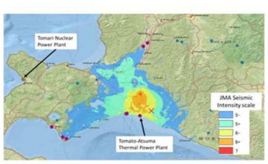

29

## Contents

- Seismic fragility analysis of water distribution pipelines
- Restoration process of water supply systems
- Interdependence between power delivery and water supply system
- Road damage detection

30

## 2018 Hokkaido Eastern Iburi Earthquake

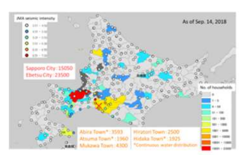



Distribution of the JMA seismic intensity and the locations of power plants

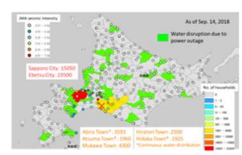
The power supply to all 2.95 million households in Hokkaido was cut on September 25, 2018 at 3:25 a.m. The blackout was triggered by the emergency shutdown of the Tomato-Atsuma Thermal Power Plant. It covered 53.2% of electric demand in Hokkaido because of the shutdown of the Tomari Nuclear Power Plant.

31

## 2018 Hokkaido Eastern Iburi earthquake



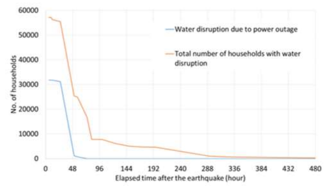

Number of households with water supply disruption




Municipalities suffered from water supply disruptions due to power outage

32

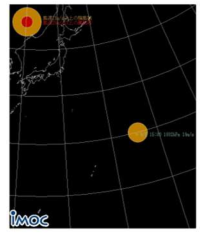
## 2018 Hokkaido Eastern Iburi earthquake

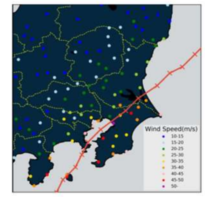



Number of households with water supply disruption with respect to the elapsed time after the earthquake

33

## 2019 Typhoon Faxai






Distribution of the maximum wind speed

34

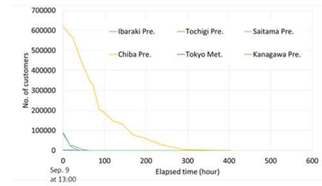
## 2019 Typhoon Faxai

The two transmission line towers were collapsed.

Approximately 2000 utility poles were damaged.

35

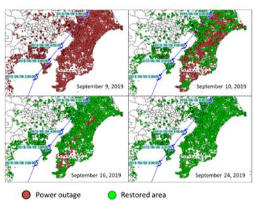
## 2019 Typhoon Faxai




Number of customers without electric power supply with respect to the elapsed time after the landfall of Typhoon Faxai

36

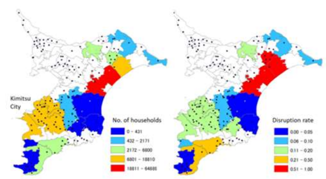
## 2019 Typhoon Faxai




Distributions of power outages in the Tokyo Metropolitan area

37

## 2019 Typhoon Faxai




Maximum number of households without water supply and the maximum disruption rate

38

## 2019 Typhoon Faxai

39

## Contents

- Seismic fragility analysis of water distribution pipelines
- Restoration process of water supply systems
- Interdependence between power delivery and water supply system
- Road damage detection

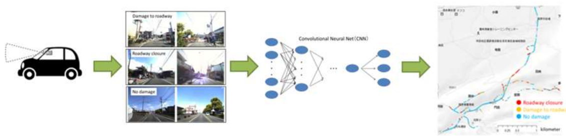
40

40

## Objective

The road network serves as the trunk line of transportation, and is important to the restoration of damage-stricken areas. The road authorities, such as the Japanese Ministry of Land, Infrastructure and Transport (MLIT), survey the damage to the road network, however, it is difficult to evaluate the damage situation soon after an earthquake.

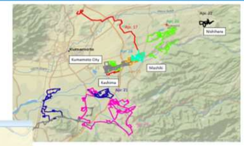
Based on the background, this study tries to detect the earthquake-induced damage to the roadways and road closures because of collapsed buildings using the images captured by a vehicle-mounted camera.




41

## Images Captured from an Automobile

Six cameras are installed.

The images were mainly acquired in Mashiki Town, Nishihara Village, and Kumamoto City from April 17 to April 28, 2016.

The images were sequentially acquired with an interval of 5 m.

42

## Development of Image Dataset

Six investigators visually inspected a total of 31,951 images captured on April 17 and 20 to classify into the three classes.

(a) damage to roadway
(b) roadway closure
(c) no damage.

The images classified into the same class by more than five investigators were used to develop an image classifier in this study.

The vehicle-mounted camera captures a 2048 × 1536 image. The bottom quarter of the image was cropped so as to focus on the roadway, and it was resized to a 512 × 75 image.

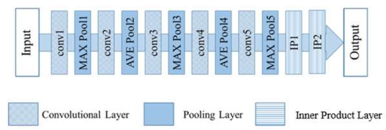
(a) damage to roadway 512 images

(b) roadway closure 673 images

(c) no damage 14,346 images

43

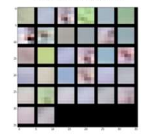
## Convolutional Neural Network Assumed in This Study




Module: Caffe
(convolutional architecture for fast feature embedding)

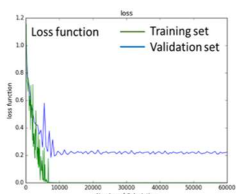
| Convolutional layer | No. of filters | Size of filter | Inner product layer | No. of output |
|---|---|---|---|---|
| conv1 | 32 | 5×5 | IP1 | 128 |
| conv2 | 32 | 5×5 | IP2 | 3 |
| conv3 | 64 | 5×5 | | |
| conv4 | 64 | 5×5 | | |
| conv5 | 128 | 5×5 | | |

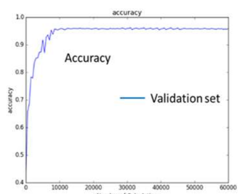
Filters of conv1



44

## Values of Loss Function and Accuracy of Classification




The values of loss function decreases as the number of iteration increases.
The accuracy of classification for the validation set reaches 0.95 as the number of iterations increases.

45

## Application of the Image Classifier

The images acquired on April 17 and 20, 2016 were employed to construct the image classifier in this study.
In order to evaluate versatility of the image classifier, it was applied to the images captured on April 22, 25, and 26, and the classification accuracy was investigated.

| | Area | Acquisition date | Number of images |
|---|---|---|---|
| (a) | Nishihara Village | April 22 | 1,483 |
| (b) | Center of Mashiki Town | April 22 | 773 |
| (c) | West of Mashiki Town | April 25 | 2,157 |
| (d) | Mifune Town and Kosa Town | April 26 | 1,586 |

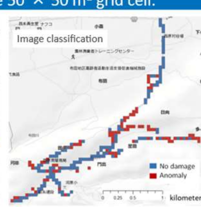
The accuracy to detect the images with no damage is quite high.
The accuracy to detect the images of roadway closures is 56.3%. Half of the images which were not properly identified were mistakenly detected as the images which captured damage to roadways.

Result of image classification ((a) Nishihara Village)

| Visual inspection | Image classification: Roadway closure | Damage to roadway | No damage | Detection accuracy | Overall accuracy |
|---|---|---|---|---|---|
| Roadway closure | 45 | 17 | 18 | 56.3% | 78.8% |
| Damage to roadway | 43 | 98 | 142 | 34.6% | |
| No damage | 36 | 59 | 1031 | 91.6% | |

46

## Comparisons between the result of visual inspection and image classification with respect to the 50 × 50 m² grid cell.


The results of visual inspection and image classification are illustrated using the 50 × 50 m² grid cells.
The grid cells which include closure or damage to roadways are shown as anomalous road sections.
According to the result, the image classifier is effective to know the road sections where anomalous conditions might be caused because of an earthquake.

47

## Thank you for your attention.

48

# Recent Studies for Enhancement of Resilient Water Supply System

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## ABSTRACT

This paper summarizes the recent studies on enhancement of resilient water supply system. The main topics of this paper are as follows:

1. Seismic fragility analysis of water distribution pipelines
2. Restoration process of water supply systems
3. Interdependence between power delivery and water supply system

## INTRODUCTION

The water supply system is an extremely important lifeline facility in modern society. Recent earthquakes in Japan occasionally caused severe damage to water distribution pipelines, and water supply was disrupted for weeks in the heavily affected area. The Kobe earthquake, which occurred on January 17, 1995 with a moment magnitude of 6.9, caused severe damage to water supply systems in Hyogo Prefecture (Isoyama et al. 2000). It took approximately 70 days for full restoration of water supply after the 1995 Kobe earthquake.

This paper summarizes the recent studies on enhancement of resilient water supply system. First, a series of seismic fragility analyses is introduced after the 1995 Kobe earthquake, the 2011 Great Tohoku earthquake and the 2016 Kumamoto earthquake. Second, the study on numerical simulation of restoration process of water supply system after an earthquake is reviewed. Lastly, interdependence between power delivery and water supply system is discussed.

## SEISMIC FRAGILITY ANALYSIS OF WATER DISTRIBUTION PIPELINES

Regarding the water supply infrastructure, the incidents of damage to buried pipes will disrupt water supply. Isoyama *et al.* (2000) developed the fragility curve of water distribution pipes based on the damage dataset from the 1995 Kobe earthquake in Japan, and this fragility curve was widely used to estimate the number of damage incidents (pipe breaks) after earthquakes. Recently, modifications have been made to estimate damage incidents of water distribution pipes. Because several events that caused damage to water distribution pipes in Japan have occurred, the fragility curve, which is constructed primarily from the damage dataset of a single event (the Kobe earthquake), can be empirically revised.

To estimate the damage ratio of water distribution pipes (i.e., the number of damage incidents per kilometer of water pipe), Isoyama *et al.* (2000) proposed the following formula:

$$R_m(v) = C_p C_d C_g C_l R(v) \tag{1}$$

where $R_m$ is the damage ratio, $C_p$, $C_d$, $C_g$, and $C_l$ are correction coefficients for the pipe material, diameter, geological condition, and liquefaction occurrence, respectively, and $v$ is the peak ground velocity (PGV).

$R(v)$ estimates the damage ratio for cast iron pipe (CIP) with a diameter of 100–150 mm and is given as

$$R(v) = 3.11 \times 10^{-3}(v - 15)^{1.30} \tag{2}$$

The Japan Water Research Center (JWRC) proposed the equations to predict the damage ratios of water distribution pipelines in 2012, and they evaluated the applicability of the equations for the damage dataset in Kumamoto City after the 2016 Kumamoto earthquake (JWRC 2016). The equations to predict the damage ratio $R_m$ are shown in Eqs. (3) and (4).

$$R_m(v) = C_p C_d C_g R(v) \tag{3}$$

$$R_m = C_p C_d R_L \tag{4}$$

$R_L$ shows the damage ratio of DIP-A with a diameter of 100-150 mm in the liquefied area, and it is set to be 5.5. $R(v)$ is defined as Eq. (5).

$$R(v) = 9.92 \times 10^{-3} \times (v - 15)^{1.14} \tag{5}$$

## RESTORATION PROCESS OF WATER SUPPLY SYSTEMS

Nojima and Sugito (2005) developed the two-step empirical model to construct the residual capacity estimation model for given seismic intensity based on the damage statistics after the 1995 Kobe earthquake. Using a logistic regression model, the probability of lifeline outage $p$ was modeled in terms of the JMA seismic intensity $I$.

$$p(I) = \frac{\exp(b_0 + b_1 I)}{1 + \exp(b_0 + b_1 I)} \tag{6}$$

The parameters $b_0$ and $b_1$ were obtained by the maximum likelihood method.

In order to evaluate the duration of lifeline disruption for given JMA seismic intensity I, the probabilistic models using gamma distribution were assumed.

$$f(t|I) = \frac{t^{\alpha(I)-1} exp\left(-\frac{t}{\beta(I)}\right)}{\beta(I)^{\alpha(I)} \Gamma(\alpha(I))} \tag{7}$$

where

$$\alpha(I) = \left(\frac{\mu(I)}{\sigma(I)}\right)^2 \tag{8}$$

$$\beta(I) = \frac{\sigma^2(I)}{\mu(I)} \tag{9}$$

$\mu(I)$ and $\sigma(I)$ are the moving average and the moving standard deviation of duration of outage, which were expressed as quadratic functions of $I$.

The residual capacity $D(t|I)$ can be expressed as

$$D(t|I) = 1 - p(I) + p(I) \int_0^t f(\tau|I) d\tau \quad (10)$$

Figure 1 shows the residual capacity curve for water supply system.

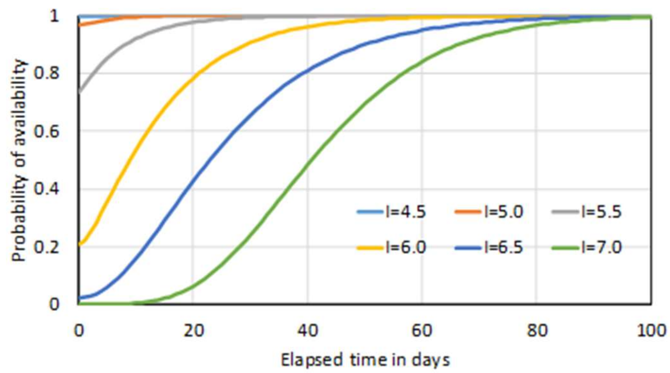


**Figure 1. Residual capacity curve for water supply system.**

## INTERDEPENDENCE BETWEEN POWER DELIVERY AND WATER SUPPLY SYSTEM

Typhoon Faxai, the 15th typhoon in 2019, was the first typhoon to strike the Kanto region since August 2016. Faxai reached its peak strength as a Category 4 typhoon just before making landfall in mainland Japan, and made landfall in Tokyo's neighboring Chiba Prefecture on September 9, 2019 at 5:00 a.m. Three people were killed and 147 others were injured because of this typhoon.

Typhoon Faxai caused power losses in approximately 934,900 households in the Tokyo Metropolitan area. The two transmission line towers were collapsed because of the strong wind of the typhoon (METI, 2019). Figure 2 shows the distributions of power outages in the Tokyo Metropolitan area on September 9, 10, 16 and 24 (Nagata et al., 2020). The continuous power outage was observed in the southern inland of Chiba Prefecture.

The water supply was disrupted in the 22 municipalities in Chiba Prefecture. The maximum number of households without water supply reported by Ministry of Health, Labour and Welfare (MHLW) and the maximum disruption rate are shown in Figure 3. The water supply was fully disrupted in the eastern part of the prefecture. The bulk water supplier in this region suffered from the power outage, and their water purifying plants did not work from September 9 to 11. Therefore, the water supply was completely stopped in this region.

The disruption of water supply continued for 17 days in Kimitsu City, the western part of the prefecture (see Figure 3). The water supply disruption was caused after the landfall of Typhoon Faxai on September 9. The additional disruption was caused on September 12 because the water in the distributing reservoir was significantly reduced. The water intake facilities in this region did not work because of the power outage. The power supply cars owned by Tokyo Electric Power Co., Inc. (TEPCO) were employed for important water supply facilities, however, the restoration work was difficult because of a number of fallen trees in the mountainous areas in this city. The roads in the mountainous areas were partially closed because of the fallen trees, and it took a lot of time and effort to reach the important water supply facilities. It should be noted that there was no damage to the water distribution pipelines in Chiba Prefecture. The main reason for the disruption of water supply was the power outages.

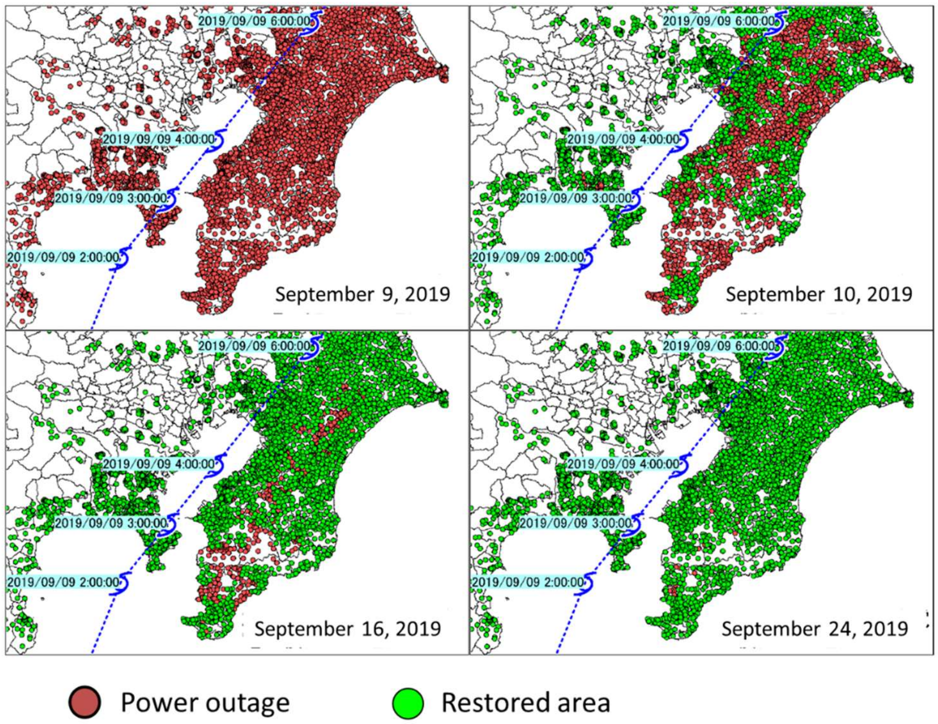


**Figure 2. Distributions of power outages in the Tokyo Metropolitan area.**

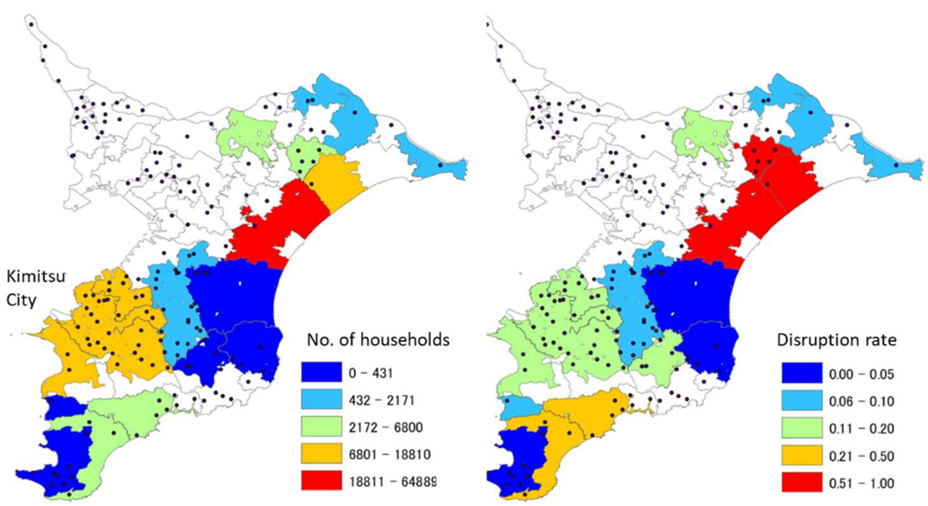


**Figure 3. Maximum number of households without water supply and the maximum disruption rate.**

## CONCLUSION

This paper briefly reviewed the recent studies on enhancement of resilient water supply system. The seismic fragility functions were continuously revised after the recent major earthquakes in Japan. The restoration process of water supply system has been considered since the 1995 Kobe earthquake. An example of water disruption because of the extensive power outage was introduced through the situations after Typhoon Faxai, the 15th typhoon in 2019.

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Ministry of Economy, Trade, and Industry. (2019). <https://www.meti.go.jp/shingikai/sankoshin/hoan_shohi/denryoku_anzen/tettou/index.html> (in Japanese)

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Nagata, S., Maruyama, Y., Suzuki, S., Sudo, S., Shimizu, S., Yoshimori , K., Yusa, A., and Toride, S. (2020). "Damage to Power Supply Facilities and Power Outages due to Typhoon Faxai (TY1915).", *Natural Disaster Research Report*, 57, 1-10. (in Japanese)

**Craig A. Davis, Presentation, C. A. Davis Engineering**
**“Hazard Resilient Design in USA and Examples of pipeline failures based on Hazard Impact Matrix”**

# Hazard Resilient Design in USA and Examples of pipeline failures based on Hazard Impact Matrix

Craig A Davis
Hazard Resilient Pipe Research Panel
3rd meeting April 25, 2023

1

Contents

1. Seismic Design Procedures used in the USA
2. Hazard Impact Matrix

2

2

## Seismic Design Procedures used in the USA

3

3

## Seismic Design Procedures for Buried Pipes

- American lifelines Alliance
  American Lifelines Alliance (ALA), 2005 “Design Guidelines for Seismic Resistant Water Pipeline Installations,” FEMA and National Institute of Building Sciences. www.americanlifelinesalliance.com.
- American Society of Civil Engineers Manual of Practice for Seismic Design of Buried Water and Wastewater Pipelines
  - Under preparation.
  - Uses similar procedure as ALA (2005)
- LADWP Resilience Program (2019)
  - Expands on the ALA (2005)
- Functional Recovery FEMA-NIST (2021)
  - Expands on the LADWP (2019) and ASCE MOP work

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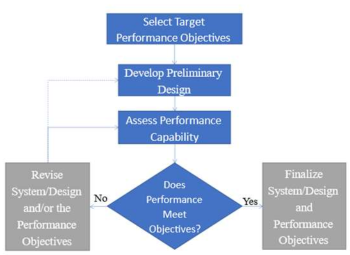
## Performance-Based Procedure

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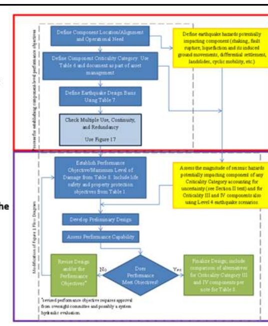
**The upper portion of this diagram will be explained first**

**Followed by a description of the lower portion of this diagram**

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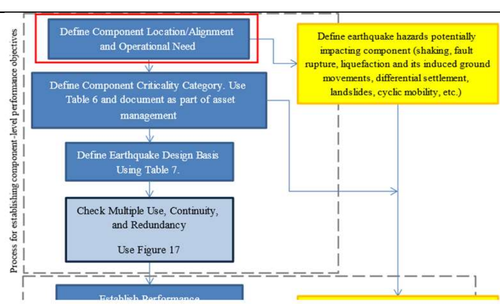


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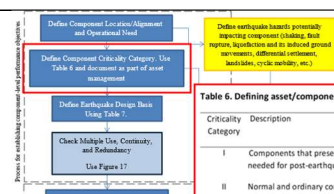


**Critical A Customers:** Public Health and Safety (e.g., hospital)

**Critical B Customers:** Important Community Resilience Activities (e.g., economic center)

**Table 6. Defining asset/component criticality levels**

| Criticality Category | Description |
|---|---|
| I | Components that present very low hazard to human life in the event of failure. Not needed for post-earthquake system performance, response, or recovery. |
| II | Normal and ordinary components. These components are needed to provide services for typical residential, commercial, and industrial use within the system and include all components not identified in Criticality Categories I, III, and IV. |
| III | Components providing services that represent a substantial hazard or mass disruption to human life in the event of failure. Failure of these components may result in significant social or economic impacts. **Critical B Customers.** |
| IV | Components needed to provide services to essential facilities for post-earthquake response, public health, and safety. These components are intended to remain functional during and following an earthquake. **Critical A Customers** |

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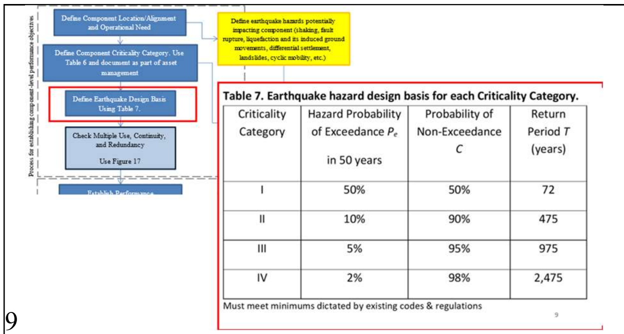

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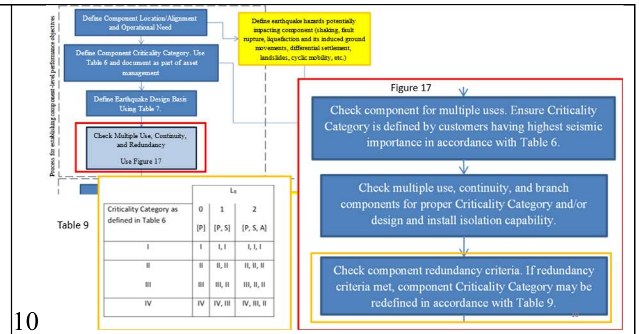

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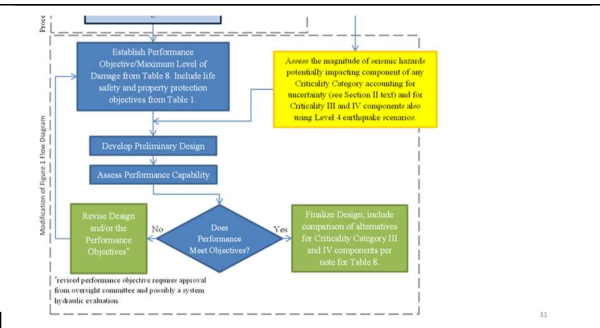

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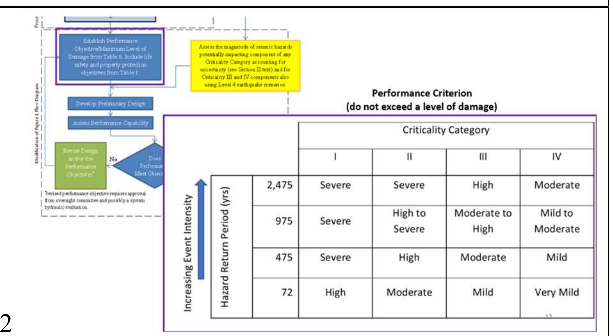

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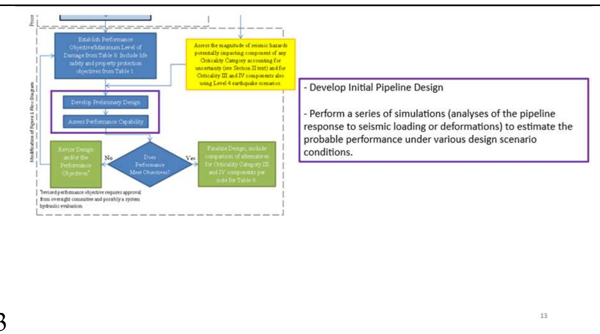

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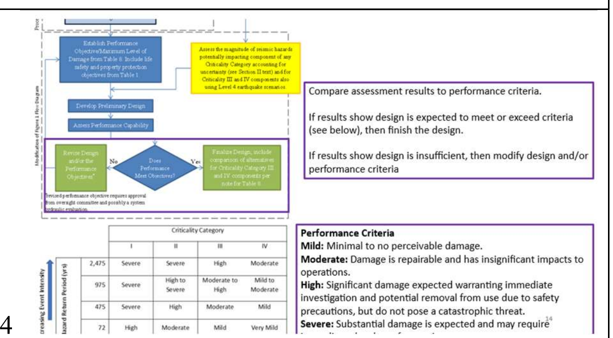

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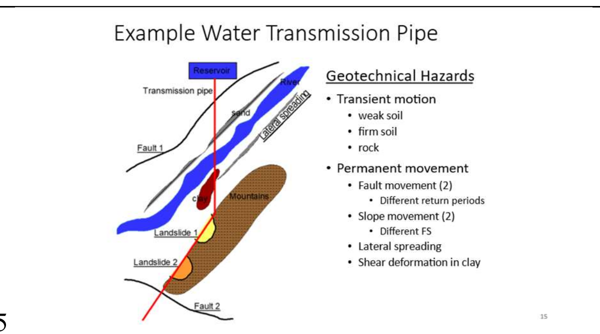

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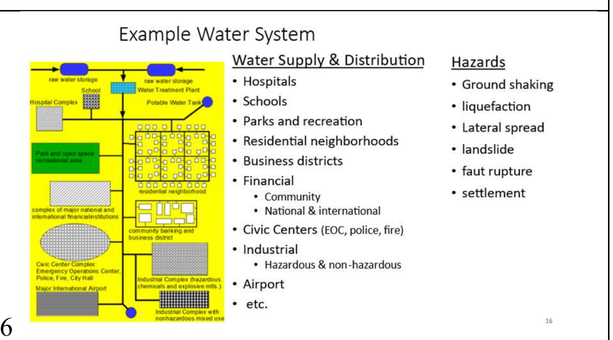

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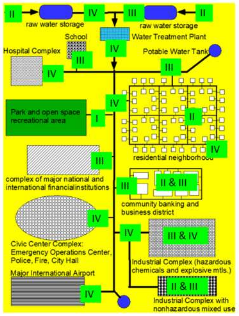


- Criticality Category examples
- IV
  - Hospitals
  - Emergency shelters
  - Civic Centers (EOC, fire, police, etc.)
  - Airport (major nat. & internat.)
  - Industrial (hazardous)
- III
  - Fire supply to Function II
  - Schools
  - Large occupancy structures
  - Financial (nat. & internat.)
- II (most common)
  - Industrial (non-hazardous)
  - Residential neighborhoods
  - Business districts
  - Financial (community)
- I
  - Parks and recreation
  - Agriculture
  - Very small communities

Design the pipes for hazards they are exposed for intensities designated by corresponding return periods

**Table 7. Earthquake hazard design basis for each Criticality Category.**

| Criticality Category | Hazard Probability of Exceedance $P_e$ in 50 years | Probability of Non-Exceedance C | Return Period T (years) |
|---|---|---|---|
| I | 50% | 50% | 72 |
| II | 10% | 90% | 475 |
| III | 5% | 95% | 975 |
| IV | 2% | 98% | 2,475 |

Must meet minimums dictated by existing codes & regulations

17

18

# Hazard Impact Matrix

18

19

## Hazard Impact Matrix (Draft Ver. 2.1)

Hazard impact on pipeline structure or water carried within the pipeline

| Hazard | Ground deformation | Others | Impact on pipeline structure: Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Impact on water quantity: Lower water flow performance | Impact on water quality: Leaching | Permeance | Contaminents | Oder, Taste Chromaticity, Turbidity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosi | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosi | Power outage | XX ※ | XX ※ | XX ※ | | X | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect, thermal strain | | XX | | ※ | | | | | | |
| Wildfire | - | Heat effect, thermal strain | | | | XX | | | XX | | | XX |
| Winter Weather | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Cold Wave | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Incluces secondary hazards
PGD: Permanent Ground Displacement

**Legend**
XX: High impact and probability of occuring
X: Possibility of impact low probability
※: Above ground pipeline

19

20

## Hazard Impact Matrix

- All the hazards in the matrix have the potential of impacting pipelines in the USA
- Professor Miyajima covered potential damages from different hazards very well.
- I will not attempt to duplicate the same for the USA, but recognize the impacts can and do occur in the USA
- Dr. Wham covered wildfire and some other impacts in meeting No. 2
- This presentation will identify:
  - Recent impacts in the USA from:
    - Extreme Cold and Hot weather,
    - Winter Freeze, and
    - Hurricane and other strong winds
    - Heavy rain and Flood
  - Additional hazards to include in the matrix

20

21

## Extreme temperature changes

**Change water and ground temperature (without freeze)**
**Results in pipe damages potentially enhanced by deterioration (References: LADWP, Arlington, others)**

Hazard impact on pipeline structure or water carried within the pipeline

| Hazard | Ground deformation | Others | Impact on pipeline structure: Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Impact on water quantity: Lower water flow performance | Impact on water quality: Leaching | Permeance | Contaminents | Oder, Taste Chromaticity, Turbidity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosi | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosi | Power outage | XX ※ | XX ※ | XX ※ | | X | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect, thermal strain | | XX | | ※ | | | | | | |
| Wildfire | - | Heat effect, thermal strain | | | | XX | | | XX | | | XX |
| Winter Weather | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Cold Wave | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Incluces secondary hazards
PGD: Permanent Ground Displacement

**Legend**
XX: High impact and probability of occuring
X: Possibility of impact low probability
※: Above ground pipeline

21

22

## Winter Freeze

**Ground freezes and heaves, thaw causes settlement when it warms; water in pipe may freeze**
**Results in damage to pipes**

Hazard impact on pipeline structure or water carried within the pipeline

| Hazard | Ground deformation | Others | Impact on pipeline structure: Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Impact on water quantity: Lower water flow performance | Impact on water quality: Leaching | Permeance | Contaminents | Oder, Taste Chromaticity, Turbidity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosi | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosi | Power outage | XX ※ | XX ※ | XX ※ | | X | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect, thermal strain | | XX | | ※ | | | | | | |
| Wildfire | - | Heat effect, thermal strain | | | | XX | | | XX | | | XX |
| Winter Weather | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Cold Wave | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Incluces secondary hazards
PGD: Permanent Ground Displacement

**Legend**
XX: High impact and probability of occuring
X: Possibility of impact low probability
※: Above ground pipeline

22

23

## Winter Freeze

Arlington Water pipe data from February 2021 winter freeze

**Pipe materials that experienced breakage**
Cast Iron – 117
Asbestos Cement – 5
PVC – 4
Ductile Iron – 3
Galvanized – 1

**Pipe Diameter**
6" – 84
8" – 23
2-2.25" – 9
4" – 9
12" – 4
16" – 1

**Repair Method**
Typical repair by installing repair clamps,
If pipe is in too poor of a condition, the deteriorated pipe is cut out and a new section of PVC or DI is sleeved in.

23

24

## Hurricane and Strong Wind

**Windcan blow over trees and blow off roofs https://www.tomorrowsworldtoday.com/2021/09/20/hurricane damageto-water-pipeslouisiana/**
**Falling trees and roofs can damage below and above ground pipes**

Hazard impact on pipeline structure or water carried within the pipeline

| Hazard | Ground deformation | Others | Impact on pipeline structure: Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Impact on water quantity: Lower water flow performance | Impact on water quality: Leaching | Permeance | Contaminents | Oder, Taste Chromaticity, Turbidity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosi | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosi | Power outage | XX ※ | XX ※ | XX ※ | | X | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect, thermal strain | | XX | | ※ | | | | | | |
| Wildfire | - | Heat effect, thermal strain | | | | XX | | | XX | | | XX |
| Winter Weather | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Cold Wave | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Incluces secondary hazards
PGD: Permanent Ground Displacement

**Legend**
XX: High impact and probability of occuring
X: Possibility of impact low probability
※: Above ground pipeline

24

## Heavy Rain and Flood

**Heavy rain and flood causes slope failures and erosion**
**Slope movement and erosion damages pipelines**

| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline: Impact on pipeline structure: Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Impact on water quantity: Lower water flow performance | Impact on water quality: Leaching | Permeance | Contaminents | Oder, Taste Chromaticity . Turbidity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosi | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosi | Power outage | XX ※ | XX ※ | XX ※ | | X | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | X | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect, thermal strain | | XX | | ※ | | | | | | |
| Wildfire | - | Heat effect, thermal strain | | | | XX | | | XX | | | XX |
| Winter Weather | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Cold Wave | Freeze heave, thaw s | Freeze bursting, thermal stra | XX | XX | XX | XX | XX | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Incluces secondary hazards
PGD: Permanent Ground Displacement

**Legend**
XX: High impact and probability of occuring
X: Possibility of impact low probability
※: Above ground pipeline

25

25

## 2022 Example Water Pipe Damages from Heavy Rain and Flood - from NACWA*

- Kentucky – 636-year flood and 1,000-year rain event
  - Perry County's water infrastructure was "totally annihilated" by flash floods
  - See images in later slides
- Death Valley – 1,000-year flood and rainfall event
  - Flooding caused a major break in the water line for the Cow Creek Water system
- Jackson, Mississippi – 1,000 year rain event
  - Jackson, Mississippi suffered from complete failure of its water infrastructure
  - failure stem from long term disinvestment in the water utility and a severe winter storm in 2021
- Alaska – Typhoon Merbok
  - Infrastructure in Alaska was not resilient enough to resist extreme weather from climate change

*National Association of Clean Water Agencies

26

26

## July 26-30, 2022 Eastern Kentucky Flash Flood

**Trench Erosion**

Courtesy Mike Whitehouse


27

27

## July 26-30, 2022 Eastern Kentucky Flash Flood

**Culvert Failure and Erosion**

Courtesy Mike Whitehouse



28

## July 26-30, 2022 Eastern Kentucky Flash Flood

**Slope Failure**

Courtesy Mike Whitehouse


29

29

## Proposed Additions to Hazard Impact Matrix

- Erosion
  - May be a primary or secondary hazard (like landslide can be)
  - Erosion may cause problems over time independent of other hazards
- Permafrost Thaw (results in settlement)
- Ground Freeze-Thaw (causes heave and settlement)
- Subsidence (may be caused by a number of events like mining, pumping ground water, hydraulic compression, etc.)
- Fluvial flooding (+flash floods)
  - Consider just listing flooding and explaining all the types of flooding possible
- Expansive soils (results in heave)
- Sinkholes (i.e. like in karst – results in settlement/subsidence)
- Thermal strain from extreme heat and cold
- Include wind-blown problems for hurricanes and other strong wind events

30

30

## Discussion on:

Hazard Resilient Design
Hazard Impact Matrix

31

# Performance-Based Seismic Design Procedure for Buried Water Pipelines

**Craig A. Davis[1], Ph.D., P.E., G.E.**

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## ABSTRACT

The seismic design of buried water pipelines in the USA has evolved to utilize performance-based methodologies over the past few decades. Buried pipelines are components making up significant portions of water systems. In many water systems buried pipelines are their greatest assets by number and value. This paper summarizes a performance-based seismic design process useful for designing buried water pipelines.

## INTRODUCTION

The seismic design of buried water pipelines over the past few decades mostly advances from the initial performance-based design methodology laid out in ALA (2005, Ch. 3). The method identifies the importance of a pipeline to delivering services to customers. The design level is determined based on the identified importance of the pipeline. Davis (2005, 2007, 2008) describes procedures for identifying the design intensity measures for common seismic geo-hazards with relatively uniform confidence. Performance-based geotechnical methodologies continue to advance (Rathje et al., 2014; Franke et al., 2021) and supersede the work of Davis (2005, 2007, 2008). These initial procedures and continued improvements are being implemented in an American Society of Civil Engineers (ASCE) manual of practice for the seismic design of buried water and wastewater pipelines (ASCE, forthcoming). The performance-based methodology is important for improving the resilience of water systems. This is why the Los Angeles Department of Water and Power (LADWP, 2019) prepared the first performance-based seismic design methodology incorporating the consistent design for all system components to target system-level service recovery times. A method for creating a seismic resilient pipe network (Davis, 2018) was developed to identify where hazard resilient pipelines should be located within the system to meet needed service recoveries consistent with the performance-based seismic design methodology.

All pipelines are components within the water system. Each component must be designed to allow the water system to recover services to customers within target service recovery times. FEMA-NIST (2021) identified the need to evolve the design of water systems, along with other lifeline infrastructure systems, using recovery-based objectives. FEMA (2024) describes a procedure for establishing water system recovery-based objectives. NIST (2024) outlines a procedure for the design of components and systems to meet the recovery-based objectives. The NIST (2024) framework advances the performance-based design procedures initially developed for buried pipelines and includes all other water system components.

The following section describes the performance-based design process. This general process is then described in more specific terms applied to buried pipelines. Using the process for buried pipelines, the basis for design is first described.

## PERFORMANCE BASED SEISMIC DESIGN PROCESS

Figure 1 presents a flow diagram of the performance-based design procedure. The process initiates by selecting target performance objectives for the buried pipeline. A preliminary pipeline design is then prepared followed by an assessment of its performance capability. The performance is then compared with the target objectives. If the objectives are met then the performance objective and pipeline design are finalized. If the objectives are not met then the design is modified to attempt to meet the objectives. In some cases when the design cannot be prepared to meet the objectives due to economic or physical constraints, then the objectives may be modified.

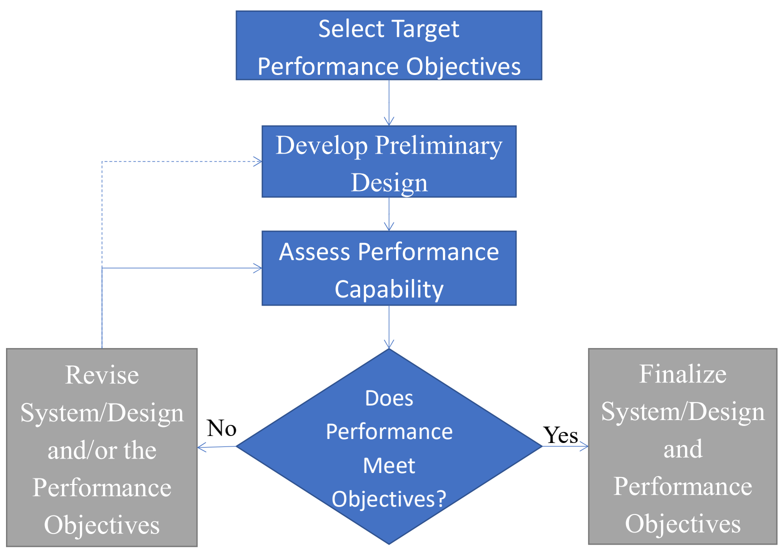


**Figure 1. Performance-based design procedure (modified from LADWP, 2019).**

## PERFORMANCE BASED SEISMIC DESIGN FOR BURIED PIPELINES

The designs for all pipelines are to incorporate life safety and property protection and follow the procedure diagrammed in Figure 2. The upper portion of Figure 2 establishes the hazard level basis for the design. The lower portion of Figure 2 performs the buried pipeline design. The right side of Figure 2 emphasizes the assessment of geotechnical earthquake hazards. Descriptions for assessing the geotechnical hazards can be found in ALA (2005), Davis (2008), Rathje et al. (2014), Franke and Kramer (2014) Franke et al. (2015; 2021), among other references.

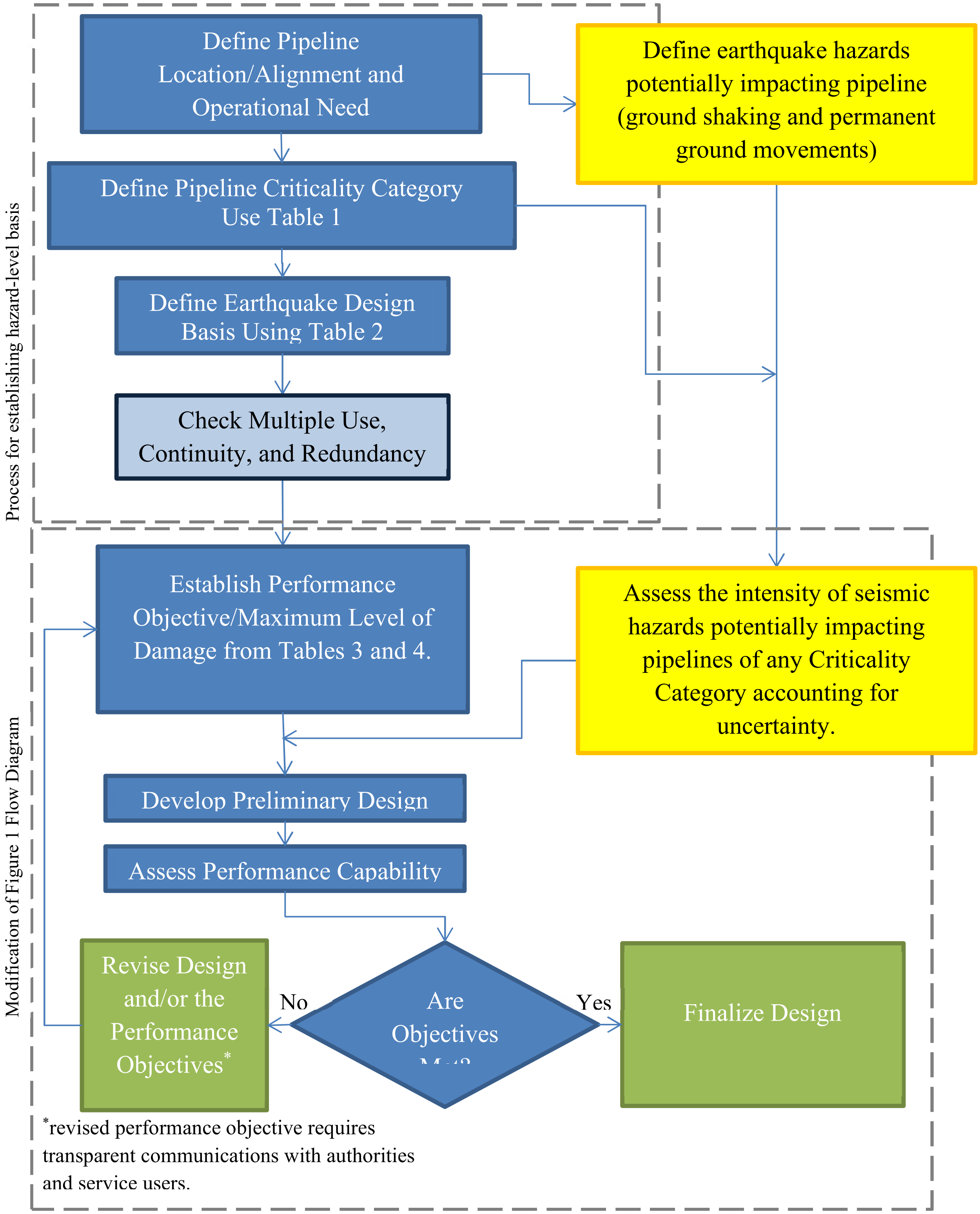


**Figure 2. Performance-based seismic design flow diagram (modified from LADWP, 2019 and Davis, 2019).**

### Establishing the Hazard-Level Basis for Design

The process in Figure 2 starts by identifying the pipeline location and its alignment (i.e., position and orientation within the network). The location is defined geographically and identifies the pipeline position within the network topology. The location also allows the exposure to seismic hazards to be defined as identified in the yellow box to the right in Figure 2. There are two yellow boxes in Figure 2 which deal with hazard intensity levels and how they affect buried pipelines. The results of a hazards assessment are used as input in the lower portion of Figure 2.

The alignment within the system identifies the criticality of pipelines to provide water services to customers. Each pipeline is designated a Criticality Category I, II, III, or IV as defined in Table 1. Designing pipelines to the defined categories aids the system in meeting overall service recovery times. System-level service recovery objectives are not described herein because they are beyond the scope of this summary paper but can be found in FEMA (2024).

**Table 1. Criticality Categories. Adapted from Davis (2008) and ALA (2005).**

| Criticality Category | Description |
|---|---|
| I | Pipelines, in the event of failure, present very low hazard to human life, no damage to property, and little to no effects on user's ability to perform their post-earthquake activities or functions. These components are not needed for post-earthquake system performance, response, or recovery. They typically serve for non-essential agricultural or irrigation usage, certain temporary facilities, or minor (non-water) storage facilities which do not have a significant role in the economy. Pipelines may provide potable water supply for a few isolated service connections but are not required for any level of fire suppression following a significant earthquake and have easy access for repair. |
| II | All components not identified in Criticality Categories I, III, and IV. This includes pipelines providing services to customers engaging in nonhazardous material storage, commercial, some non-commercial, and industrial buildings not needed for essential emergency response or initial recovery. |
| III | Pipelines providing water services to customers that represent a substantial hazard or mass disruption to human life in the event of failure, including significant levels of property damage. An extended operational outage for these pipelines may result in significant social or economic impacts and cause significant effects on users' ability to perform their activities or functions. Operational disruption of these pipelines causes long delays in post-earthquake system response or recovery. These components are needed to provide water to **Critical B Customers**. |
| IV | Pipelines providing water services to essential facilities for post-earthquake response, public health, and safety. This includes pipelines needed for primary post-earthquake firefighting. These pipelines are intended to remain operable during and following an earthquake. These also include all pipelines in the water supply chain to **Critical A Customers**. Additionally, this category includes pipelines, if rendered inoperable, that may result in secondary disasters potentially impacting life safety or public health, impeding emergency response and operations, impeding evacuation routes, or disruption to other lifeline infrastructure systems. |

Critical A customers are defined as those who need lifeline system services in support of actions for life safety and public health associated with post-earthquake emergency response and recovery. Critical B customers are defined as those who need lifeline system services in support of actions for crucial community resilience activities. Critical A and Critical B customers generally require a more rapid service restoration than other customers to ensure resilient community recovery.

Table 2 defines the earthquake hazard design basis for each Criticality Category in terms of hazard return period and uncertainty. The preferred procedure is to use the hazard return period identified from geotechnical performance-based methodologies (e.g., Rathje and Saygili, 2008; Rathje et al., 2014; Franke and Kramer, 2014; Franke et al., 2015; Franke et al., 2021). However, in the absence of performance-based geo-hazard assessments, pseudo-static procedures may be employed to provide a uniform confidence that the loads and displacements of buried pipelines should not be exceeded. The pseudo-static procedures utilize empirical equations, incorporating uncertainty using a standard deviation $\sigma$ to determine the hazard intensities as described by Davis (2008).

**Table 2. Pipeline design level in terms of hazard return period and uncertainty. $\sigma$ is the standard deviation (modified from Davis (2008).**

| Criticality Category | Hazard Return Period (years) | Uncertainty |
|---|---|---|
| I | 72 | Mean - 1σ |
| II | 475 | Mean |
| III | 975 | Mean + 0.5σ |
| IV | 2,475 | Mean + 1σ |

As shown in Figure 2, components are to be checked for multiple use, continuity, and redundancy. Details on these checks are presented in Davis (2017) and LADWP (2019).

## Target Pipeline Performance Objective

Pipeline performance objectives are established through definitions of maximum earthquake damage to meet a certain pre-defined performance level. Table 3 identifies the four primary levels of component damage: minor, moderate, high, and severe. Some targeted maximum damage states fall between levels. They are designated with dual terms, such as moderate to high while others fall on an extreme side of one of the primary levels like very minor.

Pipeline performance objectives are established through definitions of maximum targeted damage. Table 3 is a matrix showing the targeted maximum level of damage for different Criticality Categories and hazard return periods. Hazard return periods effectively represent event intensity. The top row in Table 3 is the component design level in terms Criticality Category. The left column is the hazard level experienced in terms of return period. Table 3 represents performance objectives for the design of new or the retrofit of existing pipelines. The default performance objective occurs when the pipeline experiences event intensities matching the design level. As a result, the default performance objectives lay along the diagonal of Table 3 from the upper right to the lower left. When the intensities experienced by a pipeline is less than the design level, the anticipated damage level reduces, which is reflected in the portion of Table 3 to the lower right of the diagonal. When the intensities experienced by a pipeline is greater than the design level, the anticipated damage level increases, which is reflected in the portion of Table 3 to the upper left of the diagonal. When a pipeline is designed to meet the criteria defined in Table 2, it should not experience any more damage than the levels identified in Table 3. The damage levels are described in Table 4.

**Table 3. Target maximum level of component damage based on Criticality Categories (modified from Davis (2019) and LADWP 2019).**

| | | Increasing Performance → | | | |
|---|---|---|---|---|---|
| | | Criticality Category | | | |
| | | I | II | III | IV |
| Increasing Event ↑ | Hazard Return Period (yrs) 2,475 | Severe | High to Severe | Moderate to High | Minor to Moderate |
| | 975 | High | Moderate to High | Minor to Moderate | Minor |
| | 475 | Moderate | Minor to Moderate | Minor | Very Minor |
| | 72 | Minor to Moderate | Minor | Very Minor | Very Minor |

**Preliminary Pipeline Design**

As shown in Table 3, each pipeline is to meet or exceed the design basis criteria defined in Table 1, based on the Criticality Category, or justify to the proper authorities why the targeted design criteria cannot be met. The component design shall account for the maximum tolerable damage identified in Tables 3 and 4. The designs shall incorporate hazard uncertainty consistent with the performance-based design methodology.

**Assess the Pipeline Performance and Compare with Target Objectives**

Using the preliminary pipeline design, the expected pipeline performance is assessed when subjected to the earthquake hazards to which it is exposed, using the levels designated in Table 2. This is done by performing a series of simulations (analyses of the pipeline response to seismic loading) to estimate the probable performance under various scenario conditions. Using fragility relationships, the pipeline responses are equated to damage states expressed as performance levels. Additionally, if the component being evaluated is expected to be damaged, then further effort is needed to determine if the damage state is at a level that may prevent it from operating; Table 4 can provide guidance.

**Table 4. Water System Damage Levels and Summary Descriptions**

| Damage Level | Summary Description |
|---|---|
| **Minor** | Minimal to no perceivable damage. Limited to no effects on water system operations. Trunk lines and their appurtenances have minor to no perceivable damage and transmission operations are not affected. Water distribution pipelines and appurtenances have minor damage, resulting in very few leaks and breaks which are easy to repair and impact a small number of customers. Tunnels and channels have minor to no damage requiring little to no repair (e.g., minor concrete cracking). |
| **Moderate** | Damage is repairable. Trunk lines and appurtenances may have minor leaks which require shutdown and repairs, but no serious structural damage, breaks, or significant flooding from the pipelines. Critical and essential mainlines will behave similar to trunk lines. Water distribution pipeline networks may have several leaks and breaks, potentially locally impacting services provided to customers. Tunnels and channels have moderate to minor damage requiring little to some limited repair (e.g., concrete patching), but no serious structural defects requiring immediate shutdown. |
| **High** | Significant damage is expected. Trunk lines and appurtenances may have significant structural damage, but either retain their pressure boundaries or have limited leakage, requiring them to be shut down for repairs. Critical and essential mainlines will behave structurally similar to trunk lines but may be drained due to other distribution pipe damages. Water distribution pipeline networks may have many leaks and breaks, potentially locally impacting services provided to customers. Tunnels and channels can have serious damage requiring them to be removed from use for repair. |
| **Severe** | Substantial damage is expected. Repair may not be technically feasible. Trunk lines and appurtenances have ruptures requiring immediate shutdown for repairs and releasing significant amounts of water onto the ground surface. Distribution pipeline networks have a great number of leaks and breaks, impacting services provided to a large number of customers. Tunnels and channels can have substantial damage where repairs may not be feasible, requiring complete reconstruction. |

Where fragilities are insufficient and/or the pipeline does not warrant the multiple advanced analyses, this task may be reduced to a simple exercise to confirm if the pipeline meets the performance objective. This approach may involve comparative analysis drawing from experience in past earthquakes or laboratory experiments, simple calculations using procedures independent of those used in the design to confirm expected performance, external expert review, and/or mental assessments to think through the problem to determine if the preliminary design is sufficient to meet the objectives. The analyzer may need to make some value judgements when making this assessment.

Once the simulated performance is completed, the results are compared to the target objectives. The expected level of damage from the simulations is compared to the target maximum damage levels in Tables 3 and 4. If the results do not meet or exceed the objectives, then path ‘No’ is followed in Figure 1 and either the pipeline design or the original objectives need to be modified, and the assessment repeated. There may be situations where meeting the stated objective may not be possible due to physical or cost constraints, in which case the team of designers, decisionmakers, and stakeholders may elect to modify the original objectives. LADWP (2019, page 28) describes some ways to accomplish this. Modification of objectives need to be transparently communicated to authorities and service users, and potential approvals attained. If the results do meet or exceed the objectives, then path ‘Yes’ is followed in Figure 1, the pipeline design is finalized.

## CONCLUSION

A performance-based procedure for the design of buried pipelines has been presented. The procedure establishes the seismic loading to be used as the basis for design, the target performance objective, and how to assess if the preliminary design meets the target objective. The objective is posed in terms of potential damage from the earthquake hazards that the pipeline is exposed to. Implementing the performance based seismic design methodology will significantly improve water system resilience.

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**Masakatsu Miyajima, Presentation, Kanazawa University, Professor Emeritus**
**“Examples of Pipeline Failure Based on Hazard Impact Matrix & Latest Seismic Design and Construction Guideline for Water Facilities in Japan”**

1

## Examples of Pipeline failure based on Hazard Impact Matrix & Latest seismic design and construction guideline for water facilities in Japan

Professor Emeritus of Kanazawa University

Masakatsu Miyajima

1

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2

## Contents



2

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3

## Hazard impact matrix (Draft, ver.1)

**Legend**
※ : Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability

| | Hazard | Hazard impact on pipeline structure or water carried within the pipeline | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Impact on pipeline structure | | | | | Impact on water quality | | | | |
| | | Slip-out | Breakage | Scratch/ Corrosion | Strength reduction (heat/chem., fatigue/creep) | Uplift or settlement | Lower water flow performance | Leaching | Permeance | Contaminants | Odor, Taste Chromaticity, Turbidity |
| FEMA Natural Hazard Index: 18 Natural Hazards. Includes secondary hazards | Avalanche | ※ | ※ | ※ | | | ※ | | | | |
| | Coastal Flooding | XX | XX | XX | | X | X | | X | X | X |
| | Cold Wave | | XX | | XX | | | | | | |
| | Drought | | | | | | | | | XX | XX |
| | Earthquake | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| | Hail | | ※ | ※ | | | | | | | |
| | Heat Wave | | | | ※ | | | | | | |
| | Hurricane | XX | XX | XX | | X | X | | X | X | X |
| | Ice Storm | | XX | | XX | | | | | | |
| | Landslide | XX | XX | XX | | | XX | | X | X | X |
| | Lightning | | | | | | | | | XX | XX |
| | Riverine Flooding | XX | XX | XX | | X | X | | X | X | X |
| | Strong Wind | ※ | ※ | ※ | | | ※ | | X | | |
| | Tornado | ※ | ※ | ※ | | | ※ | | X | | |
| | Tsunami | XX | XX | XX | | X | X | | X | X | X |
| | Volcanic Activity | X | X | X | XX | | X | XX | | | XX |
| | Wildfire | | | | XX | | | XX | | | XX |
| | Winter Weather | | XX | | XX | | | | | | |

3

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4

## Hazard impact matrix (Draft, ver.2)

- Sorted hazard by similarity of impact on pipeline.
- Added “Heavy rain” to the hazards list.
- Added column for hazard impact of ground deformation and other factors.
- Summarized impact on pipeline structure and water quality for each hazard impact.

| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Impact on pipeline structure | | | | | Impact on water quantity | Impact on water quality | | | |
| | | | Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Lower water flow performance | Leaching | Permeance | Contaminants | Odor, Taste Chromaticity, Turbidity |
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ※ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Includes secondary hazards
PGD: Permanent Ground Displacement

**Legend**
※ : Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability

4

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5

## Permanent ground displacement (Landslide and road shoulder collapse)

- Heavy rainfall and earthquakes cause landslides and road shoulder collapse.
- Landslides and road shoulder collapse cause damage to pipelines.


| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Impact on pipeline structure | | | | | Impact on water quantity | Impact on water quality | | | |
| | | | Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Lower water flow performance | Leaching | Permeance | Contaminants | Odor, Taste Chromaticity, Turbidity |
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ※ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Includes secondary hazards
PGD: Permanent Ground Displacement

**Legend**
※ : Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability


5

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6

## Landslide and road shoulder collapse in Japan

**Heavy rain (2017, Northern Kyushu)**

国土交通省：平成29年7月北部九州豪雨による土砂災害の概要＜速報版＞

**Typhoon (2019 Typhoon Hagibis, Gunma)**


パスコHP: 2019年10月 台風19号豪雨災害

**Earthquake (2018 Hokkaido Eastern Iburi earthquake)**



毎日新聞Web版：軽石層一気に崩壊 厚真町の土砂崩れ, 2018/9/7 07:40

6

7

## Impact of landslide and road shoulder collapse on pipeline

**Joint slip-out （6" DIP, K-Type）**
Landslide by 2004 Niigata-ken Chuetsu earthquake

美子ら：高機能ダクタイル鉄管の地滑りなど大規模な地盤変状における挙動の検証事例

**Joint slip-out （6" DIP, K-Type）**
Road shoulder collapse by heavy rain, 2004

日本水道新聞社：平成16年台風による水道施設の被害写真集



8

## Impact of landslide and road shoulder collapse on pipeline

**6",8" HRDIP (No damage)**
Road shoulder collapse by heavy rain, 2018

厚生労働省：平成 30 年（2018 年）7月豪雨
水道施設被害状況調査報告書

**8" HRDIP (No damage)**
Road shoulder collapse by heavy rain from typhoon, 2004

日本水道新聞社：平成16年台風による水道施設の被害写真集



9

## Erosion

- Heavy rainfall, flood and tsunami cause erosion of soil.
- Erosion cause damage to pipelines.

| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Impact on pipeline structure | | | | | Impact on water quantity | Impact on water quality | | | |
| | | | Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Lower water flow performance | Leaching | Permeance | Contaminants | Odor, Taste Chromaticity, Turbidity |
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ≡ | ≡ | ≡ | | | ≡ | | X | X | X |
| Strong Wind | - | Power outage | ≡ | ≡ | ≡ | | | ≡ | | X | X | X |
| Hail | - | - | | ≡ | ≡ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ≡ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ≡ | ≡ | ≡ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Includes secondary hazards
PGD: Permanent Ground Displacement

**Legend**
≡ : Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability



10

## Impact of erosion on pipeline

**Slip-out (4" DIP, Tyton) and pipe body breakage (4" PVC)**
Erosion by heavy rain from typhoon, 2004


道路（河川）崩壊による管路の被害（津名町）
（φ100 ダクタイル鋳鉄管-T形：継手抜け
φ100 塩化ビニル管：管体破損）

日本水道新聞社：平成16年台風による水道施設の被害写真集

**Pipe body leakage (4" HDPE)**
Erosion by heavy rain , 2017

水道産業新聞社：九州北部豪雨による水道施設・道路の被害写真集



11

## Impact of erosion on pipeline

**6" ERDIP (No damage)**
Erosion by typhoon, 2004


日本水道新聞社：平成16年台風による水道施設の被害写真集

**8" ERDIP (No damage)**
Erosion of river bank by Tsunami, 2011,Great East Japan Earthquake


水道産業新聞社：平成23年東日本大震災による水道施設の被害写真集



12

## Impact of erosion on pipeline

**HDPE pipeline**
Erosion and uplifting of pipeline by Tsunami, 2011Great East Japan Earthquake

Shinchi, Fukusima Prefecture

13

## Flooding or Submergence

- Submergence can cause water outage.
- Water outage can cause turbidity.

| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Impact on pipeline structure | | | | | Impact on water quantity | Impact on water quality | | | |
| | | | Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Lower water flow performance | Leaching | Permeance | Contaminants | Odor, Taste Chromaticity Turbidity |
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ※ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Includes secondary hazards
PGD: Permanent Ground Displacement

**Legend**
※ : Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability

13

14

## Flooding, Submergence

- Flooding caused sediment to flow into water supply facilities.

**Flooding of water supply facilities (2017, Northern Kyushu Heavy Rain)**

Pump control facility



水道産業新聞社：九州北部豪雨による水道施設・道路の被害写真集

14

15

## Earthquake

- Earthquakes cause various types of permanent ground displacement.

| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Impact on pipeline structure | | | | | Impact on water quantity | Impact on water quality | | | |
| | | | Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Lower water flow performance | Leaching | Permeance | Contaminants | Odor, Taste Chromaticity Turbidity |
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ※ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," Includes secondary hazards
PGD: Permanent Ground Displacement

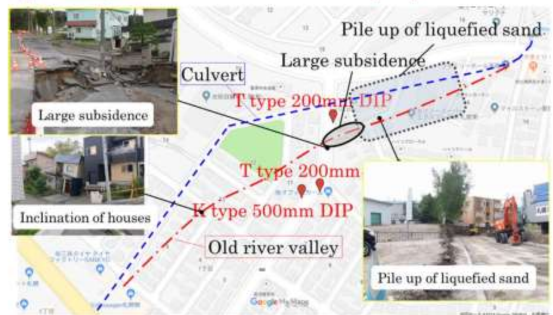
**Legend**
※ : Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability

15

16

## Earthquake (Liquefaction)

**Liquefaction (2018 Hokkaido Eastern Iburi earthquake)**




16

17

## Earthquake (Liquefaction)

**Ground deformation caused by liquefaction**

Liquefaction, 2018 Hokkaido Eastern Iburi earthquake

17

18

## Impact of liquefaction on pipeline

**Slip-out (20″ DIP, K-type)**


**Slip-out (8″ DIP, T-type)**

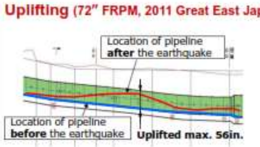

Liquefaction, 2018 Hokkaido Eastern Iburi earthquake

18

19

## Impact of liquefaction on pipeline

**Uplifting (72" FRPM, 2011 Great East Japan earthquake)**





有吉ら：平成23年(2011年)東北地方太平洋沖地震による国営隈戸川農業水利事業における農業用パイプラインの被災と復旧

**Uplifting (Water tank, 2011 Great East Japan earthquake)**

水道産業新聞社：平成23年東日本大震災による水道施設の被害写真集

19

20

## Volcanic activity

- Volcanic activity cause permanent ground displacement.

| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline: Impact on pipeline structure: Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Impact on water quantity: Lower water flow performance | Impact on water quality: Leaching | Permeance | Contaminants | Odor, Taste Chromaticity, Turbidity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ※ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," includes secondary hazards
PGD: Permanent Ground Displacement

**Legend**
※ : Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability

20

21

## Volcanic Activity

**Volcanic eruption (2000, Mount Usu)**

**Ground deformation**


ダクタイル鉄管協会：2000年有珠山噴火における水道管路被害および地盤変状調査結果報告、ダクタイル鉄管協会誌

21

22

## Impact of Volcanic Activity on pipeline

**Compression of pipeline (14" DIP, K-type)**

**Pipe body breakage (PVC)**

ダクタイル鉄管協会：2000年有珠山噴火における水道管路被害および地盤変状調査結果報告、ダクタイル鉄管協会誌

22

23

## Power outage

- Several hazards cause power outages.
- Temporary interruption of water supply due to power outages can cause low water flow and turbidity.

| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline: Impact on pipeline structure: Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Impact on water quantity: Lower water flow performance | Impact on water quality: Leaching | Permeance | Contaminants | Odor, Taste Chromaticity, Turbidity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ※ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," includes secondary hazards
PGD: Permanent Ground Displacement

**Legend**
※ : Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability

23

24

## Power outage

**Strong winds (2019 Typhoon Faxai)**


Falling of electric poles

Number of houses without power


NHK：千葉 台風15号(2019)の長期停電教訓に「マイクログリッド」
毎日新聞社：台風15号：停電・断水・死者…最大級の被害を「把握すらできなかった」国と千葉県の責任

**Lighting (2022)**

Lightning strike to purification plant



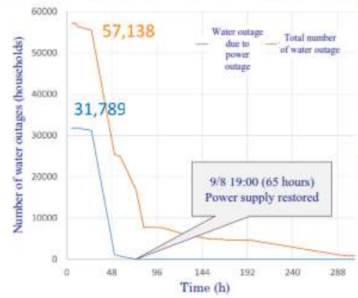
新潟新聞：水道水に濁り 静岡市葵区、駿河区の一部 落雷による停電影響、静岡新聞電子版 2022.7.26
NHK：静岡市の浄水場に落雷 浄水機能一時停止 再発防止検討へ、NHK NESW WEB

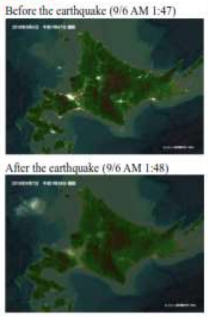
24

25

## Impact of power outage on pipeline

**Earthquake (2018 Hokkaido Eastern Iburi earthquake)**




FASCO CORPORATION, Tokyo University of Information Sciences, NASA

25

26

## Freeze bursting

- Low temperatures cause freeze bursting.

| Hazard | Hazard impact on pipeline structure or water carried within the pipeline | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ground deformation | Others | Impact on pipeline structure | | | | | Impact on water quantity | Impact on water quality | | | |
| | | | Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Lower water flow performance | Leaching | Permeance | Contaminants | Odor, Taste Chromaticity, Turbidity |
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ※ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," includes secondary hazards
PGD: Permanent Ground Displacement

**Legend**
※: Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability

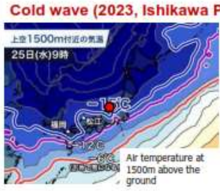
26

27

## Impact of Freezing on pipeline

- A cold wave arrived on January 26, 2023, causing many entities in Ishikawa Prefecture to experience water outages and reductions.
- The main reason for the water outages and reductions was that the amount of water discharged exceeded normal levels due to frequent leaks caused by frozen water pipes.

**Cold wave (2023, Ishikawa Pref.)**




出典:ウェザーニュースHP


輪島市における住民市の支援（提供＝日水協中部地方支部）

出典:日本水道新聞第5789号，日本水道新聞社

27

28

## Impact of Freezing on pipeline

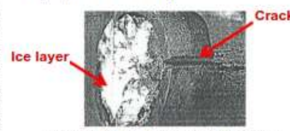
- Damage to asbestos cement pipes and gray cast iron pipes due to freezing and frost has been reported.
- Asahikawa City decided to adopt ductile iron pipes to prevent pipe damage due to freezing and frost heave.

**Breakage (Asbestos pipe )**

**Asbestos pipe damage due to freezing (Diameter and thickness are unknown)**

旭川市:積雪寒冷地の旭川市における水道施設の維持管理について，ダクタイル鉄管54号

**Cast iron pipe damage due to freezing (4", thickness 6mm)**




槙迫 貴一郎, 極東 英秀: 低温環境下の伝熱現象とその応用

28

29

## Penetration and contaminants

- Damage to above ground structures may cause contamination of drinking water.

| Hazard | Hazard impact on pipeline structure or water carried within the pipeline | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ground deformation | Others | Impact on pipeline structure | | | | | Impact on water quantity | Impact on water quality | | | |
| | | | Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Lower water flow performance | Leaching | Permeance | Contaminants | Odor, Taste Chromaticity, Turbidity |
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Strong Wind | - | Power outage | ※ | ※ | ※ | | | ※ | | X | X | X |
| Hail | - | - | | ※ | ※ | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | ※ | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | ※ | ※ | ※ | | | | | | | |

Hazard: FEMA Natural Hazard Index 18 Natural hazards and "Heavy rain," includes secondary hazards
PGD: Permanent Ground Displacement

**Legend**
※: Above ground pipeline
XX: High impact and probability of occurring
X: Possibility of impact, lower probability

29

30

## Penetration and contaminants

- In 2022, gasoline spilled from a gas station and permeated a polyethylene pipe.
- If a gas station or other facility is impacted by the hazard, organic solvents could permeate the pipeline.

**Penetration of benzene (2" PE)**



北海道新聞社：北海道新聞2022.8.10（室蘭市_水道水から基準超ベンゼン・室蘭市謝罪）
日経XTECH：樹脂製の水道管からガソリン流入、管種の選定ミスか

30

31

## Hazard impact matrix (Draft, ver.2)

- Many hazard impacts could be covered.
- Wildfires, tornados, hails, ice storms and avalanches are less frequent in Japan.
- A few hazard impact could not be found, shown in blue frame.

| Hazard | Ground deformation | Others | Hazard impact on pipeline structure or water carried within the pipeline: Impact on pipeline structure: Slip-out | Breakage | Scratch/ Corrosion | Strength reduction heat/chem., fatigue/creep | Uplift or settlement | Impact on water quantity: Lower water flow performance | Impact on water quality: Leaching | Permeance | Contaminants | Odor, Taste, Chromaticity, Turbidity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landslide | PGD | Power outage | XX | XX | XX | | | X | | X | X | X |
| Heavy rain | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Hurricane | PGD [Landslide,Erosion] | Power outage | XX | XX | XX | | | X | | X | X | X |
| Coastal Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Riverine Flooding | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Tsunami | PGD [Erosion] | Power outage, Submergence | XX | XX | XX | | X | X | | X | X | X |
| Earthquake | PGD, Ground motion | Power outage | XX | XX | XX | XX | XX | XX | | X | XX | XX |
| Volcanic Activity | PGD | Power outage, Heat effect | XX | XX | XX | XX | | X | XX | | | XX |
| Tornado | - | Power outage | X | X | X | | | X | | X | X | X |
| Strong Wind | - | Power outage | X | X | X | | | X | | X | X | X |
| Hail | - | - | | X | X | | | | | | | |
| Lightning | - | Power outage | | | | | | X | | | XX | XX |
| Drought | - | Scheduled Water outage | | | | | | | | | XX | XX |
| Heat Wave | - | Heat effect | | | | X | | | | | | |
| Wildfire | - | Heat effect | | | | XX | | | XX | | | XX |
| Winter Weather | - | Freeze bursting | | XX | | XX | | | | | | |
| Cold Wave | - | Freeze bursting | | XX | | XX | | | | | | |
| Ice Storm | - | - | | | | | | | | | | |
| Avalanche | - | - | X | X | X | | | | | | | |

Hazard: FEMA National Hazard Index 18 Natural hazards and "Heavy rain," includes s

PGD: Permanent Ground Displacement

Hazard impact shown in this presentation

Low-probability hazard in Japan

Similar to what Prof. Wham introduced at the second meeting.
(Fire impacts on water distribution infrastructure)

31

32

## Contents

1. Examples of Pipeline failure based on Hazard Impact Matrix
2. Latest seismic design and construction guideline for water facilities in Japan

32

33

## Seismic Design and Construction Guidelines for Water Facilities, revised in 2022

*Published by Japan Water Works Association
3 volumes: Main part, Reference materials , and Design calculation examples .

33

34

## 3 Topics : Seismic Design and Construction Guidelines for Water Facilities

① Seismic suitability for each type of joint and pipe
② Anti-catastrophe
③ Design of fault crossings

34

35

## Seismic suitability for each type of joint and pipe

| Pipe (Joint) | Seismic performance of distribution pipes: It is possible to maintain the functions of Level 1 earthquake even if minor damage occurs individually. | Seismic performance of trunk lines: No damage to Level 1 earthquake, in principle | Seismic performance of trunk lines: It is possible to maintain the functions of Level 2 earthquake even if minor damage occurs individually. |
|---|---|---|---|
| **Ductile iron pipe (NS Type Joint, etc.)** HRDIP | **O** | **O** | **O** |
| Ductile iron pipe (K Type Joint, etc.) | O | O | Note 1 |
| Ductile iron pipe (A Type Joint, etc.) | O | △ | × |
| Cast iron pipe | × | × | × |
| **Steel pipe (Welded Joint)** | **O** | **O** | **O** |
| Polyethylene pipe (Fusion Joint) Note 2 | O | O | Note 3 |
| Polyethylene pipe (Cold Joint) | O | △ | × |
| Polyvinyl chloride pipe (RR Long Joint) Note 4 | O | Note 5 | |
| Polyvinyl chloride pipe (RR Joint) | O | △ | × |
| Polyvinyl chloride pipe (TS Joint) | × | × | × |
| Asbestos cement pipe | × | × | × |

(Note 1) [illegible]
(Note 2) [illegible]
(Note 3) [illegible]
(Note 4) [illegible]
(Note 5) [illegible]

Legend) □: Seismic suitability
×: No seismic compatibility
△: Items that have relatively low damage rates but are not clearly earthquake resistant.

35

36

## Anti-catastrophe

**Consider "anti-catastrophe," which is a performance that reduces the possibility of water supply facilities reaching a critical situation when safety is compromised by unexpected earthquake, tsunami, wind or flood damage.**

Examples of Countermeasure for Pipelines
- Pipeline Duplication
- Block Distribution System
- Installation of backup pipelines
- Adoption of bridge fall prevention devices (water pipe bridge)
- Selection of pipe types considering earthquake resistance

Bridge fall prevention devices (water pipe bridge)

36

37

## Basic concept of anti-seismic measures for pipeline considering geological features and faults

① Adequate earthquake countermeasures should be especially implemented in areas where geological and topographical considerations are required or where structural considerations are required.

② When the existence of an active fault is clearly understood, it is a basic rule to avoid planning and designing such an important line, such as a trunk pipeline, to cross it.
If it is unavoidable, it is necessary to use highly earthquake-resistant pipe types and joints for the entire pipeline and to provide sufficient expansion and contraction flexibility, taking into account the extent of impact caused by an active fault.

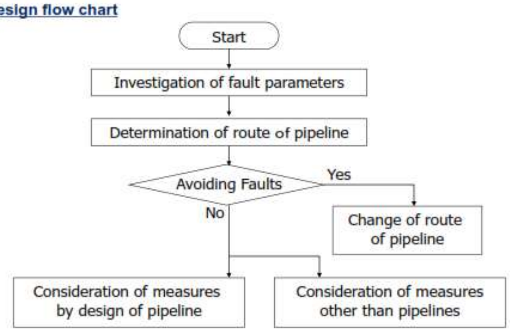
37

38

## Design of fault crossings

**The design of fault cross-sections was added to the guidelines.**

**Design flow chart**

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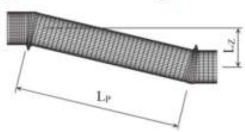
39

## Design of fault crossings

**Example of measures by design of pipeline**

**Design using steel pipe for fault crossing.**




**Design using HRDIP and long collar**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Thank you for your attention

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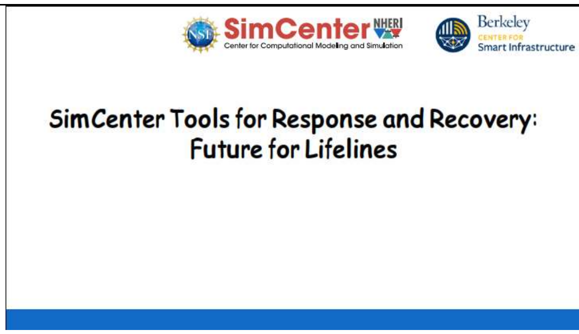
**Kenichi Soga, Presentation, University of California, Berkeley, Professor**
**"SimCenter Tools for Response and Recovery: Future for Lifelines"**



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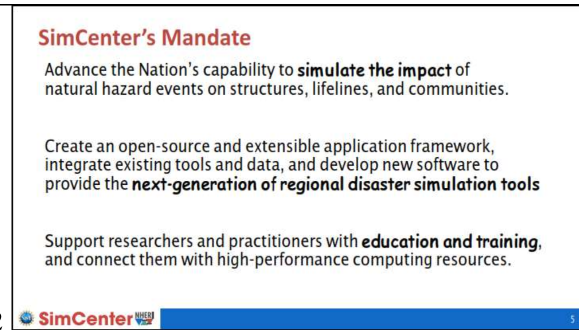

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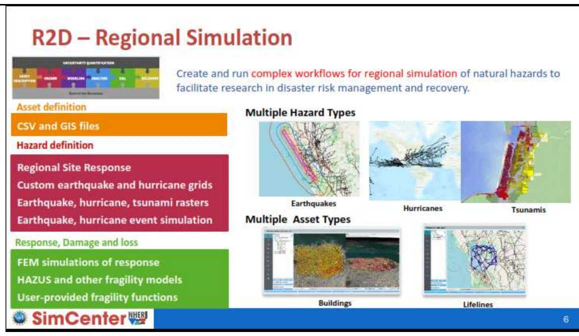

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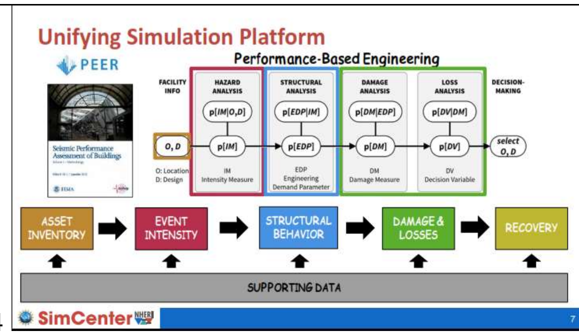

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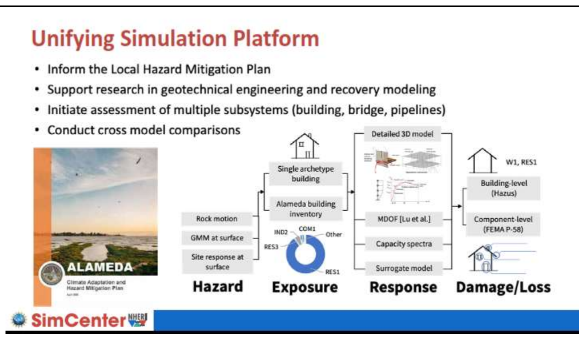

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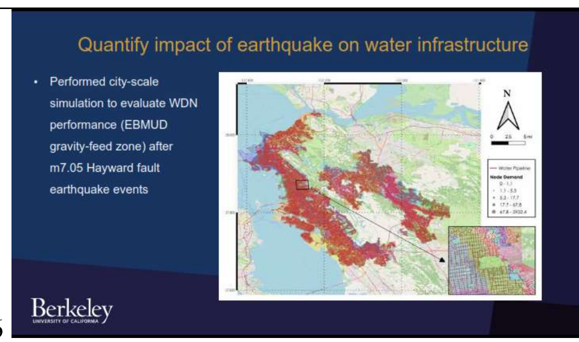

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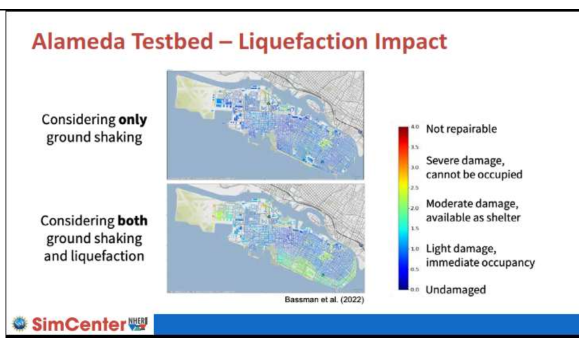

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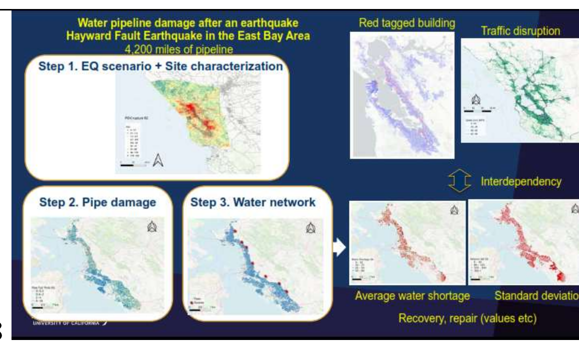

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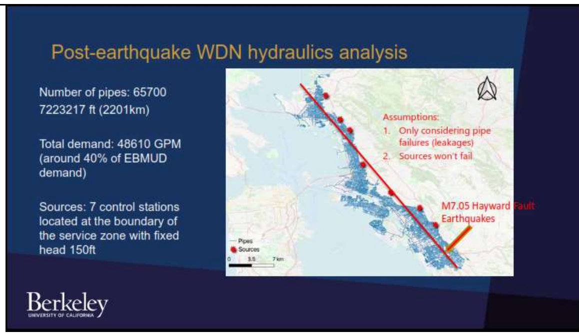


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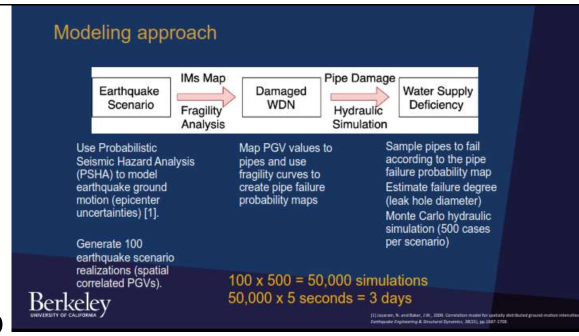


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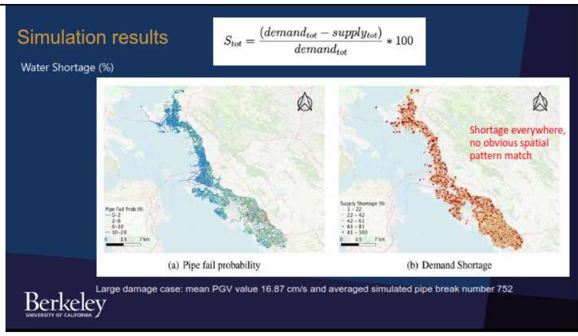


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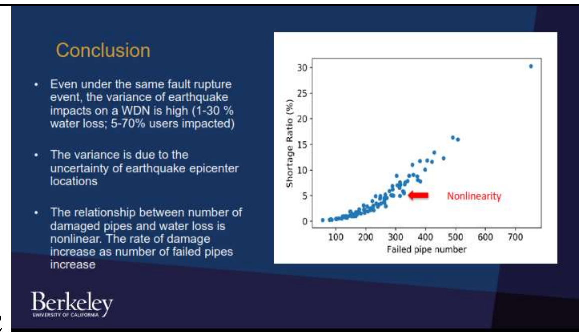


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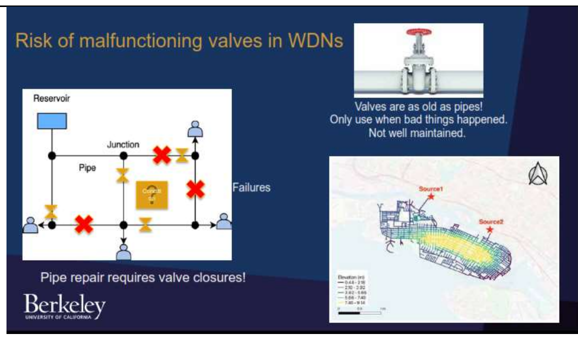


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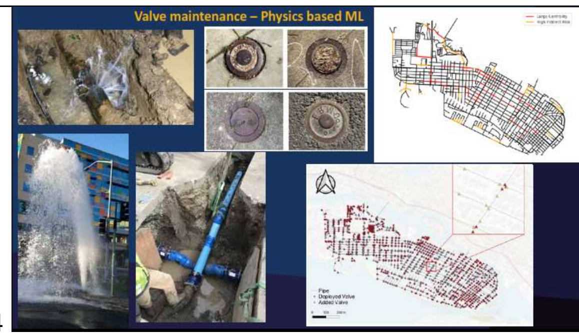


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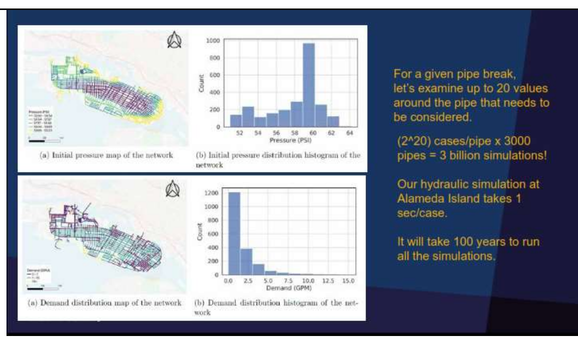


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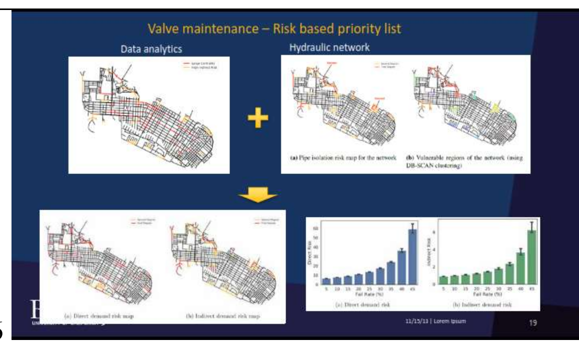


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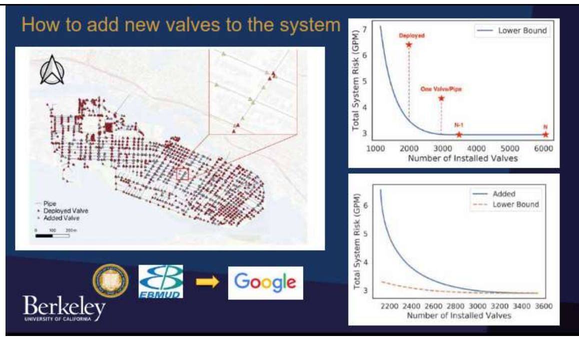


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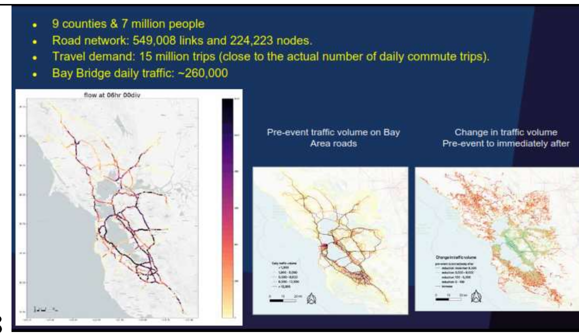


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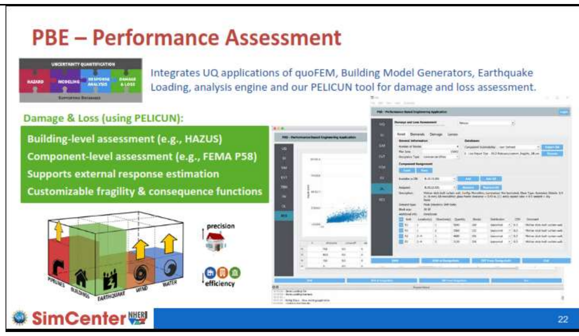


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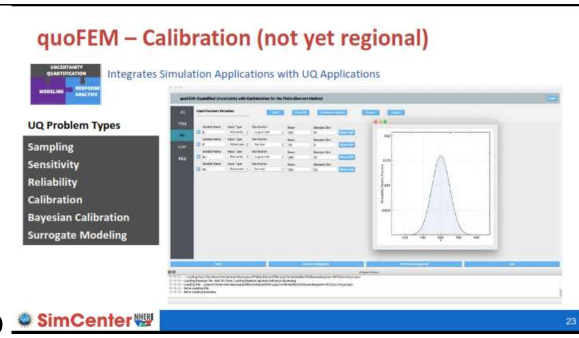


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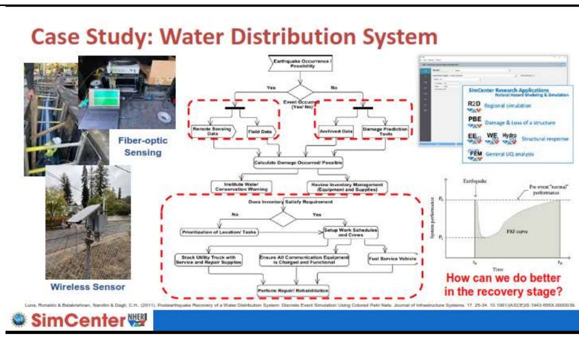


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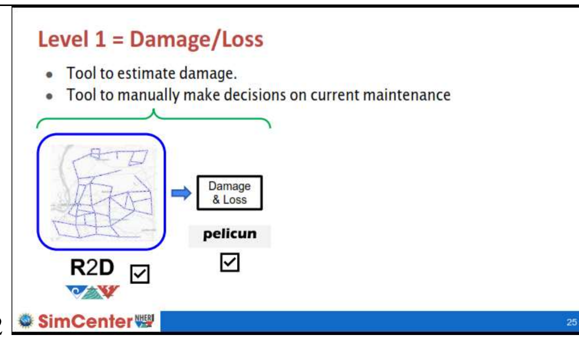


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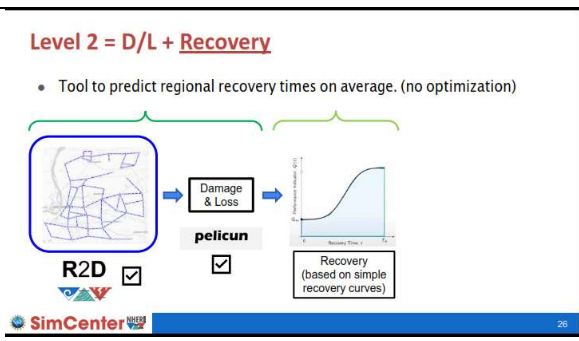


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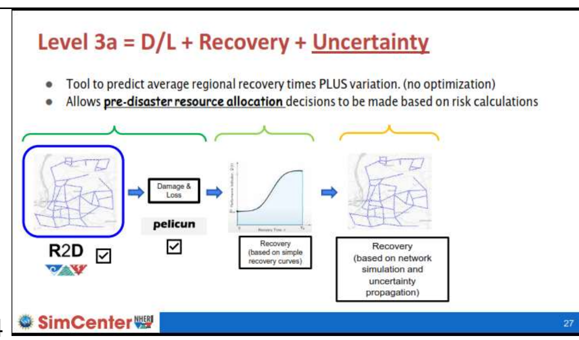
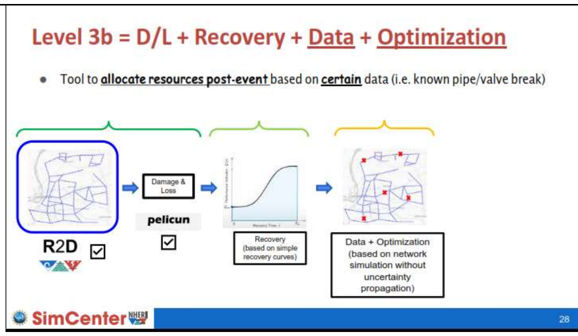
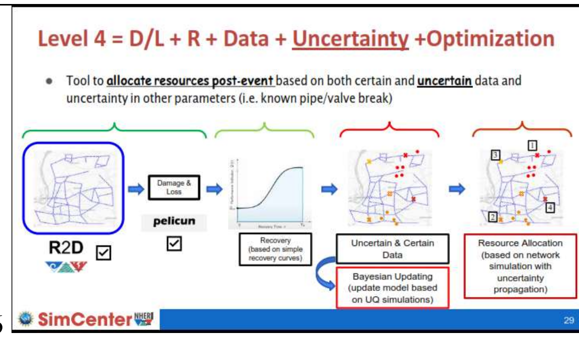



Level 3b = D/L + Recovery + Data + Optimization
Tool to allocate resources post-event based on certain data (i.e. known pipe/valve break)
Damage & Loss
pelicun
R2D
Recovery (based on simple recovery curves)
Data + Optimization (based on network simulation without uncertainty propagation)
SimCenter
28
25


Level 4 = D/L + R + Data + Uncertainty +Optimization
Tool to allocate resources post-event based on both certain and uncertain data and uncertainty in other parameters (i.e. known pipe/valve break)
Damage & Loss
pelicun
R2D
Recovery (based on simple recovery curves)
Uncertain & Certain Data
Bayesian Updating (update model based on UQ simulations)
Resource Allocation (based on network simulation with uncertainty propagation)
SimCenter
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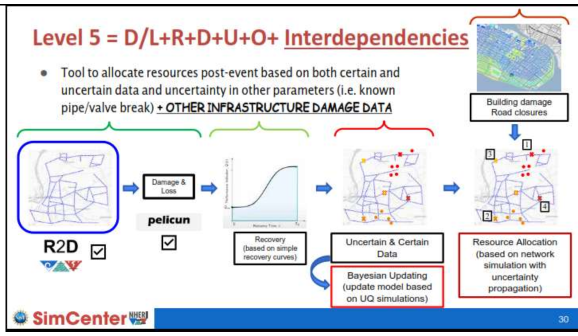
Level 5 = D/L+R+D+U+O+ Interdependencies
Tool to allocate resources post-event based on both certain and uncertain data and uncertainty in other parameters (i.e. known pipe/valve break) + OTHER INFRASTRUCTURE DAMAGE DATA
Building damage
Road closures
Damage & Loss
pelicun
R2D
Recovery (based on simple recovery curves)
Uncertain & Certain Data
Bayesian Updating (update model based on UQ simulations)
Resource Allocation (based on network simulation with uncertainty propagation)
SimCenter
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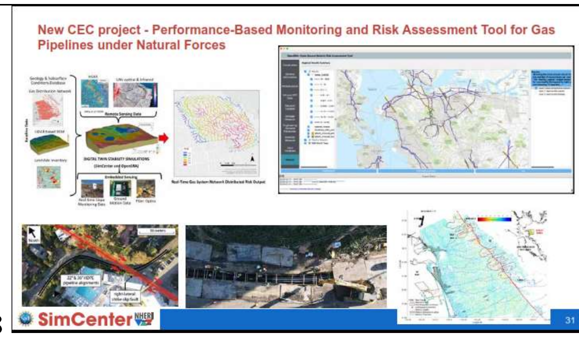

New CEC project - Performance-Based Monitoring and Risk Assessment Tool for Gas Pipelines under Natural Forces
SimCenter
31
28

**Tetsuo Tobita, Presentation, Kansai University, Professor**
**"Pipeline Damage: Case, Physical and Numerical Studies"**

HRDIP Hazard Resilient Ductile Iron Pipe 自然災害に対して 復元力の高い、または しなやかな強靱性を持った ダクタイル鉄管 HAZARD RESILIENT

Hazard Resilient Pipe Research Panel (HRPRP) 4th Meeting:
2023.11.7-8 at Nagoya University

Pipeline damage:
Case, physical and numerical studies

Tetsuo Tobita, Kansai University

1

1

2

Topics

- Case study on irrigation pipeline damage after the 2011 Tohoku Earthquake
- Centrifuge model testing on mitigation of pipe uplift due to liquefaction
- Numerical modelling on mitigation of pipe uplift due to liquefaction

3

NARO (National Agliculture and Food Research Organization) Report, 213, 201 -215, 2012

**Damage and Restoration of Agricultural Pipeline at Kumadogawa Irrigation Project by the 2011 off the Pacific coast of Tohoku Earthquake**

ARIYOSHI Mitsuru, MOHRI Yoshiyuki, ASANO Isamu and UENO Kazuhiro

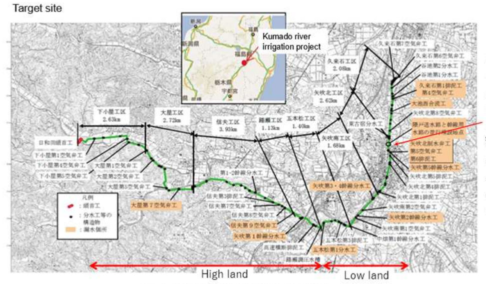
**Summary**

Large diameter pipelines for agriculture in Kumado distinct, Fukushima prefecture, were damaged by 2011 Tohoku earthquake. Separations of joints around deformed pipes, uplifts of straight pipes and structures, and settlements of backfill materials occurred in the distinct. The damages were heavy in the plain due to liquefaction of backfill materials. All buried pipelines are 17.8 kilometers and nearly 17% of them ware need for reconstruction. When the pipelines are restored, gravels are used as backfill material to prevent liquefaction. And the damaged pipelines are reused due to cost reduction. There are growing concerns about large earthquakes like Tonankai and Nankai earthquakes. Pipelines need to be made more earthquake resistant.

**Keywords** : 2011 Tohoku earthquake, agricultural pipeline, liquefaction, field investigation, restration

4

Target site



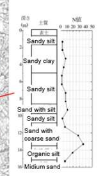




Fig. 1 国営隈戸川地区の幹線パイプライン平面図
Plan view of Kumadogawa irrigation project

Fig. 2 ボーリング柱状図
Boring log

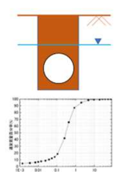
Ariyoshi et al. (2012)

5

Damage pattern of pipeline depends on;

1. Type and stiffness of the subgrade and backfill material

Highland: (Weathered) Tuff
Lowland: Fill, clayey, sandy material



2. Type of pipes and joints

Major: FRPM
Minor: Ductile Iron and Steel
Diameter. 1.35 m- 2.6 m

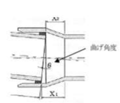
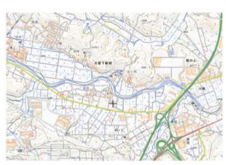



Fig. 7 継手の曲げ角度
Joint bend angle

3. Topography of the pipe-laying area

Mountainous to lowland



Ariyoshi et al. (2012)

2

6

Hazard matrix

| Hazard | Ground deformation or *Others* | Impact Likelihood: On Pipeline Structure: Slip-out | Breakage /Collapse | Scratch/ Corrosion | Strength Reduction Heat/Chem., Fatigue/Creep | Uplift or Settlement | Concurrent on Multiple Pipelines | Likelihood of Service Disruption To: Water Delivery, Fire Flow, Quantity | Water Quality: (Water quality) Leaching | (Water quality) Odor,Taste, Chromaticity, Turbidity | Service Disruption Consequence |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Earthquake | TGD (Shaking) ● | XX | XX | XX | XX | XX | XXX | XX | | XX | M-H |
| | PGD (Landslide, etc.) ● | XXX | XXX | XX | XX | XXX | XXX | XXX | | XX | H |
| | Fault | XXX | XXX | XX | XX | XXX | XX | XXX | | XX | H |
| | Liquefuction ● | XX | XX | XX | XX | XXX | XXX | XXX | | XX | H |
| Landslide | PGD ● | XXX | XXX | XX | | XXX | X | XXX | | | L-M |
| Erosion | PGD ● | XX | XX | XX | | X | X | XX | | | L-M |
| Subsidence | PGD ● | XX | XX | XX | | XXX | XX | XXX | | | M |
| Heavy rain | PGD (Landslide, etc.) ● | XXX | XXX | XX | | XXX | X | XXX | | | L-M |
| | Erosion ● | XX | XX | XX | | XX | X | XX | | | L-M |
| Hurricane | PGD (Landslide, etc.) ● | XXX | XXX | XX | | XXX | X | XXX | | | L-M |
| | Erosion ● | XX | XX | XX | | XX | X | XX | | | L-M |
| | *Strong wind* | X | X | | | | | X | | | L |
| Flooding | PGD (Erosion) ● | XX | XX | XX | | XX | XX | XX | | X | M |
| | *Impact force by water and driftage* | XX | XX | XX | | | XX | XX | | | M |
| Tsunami | PGD (Erosion) | XX | XX | XX | | X | XX | XX | | X | M |
| | *Impact force by water and driftage* | XX | XX | XX | | | XX | XX | | | M |

HRPRP Final Report Draft v3.0 sent to HRPRP for review.docx

7

Damage to the pipeline in Kumado River Project (after Ariyoshi et al. 2012)

| Damaged Facilities | Damage Type | |
|---|---|---|
| Pipeline | Pipe slip-out | 3 |
| | Pipe deflection of 5% of diameter (allowable deflection rate) or more | 39 |
| | Joint spacing is greater than the allowable value | 101 |
| | Joint spacing is within the allowable limit, but joint test (test water pressure with a test band) was unsatisfactory. | 4 |
| | Joint spacing at joint rings exceeds the allowable value | 1 |
| | Stagnant water depth inside the pipe is 5 cm or more | 77 |
| Ancillary | Uplifting and subsidence of ancillary facilities | 11 |
| | Deformation of diversion pipes and drainage pipes | 7 |
| | Deformation of exterior structures and pavement around ancillary facilities | 9 |
| Control road | Deformation of the road surface above the control road pipe | 26 |

8

Characteristics of pipeline damage known from the past earthquakes in Japan (JSAIR 2009)

(1) Pipe slip-out at connections with ancillary facilities such as manholes and thrust blocks
(2) Pipe slip-out at the boundary where soft ground, topography, or geology changes
(3) Pipe uplift/settlement due to liquefaction of backfilling sand or the original ground
(4) Pipe movement due to slope failure
(5) Pipe slip-out around structures installed on the shoulder of a slope

In addition, for pipelines with internal water pressure, leakage due to the slip-out of the pipeline can lead to secondary damage, such as ground runoff and traffic obstructions.

Ariyoshi et al. (2012)

**Fig. 26** 五本松第 1 分水工周辺の片落管の離脱
Separation of a reducer around Gohonmatsu No.1 division works


**Fig. 27** 五本松第 1 分水工の浮上
Uplift of Gohonmatsu No.1 division works

9

**Fig. 34** パイプ敷設道路の亀裂（矢吹南第 2 空気弁工周辺）
Cracks on the road around Yabukiminami No.2 air valve


**Fig. 35** パイプ敷設道路の亀裂（矢吹南第 2 空気弁工）
Cracks on the road around Yabukiminami No.2 air valve

10

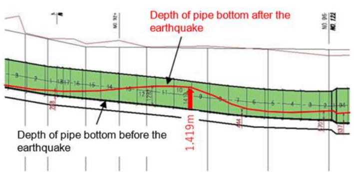



**Fig. 33** 矢吹南第 2 幹線分水工周辺（Fig.30）の縦断図（赤：地震後の位置，単位 mm）
Longitudinal profile at the point of fig.30

ϕ 2200

**Fig. 37** 不陸により滞水しているパイプ（矢吹南工区）
Stagnant water due to unevenness of pipe at Yabukiminami subsection

11


**Fig. 36** 矢吹南第 2 空気弁工の浮上
Uplift of Yabukiminami No.2 air valve

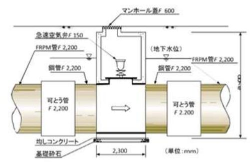



**Fig. 38** 矢吹南第 2 空気弁工の断面図
Cross section of Yabukiminami No.2 air valve

12

**Fig. 42** スラストブロックの破損（矢吹南工区）
Damage to thrust block at Yabukiminami subsection

**Fig. 45** パイプ埋戻し材料の噴砂（矢吹北第 5 排泥工周辺）
Sand boil on a road around Yabukikita No.5 blow off

13

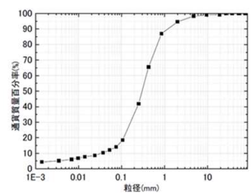



**Fig. 57** 矢吹南工区における基礎材料の粒径加積曲線
Particle size distribution curves of embedment material at Yabukiminami subsection

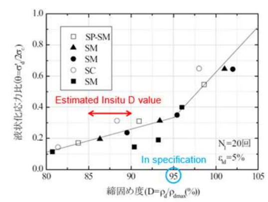



**Fig. 58** 締固め度と液状化応力比の関係
（出典：土地改良事業計画設計基準及び運用・解説設計「パイプライン」）
Relationship between compaction degree and liquefaction

14

## Summary

Damage to the pipelines in the Kumado River area in the 2011 Tohoku earthquake

The damage occurred not only in irregularly shaped pipe sections such as curved pipes and near ancillary structures, but also in straight sections due to liquefaction of the foundation material.

The use of geomaterials with a high coefficient of ground reaction, such as cement stabilized soil, and pipe types with seismic-resistant joints should be adopted in the areas around the deformed pipes and structures and at points of topographical and geological changes.

Ariyoshi et al. (2012)

15

## EXPERIMENTAL STUDY OF THE COUNTERMEASURE ON PIPELINE UPLIFT DUE TO LIQUEFACTION

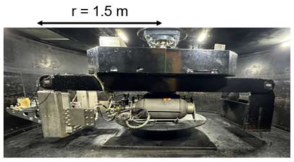
Presented at the 43rd Earthquake Engineering Symposium, JSCE (2023)

Hyukkee HONG, Tetsuo TOBITA
KANSAI UNIVERSITY

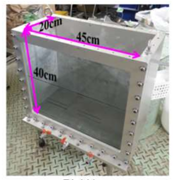
Katsutoshi MIYAMOTO and Yasuhiko KONISHI
Nihon Suido Consultants Co., Ltd.

16

## Experimental equipment




Geotechnical Centrifuge at Kansai University




Rigid box

17

## Model pipe

Pipe

| | | Model scale | Prototype scale |
|---|---|---|---|
| Length | cm | 18.0 | 9 x $10^2$ |
| Diameter | cm | 5.0 | 2.5 x $10^2$ |
| Volume | $cm^3$ | 353.4 | 4.4 x $10^7$ |
| Weight | gf | 72 | 9 x $10^6$ |
| Density | $g/cm^3$ | 0.20 | |

$\rho_{water} < \rho_{pipe} < \rho_{soil}$

18

## Cases of centrifuge model tests

| Case | Countermeasure | Pipe depth (m) | Note |
|---|---|---|---|
| 1 | Stone column | 2.5 | Verification of preliminary research. |
| 2 | Added weight | 2.5 | |
| 3 | | 3.0 | |
| 4 | | 3.5 | |

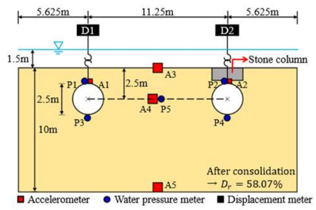
Installation of the stone column

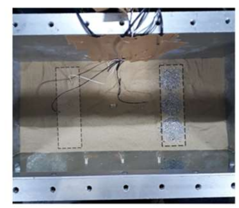
Added weight (578 g = 8 times of pipe weight)


19

## Centrifuge mode (Case 1)

(Centrifugal acceleration: 50G)

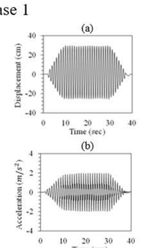


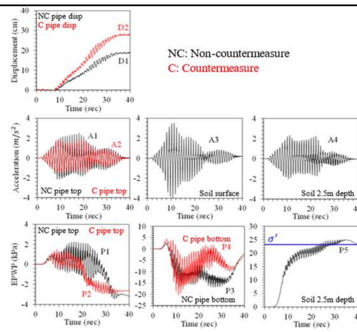
Top view

20

Case 1

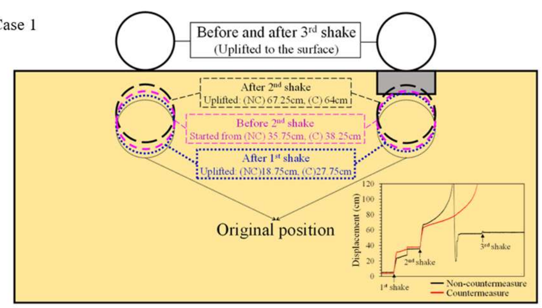



Input motion (Prototype scale)
(a) Displacement, (b) Acceleration



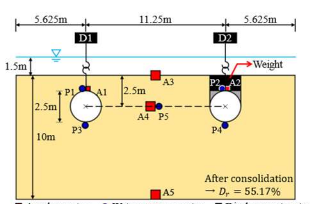

21

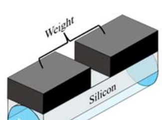
Case 1




22

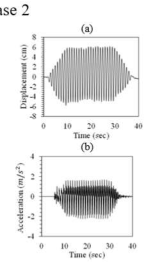
Case 2



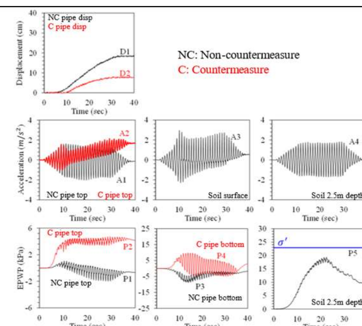




23

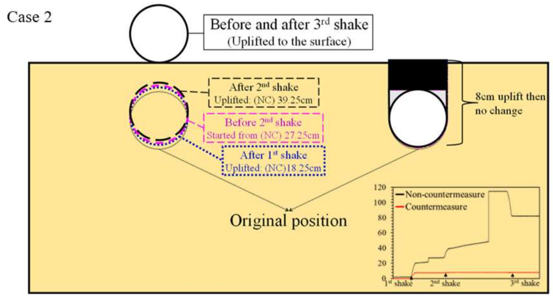
Case 2




Input motion (Prototype scale)
(a) Displacement, (b) Acceleration




24




25

## Summary

| Case | Content | Advantage | Disadvantage |
|---|---|---|---|
| 1 | Stone column | EPWP mitigation | Decreased suction force might have caused larger uplift |
| 2 | Added weight | Reducing the uplift especially shallow condition | Rotation of the pipe observed |
| 3 | | | |
| 4 | | | Not significant in deep condition |

26

## Numerical analysis of floatation characteristics of buried pipelines due to liquefaction and countermeasure

Presented at the 43rd Earthquake Engineering Symposium, JSCE (2023)

Katsutoshi MIYAMOTO, Masahiko FUKUYAMA, Kenichi IMAMURA

Nihon Suido Consultants Co., Ltd.
Water and Environmental Consultants

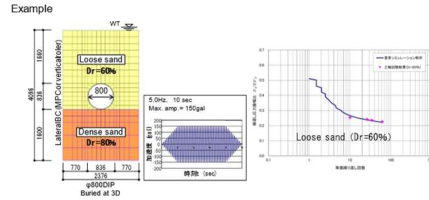
Tetsuo TOBITA

KANSAI UNIVERSITY

27

## Numerical model

Example




Numerical model Input wave Liquefaction strength curve (Silica sand #6)

28

28

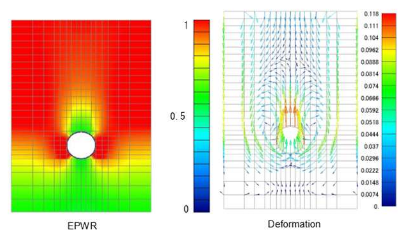
## Numerical model

- ✓ Elasto-plastic model of the ground: Oka model applied
- ✓ Element simulation analysis using liquefaction test results to set various ground parameters
- ✓ Analysis code: LIQCA
- ✓ Self-weight analysis as initial condition
  - + Dynamic analysis (direct integration method) for earthquake analysis
  - + Consolidation analysis to evaluate the dissipation process of excess pore water pressure after the earthquake
- ✓ Numerical integration method: Newmark's beta method (beta=1/4)
- ✓ Analysis time interval: 0.001 sec.

29

29

## Results of numerical analysis (No measures)




No countermeasure

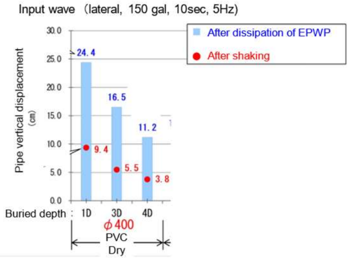
(φ400PVC・not filled・buried at 4D・MPC・150gal・after consolidation)

30

30

## Results of numerical analysis (No measures)

Input wave (lateral, 150 gal, 10sec, 5Hz)

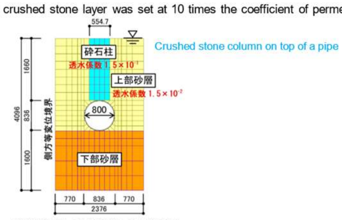



31

31

## Numerical analysis with a crushed stone column

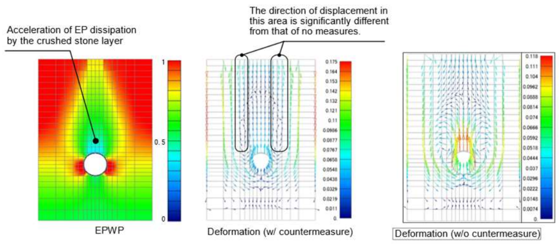
- Dissipation of excess pore water pressure is expected to be accelerated by the drainage effect of the crushed stone column, thereby increasing the resisting force of the ground above the pipe.
- The ground condition of the crushed stone layer was set at 10 times the coefficient of permeability of the sand layer.




32

32

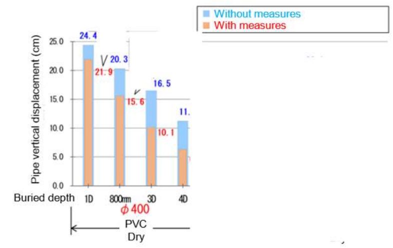
### Results of numerical analysis with measures




(φ400PVC, Dry, Buried depth 4D,MPC, 150gal, After consolidation)

33 33

### Comparison w/ and w/o measures




34 34

### Summary

- Analytical studies have, to some extent, confirmed the floating characteristics/mechanics of buried pipes due to liquefaction. However, the mechanisms and factors are very complex.
- Importance and effectiveness of considering the resistance of liquefied soil above the pipeline, which has not been taken into account in the existing simplified evaluation formulas for pipeline uplift, was also confirmed.
- Further research is needed to propose more accurate evaluation method of pipe uplifting and more rational seismic countermeasures in design practice.

35 35

## Topics covered

- Case study on irrigation pipeline damage after the 2011 Tohoku Earthquake
- Centrifuge model testing on mitigation of pipe uplift due to liquefaction
- Numerica modelling on mitigation of pipe uplift due to liquefaction

36

## Annex 3

## Meeting Minutes

**Annex 3 Table of Contents**

# Minutes

### U.S.-Japan Hazard Resilient Pipeline Research Panel (HRPRP) 1st meeting

Date & Time: U.S, April 12nd 2022, 15:00～18:00 (PDT)

JPN, April 13th 2022, 7:00~10:00 (JST)

Location: WEB Meeting

Attendees：

The HRPRP Member:

Craig A. Davis

Nagahisa Hirayama

Thomas D. O’Rourke

Yoshihisa Maruyama

Kenichi Soga

Masakatsu Miyajima

Brad Parker Wham

Tetsuo Tobita

Katerina Ziotopoulou

The HRPRP Meeting Coordinator:

Takeshi Hara, Takaaki Kagawa, Keita Oda, Toshio Toshima

**１．Opening(Dr. Davis)**

(1) Today’s schedule

(2) Updating HRPRP overview document

Two following major updated points are added to HRPRP activities.

a) Review the research of other’s related to the meeting topic will be included in the presentation and discussed

b) U.S.- JPN collaborative research including experiments will be conducted.

Note: Please refer to Prof. Tobita email of the update.

## 2．Overview Presentation

The following is the digest of Q&A.

(1) Prof. O'Rourke

Title: Lifeline Earthquake Engineering: Legacy & Lessons Learned

[Q&A]

Q.1) How should we hand over the old infrastructures to the next generation? (Prof. Soga)

A.1) There are two aspects to be promoted. One is new technologies and the other is partnership between academic side and practical side (water utilities). Many examples are introduced as we have to continue to improve the solution and support the advocates. (Prof. O'Rourke)

Q.2) What is the collaboration between water utilities and FEMA/AWWA/Water Research foundation? (Prof. Hirayama)

A.2) Each utility has their own solution and perspectives for their issue, they need to solve the problem not only technically but also institutionally. Regardless of local government and national government, they often counter the same issue like earthquake and wildfire, so that the leading organization should get the project budget from the government and solve the issues. (Prof. O'Rourke)

Q.3) What is the key point to beyond sectionalism between university and government? (Prof. Hirayama)

A.3) Partnership will be important. Researcher (especially for lifeline field) should not only develop new technology, but also to consider the social connection to engage the community goal.

Q.4) What should we think about social aspect when they develop the technology? (Prof. Wham)

A.4) Infrastructure system must be looked at through the lens of advance technology and social science. (Prof. O'Rourke)

(2) Prof. Miyajima

Title: Resilience of water pipelines and facilities against natural hazards such as earthquakes and heavy rains

[Q&A]

Q.1) What is the current states of mind of utilities for using Earthquake Resilient Ductile Iron Pipe (ERDIP) for flood? (Prof. O'Rourke)

A.1) In Japan, ERDIP is used not only for the earthquake but also for landslide caused by heavy rain. (Prof. Miyajima)

Q.2) To show documented evidence which utilities use ERDIP for the areas of flood and large ground deformation is very important. (Prof. O'Rourke)

A.2) That's why Kubota changed the name of "Earthquake Resistant Ductile Iron Pipe" to "Hazard Resistant Ductile Iron Pipe". This is the very important for the user to recognize. (Prof. Miyajima)

Q.3) Is Atsuma purification plant working now? (Prof. Wham)

A.3) The plant is working now. (Prof. Miyajima)

Q.4) What is the effect of rainfall before earthquake? (Prof. Hirayama)

A.4) The countermeasure for only earthquake is not enough, but it is difficult to prepare for multi hazard. The performance-oriented design of water supply system is important. The performance is not water outage but duration of outage (Prof. Miyajima)

Q.5) What is the situation of performance evaluation of lifeline system in U.S.?

(Prof. Hirayama)

A.5) We are working on establishing the performance evaluation in design process. The performance should be evaluated not for single pipeline/facility, we must look at system performance. We need to consider how long can we go without services. That establish required system level performance. (Dr. Davis)

A.6) SFPUC set the system goal. For example, in San Francisco's water system improvement project, the goal was recovering some quantity of water supply in 24 hours and in 30 days after the earthquake. Through their analysis of assuming damage of their backbone systems, they set the confidence limit of archiving water supply. Although many cites did the system analysis and set their goal, it can be improved with latest technology. (Prof. O'Rourke)

## 3. Discussion

(1) Keywords for the later meetings (Prof. Hirayama)

Word cloud was created through text mining from the 80 major papers of all of attendees.

This analysis would be used to give the related keywords for the later meetings.

(2) 2nd meeting (Dr. Davis)

a) Presenter

U.S. member: Prof. Ziotopoulou, Prof. Brad

JPN member: Prof. Maruyama, Prof. Tobita, Prof. Hirayama

b) Date

10/15/2022~11/18/2022 (Date should be determined by Google Form)

c) Location

UCLA or UC Davis or UC Berkeley or University of Colorado Boulder (TBD)

d) Other

To invite the water agencies such as EBMUD or SFPUC and ask them to make a presentation of their unique project would be great opportunities (Prof. O'Rourke)

４． **Next Step**

(1) Determine the second meeting date and location.

(2) Invite some water utilities for the 2$^{nd}$ meeting

End

# Minutes

**U.S.-Japan Hazard Resilient Pipeline Research Panel (HRPRP) 2nd meeting**

Date & Time: U.S, November 8th 2022, 8:30～17:00 (PST)

Location: U.C. Berkeley (Center for Smart Infrastructure)

Attendees：

The HRPRP Member:

Craig A. Davis
Nagahisa Hirayama
Thomas D. O'Rourke
Yoshihisa Maruyama
Kenichi Soga
Masakatsu Miyajima
Brad Parker Wham
Tetsuo Tobita
Katerina Ziotopoulou (Online)

The HRPRP Meeting Coordinator:

Takeshi Hara, Takaaki Kagawa, Keita Oda, Yoshinori Itani

U.C. Berkeley

Shakhzod Takhirov

Queen's University

Neil Hoult

LADWP

Bart King, Todd Lee, Sofia Marcus, Jianping Hu, Genevieve Han (Online)

MWD

Winston Chai

EBMUD

David Katzev

SFPUC

Tedman C. Lee (Online)

WRF

Jian Zhang

Thornton Tomasetti

Blake Berger

**1. Greeting (Dr. Davis & Prof. Soga)**

(1) Today's schedule

(2) Overview of Center of Smart Infrastructures

**2. Review of 1st meeting and Goal of HRPRP (Dr. Davis)**

(1) HRPRP Purpose, Objectives & Charge

(2) Activities and Products

(3) Duration & Meeting schedule of HRPRP

(4) Goals of HRPRP (Update the content of Final report)

(5) Hazard Impact Matrix, Research Proposals

**3. Topics Presentation-1 (Understanding risks/Pipeline damage)**

(1) Prof. Tobita

Title: Understanding risks/Pipeline damage Geohazards, Man-made land and ground monitoring

[Q&A, Comments]

Q.1) In the Hokkaido earthquake, there was a multi-hazard situation, landslide was induced by earthquake and high-water table caused by heavy rain, how do engineers have to consider the multi-hazard situation? (Prof. Wham)

A.1) Engineers are not considering the worst-case scenario like a climate change now, but we need to consider multi-hazard in the near future.

Q.2) Which had more effect to cause these huge landslides? Pumice or high-water table?

A.2） Both. The pumice contained a lot of water in Hokkaido. Many landslides occurred not only Hokkaido but also other areas in Japan where there were earthquake and had similar soil conditions. (Prof. Tobita)

Q.3) What was the most challenging of the 1 year temporally WTP work and replacement? (LADWP; Sophia)

A.3) These data will be shown in 2023 Japan-U.S.-Taiwan conference. (Prof. Tobita)

Q.4) Where and what type of pipeline damage occurred in 2011 Japan earthquake? (LADWP; Todd)

A.4) The damage was concentrated on the boundary between filling and cutting land. But joints were not hazard resilience ductile iron pipe. (Prof. Tobita)

Q.5) How will you evaluate ERDIP pipeline if ERDIP are compressed/expanded at these large ground deformations. (LADWP: Bart)

A.5) Monitoring technologies such as optical fiber will help evaluate the pipeline performance after earthquake. (Prof. Soga)

(2) Prof. Ziotopoulou (Online)

Title: Ground & pipeline failures in Balboa Blvd. (1994 Northridge): Suspected mechanisms of liquefaction & cyclic softening, and predictive capabilities

[Q&A, Comments]

Q.1) Conventionally, Ic:2.6 is used for cut off the sand, but your data shows Ic:2.9 would be better fit, what is your overall view of the value of Ic? (Prof. O'Rourke).

A.1) My opinion is based on what I have seen, to get more satisfactory Ic, 2.9 is very comfortable, but I am uncomfortable proposing 2.9 for everything. (Prof. Katerina)

C.1) LADWP kicks off replacing the trunklines near the area, which are the Granada and Rinaldi Trunklines, but we have never seen these data. These data are very knowledgeable for our projects. (LADWP; Todd)

C.2) There were 11 breaks in a mile on Roscoe Blvd. without surface rupture, it's extremely unusual, but we don't know why the damage were so extensive. We should work together to improve your pipeline. (Dr. Davis)

Q.2) Based on these soil data, how do you design seismic measurement for LADWP pipeline? (EBMUD; David)

A.2) There are many kinds of earthquake resistant pipes manufactured by Kubota, U.S. Pipe, JFE, etc., we are now installing those pipes to mitigate seismic events. And we will have more ERDIP projects in the near future (LADWP; Todd)

Q.3) Our biggest challenge of ERDIP is how to design each joint gap (install with compression/neutral/extension) to fit ground movement, but we don't have clear procedure to design ERDIP joint gap. (EBMUD; David)

A.3) Both 1971 San Fernando and 1994 Northridge earthquake, final damage observation showed some discrepancies between actual ground behavior and the pipeline damage mechanism, the ground had large tension crack but pipe failed at compression. So, putting on all in compression or in extension may not be the best solution. (Dr. Craig)

Q.4) Roscoe trunk line was replaced with HDPE after 1994 earthquake and it will be replaced in 2024 again, do we have additional study before installing? (LADWP; Genevieve)

A.4) LADWP should give soil condition and pipe information about the project to Prof. Katerina then, we should setup a separate meeting to discuss offline. (Dr. Davis).

C.1) We did some work in Roscoe Blvd. in 1997, that area was investigated. And there was 2 to 3ft of movement from the strong shaking record if you do a Newmark sliding box type model analysis. This is enough to cause serious damage to the pipeline. (Prof. O'Rourke)

**4. Topics Presentation-2 (Understanding risks/Impacts on Infrastructure)**

(3) Prof. Hirayama

Title: Water Outage and Fire Fighting Water

[Q&A, Comments]

Q.1) Who provides the google map information for the emergency water station?

How real time is it? (LADWP; Sophia)

A.1) The first step of research activities for emergency response is collaboration between water utilities and another department. The final objective of this research activity is sharing information between water utilities and residence. Also, residence take pictures and share that information. Google is not expensive to share photo information. Actually, there was water outage in Shizuoka this September. The first step of initial response was to use google map and sharing between academia and water utilities, then the next step is to open it up to the public. Some of the research institutes of disaster mitigation have developed their own disaster response system, but this is one of the barriers to share the information, Google map is the one of the approaches. (Prof. Hirayama)

(4) Prof. Wham

Title: Pipeline Damage and Assessment for Natural Hazards

[Q&A, Comments]

Q.1) What pipe size does ASCE MOP cover? (MWD; Winston)

A.1) ASCE MOP covers all size of pipes. (Prof. Wham)

C.1) In large size pipe case, more advanced analysis should be done to evaluate the pipeline resiliency (Dr. Craig)

Q.2) Is there any guideline for CFC (Connection Force Capacity) of welded steel pipe? (LADWP; Todd)

A.2) I don't know of a seismic guideline for steel pipe similar to ISO 16134 standard for ductile iron pipe. Therefore, large diameter tests with steel pipe are really important for this industry. (Prof. Wham)

Q.3) What is the effect of thrust block for seismic pipeline performance? (LADWP; Genevieve)

A.3) I haven't done many tests about thrust block, so that I can't answer directly now, but thrust block design is a challenging matter for water utilities. (Prof. Wham)

Q.4) Will field lock gasket performance be included in the ASCE MOP? (LADWP; Genevieve)

A.4) My understanding of those gaskets is that the gaskets work on the water pressure. But we have a lot of information which we tested the gaskets with high water pressure to evaluate the performance. (Prof. Wham)

Q.5) When will the ASCE MOP be released? (LADWP; Genevieve)

A.5) Hopefully, next year 2023. But we are not accounting for all specific jointing and conditions yet. It's intended to be material independent so that we don't have to deal with certain type of pipes.

Q.6) How do you consider host pipe (ACP) condition to evaluate life cycle analysis of CIPP Lining? (EBMUD; David)

A.6) We'll have the section of the system that 6" to 12" gap where there is no host pipe at all. We'll do testing under this condition and under condition where host pipe has a have round crack. These test conditions are where the host pipe is present but there is no structural support at all. (Prof. Wham)

Q.7) LADWP continues to build up seismic resilience pipeline network, distribution system (20" and below) connected to services and fire hydrant laterals, so continuing to develop the guideline including distribution system in the future research would be appreciated for us. (LADWP; Genevieve)

A.7) Service connections are extremely important, CSI did couple of tests with service connections. We will continue to test including fire-hydrant and large diameter branch connection. (Prof. Wham)

**5. Topics Presentation-3 (Technologies/Upgrading pipeline)**

(5) Prof. Maruyama

Title: Recent Studies for Enhancement of Resilient Water Supply System

[Q&A, Comments]

Q.1) Did the backup system work in the time of power outage? (LADWP; Sophia)

A.1) Yes, but only 30% of the water supply in Chiba prefecture had backup system. (Prof. Maruyama)

(6) Prof. Soga

Title: Initiatives at the Center for Smart Infrastructure

[Q&A, Comments]

Q.1) Is the self-driving tunnel machine manufacturing phase or still in the research phase? (LADWP; Jianping)

A.1) We are still working on the system integrator for the self-driving tunnel machine (Prof. Soga).

Q.2) LADWP is trying to use Ground Penetration Rader (GPR). How deep can your GPR go? (LADWP; Jianping)

A.2) The company which we are working with is located in LA and working for city of LA. They said LA is easier than here because underground water table is low, but water table of Berkeley is high, and we have clay soil. The data they showed me looked great, depth was probably 6ft and will be valuable. (Prof. Soga)

C.1) At the LADWP's in house pilot project of GPR, we could measure up to 10ft. (LADWP; Jianping)

Q.3) There are so many utilities under the ground in LA, are there any interference concern of this fiber optics to other utilities? Such as electric magnetic impact (LADWP; Genevieve)

A.3) Electric magnetic is no issue at all. Fiber optic is a totally different way of measuring. The signal is light, and the cable itself is made of silica. Also, we can set a filter to remove specific noise (Prof. Soga)

Q.4) How is the cyber security issue? (LADWP; Genevieve)

A.4) U.C. Berkeley has an expert of cyber security, and cyber security is a common issue, so the university can bring the expert and work together. (Prof. Soga)

Q.5) How accurate is the GPR of U.C. Berkeley, some of current GPR technology which LADWP tried were not accurate. (LADWP; Genevieve)

A.5.1) What we want to do in next 6 months is to work together with construction crews and how they can shorten the construction period. And we will evaluate the value that we can get. (Prof. Soga)

A.5.2) Accuracy is not what we want right now, we did a pilot project this summer, and didn't catch everything that was there, so we are learning how GPR works. Accuracy is the next step for us. (EBMUD; David)

Q.6) How much is the cost of the analyzer for fiber optics (Prof. Wham)

A.6) Originally the analyzer cost was \$100K-\$200K, but we can make our own analyzer in the \$20K range. But we think that people need to the value of the technology, that's why we are working with EBMUD and the power company, etc. And if the market is growing it's the time to introduce the analyzer. (Prof. Soga)

Q.7) How can the municipality use the data which they get from the fiber optics? (Prof. Wham)

A.7) Data is quite different from traditional data set. It takes time to understand how the data will get out. To understand the data may take one Ph.D. cycle. But once you get how to analyze the data, it's easy to handle them.

For example, data goes up to the cloud and analyze it on the cloud, then results are sent back to the site so that people in the field can get the results right away.

Q.8) How do you use fiber optics for the EBMUD pipeline? (LADWP: Bart)

A.8) We put two cables under the creeping ground, one is along the HDPE pipeline, the other one is just buried. We gather the data once a month, and analyze ground and pipeline behavior.

But data itself is recorded 24/7. (Prof. Soga)

Q.9) Will this data be able to be connected to the smart phone and etc.? (Prof. Hirayama)

A.9) I'm not sure what is the value of putting the data into smart phone. It's difficult to realize, but new generation (young people) have more large data analysis skill than ours. We will get more data from this technology and it'll be useful for a new generation. (Prof. Soga)

Q.10) When it comes to calibration of the fiber optics, how to do you calibrate in long term?

(Prof. Tobita)

A.10) Fiber optics material is crystal material, since silica is stable material, there will not be a problem. But the cable coating is not stable, so that interface between cable and coating material will be an issue. If Kubota can be embedding the cable during manufacturing process, it much better because there is less issue in terms of how to attach the cable to the pipeline. (Prof. Soga)

**6. Discussion**

**(1) Status of Collaboration research (Prof. Tobita)**

Unfortunately, this collaboration research was declined by the Japan government last month. (Prof. Tobita)

C.1) If there is good location to measure ground deformation, it will be great opportunity to do collaborative research. (Prof. Soga)

C.2) USGS is monitoring the ground movement using GPS, it may help to find out the key location. It doesn't need to be creep location. (Dr. Craig)

C.3) Hurricane is also big issue same as Earthquakes, technologies for the ground deformation might have good solution for both. For example, hurricane Sandy attacked New York city, and there were 23 tunnels, a lot of water got into the tunnels, and cost of repairing the tunnels were huge ($200 million). There are many low elevation sewage treatment plants, if there is a hurricane there will be dramatic impact for those facilities. If we talk about sensers, hurricane protection system may work.

How hot the pipeline location at wild fire is also interesting subject to research plastic pipe melting effect the water quality. (Prof. O'Rourke)

C.4) There are a lot of below sea level areas in Tokyo, Osaka and Nagoya, those cities are quite dangerous for high tide. (Prof. Tobita)

C,5) The collaborative research should include several different hazards beyond earthquake related and should address more than just ground deformation effects. (Prof. O'Rourke)

**(2) Case study of Hazard resilience pipeline (EBMUD; David)**

Title: Pipeline Rebuild, Design & Installation of Hazard Resilient Pipelines

[Q&A, Comments]

Q.1) Does water pressure affect distribution break rate in the long term? What is the impact of the water pressure to the life of the pipeline? Will low pressure reduce the water break ratio? (LADWP: Sophia)

A.1) We have a lot of high-pressure zones (100-120psi) where those zones are isolated. And we see the water break, also we reduce the water pressure to some zones to see the difference. We will continue to look at the data. (EBMUD; David)

Q.2) What are the most common failure mechanisms of cast iron pipe? (Prof. Wham)

A.2) When the area is a fault zone, the failure type is joint shifting (pulling apart). Otherwise, most of the failure are caused by corrosion. (EBMUD; David)

Q.3) Is corrosion type pinhole or longitudinal split? (Prof. Wham)

A.3) Most cases are longitudinal split. (EBMUD; David)

Q.4) It looks like your PVC are restrained. Is this for water pressure or seismic? (LADWP: Todd)

A.4) Mostly it's for resiliency, our all joints are restrained. We are not installing unrestrained joints right now. (EBMUD; David)

Q.5) What is the life expectancy of existing and new PVC? (LADWP: Todd)

A.5) We only use i-PVC, the manufacture of i-PVC gives us 100 years warranty. (EBMUD; David)

Q.6) Why do you use DIP fitting for PVC pipeline? (LADWP: Todd)

A.6) Mostly productivity of construction. We have a lot of stable (non-ground deformation concern) areas, in those area productivity is the main concern. (EBMUD; David)

Q.7) Why didn't you use ERDIP or steel pipe in landslide area? (LADWP: Todd)

A.7) There were 2 locations. One is very congestion area, so there is no room for installation of ERDIP and steel pipe. The another is due to paving moratorium of county rule, which we can't open trench for 5 years. Therefore, we used liner method in these cases. (EBMUD; David)

Q.8) What is the criteria of choosing pipe materials? (LADWP: Genevieve)

A.8) Our annual goal is 22.5mile pipe installing. We can't install 22.5mile ERDIP with our 12 construction crews. To reach the goal, we are looking to balance of installation of ERDIP, steel and i-PVC. (EBMUD; David)

Q.9) LADWP recently changed the DI pipe thickness to class 53 to achieve 100-year life. How about you? (LADWP: Genevieve)

A.9) We also spec. out thickness class 53 with zinc coating and polyethylene wrap. We had used joint bonding until last year, but since the joint bonding didn't work well, there was connectivity problems and speed of installation and safety issues, therefore we don't use the joint bonding now. (EBMUD; David)

Q.10) Do you use slurry backfill? (LADWP: Todd)

A.10) No, we don't use slurry backfill. (EBMUD; David)

Q.11) Why do you use i-PVC instead of HDPE? For the plastic pipe, HDPE is commonly used in Japan as Hazard resilience pipe, but not PVC. (Kubota; Hara)

A.11) We had many troubles with HDPE in terms of installing service pipe. Service saddles were popped off. Also, HDPE needs to be dry for electro fusion bonding, but we have a lot of wet situations. Also, there are repair fitting matters, in case of repairing HDPE, mechanical fitting was used. But after 1 week later we need to retighten the mechanical joint portion, because mechanical joint portion became loose, caused by plastic relaxing. (EBMUD; David)

Q.12) How much slip-out resistant force does the i-PVC have? (Kubota; Hara)

A.12) Probably half of ERDIP. Since plastic pipe can stretch, the slip-out resistance force might be enough for residence area (stable ground area), That's why they used i-PVC for residence area and ERDIP for critical area (Prof. Wham)

Q.13) Do you use i-PVC instead of PVCO completely? (LADWP; Bart)

A.13) We like PVCO too, we know PVCO has good test results in Cornell Univ. and good productivity. But when we think about repairing, we have to use standard C900 for i-PVC and C909 for PVCO. To avoid confusion, we are using only i-PVC. (EBMUD; David)

C.1) We also use PVCO and i-PVC in corrosive soil area to replace CIP, but still fitting of these pipelines are DIP. (LADWP; Bart)

**(3) Discussion for 3rd meeting (Dr. Davis)**

a) Presenter

U.S. member: Dr. Craig

JPN member: TBD

b) Date

Spring in 2023 (Date should be determined by Google Form)

c) Time

2-3 hours

d) Location

Online

e) Other

Other attendees might join

**7. Next Step**

(1) Provide extended abstracts of presentation by presenters (template provided). The deadline of submission is 3 months after the meeting (2/8/2022). The sending address will be Dr. Craig Davis (cadavisengr@yahoo.com) or Takeshi (Takeshi.hara2@kubota.com).

(2) Presentation will be shared for all attendees.

(3) Provide input on the Hazard impact Matrix (electronic copy provided).

(4) Prepare/Develop 1-page research proposals (template provided).

End

2023/05/05

# Minutes

**U.S.-Japan Hazard Resilient Pipeline Research Panel (HRPRP) 3rd meeting**

Date & Time: U.S, April 25th 2023, 15:00～18:00 (PDT)

JPN, April 26th 2023, 7:00~10:00 (JST)

Location: WEB Meeting

Attendees：

The HRPRP Member:

Craig A. Davis

Nagahisa Hirayama

Thomas D. O'Rourke

Yoshihisa Maruyama

Kenichi Soga

Masakatsu Miyajima

Brad Parker Wham

Tetsuo Tobita

Katerina Ziotopoulou

The HRPRP Meeting Coordinator:

Takeshi Hara, Takaaki Kagawa, Keita Oda, Yoshinori Itani, Shozo Kishi

## 1. Opening (Dr. Davis)

(1) Review of 2nd meeting and Today's schedule and goal.

(2) HRPRP member assignments confirmation

1) Extended abstract of presentations (template provided)

2) Approval for printing the presentation slides (remove slides having copyright concerns.)

3) Provide input on the Hazard Impact Matrix (electronic copy provided)

4) Prepare/develop 1-page research proposals (template provided)

## 2. Topics Presentation -3 (Technologies/Hazard resilient design)

Prof. Miyajima and Dr. Davis presented examples of pipeline damages with hazard impact matrix and current seismic/hazard guidelines/concept in Japan and in the USA respectively.

The following is the digest of Q&A.

(1) Prof. Miyajima

**Title: Example of Pipeline failure based on Hazard Impact Matrix & Latest seismic design and construction guideline for water facilities in Japan**

[Q&A]

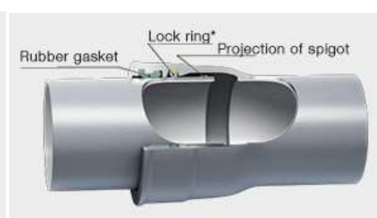
Q.1) What is the joint type of K-type, A-type and T-type? Cross-sections of the joints are helpful to understand (Prof. O'Rourke)

A.1) A-type and T-type joints are very old joint. K-type is mechanical joint. But these joints don't have pull our resistance performance. GX-type, NS-type and S-type are the ERDIP. Therefore, for the fault crossing location, GX-type, NS-type or S-type must be used. In case of fault displacement is less than 1 or 2m, ERDIP joint are effective, but in case the displacement is more than 1 or 2m, long collar joint is needed to absorb large ground displacement.

(Prof. Miyajima)

The below is the cross section of the joints.






T-type (push-on) joint K-type (mechanical) joint GX-type(ERDIP) joint

*A-type is old K-type (without O-ring shape: Similar to AWWA C 110 &153)

Q.2) In the slide 11, the HDPE looked like it had a coupling. In the USA, butt fused is commonly used for HDPE. What is the difference between coupling HDPE and butt fused HDPE? (Prof. Wham)

A.2) Coupling HDPE is also electric fused, pipe length is 5m and each HDPE pipe is connected by couplings. (Prof. Miyajima).

<u>(2) Dr. Davis</u>

**Title: Hazard Resilient Design in USA and Examples of pipeline failures based on Hazard Impact Matrix**

[Q&A]

Q.1) As for damage of Arlington in Texas, how large area was investigated? How many damages are supposed to occur in large area? (Prof. Wham)

A.1) Arlington has a few hundred thousand people, so it seems to be middle size city in U.S.

But all of Texas was severely impacted by this snow storm. So, we could estimate the number of wide area damage by multiplying it across.

Also, Oklahoma, Louisiana and Alabama were impacted by this snow storm too. This snow storm had large impact to wide area though each city had a different problem. (Dr. Davis)

C.1) There were many damages of roads and pipelines in north east to middle east too. It's an issue that's related to climate change, because there's bigger rainstorms than they designed for now.

The drainages designed in hundred years ago are having damages every year, the design was supposed to design to withstand huge storm which comes once a hundred years. So, a hundred years storm can't be a hundred years storm now. And drainage pipelines are usually not pressurized, so when huge water flow occurred by heavy rain, it's easy to have damage at the joint because drainage are pressured by a lot of water flow. Therefore, using pressurized pipeline for drainage is one of the solutions to have resiliency for the drainage. So, let's call it stage1 flooding condition. But more significant water flow sometimes break culvert because over flow water erodes around culvert, then break the culvert and entire road. It's called stage2 flooding condition. Culvert damage cause road collapse and road collapse cause damage of water, electric and sewer pipeline etc. (Prof. O'Rourke)

Q.2) How do you evaluate or consider valves resiliency in pipeline network? (Prof. Soga)

A.2) The matrix does not consider valve's resiliency. So, that would be additional concept such as about functionary recovery.

To use valve effectively, we can create resilient pipeline network. For example, if we can't avoid damage at one location in the pipeline, we should install valve upstream and downstream at the location, so that pipeline can connect to the backup pipeline and save the water and work as tank for emergency water supply. So, the valve should sense ground motion and pressure changes at the earthquake and should be shut down automatically. That is important aspect of creating resilient pipeline network. We should consider redundancy pipeline network like a loop, block system, isolation to create resilient pipeline network. Climate change is inducing big changes, so we should know what will happen, where it will happen and what we should do? The matrix is the one to start conversation. (Dr. Davis)

Q.3) What is the hard line between natural hazard and standard operating conditions?

For example, city of Sacramento has huge failures of cast iron pipelines every fall because of expansive soils by rains. (Prof. Ziotopoulou)

A.3) I think basic definitions of hazard is the one that threaten people or make people havoc. When same damages occurred in different locations, for one location it might be normal, but for other locations it might be unnormal. I would say expansive soil is hazard, it will cause a damage, we have to know and deal with this. I'll add it into hazard matrix.

What is hazard resilient pipe? The pipe needs to handle it. We should identify those hazards and handle them. We can't replace all of critical pipes at the same time, so we should make pipe replacement program with right pipes for right locations that will improve pipeline system annual basis. That is minor change of the investment but it will make big change in the long run (Dr. Davis)

Q.4) What is the value of water network simulation for the users/customers associated with not only the pipeline damage but also the impact of usage side? (Prof. Soga)

A.4-1) There are 2 aspects. For the limited area hazard such as 2 block expansive soil or quarter-mile stretch of pipeline, I don't think it's a value because we don't have an operation or maintenance issue if we put hazard resilient pipe in this area.

On the other hand, for large more regional types of hazards such as earthquake, winter storm or wild fire, it has value for us because it informs owners and operators prepare for the event. (Dr. Davis)

A.4-2) A lot of these can be unified by probabilities. You can create probabilistic approach which allows an owner or operator to set up hierarchy of what they need to prepare. If you have a number of different hazards or different probabilities that are affecting a given facility, you just put together the joint probability and you can rank this thing when we do network analyzes. And you can set up a hierarchy of projects that bring about the good performance in a system more rapidly and more rationally than just dealing with things on a haphazard.

The simulation approach becomes much comfortable these days. There is a lot of expectation for monitoring technology. It can reduce the risk of facilities because you have better feedback on its current performance. (Prof. O'Rourke).

## ３． Discussion

(1) Hazard Impact Matrix

C-1) I think it is valuable as an inventory of potential hazards that could affect. It will help to design particular facilities against particular aspects for those hazards.

But there are some ambiguities, those should have some interpretation. Each hazard should have narrative definition. (Prof. O'Rourke)

C-2) For the narrative definitions, starting with "What is a hazard?", then mentioned that the primary hazard and cascading or secondary hazards will need to be defined. (Dr. Davis)

C-3) I think it is useful as a kind of list. How about adding a few columns/descriptions for designer to use in practice. (Prof. Wham)

C-4) It can help people know what hazard has impact for their facilities which could be a proactive tool. It will help if we could add suggestion for each hazard, and universities will take something in a research field and say some suggestions. (Dr. Davis)

C-5) When it comes to building design, they have already considered climate change effect because of $CO_2$ emission. I guess there's some potentially link some of the advancement done in that area. (Prof. Soga)

C-6) This matrix might be good one to discuss continuously after HRPRP with this group. And further research might be done to link in creating resilient network. (Dr. Davis)

C-7) The guideline of gas and oil pipeline has similar tables in chater2 which describes these hazards caused by earthquake that might cause pipeline damage, we can expand on that to whole hazard. (Prof. O'Rourke)

C-8) This matrix is useful developing the hazard map. Let say if there are some kinds of layers such as earthquake, flood or faults, and the map shows vulnerable pipeline for each hazard. Also, if the system can analyze water quality issues, that would be interesting. (Prof. Tabita)

C-9) Some hazards link to other hazards, so drawing some links between them is useful. (Prof. Wham)

(2) Collaboration research proposal

C-1) At the 2nd HRPRP meeting, Prof. Ziotopoulou made a great presentation about trunk line damages along Balboa Blvd. at Northridge earthquake. After the meeting Prof. Miyajima suggested Kubota to conduct FEM analysis to evaluate pipeline performance using data of Prof. Ziotopoulou. So, Kubota would like to propose having collaboration research evaluating pipeline performance for Northridge earthquake in case pipeline was HRDIP. LADWP is now planning to replace trunk line along Balboa Blvd. so, this collaboration research result would be helpful for LADWP. (Mr. Hara)

C-2) Prof. O'Rourke, Prof. Ziotopoulou and Dr. Davis are familiar with this damage. I think we can contribute to this collaboration. (Dr. Davis)

C-3) We will have a separate meeting to discuss how to proceed this research.

(Prof. Ziotopoulou & Dr. Davis)

(3) 4th meeting (Dr. Davis)

a) Date

11/7/2023 (Tue.)

b) Location

Nagoya university in Japan (In person)

c) Optional tour

11/8/2023 (Thu): Location: TBD (Near Nagaya university)

## ４. **Next Step**

(1) Input on the Hazard Impact Matrix and/or research proposals to Dr. Davis.

(2) Plan 4$^{th}$ meeting topics.

End

2023/11/29

# Minutes

**U.S.-Japan Hazard Resilient Pipeline Research Panel (HRPRP) 4th meeting**

Date & Time: JPN, November 7th, 2023, 9:00～16:00 (JST)

Location: Nagoya University (Disaster Mitigation Research Center)

Attendees：

The HRPRP Members:

Craig A. Davis

Nagahisa Hirayama

Thomas D. O’Rourke

Masakatsu Miyajima

Kenichi Soga (Online)

Tetsuo Tobita

Katerina Ziotopoulou

Yoshihisa Maruyama

Brad P. Wham

The HRPRP Meeting Coordinators:

Takeshi Hara, Takaaki Kagawa, Satoshi Masuko, Keita Oda, Ryunosuke Tanaka, Mitsuo Hayashi, Shozo Kishi

## 1. Opening Remarks (Prof. Hirayama)

## 2. Greeting: Mr. Ichikawa (Kubota Corp.)

## 3. Review of 3rd meeting and goal of HRPRP (Dr. Davis)

## 4. Draft deliverables of HRPRP: (Dr. Davis)

(1) Final Report

The draft of final report was prepared by Dr. Davis and sent to all HRPRP members in advance of the meeting.

C.1) The final report main body should only be a few pages to understand easily what was discussed at HRPRP meetings; details are provided in the Annexes. (Dr. Davis)

C.2) All members should review the contents of the report and provide feedback to Dr. Davis by end of November. If there are no comments, it is understood that all agree to the contents. (Dr. Davis)

→ Attendees agreed in general to the contents of the final report and how to prepare the final version.

C.3) The summary papers and PowerPoint presentations in Annex 2 should be reviewed by other HRPRP members. Japanese members review and provide feedback comments to U.S. members, and U.S. members review and provide feedback comments to Japanese members. （Prof. Wham）

→ Attendees agreed to Prof. Wham's proposal and decided on the following assignments and deadline. The reviews are to be completed and sent to original authors by 12/1/2023 (copy Dr. Davis) and then any edits are to be completed by the authors and sent to Dr. Davis.

[Assignment]

| Reviewer | Who's PPT and paper |
|---|---|
| Prof. Hirayama | Prof. Wham |
| Prof. Ziotopoulou | Prof. Miyajima |
| Prof. Miyajima | Prof. Ziotopoulou |
| Prof. Wham | Prof. Tobita |
| Prof. Tobita | Dr. Davis |
| Prof. Maruyama | Prof. Soga |
| Dr. Davis | Prof. Hirayama |
| Dr. Davis | Prof. O'Rourke |
| Prof. Soga | Prof. Maruyama |

(2) Purpose of Proposal including Hazard Matrix

The draft report includes a proposal in the last section (Conclusion and Proposal), The purpose for this section is to describe the Conclusion and Proposal of the HRPRP

C.1) The proposal should be advertised as a tool for water agencies in all countries, not only Japan and the U.S. West Coast. Hazard Resilient Pipelines are effective not only for earthquakes, but for all natural hazards that cause ground deformation and strain. (Dr. Davis)

C.2) The proposal can be used separately from the final report. It is created to fit on a single sheet, double sided when printed separate from the rest of the report (Dr. Davis)

→ All attendees agreed to the purpose.

(3) Conclusion and Proposal of the HRPRP

Q.1) Does the word "pipelines" in the proposal mean only pipes? Does it include valves and fittings? Fittings are more vulnerable for ground deformation. We need to define "pipeline" (Prof. Tobita)

A.1) I think the word "pipeline" means the whole system of water pipelines (Dr. Davis)

A.2) As a minimum definition, pipeline means pipes and joints. It also includes fittings such as valves and reducers. (Prof. O'Rourke)

C.1) I think we should add fittings to the "pipeline" definition because fittings in the pipeline are vulnerable. (Prof. Tobita)

C.2) Fittings vulnerable to hazards can be moved out of those areas. Could Prof. Tobita suggest first cut of definition of the word "pipeline" (Dr.Davis)

→ Prof. Tobita agreed to propose the definition of "pipeline".

(4) Hazard Matrix

C.1) This tool's primary audience involves managers and operators of water systems as well as secondary audiences, such as consultants, students, etc. The matrix can be used in two ways. One way is top down in which the decision makers (water agencies) use the hazard matrix to locate where hazard resilient pipelines would be designed (consultants). The other way is bottom up, for which the designer suggests to the decision maker the use of hazard resilient pipelines. (Dr. Davis)

C.2) This matrix is useful for water agencies to identify pipeline locations vulnerable to permanent ground deformation. (Prof. O'Rourke)

C.3) Engineers understand the risk of natural hazards, they understand what hazards are critical for their area, but it is more difficult for some decision makers to recognize it. This tool can work to educate those decision makers. (Dr. Davis)

C.4) Definitions are based on those proposed by USGS and FEMA. If a Japanese member wants to add/revise definitions from some Japanese sources, please send a version in English. (Dr. Davis)

C.5) "Cold wave" should be changed to "weather-related cold temperature". Such wording will cover sudden drops in temperature that accompany cold waves as well as low temperatures associated with severe winters. (Prof. O'Rourke)

→ Attendees agreed.

Q.1) An earthquake can affect the water quality in an aquifer, but the matrix shows mainly how pipelines affect water quality, is that correct? (Prof. Wham)

A.1) That is correct. (Dr. Davis)

Q.2) Hazards in this matrix look like they are natural hazards, but do we also think about man-made (anthropogenic) hazards? (Prof. Wham)

A2.1) The scope will become too broad if we include human disasters such as terrorism. (Dr. Davis)

A.2.2) I think we can narrow the scope. Ground strain caused by human activities can cause pipeline damage. Actually in New York construction activities cause differential settlement. Permanent ground movement is caused by construction activity. (Prof. O'Rourke)

→ Attendees agreed to add "Construction-related activities" in the first column and "PGD and Subsidence" in second column.

→ We need to add definition of "construction-related activities" in Annex.4. (Dr. Davis)

Q.3) In case a joint is pulled out, water can be washed out and cause a secondary hazard by undermining nearby pipelines. How do we show such effects in the matrix? (Prof. Tobita)

A.3) That's a great point, but if we add such effects in the matrix, it may become more complex and difficult to use. Therefore, we should add some notes about this to the main body of the paper. (Dr. Davis)

→ Attendees agreed.

Q.4) Do material properties need to be considered for the impact of pipe failure? (Prof. Ziotopoulou)

A.4) No, it should be based on ground deformation and ground strains. We try not to consider material dependencies. (Dr. Davis)

C.6) If attendees have any other perspective of the hazard matrix, please send an email to Dr. Davis. Also frequency (“x”, ”xx”, and “xxx”) should be checked by all attendees because you are the expert of those hazards. (Dr. Davis)

C.7) If there is no response, that means all agree. In English Common Law, silence is consent (Prof. O’Rourke)

→ Attendees agreed.

## 5. Hazard Map related Presentation

(1) Prof. Soga

**Title: SimCenter Tools for Response and Recovery: Future for Lifelines**

[Q&A]

Q.1) What software are you using to study the unsteady state flows? (Prof. O’Rourke)

A.1) We created our own program which can run very fast for large scale water network simulation. (Prof. Soga)

Q.2) How do you evaluate pipeline failure? (Prof. O’Rourke)

A.2) We have material data for many pipelines and failure prediction equation based on PGV from EBMUD. (Prof. Soga)

Q.3) How long is one node? (Prof. O’Rourke)

A.3) One node is one street block. (Prof. Soga)

C.1) How to model the reservoir is very important, if we lose reservoirs, entire sections of pipelines around the reservoirs are lost. Also, as time goes by after an earthquake, water exiting broken pipe and fittings will empty a reservoir and change its head, so considering the time aspect is an important part of the evaluation. (Prof. O’Rourke)

C.2) That’s a good point. I will start considering it. (Prof. Soga)

Q.4) What is the next step? (Prof. O’Rourke)

A.4) One of our next steps is the California Energy Commission (CEC) project, also we are discussing with MWD, LADWP and EBMUD how SimCenter tools can be used for their project. (Prof. Soga)

C.3) We will have joint deflection test with 48 inch. U.S. pipe TR-XTREAM in 12/13/2023.

(2) Prof. Tobita

**Title: 1. Pipeline damage: Case, physical and numerical studies**

**2. Experimental study of the countermeasure on pipeline uplift due to liquefaction**

**3. Numerical analysis of floatation characteristics of buried pipelines due to liquefaction and countermeasure**

[Q&A]

Q.1) Was the damaged irrigation pipe empty? (Dr. Davis)

A.1) I think it was empty, because the earthquake occurred in March, usually irrigation pipe is filled with water in April or May for use in rice fields. (Prof. Tobita)

Q.2) Do you usually use slurry cement for back filling? (Prof. Tobita)

A.2) No, it is not common in the USA. But, in Los Angeles, it is a requirement from the Bureau of Engineering. (Dr. Davis)

C.1) During the earthquake in New Zealand on 13 June 2011, electric cables in structural or cement slurry backfill had substantial damage in liquefaction areas. The hardened cement slurry developed cracks, which in turn concentrated deformation and strain in the electrical conduits. The slurry backfill also generated greater resistance to lateral movement than soil backfill. (Prof. O'Rourke)

Q.3) What is the soil dilation effect to the lateral movement of the pipeline? This was observed in the studies of the BART tube in the Bay Area. Does pipeline get more reaction force from the soil? (Prof. Ziotopoulou)

A.3) We did not test lateral movement of the pipe, but the mechanism could be the same. As I showed in my slide, if there is a non-liquefiable soil on the top of liquefiable soil, that kind of ground crack will occur. In that case, damage could be significant. (Prof. Tobita)

Q.4) How did you decide the weight of tested acrylic pipe and weight of adding material? (Prof. Wham)

A.4) We didn't adjust weight of the acrylic pipe to fit actual pipe, but the weight of adding material was calculated based on safety factor under liquefiable soil, the weight of adding material was 8 times heavier than the weight of pipe. (Prof. Tobita)

## 6. Tour of Disaster Mitigation Research Center

## 7. Future activities of HRPRP

(1) Hazard maps

C.1) Hazard maps which have sufficient scale to evaluate the risk of hazards for pipeline need to be created at some point, possibly activities by the SimCenter can help get them created. (Dr. Davis)

(2) Presentation at international conference in 2024

C.1) The outcome of HRPRP will be presented at AWWA ACE 2024 in Anaheim and ASCE pipeline conference 2024 in Calgary, Dr. Davis already submitted abstracts and they were approved. (Dr. Davis)

C.2) In Japan, the outcome of HRPRP will be presented at JWWA annual conference 2024 in Kobe. (Prof. Hirayama)

(3) Collaboration research

C.1) Prof. Miyajima, Prof. Ziotopoulou, Dr. Davis and LADWP will start collaboration research about pipeline damage along Balboa Blvd. from the 1994 Northridge earthquake. (Dr. Davis)

C.2) Kakenhi (like NSF funding in Japan) type-B was submitted this year by Prof. Tobita, and all HRPRP members' names were registered on it. The results of the proposal evaluation will be available in December 2023. If that funding is approved, we will be able to run an experiment in the facility of Kubota or U.C. Berkeley. (Prof. Tobita)

(4) Center of Smart Infrastructure activities at U.C. Berkeley

Q.1) U.C. Berkeley is creating facilities for experiments and they will work with water agencies in U.S., what is your plan of future activities? (Prof. O'Rourke)

A.1) We (CSI & EBMUD) are discussing with LADWP, MWD and SFPUC what needs there are and how to build up the facilities. Also, we try to invite other water agencies in the West Coast, Denver, and startup companies. And as a next step, we will try to invite some consulting companies to work. We will have an event in December 2023. We also have interests in how to deal with watersheds, in addition to pipelines. (Prof. Soga)

C.1) It will be a good opportunity to develop a workforce familiar with hazard resilient pipelines. (Prof. O'Rourke)

(5) Other technical issues

C.1) Lateral response to the ground movement of different types of pipe system should be studied, especially moment capacity of the joint. That would be useful for pipeline design with various levels of conservativeness. (Prof. Wham)

C.2) There are no clear guidelines for evaluating joint response/performance to lateral movement. We need to undertake some work to address this aspect. (Dr. Davis)

C.3) At Cornell Univ., we conducted tests in which tension and bending moment were applied at the same time, and the tension force reduced moment capacities by 10-15% at failure. (Prof. O'Rourke)

C.4) I'm curious how to repair/adjust hazard resilient pipe after an earthquake. How do we know the expansion/contraction situation of the joint? If we could know that we can think about what we should do. (Prof. Tobita)

C.5) That's what we want to do using fiber optics. We could evaluate the pipeline situation after earthquakes without digging, and judge when to replace the pipeline. (Prof. Soga)

(6) HRPRP

Q.1) Do we continue to have HRPRP meetings after this meeting? If so, how do we obtain funding? (Dr. Craig)

A.1-1) We should decide on a question/topic and what needs to be answered first, then we could decide who will be the sponsors. I think there are a lot of questions. (Prof. Ziotopoulou)

A.1-2) We have developed a hazard matrix and final report. Moreover, we will make presentations at conferences and workshops. That is worth the price of the HRPRP. This program will increase the awareness of hazard resilient pipelines. Some water agencies will contact the Center for Smart Infrastructure to fund research on hazard resilient pipelines and fittings. (Prof. O'Rourke)

C.1) We need to prepare documents that both increase the awareness of natural hazards and expand on ways to make them resilient to hazards. This work should not advertise a single product. (Prof. O'Rourke)

C.2) The final HRPRP report should be uploaded to websites at CSI, Colorado University, and Cornell so it can be disseminated more efficiently (Prof. O'Rourke)

C.3) This activity was very beneficial. We should share feedback from water agencies response after the presentations then we can decide what we should do next. (Prof. Hirayama)

A.1-3) Let's get feedback at the JWWA, AWWA and ASCE conferences and share them among this group. Then we can decide what we should do next, 1 year later. (Dr. Davis)

## 8. Wrap-up and Closing (Prof. Miyajima)

## 9. Action items

1) Final Report: Review the draft and provide feedback to Dr. Davis. All, by December 1st.

2) Peer review: Review PowerPoint and short papers for each other (see Page.2), by Dec. 1st.

3) Definition of "Pipeline": Propose the draft to Dr. Davis, Prof. Tobita, by mid of Dec.

4) Complete the final report based on the feedback of all members, Dr. Davis, by mid of Dec.

5) Share the feedback at JWWA, AWWA, and ASCE conferences and discuss the next step, all members, 1 year later.

End

## Annex 4 – Hazard Definitions

### RESILIENCE OF BURIED PIPELINES TO WHAT?

Resilience should be understood in terms of resilience ‘of what’ ‘to what’. This research panel is focused on buried pipelines, so the resilience ‘of what’ is the resilience of buried pipelines. The resilience of buried pipelines should be defined in terms of the effects occurring from different hazards (resilient ‘to what’). The matrix identifies several natural and anthropogenic hazards which may impact different regions in the USA. Buried pipelines need to be resilient to the effects of these different hazards. The matrix helps to understand the resilience of buried pipelines to hazards.

### HAZARDS DEFINITIONS

This section lists and defines the hazards included in the matrix. A hazard is an event that has the potential to cause harm (USGS, 2023a). When a hazard occurs, it is said to have struck or has been triggered. A described hazard may be associated with coincident hazards (e.g., a hurricane, the described primary hazard, includes coincident wind, heavy rain, wave surge and tornado hazards). Additional hazards may be triggered after an initial primary hazard has struck (e.g., earthquake shaking can trigger landslides and liquefaction). A cascading hazard is one which is initiated by another hazard (Kirschbaum et al, 2019). A multihazard event occurs when a primary hazard has coincident hazards and/or triggers other hazards. The definitions below describe the primary hazard. For multihazard events, the common coincident and associated cascading hazards are defined as a part of the primary hazard and should be considered when addressing that primary hazard.

One common cascading hazard comes from pipelines vulnerable to the listed hazards. It is the release of water, usually pressurized, from the pipeline when damaged. If a pipeline breaks, which can occur in the main barrel of the pipeline or at vulnerable joints, valves, or fittings by separating from the pipeline when displaced. The pressurized water will flow into the ground creating the possibility of service disruption and cascade to threatening the undermining of and potential damage to other nearby buried pipelines. Damaged pipelines cause surrounding environmental impacts including the erosion of holes, surface runoff that can flood buildings and surrounding areas, traffic disruption, among others. However, this document does not attempt to trace how cascading hazards, including pipeline breaks, may affect buried pipelines or the surrounding environment.

Attempts are made to list common coincident and cascading hazards associated with a primary hazard, but not all coincident and cascading hazards are defined in the listing below. The listings identify and provide a formal definition of the hazard. A description of the potential impacts of the hazard on buried pipelines is provided and the potential local and regional consequences as described in Table 1.

**Hazard Definition List (in alphabetical order)**

Construction-Related Activities: Ground movements caused by construction activities, which may be principally permanent ground deformations associated with excavations and load changes or transient ground deformation related vibrations.

- Excavation: Includes those related to deep excavations for metro stations and buildings as well as water, wastewater, and other facilities. They include movements resulting from tunneling and displacements caused by adjacent trench construction, primarily for utility lines. Construction in trenches is frequently supported by trench boxes that are designed for worker safety, but not for the control of ground displacements. Even shored trenches can deform and damage vulnerable pipelines.
- Load Change: May be caused by repaving roads, which often involves the removal of an existing pavement. Heavy construction equipment is operated over reduced depths after pavement removal, thereby increasing deformation in existing pipelines.
- Vibration: Vibratory hammers can generate vibrations in the surrounding ground, thereby causing volume loss and settlement in relatively loose, coarse-grained soils. Pile driving and blasting can cause vibrations in nearby pipelines.

Drought: A period of drier-than-normal conditions that results in water-related problems (USGS, 2023b).

Earthquake: The sudden slip on a subsurface fault and the resulting ground shaking and radiated seismic energy caused by the slip. An earthquake is a multihazard event. The term earthquake in the matrix includes all the associated earthquake hazards that may be triggered by the subsurface fault rupture and resulting ground shaking such as: surface fault rupture, ground shaking, landslide, liquefaction, lateral spread, tectonic deformation, differential ground settlement, tsunamis, and seiches (USGS, 2023c). ASCE (1984) provides more detailed descriptions of the earthquake hazards.

Erosion: The wearing away of the lands by running water, glaciers, winds, and waves; can be subdivided into three processes: Corrasion (mechanically removed or worn away), Corrosion (chemical erosion), and Transportation (moved by force of flowing water) (NOAA, 2023a).

Expansive Soil: Types of soil that shrink or swell as the moisture content decreases or increases. Structures built in or on these soils may experience shifting, cracking, and breaking damage as soils shrink and subside or expand (USGS, 2023f).

Flood: Any high flow, overflow, or inundation by water which causes or threatens damage (NOAA, 2023a). Floods may be caused by several different types of natural phenomena. Floods can be multihazard. They commonly cause erosion and may be associated with creating landslides through the combination of slope erosion and ground saturation.

- Coastal Flooding: The inundation of land areas caused by sea waters over and above normal tidal action (NOAA, 2023a). Coastal flooding also results from and is intensified by sea-level rise.
- Fluvial Flooding: The flooding of typically dry areas caused by the increased water level of an established river or stream when water overflows onto surrounding banks, shores, and neighboring land. Synonym of riverine flooding.
- Pluvial Flooding: Heavy flooding brought about by precipitation (e.g., rainfall) that is independent of an overflowing body of water.

- Flash Flood: A rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream or creek above a predetermined flood level (NOAA, 2023a). A flash flood is a type of pluvial flooding.

Heavy Rain: Rainfall exceeding what normally occurs in a region in intensity and duration. This may result in significant ground saturation, large amount of surface water runoff, and potential flooding. Also referred to as torrential rain or excessive rain.

Hurricane: A tropical cyclone in which the maximum sustained surface wind is 74 mph (119 km/hr) or more. The term hurricane is used for Northern Hemisphere tropical cyclones east of the International Dateline to the Greenwich Meridian. The term typhoon is used for Pacific tropical cyclones north of the Equator west of the International Dateline. Cyclones are an atmospheric circulation rotating counterclockwise. Hurricanes and typhoons have coincident strong wind (see wind hazard), tornadoes, heavy rain, and coastal flooding from storm surge. The heavy rain can also result in flooding. (NOAA, 2023b)

Landslide: The movement of a mass of rock, debris, or earth down a slope. Landslides encompass five modes of slope movement: falls, topples, slides, spreads, and flows (USGS, 2023e).

Temperature Change: Variation in temperature which may be caused by seasonal changes or induced by human installation of hot or cold influences. This hazard includes the effect of cold and hot temperatures resulting in freezing and thawing of ground and water.

- Seasonal Temperature Change: The annual variation in temperature resulting from tilt of the earth's axis. In the northern hemisphere this results in colder temperatures in the winter and hotter temperatures in the summer. These temperature changes respectively cool and warm the ground and the water flowing through buried pipelines which cause thermal contraction and expansion in the pipeline materials. This hazard is closely related to the heat and cold wave hazards, which are extreme variations in temperature change.
- Weather-Related Hot Temperature: High temperatures associated with severe summers. Includes heat wave which is a period of abnormally and uncomfortably hot and unusually humid weather typically lasting two or more days with temperatures outside the historical averages for a given area (FEMA, 2023). This hazard is closely related to the permafrost thaw hazard.
- Weather-Related Cold Temperature: Low temperatures associated with severe winters. Includes cold wave which is a rapid fall in temperature within 24 hours and extreme low temperatures for an extended period (FEMA, 2023). This hazard is closely related to the Ground Freeze-Thaw hazard.
- Ground Freeze-Thaw: The cycle of ground freezing and thawing from temperature changes. This cycle results in the ground heaving and settling respectively during the freeze and thaw portions of the cycle. Freezing is commonly associated with water in the ground that expands as it turns to ice. This cycle may be seasonal in some locations. It may be rare and periodic caused by uncommon cold waves. The depth of ground freeze may reach several feet. The ground deformations resulting from freezing is also called frost heaving.
- Permafrost Thaw: Permafrost is the thick layer of normally permanently frozen ground found in the arctic and boreal regions (USGS, 2023g). Clearing land and warming global temperatures cause the near-surface layer of permafrost to thaw. The thawing results in

soil creep and landslides (Solifluction), slumping and irregular subsidence, icings, and severe frost heaving. Permafrost thawing enhances the effects of an annual freeze-thaw cycle (Ray, undated)

- Induced Temperature Change: Human activities resulting in changes in underground temperatures which can affect pipelines. For example, cold areas around compressor stations, hot areas near steam lines, and warming of the underground resulting from large underground urban construction.

Subsidence: The gradual settling or sudden sinking of the earth's surface due to removal or displacement of subsurface earth materials (USGS, 2019). Subsidence is not restricted in rate, magnitude, or area involved. Subsidence may be caused by natural geologic processes, such as solution, compaction, or withdrawal of fluid lava from beneath a solid crust. Human activity such as subsurface mining or the pumping of oil or ground water may also cause subsidence (USGS, 2023f). Subsidence can cause the creation of growth faults which may form sudden ground surface displacements.

Sinkhole: Sinkholes happen when the ground below the land surface cannot support the land surface. Sinkholes are a form of ground subsidence and are commonly associated with the sudden collapse of the ground surface. A sinkhole is a depression in the ground that has no natural external surface drainage (USGS, 2018).

Tsunami: Ocean waves triggered by large earthquakes that occur near or under the ocean, volcanic eruptions, submarine landslides, or onshore landslides in which large volumes of debris fall into the water (USGS, 2023h)

Volcanic Activity: Volcanoes are openings, or vents where lava, tephra (small rocks), and steam erupt onto the Earth's surface. Common hazards associated with volcanic activities include ground uplift and subsidence, lava flows, tephra debris, release of steam and other toxic gases into the surrounding ground and atmosphere, ash, pyroclastic flows, earthquakes, landslides, and lahars (USGS, 2023d).

Wildfire: An unplanned fire burning in natural or wildland areas such as forests, shrub lands, grasslands, or prairies (FEMA, 2023). Wildfire can cause air and water quality concerns with ash and debris. It may also instigate cascading effects from debris flows from slopes denuded from the burning then saturated from rain during storms which may occur during normal rain season events. Wildfires are also commonly associated with drought and strong winds, and therefore are part of a multihazard process. For pipelines that are at or near the ground surface (e.g., backflow preventers, in vaults or meter boxes, shallow buried), fire can (1) change pipe material properties including melting of plastic and composite materials, and (2) damage pipe coatings on pipelines.

Wind: This definition intends to address strong wind in association with the hurricane hazard. It also applies to other wind events. Wind is an atmospheric condition when the air moves in horizontal motion past a given point due to pressure differential, commonly resulting from uneven heating of the earth. The greater the pressure differential the greater the resulting force on objects (NOAA, 2023a). Wind is usually associated with tropical storms and thermal gradients. Strong winds have speeds of 58 mph or more (FEMA, 2023). Wind normally does not directly affect buried pipelines. However, it can indirectly affect buried pipelines by the strong wind forces toppling trees, poles, and other surface features located near buried pipelines which can and have resulted in pipe breaks; toppling of surface features may be bolstered by ground saturation.

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