



Technical Memorandum

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| Date June 20, 2012 | Job Lake Oswego Seismic Pipeline Design |
| To Joel Komarek - Lake Oswego David Prock – Lake Oswego | Job Number B2863004.00 |
| From Don Ballantyne cc. Brad Moore – Kennedy Jenks | Subject Seismic Design Memorandum Final |

Introduction and Overview

This memorandum reviews the seismic hazards and presents the pipeline mitigation proposed for the 42-inch raw water pipeline (RWP) and 48-inch finished water pipeline (FWP) for the Lake Oswego-Tigard Water Project (refer to Figure 1). The seismic hazard information on which this memorandum is based is contained in the attached letter from Kleinfelder to Kennedy/Jenks Consultants (K/J) dated June 20, 2012 and titled *West Linn Land Use Application Seismic and Geologic Hazards*. The identified risks and goals of this pipeline design are consistent with the *West Linn Natural Hazards Mitigation Plan*.

Historically, water pipelines have been vulnerable to earthquakes, particularly permanent ground deformation (PGD) due to liquefaction and associated lateral spreading. Many older pipeline systems were constructed with brittle pipe materials, unrestrained joints, and brittle welds all of which contributed to failures in earthquakes. Over the past several decades, engineers have developed pipeline systems that are resistant to these PGD hazards. The pipeline systems that perform the best when subjected to PGD include steel pipe with welded joints, ductile iron pipe (DIP) with restrained joints, and high density polyethylene pipe (HDPE) with fused joints (Ballantyne, 1994). The Owner/Engineer team has selected steel pipe with welded joints for this project. Steel pipe with welded joints is one of the best seismic resistant pipeline systems and will provide adequate mitigation for this project’s seismic environment.

Earthquake Risk and Geologic Hazards

Pipelines may be vulnerable to earthquake hazards including shaking and PGD. PGD includes liquefaction and associated settlement and lateral spread, landslide, lurching (movement of blocks of soil occurring in very intense shaking), and fault displacement. Lateral spread displacements occur when a layer of soil liquefies, and the soils above it flow downhill or towards a free face. Displacements can range from less than an inch to tens of feet.

The shaking intensity and probability and extent of PGD are a function of the specific earthquake event. The selected earthquake groundmotion is probabilistic, that is an earthquake with a probability of occurrence within 50 years and associated recurrence interval will produce a given groundmotion.

The American Society of Civil Engineers (ASCE) Section 7 and the International Building Code (IBC) approach the development of a seismic design event by starting with the groundmotion from an earthquake with a 2 percent probability of exceedance in 50 years (2,475 year return) and then multiplying that number by a factor of two-thirds for general building design. That seismic design event is then increased by a factor of 25 percent for important structures and by 50 percent for very important structures. The water system, including pipelines, can be considered very important because it provides water used for fire suppression following earthquakes. When the general building seismic design event is increased by a factor of 50 percent, the resulting design event is the full 2 percent in 50-year earthquake groundmotion. The design earthquake selected for the RWP and FWP projects is the 2 percent in 50-year groundmotion, which is consistent with the Lake Oswego Water Treatment Plant (WTP) upgrade design event. This level of earthquake is also consistent with the highest level of earthquake that is currently accepted worldwide for design and is typically used for life sustaining structures such as hospitals and other emergency response buildings.

Earthquake shaking results in differential movement of the soil along the pipeline corridor. Shaking may result in differential movement between pipe segments or, for continuous pipe, may impart strains along the pipe.

Liquefaction may result in consolidation of any existing liquefiable layers and may result in differential settlement in the overlying soils. Differential settlement is a function of the changing thickness of the liquefiable layer. If the liquefiable soils, or soil blocks above liquefiable soils are on a slope, they can move laterally down gradient, commonly referred to as lateral spread. A pipe that is buried in these moving soils will either be strained, or, if not properly designed, may have its joints pulled apart. In a similar fashion, landslides can exert strains on buried pipe. The goal of pipeline seismic design is to design a pipeline that will be able to withstand the stress and movement imparted into the pipe resulting from shaking and PGD. The next section of this report identifies design practices that enable pipelines to withstand these risks.

Mitigation – Pipe Design

There is no widely adopted seismic design code, standard, or guideline for water pipelines. The San Francisco Public Utility Commission (SFPUC) and the Los Angeles Department of Water and Power (LAPWP) are agencies that are on the forefront of addressing earthquake design issues, and are designing for levels of risk reduction comparable to those proposed for this project. The SFPUC has used welded steel pipe through much of its transmission system and installs welded steel pipe for all new pipe in its transmission system. In areas subjected to high values of PGD, SFPUC designs the joints to accommodate the expected stresses and strains using double lap weld joints and butt welded joints depending on the situation. The Los Angeles Department of Water and Power (LADWP) also uses steel pipe with welded joints for new pipe installed in their transmission system. In areas that are expected to be subject to high values of PGD, LADWP adjusts steel pipe wall thickness and welded joint design to accommodate the expected stresses and strains.

Using the design approaches of these utilities in highly seismic areas, most earthquake hazards that affect buried pipelines can be mitigated through proper selection and design of the pipe system. While soil improvement techniques have been shown to mitigate certain seismic risks such as liquefaction, lateral spread and differential settlement, for long linear pipe systems, such techniques are cost prohibitive. For long linear pipelines like those proposed for the RWP and FWP projects, these risks are best mitigated through proper selection of pipe materials, joint design and stringent quality control and quality assurance practices for weld inspection and installation.

The *Pipeline Research Council International Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines* (Honegger, 2004) provides guidelines for welded steel pipe design subjected to seismic loading. For bending such as due to differential settlement, pipe strains are a function of the pipe diameter. The pipe's resistance to buckling is a function of the pipe steel properties, the wall thickness, and joint design. The document provides two performance levels:

1. Maintain Pressure Integrity
2. Maintain Normal Operation.

The Maintain Pressure Integrity performance level allows the pipe to become oval and/or wrinkle as long as the pipe does not develop a leak. Pipe designed to this level of performance may have to be replaced in the years following the design earthquake, but will not rupture or leak. The Maintain Normal Operation performance limits stresses and strains in the pipe to a level which will prevent the pipe from ever experiencing ovaling and/or wrinkling. For this project, the Maintain Pressure Integrity performance criteria will be used.

Specific Design Considerations for Seismic Hazards

The following pipeline design factors are commonly considered for proper seismic mitigation. Seismic risks can be mitigated through pipe material selection, pipe joint selection, use of flexible joints, use of expansion sleeves, and use of pipe coatings and wrappings. This section will discuss the available options within each of these design considerations and the pros and cons of each option.

Pipe Material:

The current industry standard pipe material for pressurized water transmission lines similar to the RWP and FWP is either steel or ductile iron.

- Welded Steel Pipe – The welded steel pipe barrel has sufficient ductility to accommodate strains induced by ground shaking and PGD. Welded steel pipe wall thickness is customizable and can be slightly increased to provide additional accommodation to strains induced by seismic loading without overly affecting cost. Welded steel pipe is the standard used by many water utilities in high seismic risk areas, such as SFPUC and LADWP as previously discussed.
- Ductile Iron Pipe – Ductile iron pipe has sufficient ductility to accommodate bending loads due to PGD. The pipe is designed to accommodate PGD in its joints and is only considered equal to welded steel pipe when restrained joints and supplemental expansion joints are employed along the alignment.

Pipe Joint Connections:

Steel pipe welded joints must be sufficiently robust to be able to withstand stresses and strains induced by ground shaking and PGD. Ductile iron pipe joints must be designed to stay together and relieve strain in cases where significant PGD may be experienced. Ductile iron pipe systems sometimes employ expansion sleeves to relieve excess pipe strain that cannot be accommodated in the joints.

- Welded Steel Pipe – There are several different methods to weld joints together for welded steel pipe. Welding methodologies include butt welding, double-lap welding, and single lap welding. Additionally, some steel pipe uses gasketed bell and spigot joints.
 - Butt Welding – Butt welding involves welding two flush pieces of pipe together end to end. Steel pipelines with butt welded joints are commonly used in the oil and gas industry and are the strongest welded joint currently used for steel pipe. In the water industry, they are used where pipelines can be subjected to significant PGDs such as at fault crossings and areas of lateral spread. Butt welds are 1-1/2 to 2 times stronger than double-lap welds. This difference can be made up by using thicker wall pipe if using double-lap welds. Butt welding may result in longer construction durations than other steel pipe welding designs.
 - Double-lap Welding – Double-lap welding involves welding two pieces of pipe together where the spigot end slides inside the bell end. One weld is made on the outside and one on the inside of the pipe. As noted above, double-lap weld pipeline systems can be made as strong as butt-weld pipe systems by increasing the pipe wall thickness. This double weld geometry makes the longitudinal loading along the pipe wall more symmetrical across the joint. Steel pipelines with gasketed bell and spigot joints sometimes employ lap welds near bends to provide restraint for thrust. Installing pipe with double-lap welds is faster than with butt welds.
 - Single Lap Weld – Single lap welding is the industry standard for welded steel pipe water lines. It is similar to double-lap welding, but only the inside or the outside of the pipe bell connection is welded. Many agencies in high seismic areas such as the SFPUC and LADWP use single lap welds for pipelines except for where PGD and/or particularly high ground motions are expected.
 - Restrained Push-On Joints – Restrained bell and spigot steel joints are sometimes used for thrust resistance in a pipeline system otherwise using unrestrained joints. Restrained joints are suitable for use in seismic areas as they can be designed to accommodate bending.
 - Unrestrained Push-On Joints – Unrestrained bell and spigot steel joints are commonly used in areas where restrained pipeline joints are not needed. These joints are comparable to standard ductile iron push-on joint pipe. Unrestrained joints are typically not recommended in areas with shaking that is significant enough to result in joint separation.
- Ductile Iron Pipe – There are two main ways that sticks of ductile iron pipe are connected, restrained and unrestrained push-on joints.

- Restrained Push-On Joints – Restrained ductile iron joints are achieved by modifying typical ductile iron unrestrained push-on joints with a mechanical restraining device. There is a limited amount of ductile iron pipe with restrained joints that has been subjected to earthquakes. While ductile iron pipe has been used since the 1970s, very small amounts have been installed with joint restraints, typically used for thrust restraint. The last major earthquake in the U.S. mainland was in 1994. However, the Japanese have been using ductile iron pipe with a special seismic joint with significant exposure in major earthquakes starting with Kobe in 1995. The special seismic joint provides restraint as well as some extension/compression capacity. There have been no reported failures of this type of pipe. Additional expansion sleeves must be added to the pipe system to relieve pipe strain in areas with high expected PGD values.
- Unrestrained Push-On Joints – Unrestrained bell and spigot ductile iron joints are commonly used in areas where restrained pipeline joints are not needed. These joints are comparable to unrestrained push-on joint steel pipe. Unrestrained joints are typically not recommended in areas with shaking or PGD that is significant enough to result in joint separation.

Flexible Joints and Expansion Sleeves:

Mechanical joints and/or expansion sleeves are used to allow movement in location where PGD would otherwise create stresses too high for the pipe material or pipe joints to handle.

- Flexible Joints – Flexible joints are designed to allow joint rotation. They are used in pipe systems where the pipe joints cannot accommodate the expected rotation that may occur as a result of differential settlement such as the interfaces between pile supported structures and direct buried pipe. A segmented ductile iron pipe system with flexible joints installed at regular intervals can be designed to withstand shaking and PGD forces equivalent to a continuous welded steel pipe system.
- Expansion Sleeves – Expansion sleeves are used to relieve the expected strain due to lateral spread or landslide. They would be used if the pipe does not have adequate ductility to accommodate the pipe strain. A segmented ductile iron pipe system with expansion sleeves integrated into the system at regular intervals can be designed to withstand shaking and PGD forces equivalent to a continuous welded steel pipe system. The City of Seattle has employed this design in a liquefaction area.

Pipe Coatings and Wrappings:

The pipe will be lined and coated with a ductile material that will move with the pipe wall up to 2% strain. If mortar coating is used on the interior, there is potential for it to crack off when the pipe deforms. While this is not a structural issue, it can hamper pipeline operation following an earthquake. The pipe will be tape wrapped which will allow the steel pipe wall to maintain its ductility, important to achieve its intended seismic performance.

A combination of a pipe coating and wrapping, or two layers of wrapping should be used to reduce friction between the pipeline and surrounding soils if the pipe is designed to move through the soil when subjected to lateral spreading.

Design for Specific Hazards

The specific risks of ground surface rupture, ground shaking, wave propagation, liquefaction and seismically induced settlement, lateral spreading potential, and seismically induced slope failures as identified in the Kleinfelder seismic hazard identification letter are discussed in this section. A general design methodology is provided as a framework for each identified risk. The general design methodology framework will then be applied to determine the seismic design recommendations for each specific Seismic Reach as defined by Kleinfelder.

Ground Surface Rupture

There is negligible to low risk of ground surface rupture. There are no active faults (activity within the last 10,000 years) within the area where the pipelines will be installed.

Ground Shaking

These are measures of shaking intensity. The peak ground acceleration (PGA) is 0.55 times gravity for the design earthquake (2,475-year return period or 2 percent probability of exceedance in 50 years). This is used to determine the potential for the occurrence of various geotechnical hazards. The 1-second spectral acceleration is 0.70 times gravity and is related to the PGA. The spectral acceleration is used to calculate the peak ground velocity (PGV) that is used to assess the reliability of the pipe joint. The maximum PGV is 37.7 inches per second. Steel pipe with welded joints can accommodate this level of PGV without damage.

Liquefaction, Seismically Induced Settlement, and Seismically Induced Differential Settlement

The liquefaction potential is based on PGA, duration of shaking, the groundwater table, and various soil properties. Seismically induced settlement is based on the thickness and properties of the liquefiable soil layer. Liquefaction settlement does not directly affect the pipeline design except at the interface between pile supported and direct buried pipe. The seismically induced differential settlement is a function of the varying thickness of the liquefiable layer and the non-homogeneity of the liquefiable layer. These three parameters vary by Pipeline Reach. Refer to Table 1 for values by Reach.

Lateral Spreading Potential

Lateral spreading potential for Reach 1 is none to very low because the liquefaction potential is none to very low. The lateral spread potential for Pipeline Reaches 2 and 3 is low because of the presence of a shallow basalt ridge which serves as a buttress. The Kleinfelder letter states that the potential for lateral spreading is low for Reach 4 but that additional borings will be conducted to confirm the lateral spread potential. The pipeline design in Pipeline Reach 4 is based on a low potential for lateral spreading, and will be modified if the potential for lateral spreading is higher than currently understood. The pipe wall thickness/joint combination will be designed in accordance with *Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Fuel Hydrocarbon Pipelines* (Honegger, 2004) to the “Maintain Pressure Integrity” level of service.

Seismically Induced Slope Failures

Based on the Kleinfelder letter, the risk of seismically induced slope failure for Reaches 1 through 4 is low.

Hazard Evaluation and Proposed Mitigation by Pipeline Reach

The RWP and FWP pipelines are shown in “reaches” on Figure 1. The liquefaction potential, liquefaction settlement, and differential settlement for each of those reaches are summarized in Table 1. The earthquake risk for the other hazards discussed above is none to low.

**Table 1. Liquefaction Potential and Liquefaction-Induced Settlement
(from Kleinfelder Letter)**

| Pipeline | Reach | Liquefaction Potential | Liquefaction Settlement (inch) | Differential Settlement (inch) | Pipe Wall Thickness |
|---------------------|-------|--|--------------------------------|--------------------------------|---------------------|
| RWP | 1 | None to very low | Negligible | Negligible | ¼ inch |
| | 2 | Moderate to High | 2.5 to 3.5 | 0.6 to 1.6 over 40 feet | ¼ inch |
| WTP and access area | 3 | High | Up to 7 ½ Inches | 0.6 to 1.6 over 40 feet | ¼ inch |
| FWP | 4 | Moderate to high except low potential at the borings including FWP-5, -7,-8, and -65 | 3 to 4 | 0.6 to 1.6 over 40 feet | ¼ inch (Note 1) |

Note 1 – Additional borings will be performed to confirm no lateral spreading is expected.

Steel pipe will be used for the RWP and FWP within West Linn city limits. The steel pipe will be designed in accordance with *Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines* (Honegger, 2004). The steel pipe will use a minimum 36 ksi yield strength steel. The pipe wall thickness is as shown on Table 1. The steel stress-strain curve should contain no plateau regions so as to redistribute strains when plastic deformation begins to occur (PRCI, 2004).

Reach 1

Reach 1 is subjected to negligible liquefaction and differential induced settlement and low potential for seismically induced slope failures. Welded steel pipe with a wall thickness of ¼” with double-lap welds will be able to accommodate these earthquake hazards.

Reach 2

Reach 2 is subjected up to 1.6 inches in differential settlement and low potential for seismically induced slope failures. Welded steel pipe with a wall thickness of 1/4" with double-lap welds will be able to accommodate these earthquake hazards.

Reach 3

Reach 3 is subjected up to 1.6 inches in differential settlement and low potential for seismically induced slope failures. Welded steel pipe with a wall thickness of 1/4" with double-lap welds will be able to accommodate these earthquake hazards. Reach 3 is subjected up to 7-1/2 inches of liquefaction settlement. A specially designed mechanical pipe connection system (such as two ball joints separated by an expansion sleeve) designed to accommodate differential settlement between the WTP pile supported structures and the direct buried pipe should be employed.

Reach 4

Reach 4 is subjected up to 1.6 inches in differential settlement and low potential for seismically induced slope failures. Welded steel pipe with a wall thickness of 1/4" with double-lap welds will be able to accommodate these earthquake hazards. Additional borings and analysis will be performed to confirm that no lateral spread is expected. If the potential for lateral spread is identified, the pipe wall thickness and joint design will be modified accordingly.

Conclusion

This memo addresses the seismic risks identified in the attached letter from Kleinfelder and proposes design mitigation so the pipelines will be able to withstand the design seismic event. The design earthquake used to identify pipeline seismic risks has a recurrence of 2,475 years and is consistent with the standards used for hospitals and other emergency response buildings. These risks will be minimized and mitigated through the proposed design methods in this memorandum. The pipeline is being seismically designed in accordance with the *Pipeline Research Council International Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines* (Honegger, 2004) to the Maintain Pressure Integrity performance level. Welded steel pipe with a 1/4-inch wall thickness will be used with double-lap welds to accommodate earthquake hazards identified in the Kleinfelder letter. Additional geotechnical borings and analysis will be performed to confirm the proposed pipeline design approach in Reach 4 along Highway 43.

References

American Society of Civil Engineers, 2010, *ASCE/SEI 7-10, Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, Washington, DC.

Ballantyne, Donald, 1994, *Minimizing Earthquake Damage, A Guide for Water Utilities*, American Water Works Association, Denver Colorado.

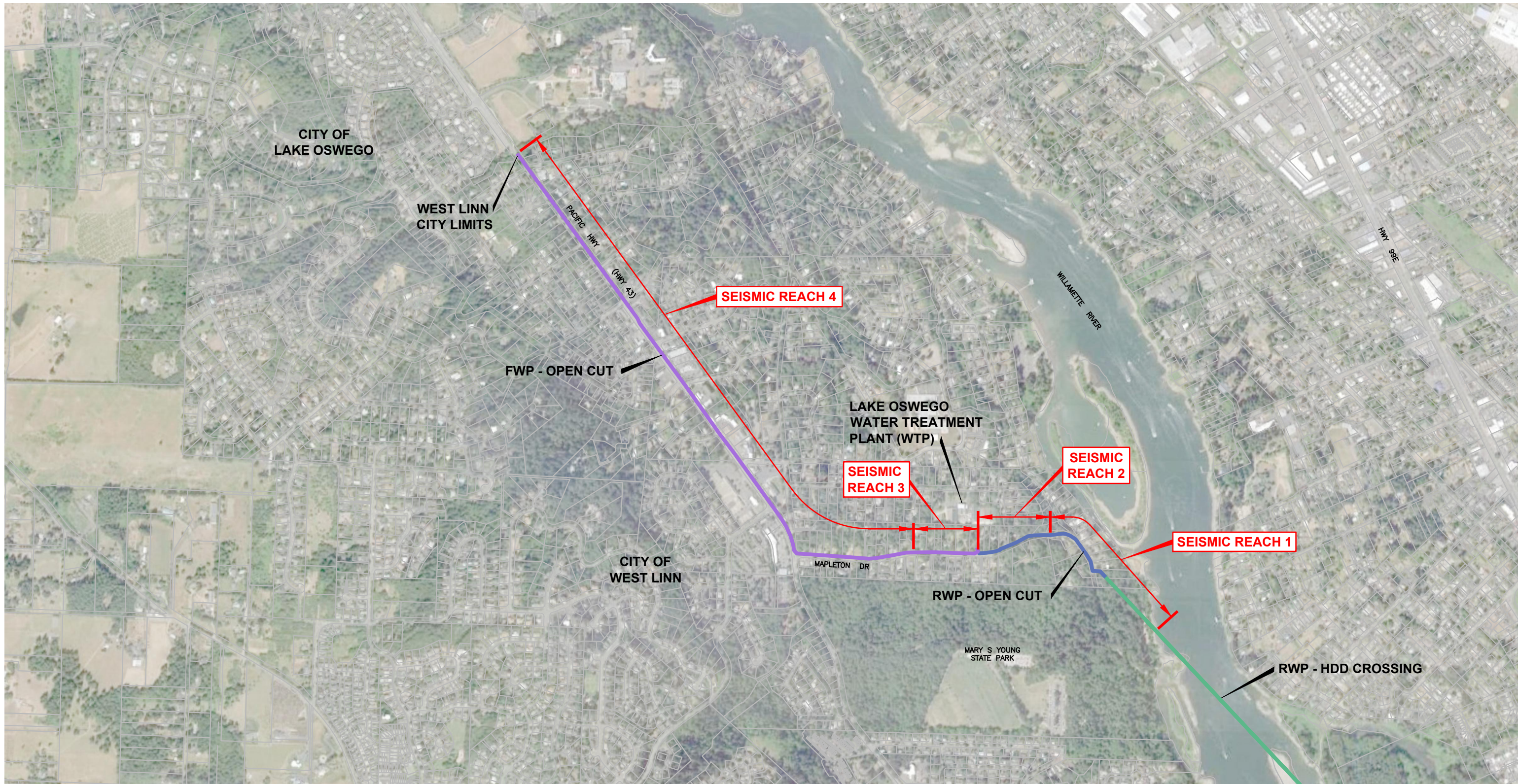
Ballantyne, Donald; CB Crouse, 1997, *Reliability and Restoration of Water Supply Systems for Fire Suppression and Drinking Water Following Earthquakes*, NIST GCR 97-730, National Institute of Standard and Technology, Gaithersburg Maryland.

Ballantyne, Donald, 2010, “Seismic Vulnerability Assessment and Design of Pipelines”, *Journal of the American Water Works Association* 102:5, AWWA, Denver Colorado, May.

International Building Code, 2012, International Code Council, Washington, DC.

Honegger, D.G., and D.J Nyman, 2004, *Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Fuel Hydrocarbon Pipelines*, prepared for the Pipeline Design, Construction & Operations Committee of the Pipeline Research Council International, Contract PR-268-9823, Houston Texas.

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LEGEND

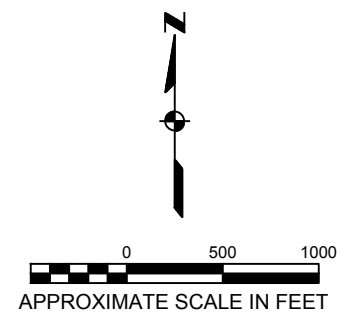
- RWP - OPEN CUT
- RWP - HDD CROSSING
- FWP - OPEN CUT

Degenkolb Kennedy/Jenks Consultants

LAKE OSWEGO-TIGARD WATER PARTNERSHIP
 FINISHED WATER PIPELINE (FWP)
 AND RAW WATER PIPELINE (RWP)
 CITY OF WEST LINN

**RAW WATER PIPELINE AND FINISHED
 WATER PIPELINE SEISMIC REACHES
 WEST LINN CITY LIMITS**

K/J 1191016.10
 FIGURE 1





June 20, 2012
Project No. 120589

Kennedy-Jenks Consultants
200 SW market St., Suite 500
Portland, Oregon 97201

Attn: Mr. Brad Moore, P.E., Senior Water Resources Engineer

**Subject: West Linn Land Use Application
Seismic and Geologic Hazards
LOTWP Raw & Finished Water Pipelines
Lake Oswego, Oregon**

Dear Brad:

INTRODUCTION

As part of the Land Use Application, Kleinfelder has reviewed and evaluated the seismic hazards for the pipeline segment in the West Linn Area, which includes portions of the Raw and Finished Water Pipelines. The following reports were used for review and summary of the geologic and seismic conditions of the pipeline alignment through West Linn, Oregon.

- Geotechnical Data Report: Willamette River Crossing Alternatives, Lake Oswego Water Pipeline, Clackamas County, Oregon, GeoDesign, Inc., March 30, 2012.
- Seismic Hazard Assessment, GeoDesign, Inc., 2011
- Geotechnical Report: Finished Water Pipeline, GeoDesign, Inc., 2011
- Geotechnical Data Report: Raw Water Pipeline – Lake Oswego Water Pipeline, Clackamas County, Oregon, GeoDesign, Inc., November 2010
- Liquefaction Analysis of Lake Oswego Tigard Water Treatment Plant, Shannon & Wilson, October, 2011.

Kleinfelder did not perform subsurface explorations or field mapping in the West Linn project area. Therefore, the information provided in the GeoDesign, Inc. (GeoDesign) reports is reviewed and summarized in this letter. Kleinfelder updated the seismic

evaluation from the USGS 2002 used by GeoDesign to the 2008 version. In addition, the seismic event return period of 5 percent in 50 years (975 years return period) identified in the GeoDesign Report was not used in this report, but rather the more conservative return period of 2 percent in 50 years (2,475 years return period) to correspond with Shannon & Wilson's seismic report for the Water Treatment Plant (WTP) in West Linn.

PIPELINE SUMMARY THROUGH WEST LINN

The new pipeline will convey water from a River Intake Pump Station (RIPS) located on the Clackamas River in Gladstone to the Bonita Pump Station (BPS) in Tigard. The area included in this Land Use Application is the western portion of the Raw Water pipeline on the west side of the Willamette River to the WTP and the Finished Water Pipeline from the WTP to the City of Lake Oswego southern city limit near Arbor Drive along Highway 43. The Raw Water Pipeline (RWP) in this area will convey water from the west bank of the Willamette River by way of a horizontal directional drill underneath Mary S. Young Park, along Mapleton Drive, and terminate at the WTP. The Finished Water Pipeline (FWP) will convey water from the WTP, along Mapleton Drive, and along Willamette Drive/Pacific Highway (OR Highway 43) into Lake Oswego. The project area has been separated into reaches based on the geology and seismic hazards (Figure 1).

GEOLOGIC SUMMARY

GeoDesign drilled 23 borings to depths of about 13 feet below ground surface (bgs) at 250- to 1000-foot spacings along the Raw and Finished Water alignments in West Linn. Additional GeoDesign borings were also drilled to depths between 100 and 192 feet bgs along the Willamette shoreline and Mapleton Drive for the HDD crossing. Shannon and Wilson drilled five borings and seven CPTs advanced up to 65 feet below ground surface (bgs) at the WTP site. In addition to the subsurface explorations, GeoDesign also mapped and field verified landslide and potential landslide locations along the west bank of the Willamette River and Highway 43. Information included in the GeoDesign reports was reviewed and is summarized in the landslide identification and fault sections below. The geology, known landslide and fault locations are presented on Figures 2A, 2B, 3A, or 3B.

Geology

The geology surrounding the West Linn project area is generally mapped as Pleistocene fine-grained facies deposits (Qff) by Beeson and Tolan (1989) originating from the Missoula Floods with exposed outcrops of Columbia River Basalt Group (CRBG) bedrock along the Willamette River bank and Highway 43. The Qff consists of unconsolidated sand, silt, and gravel that extended below GeoDesign's deepest boring (40 feet). The CRBG bedrock outcrops were observed by GeoDesign north of the existing pipeline and at shallow depth (6 feet) in Boring HDD-5 near the river bank. Recent Quaternary alluvium (Qal) and Springwater Formation (QTs) are mapped along the river shoreline and on the east side of Mapleton Drive, respectively. The CRBG underlies all of these surficial deposits.

Based on existing borings performed by GeoDesign, alluvial sediments (Qal, QTs, and Qff) extended to at least the depth explored in the RWP portion east of Boring HDD-5. However, as the pipeline parallels Highway 43 in the FWP portion, the Qff deposit thicknesses are as thin as about 2 feet. The depths to rock were variable. In general, the thickness of the Qff above the CRBG was greater than 20 feet along Highway 43.

Landslides

Department of Geology and Mineral Industries (DOGAMI) LiDAR maps identify recent and historical landslides along the proposed alignment. The closest landslide to the RWP alignment as identified in the LiDAR imagery is approximately 300 feet north of the RWP alignment at the location the pipeline turns west along Mapleton Drive from the intersection with Nixon Drive, as shown in Figure 2A. No other landslides were identified on the LiDAR imagery or Statewide Landslide Inventory Database for Oregon (SLIDO-2). Based on an analysis of slope gradients derived from the LiDAR imagery, GeoDesign performed reconnaissance of slopes in Mary S. Young State Park, Highway 43 near Walling Circle, Highway 43 near Lazy River Drive, and Highway 43 near Arbor Drive in the West Linn area. Of these areas, a slope within Mary S. Young State Park was identified as a potential seismically-induced landslide hazard as shown in Figure 2A in the area marked with blue hatch marks. The area is primarily west of the alignment, but may extend towards the river's edge.

Local Faults

Review of available literature shows twelve faults mapped near the Portland Metro Area. Table 1 provided by GeoDesign shows the distances of the faults from the pipeline alignment and their estimated age. The only fault within the vicinity of the RWP and FWP alignments within the City of West Linn is the Bolton Fault at approximately 0.2 miles from the pipeline alignment. This fault extends north-south and is located to the west of Highway 43. Figures 2A, 2B, 3A, and 3B illustrate the location of the Bolton Fault. As can be seen in the Figures, the FWP alignment does not cross the Bolton Fault. The seismic potential resulting from each of these faults is discussed later in this report.

Table 1. Local Faults in the Proximity of the Pipeline (GeoDesign (2011))

| Fault Name | Proximity to Site (surface projection in miles) | Estimated Displacement Description | Estimated Age |
|------------------------|--|--|--|
| Bolton | 0.2 | Offsets Columbia River Basalt flows and overlying fluvial and lacustrine deposits. Does not offset Missoula Flood deposits. | Quaternary (< 1.6 million years before present) |
| Oatfield | 0.5 | Offsets Columbia River Basalt flows and Boring Lava. Does not offset Missoula Flood deposits. | Quaternary (< 1.6 million years before present) |
| Canby-Molalla | 1 | Probable offset of Missoula Flood deposits. | Late Quaternary (< 15,000 years before present) |
| Portland Hills | 1.5 | Potential offset of Missoula Flood deposits by means of geophysical techniques and trench excavation. | Late Quaternary (< 15,000 years before present) |
| Grant Butte | 4 | Offsets Plio-Pleistocene deposits and Boring Lava. Does not offset Missoula Flood deposits. | Middle to Late Quaternary (< 750,000 years before present) |
| East Bank | 6 | Probable offset of unconformities and paleochannels associated with the Missoula Flood deposits. | Late Quaternary (< 15,000 years before present) |
| Beaverton Fault Zone | 7 | Offsets Columbia River Basalt flows and overlying fluvial and lacustrine deposits. Does not offset Missoula Flood deposits. | Middle to Late Quaternary (< 750,000 years before present) |
| Helvetia | 12 | Offsets Columbia River Basalt flows and overlying fluvial and lacustrine deposits. Does not offset Missoula Flood deposits. | Quaternary (< 1.6 million years before present) |
| Newberg | 15 | Controlled emplacement of Columbia River Basalt flows. No documented offset of overlying younger deposits. | Quaternary (< 1.6 million years before present) |
| Lacamas Lake | 17 | Offsets Plio-Pleistocene deposits and Boring Lava. Does not offset Missoula Flood deposits. | Middle to Late Quaternary (< 750,000 years before present) |
| Gales Creek Fault Zone | 20 | Offsets Columbia River Basalt flows and overlying fluvial and lacustrine deposits. Does not offset Missoula Flood deposits. | Quaternary (< 1.6 million years before present) |
| Mount Angel | 20 | Offsets late Pleistocene and Holocene deposits. Associated with earthquake swarms near Woodburn (1990) and ML 5.6 earthquake near Scotts Mills (1993). | Late Quaternary (< 15,000 years before present) |

Regional Faults

The Cascadia Subduction Zone (CSZ) is the primary regional fault system in the site area and was created by the Juan de Fuca Plate subducting beneath the North American Plate. The subduction is occurring in the coastal region between Vancouver Island, British Columbia, Canada and the Mendocino Triple Junction in northern California.

SITE SEISMICITY

The project's seismicity was evaluated and provided in the Seismic Hazard Assessment report by GeoDesign dated March 11, 2011. Kleinfelder performed additional analyses to evaluate and confirm GeoDesign's findings and update the information based on the USGS 2008 information. Based on these analyses, three earthquake sources have the potential to affect the proposed FWP alignment:

- Cascadia Subduction Zone (CSZ) interface earthquakes
- CSZ intraplate earthquakes
- Local crustal earthquakes

The CSZ is the region where the Juan de Fuca Plate is being subducted under the North American Plate. The CSZ earthquake events have the potential to generate earthquake magnitudes up to 9.0.

Major earthquake events can occur from local crustal earthquakes as well. GeoDesign identified 12 local crustal faults as noted in Table 1, within 20 miles of the proposed pipeline alignment that have the potential to be active based on DOGAMI and/or USGS interpretations.

GeoDesign summarized the peak ground acceleration (PGA) for three soil/rock site classes found along the proposed alignment. Site Class B represents shallow bedrock. Site Class C represents firm soils and gravels or where up to 10 feet of soil overlays bedrock. Site Class D represents alluvial soils. Based on the borings, West Linn is primarily considered Site Class D. The PGA values generated by GeoDesign were based on 2002 Geohazard Maps developed by the USGS for a return period of 975 years, which resulted in a PGA of 0.38. The updated PGA values are based on 2008 USGS for a return period of 2,475 years with an estimated PGA of 0.55. The PGA value was updated in the analysis based on 2008 NSHMP Interactive Deaggregation

tool by the USGS. Table 2 below presents the contribution of the individual seismic sources to the PGA.

Table 2. Seismic Source Data

| Spectral Acceleration Period (sec) | Seismic Source | Contribution to Seismic Hazard (percent) | Approx. Distance from Site (km) | Postulated Magnitude (M _w) |
|---|------------------------------------|--|---------------------------------|--|
| 2 Percent in 50 years (2475-year event) | | | | |
| PGA | CSZ Floating | 20.2 | 113.3 | 8.5 |
| | CSZ Megathrust | 41.8 | 106.8 | 9.0 |
| | WA-OR Cascades-West crustal faults | 15.5 | 4.3 | 6.7 |
| | WUS Gridded | 7.1 | 8.7 | 6.4 |
| | CSZ Intraplate | 12.7 | 63.1 | 7.0 |
| | Individual Crustal Faults | | | |
| | Portland Hills fault | 5.2 | 3.7 | 7.0 |
| | Portland Hills fault, GR | 6.8 | 5.0 | 6.8 |
| | Bolton fault | 2.8 | 0.4 | 6.2 |
| 1sec | CSZ Floating | 8.8 | 102.3 | 8.5 |
| | CSZ Megathrust | 23.8 | 102.5 | 9.0 |
| | WA-OR Cascades-West crustal faults | 24.1 | 4.7 | 6.7 |
| | WUS Gridded | 26.7 | 9.3 | 6.0 |
| | CSZ Intraplate | 15.6 | 65.0 | 6.9 |
| | Individual Crustal Faults | | | |
| | Portland Hills fault | 7.0 | 3.7 | 7.0 |
| | Portland Hills fault, GR | 10.2 | 5.3 | 6.8 |
| | Bolton fault | 5.0 | 0.4 | 6.2 |

SEISMIC HAZARD ANALYSIS

To address the potential hazards to the RWP and FWP pipelines through West Linn and the remaining alignment, we completed the following analyses based on the Site Class D and subsurface and groundwater conditions:

- Ground Surface Rupture
- Ground Shaking
- Wave Propagation Damage
- Liquefaction Hazard and Seismically Induced Settlement
- Lateral Spreading Potential
- Seismically Induced Slope Failure

The selection of these analysis methods is based on guidance from the following sources and our professional judgment:

- American Lifeline Alliance (ALA) Seismic Manual published by the American Society of Civil Engineers (ASCE), 2001
- Geotechnical Earthquake Engineering by S. Kramer, 1996
- Geotechnical Earthquake Engineering Manual by FHWA, 1999

Ground Surface Rupture

Based on USGS deaggregated data, relatively significant crustal seismic sources in the RWP and FWP segments in the vicinity of the pipeline in West Linn include the Bolton Fault, the Marythrust Fault, and the River Forest Fault. We consider the risk of fault rupture from these faults to be negligible to low during the pipeline design life based on a lack of displacement evidence during the Quaternary (1.6 million years to present) as well as the mapped locations.

Ground Shaking

Based on the boring logs and site geology, the site class in the West Linn area is "D". For the pipeline, Kleinfelder considered the ground shaking associated with return period of 2,475 years (i.e., 2% probability of exceedance in 50 years). The peak ground accelerations (PGA), spectral acceleration at a period of 1 second (S_1), and associated mean and modal magnitudes were estimated using USGS interactive deaggregation tool (2008). The results are summarized in Table 3 and were generated from the WTP located at latitude and longitude 45.3855°N and -122.636°W, respectively. The values of PGA and magnitude were used to evaluate liquefaction potential. The value of S_1 is used to estimate wave propagation.

Table 3. Estimated PGA and S₁ (Return Period = 2475 years)

| Site Class | PGV (inches/sec) | Spectral Acceleration Period | Spectral Acceleration | Mean Magnitude & Distance | Modal Magnitude & Distance |
|------------|---------------------|------------------------------------|--------------------------|---------------------------------|----------------------------------|
| D | 28.5 to 37.7 | PGA | 0.55 g | 7.5 (62.6 km) | 9.0 (93.1 km) |
| | | S ₁ | 0.70 g | 8.2 (81.1 km) | 9.0 (93.1 km) |

Site Class D is based on an assumed V_s^{30} of 270 m/sec.

$$S_1 = S_{1_site\ B} \times F_v = 0.370 \times 1.66 = 0.61$$

Wave Propagation

We estimated the pipe damage associated with wave propagation using the empirical correlation presented in ALA (April 2001). For the West Linn area, we estimated the spectral acceleration at the period of 1 second (S₁) for the return period of 2,475 years by using the correlation of peak ground velocity (PGV) with S₁ that Norm Abrahamson developed (NCHRP 611, 2008). Using a value of S₁ of 0.70g as shown in Table 3, we estimated PGV values ranging from 28.5 to 37.7 inches/sec.

Liquefaction Hazard and Seismically-Induced Settlement

Earthquake-induced soil liquefaction can be described as a significant loss of soil strength and stiffness caused by an increase in pore water pressure resulting from cyclic loading during shaking. Liquefaction is most prevalent in loose to medium dense, sandy and gravelly soils below the groundwater table, but it can also occur in low- and non-plastic silts. In the process, the soil acquires mobility sufficient to permit both horizontal and vertical movements if the soil mass is not confined. If liquefaction occurs, ground surface settlement will generally be expected.

The geologic profile along most of the West Linn area is mapped as Missoula Flood deposits (fine-grained facies). The unit consists of poorly consolidated sand to silt deposited as backwater flood sediments. Based on DOGAMI maps for the site vicinity, the deposits are reported to range from 30 to 60 feet thick (Madin, 1990). Along this pipeline segment the flood deposits are likely underlain by Springwater Formation gravels. Subsurface data documented from deep water wells near the site vicinity indicate the Springwater Formation is up to 90 feet thick (Madin, 1990).

For our liquefaction analysis, we assumed the groundwater is located at 10 feet below ground surface for borings where groundwater was not encountered. We selected borings for the liquefaction evaluation by considering the soil type and SPT blow counts.

We screened out the boring when the soil type is clay or rock, and SPT blow counts with correction for overburden and hammer energy are greater than 30.

For the selected boring data, we evaluated liquefaction susceptibility triggering using methodologies proposed by Cetin et al. (2004), Moss et al. (2006), and Idriss & Boulanger (2006, 2008). In interpreting the variable results observed with these three methods, we generally considered a soil layer liquefiable if two or more of the methods showed factors of safety less than about 1.1. Post-liquefaction reconsolidation settlements were analyzed using the methods of Cetin et al (2009), and Idriss & Boulanger (2008). For the analyses, we used a peak ground acceleration of 0.55 g and the magnitude of M9.0 as shown in Table 3.

The liquefaction potential of soil is affected by fine contents and plasticity, especially when the soil is silt. The likelihood of liquefaction can vary depending on uncertainties in soil density, ground water location, and lack of information such as laboratory data. Therefore, the liquefaction potential is often expressed in a descriptive manner such as “low”, “moderate”, and “high”.

Along the Pacific Highway from Glenmorrie Drive to Lake Oswego Water Treatment Plant including borings FWP-10 through -1 and FWP-66 through -64, the liquefaction potential is generally moderate to high except at a few boring locations with low potential: borings FWP-5, -7,-8, and -65. Within 13.5 feet of boring depth and below the groundwater depth of 10 feet, most of the soil type is loose sandy silt. Based on the liquefaction analysis on FWP-3 within West Linn (from the WTP, west along Mapleton, and north along Highway 43 to Arbor Drive), we estimated 3 to 4 inches of settlement including approximate additional settlement of 2 inches in the soils below 13.5 ft. For the RWP between Mary S. Young State Park and the WTP along Mapleton Drive (including MA-1 through MA-4), the liquefaction potential is none to low except MA-4. The liquefaction analysis on MA-4 indicated about 2.5 to 3.5 inches of liquefaction-induced settlement.

At Lake Oswego Water Treatment Plant, GeoDesign report (2011) addressed that a 1975 boring completed by CH2MHill indicates the presence of very loose to loose sand between approximately 30 and 40 feet below ground surface. The report addressed that the liquefaction-induced settlement at the surface is low because the measured groundwater table is 30 feet below the ground surface and the upper soils are not

subject to liquefaction. However, Shannon & Wilson performed a liquefaction evaluation at the water treatment plant site in October 2011 and determined up to 7½ inches of total liquefaction settlement and differential settlement of up to 1.6 inches over a distance of 40 feet could occur during a seismic event. Their findings were based on five borings and seven CPTs advanced up to 65 feet below ground surface (bgs). The pipeline design must include appropriate liquefaction mitigation to ensure that no damage will occur as a result of liquefaction during a major seismic event. Since the treatment plant site is situated within an area of relatively deep alluvium and the hills to the west are underlain by shallow bedrock and a boring near the river indicated shallow bedrock to the east, the transition between the liquefiable and non-liquefiable areas along the pipeline alignment is anticipated to be located near the east edge of the alluvium near Boring MA-3. Another type of seismically induced ground failure that can occur as a result of seismic shaking is dynamic compaction or seismic settlement. Such phenomena typically occur in unsaturated, loose, granular material or uncompacted fill soils. The subsurface conditions encountered in the borings performed for this study are not considered conducive to such seismically induced ground failures. Therefore, the potential for their occurrence along the proposed alignment is considered low. The estimated liquefaction induced settlement along specific locations of the RWP and FWP pipeline alignment is summarized in Table 4. The locations listed in Table 4 are approximate based on the current available boring data from GeoDesign and Shannon and Wilson.

Table 4. Liquefaction Potential and Liquefaction-Induced Settlement

| Pipeline | Reach | Location | Boring | Liquefaction Potential | Liquefaction Settlement (inch) | Differential Settlement (inch) |
|---------------------|-------|---|---|---|--------------------------------|--------------------------------|
| RWP | 1 | HDD crossing, lower portion of Mapleton Drive slope | MA-1 through MA-3 | None to very low | Negligible | Negligible |
| | 2 | Middle portion of Mapleton Drive slope to 300 feet east of WTP | MA-4 | Moderate to High | 2.5 to 3.5 | 0.6 to 1.6 over 40 feet |
| WTP and access area | 3 | Mapleton Drive within 300 feet of the WTP to east and west | B-1 to B-5; CPT-1 to CPT-7 ^(a) | High | Up to 7 ½ Inches | 0.6 to 1.6 over 40 feet |
| FWP | 4 | Mapleton Drive 300 feet west of WTP, along HWY 43, to Arbor Drive | FWP-10 through -1 and FWP-66 through -64 | Moderate to high except low potential at the borings including FWP-5, -7, -8, and -65 | 3 to 4 | 0.6 to 1.6 over 40 feet |

^(a) – Shannon & Wilson borings and CPTs (2011)

Lateral Spreading Potential

Lateral spreading is a post-liquefaction phenomenon consisting of blocks of soil “laterally spreading” due to either a gently sloping ground or an open face such as an open creek channel. During lateral spreading, blocks of non-liquefied soil could “float” on top of liquefied soils below. Lateral spreading has been observed in previous large earthquakes, even for gently sloping sites (slopes less than 0.5% slope). Lateral spread

movements are typically greatest near a free face (such as the creek channels) and diminish with distance from the free face (Youd et al., 2002 and Zhang et al., 2004).

Due to low potential of liquefaction, lateral spreading potential is very low in Reach 1. Although liquefaction potential is high in Reaches 2 and 3, due to presence of relatively shallow basalt ridge near the river which serves as a buttress, the potential of lateral spreading is low. For Reach 4, the potential for liquefaction is moderate to high and based on the available information, depth to basalt is not known at this time. However, since the distance from the pipeline alignment to the free face is large (in excess of 3,000 feet), we believe that the potential for lateral spreading is also low in Reach 4. Based on recent developments in the pipeline seismic design process, it has been determined that additional geotechnical investigation borings should be conducted to confirm the lateral spreading hazard potential. These borings will be drilled up to 40 feet deep and will supplement more shallow borings previously obtained along Highway 43. The results of the deeper borings and subsequent geotechnical analysis will be provided to the City of West Linn at a later date in the land use application process.

Seismically Induced Slope Failure

GeoDesign (2011) performed an infinite slope stability analysis to estimate the slope gradient for which failure could occur during a seismic event. Then, the critical slope gradient was compared with ground slopes gradient mapping from LiDAR data contours. After field reconnaissance, GeoDesign identified a high slope gradient area within and near Mary S. Young State Park. GeoDesign's 2011 report indicated a potential for seismically induced slope failure and considered the hazard was low to moderate in this area. The RWP alignment and installation method have been revised since the 2011 GeoDesign slope failure analysis. The RWP will now be installed via HDD methods to a location north of boring MSY-4 and MSY-5 and outside of the slope gradient area that GeoDesign determined had a low to moderate risk (see Figure 2A). The HDD alignment will be 30 to 60 feet below ground surface (bgs) within this area. The potential for slope failure affecting the HDD alignment at this location will be low because of its deep profile in rock. Based on GeoDesign's report, the open-cut portion of Reach 1 (starting north of MSY-4, MSY-5, and the slope gradient area) and Reaches 2, 3, and 4 have a low potential for seismically induced slope failure.

SUMMARY OF FINDINGS

Based on our review of the data, we have the following findings:

- Ground Surface Rupture – Based on the present analysis, the threat of damage to the RWP and FWP pipelines due to ground surface rupture is considered negligible to low. No additional design considerations are required to mitigate ground surface rupture.
- Ground Shaking – Pipeline design of the RWP and FWP should be based on a peak ground acceleration (PGA) of 0.55 g and a spectral acceleration at a 1 second period (S_1) of 0.7 g.
- Wave Propagation Damage – There is a low potential for RWP or FWP damage from seismic wave propagation. Pipeline design for the RWP and FWP shall be based on a peak ground velocity (PGV) of 28.5 to 37.7 inches per second.
- Liquefaction Hazard and Seismically-Induced Settlement – Based on data provided by GeoDesign and Shannon and Wilson, the liquefaction hazard along the RWP and FWP ranges from negligible to high depending on location. See Table 4 for expected seismically-induced settlement values that shall be used for RWP and FWP pipeline design. Total settlement values range from negligible at the HDD entrance location (at the bottom of Mapleton Drive) to 7.5 inches at the WTP site. Whereas, the differential settlement values range from 0.6 to 1.6 inches within a distance of 40 feet. These settlements should be considered in the pipeline design.
- Lateral Spreading Potential – Based on the available subsurface data, GeoDesign's seismic report, and the preliminary liquefaction analyses, the potential for lateral spreading around the pipelines is low. Based on recent developments in the pipeline seismic design process, it has been determined that deeper geotechnical borings should be conducted along Reach 4 to confirm the lateral spreading hazard potential. The results of these borings and subsequent analysis will be provided to the City of West Linn at a later date in the land use application process.
- Seismically Induced Slope Failure – GeoDesign (2011) performed an infinite slope stability analysis to estimate the slope gradient for which failure could occur during a seismic event. Then, the critical slope gradient was compared with ground slope gradient mapping from LiDAR data contours. The risk of seismically induced slope failure for the open-cut portion of Reach 1 (north of

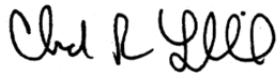
MSY-4 on Figure 2A) and Reaches 2, 3, and 4 is considered low. No additional design considerations are required to mitigate the potential for seismically induced slope failures at this time.

CLOSURE

We appreciate the opportunity to provide these services to Kennedy-Jenks for the LOTWP project. Should you require additional information or have questions, please feel free to call Chad at (425) 636-7900 or Mark at (503) 644-9447.

Sincerely,

KLEINFELDER, INC.

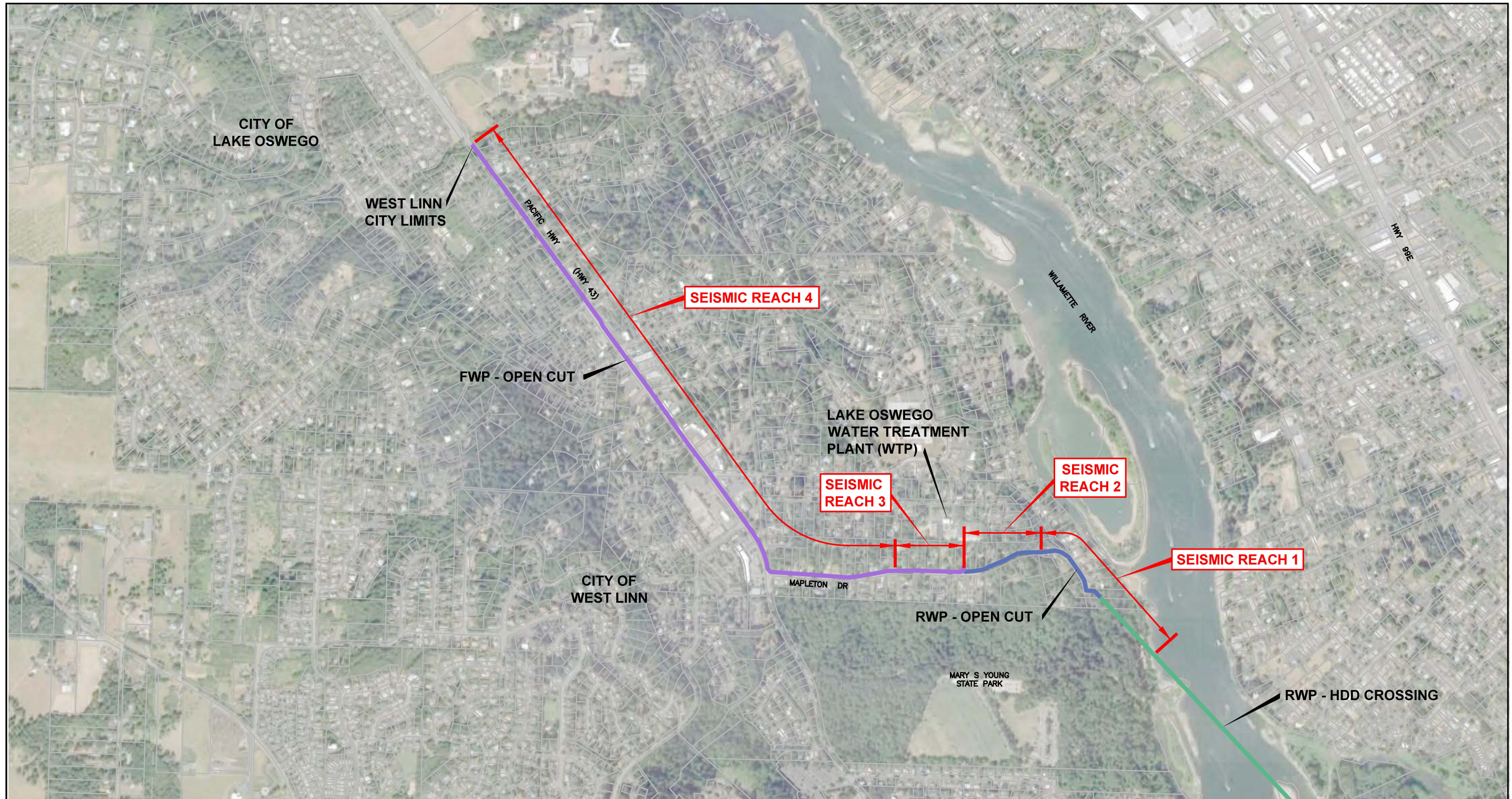


Chad R. Lukkarila, PE
Senior Geological Engineer



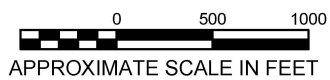
Mark Swank, RG, CEG
Senior Engineering Geologist

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LEGEND

- RWP - OPEN CUT
- RWP - HDD CROSSING
- FWP - OPEN CUT



Reference: Kennedy-Jenks Consultants
 June 2012

| | |
|-------------|------------------|
| PROJECT NO. | 120587 |
| DRAWN: | MAY 2012 |
| DRAWN BY: | JDS |
| CHECKED BY: | MS |
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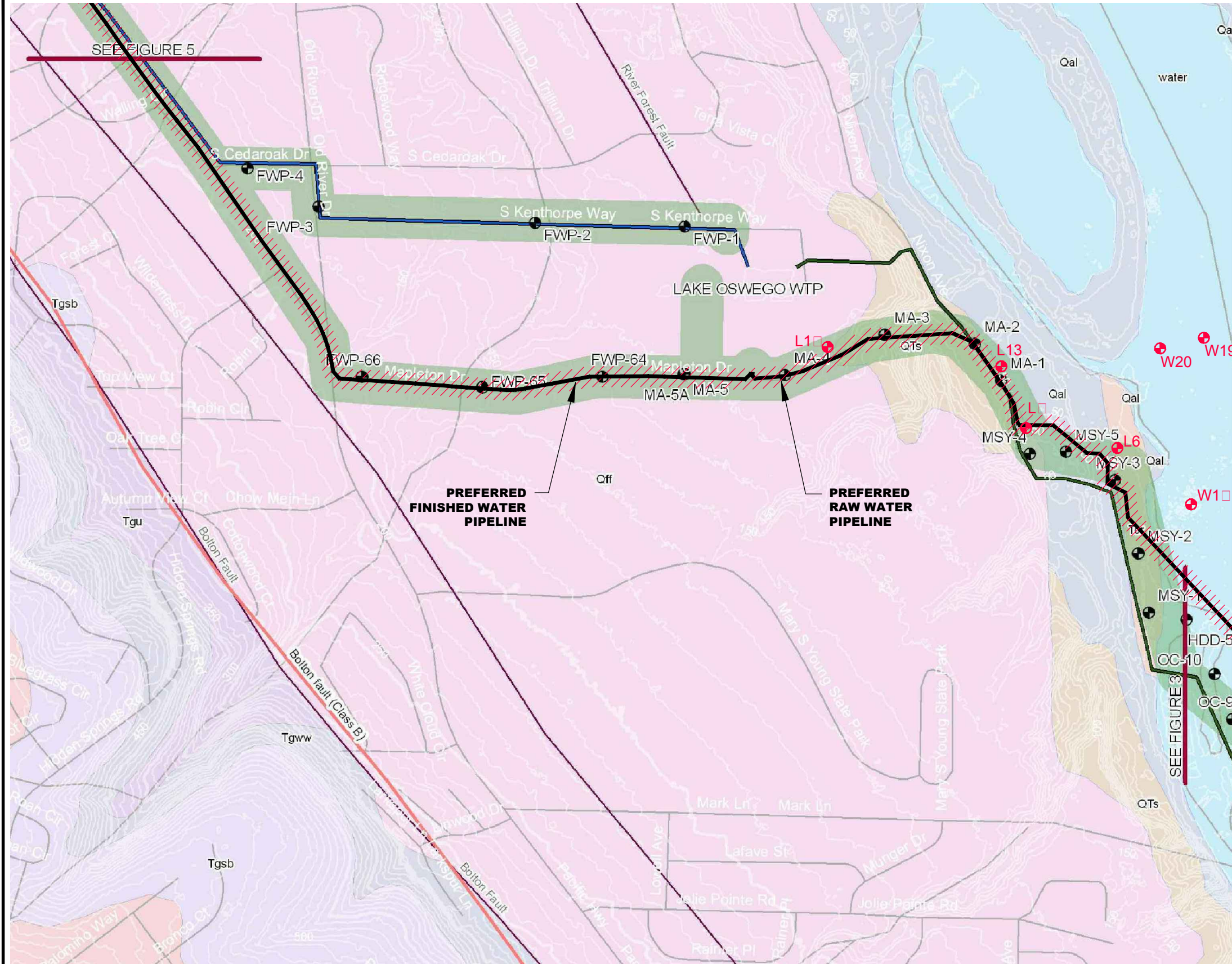
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| REACH MAP |
| LAKE OSWEGO RAW WATER PIPELINE CLACKAMAS COUNTY, OREGON |

PLATE
1

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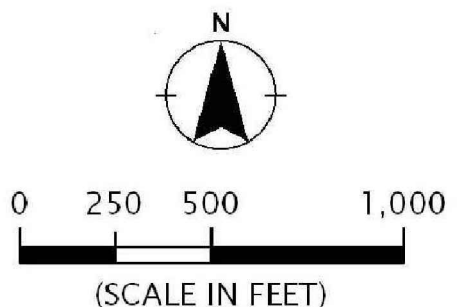
LEGEND

- FWP-1 BORING
- EXISTING FINISHED WATER PIPELINE
- EXISTING RAW WATER PIPELINE
- QUATERNARY FAULTS (USGS)
- FAULTS (ODGC)
- MATCH LINE
- PREFERRED ALIGNMENT
- BORINGS (2011)

GEOLOGIC MAP UNIT

- WATER
- QTs, Springwater Formation
- Qal, Alluvium
- Qff, Catastrophic flood deposits, fine grained
- Tcr, Columbia River Basalt Group
- Tfg, Basalt of Ginko
- Tgsb, Sentinel Bluffs unit
- Tgu, Umtanum unit
- Tgww, Winter Water unit

REFERENCE:
 GeoDesign Inc. Site Plan
 Figure 5A and 5 dated March 2011
 GeoDesign Inc. Willamette River Crossing Alignment
 Alternatives Site Plan Figure 2 dated March 2012



10-FOOT TOPOGRAPHIC CONTOURS DERIVED FROM 2007 OREGON LIDAR CONSORTIUM
 BORING LOCATIONS SURVEYED BY WESTLAKE CONSULTANTS OF LAKE OSWEGO, OREGON, OR FIELD
 LOCATED BY GEODESIGN PERSONNEL

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GEOLOGIC DATA DERIVED FROM OGDC (MA, 2009)
 QUATERNARY FAULT DATA DERIVED FROM USGS (2009) ONLINE DATABASE

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| PROJECT NO. | 1205 |
| DRAWN: | JUNE 2012 |
| DRAWN BY: | JDS |
| CHECKED BY: | MS |
| FILE NAME: | rw\eline.dwg |

| | | |
|---|--|-------|
| SITE PLAN | | PLATE |
| 2B | | |
| LAKE OSWEGO RAW WATER PIPELINE CLACKAMAS COUNTY OREGON | | |



LEGEND

- FWP-1 BORING
- EXISTING FINISHED WATER PIPELINE
- EXISTING RAW WATER PIPELINE
- QUATERNARY FAULTS (USGS)
- FAULTS (ODGC)
- MATCH LINE
- FIELD-OBSERVED SLOPES
- PREFERRED ALIGNMENT

PERCENT SLOPE

- <24%
- 24% - 33%
- 33% - 50%
- 50% - 100%
- >100%

--- LANDSLIDE SCARP

LANDSLIDE FAILURE DEPTH

- DEEP-SEATED (>4.5 M)
- SHALLOW-SEATED (<4.5 M)

LANDSLIDE ACTIVITY

- HISTORIC (<150yrs)
- PRE-HISTORIC (>150yrs)

N

0 250 500 1,000

(SCALE IN FEET)

10-FOOT TOPOGRAPHIC CONTOURS DERIVED FROM 2007 OREGON LIDAR CONSORTIUM
 BORING LOCATIONS SURVEYED BY WESTLAKE CONSULTANTS OF LAKE OSWEGO, OREGON, OR FIELD
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LANDSLIDE DATA FROM DOGAMI LANDSLIDE INVENTORY (2010)
 ORTHOPHOTO FROM OREGON IMAGERY EXPLORER
 QUATERNARY FAULT DATA DERIVED FROM USGS (2009) ONLINE DATABASE

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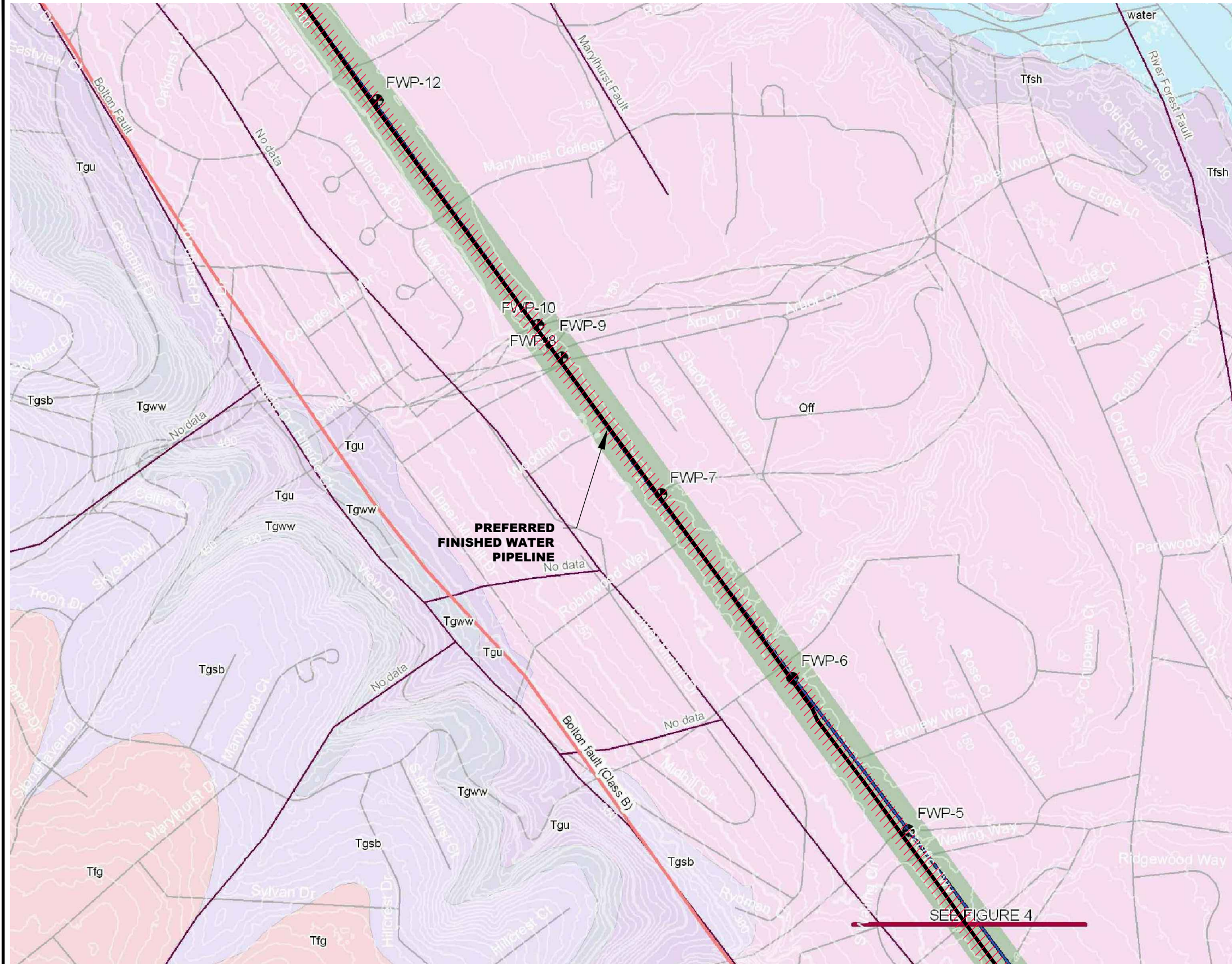
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| DRAWN: | MAY 2012 |
| DRAWN BY: | JDS |
| CHECKED BY: | MS |
| FILE NAME: | rw_pipeline.dwg |

| | |
|--|--|
| SITE PLAN | |
| LAKE OSWEGO RAW WATER PIPELINE CLACKAMAS COUNTY, OREGON | |

PLATE
3A

REFERENCE:
 GeoDesign Inc. Site Plan Figure A-5A and 5B dated March 2011

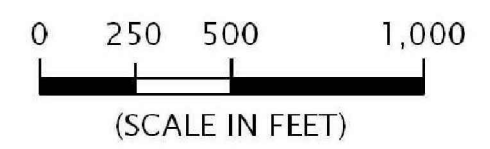
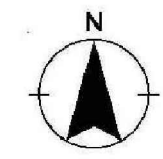
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- LEGEND**
- FWP-1 BORING
 - EXISTING FINISHED WATER PIPELINE
 - EXISTING RAW WATER PIPELINE
 - QUATERNARY FAULTS (USGS)
 - FAULTS (ODGC)
 - MATCH LINE
 - PREFERRED ALIGNMENT

- GEOLOGIC MAP UNIT**
- WATER
 - QTs, Springwater Formation
 - Qal, Alluvium
 - Qf, Catastrophic flood deposits, fine grained
 - Tcr, Columbia River Basalt Group
 - Tfg, Basalt of Ginko
 - Tgsb, Sentinel Bluffs unit
 - Tgu, Umtanum unit
 - Tgww, Winter Water unit

REFERENCE:
 GeoDesign Inc. Site Plan
 Figure A-5A and 5B dated March 2011



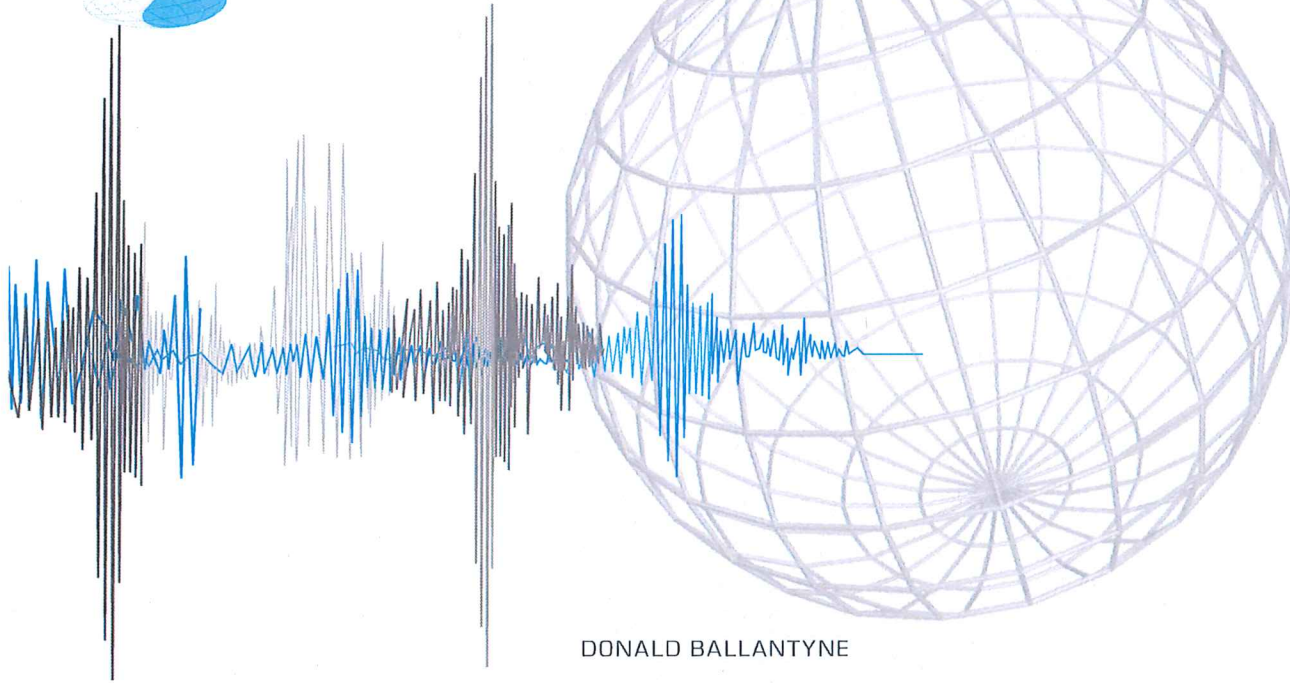
10-FOOT TOPOGRAPHIC CONTOURS DERIVED FROM 2007 OREGON LIDAR CONSORTIUM
 BORING LOCATIONS SURVEYED BY WESTLAKE CONSULTANTS OF LAKE OSWEGO, OREGON, OR FIELD
 LOCATED BY GEODESIGN PERSONNEL

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GEOLOGIC DATA DERIVED FROM ODGC (MA, 2009)
 QUATERNARY FAULT DATA DERIVED FROM USGS (2009) ONLINE DATABASE

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|-------------|-----------------|
| PROJECT NO. | 1205 |
| DRAWN: | MAY 2012 |
| DRAWN BY: | JDS |
| CHECKED BY: | MS |
| FILE NAME: | rw_pipeline.dwg |

| | | |
|--|--|-----------|
| SITE PLAN | | PLATE |
| LAKE OSWEGO RAW WATER PIPELINE CLACKAMAS COUNTY, OREGON | | 3B |



DONALD BALLANTYNE

Seismic vulnerability assessment and design of pipelines

ASSESSING HOW PIPE WILL PERFORM DURING AN EARTHQUAKE DEPENDS ON EXAMINING FOUR PRIMARY PIPE CHARACTERISTICS AS WELL AS UNDERSTANDING SEISMIC EFFECTS LIKELY TO OCCUR IN A SPECIFIC AREA.

Pipeline damage caused by earthquake shaking and permanent ground deformation (PGD) is historically the most significant contributing factor to system failure in earthquakes. Shaking is caused by earthquake wave propagation, and PGD is caused by liquefaction/lateral spread, lurching, landslide, and fault movement. Mapping of these hazards is critical both in evaluating existing systems and in designing new ones.

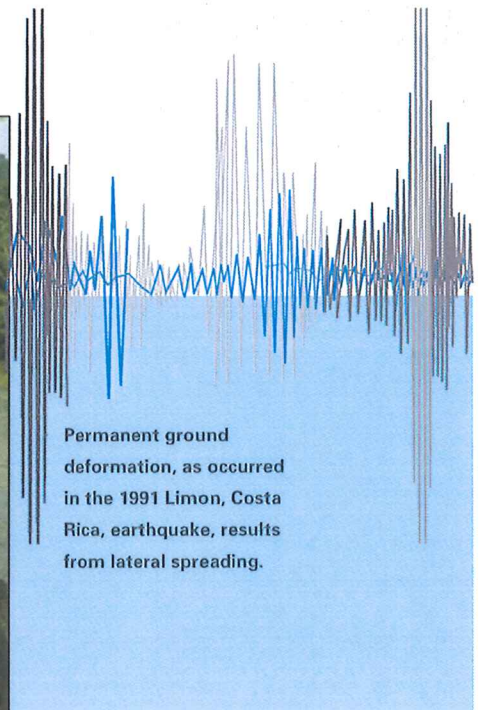
Pipe performance during an earthquake depends on four parameters: ruggedness, resistance to bending, joint flexibility, and joint restraint. Pipe materials are rated in this article for each of these parameters to help utilities select the appropriate pipe for the job.

Analytical methods are sometimes used, especially for large-diameter pipe, to determine the seismic design of new pipelines. For smaller pipe, however, off-the-shelf specifications are often used that may not address seismic issues. Recommendations are provided for seismic design of pipe in moderate and high shaking intensity environments and for pipelines subjected to PGD. System mitigation can include pipe replacement over the long term but can rely on system monitoring and control and emergency response in the short term. Life cycle cost assessments have shown that pipeline replacement cannot be justified on the basis of seismic performance alone.

PERFORMANCE IN PAST EARTHQUAKES

Pipeline damage is the leading cause of water system outage following earthquakes. After an earthquake, the resulting lack of water for fire sup-

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Permanent ground deformation, as occurred in the 1991 Limon, Costa Rica, earthquake, results from lateral spreading.

pression and earthquake-induced fire ignitions has led to extreme fires. Extended periods of water outage have had significant effects on customers as well as community business operations. In addition, the availability of potable water for drinking and public health is critical following a disaster (Ballantyne, 1994). Water system performances in seven earthquakes, one flood, and one wildfire are summarized in Table 1. These nine events were selected because each involved a water system failure caused by a natural disaster and each resulted in some form of fire-related damage. There have been other recent major earthquakes in which fire was not a significant issue, including Izmit, Turkey (1999); Chichi, Taiwan (1999); Bhuj, India (2001); Nisqually, Wash. (2001); the west coast of northern Sumatra (2004); Port-au-Prince, Haiti (2010); and Concepción, Chile (2010). The summary descriptions provided in the table are organized by consequences of water system failure and system component failure that caused system dysfunction.

There is a correlation between incidents where there was inadequate water for fire suppression and those where fire became a significant issue.

There is also a strong correlation between the three most significant fires—San Francisco (Calif.) in 1906, Kanto (Japan) in 1923, and Kobe (Japan) in 1995—and the ineffective use or unavailability of an alternate water supply. As shown in Table 1, system component failures can be grouped by their significance of impact on system dysfunction as follows: (1) high impact: pipe damage—PGD and/or wave propagation, raw

EARTHQUAKE HAZARDS AFFECT BURIED PIPELINES

Earthquake ground motions (shaking) and PGD cause pipelines to fail. Peak ground velocity (PGV), a measure of shaking intensity, correlates best with pipeline damage in earthquakes where PGD is not an issue. Ground motions used for pipeline evaluation can either be probabilistic (e.g., 50, 10, and 2% probabilities of previous PGV activity being exceeded

After an earthquake, the resulting lack of water for fire suppression and earthquake-induced fire ignitions has led to extreme fires.

water transmission pipelines (see the photograph on page 91); (2) moderate impact: water treatment plant damage, loss of power, tank damage (inlet/outlet pipe damage); and (3) low impact: tank damage (shell/structural damage), surface supply failure, well casing/equipment damage. Pipeline damage resulting from PGD and wave propagation in both transmission and distribution systems had the greatest impact in most of the events (see the photograph above).

in 50 years [72-year, 475-year, and 2,475-year return, respectively]) or be based on a specific scenario (e.g., magnitude 7.0 on a known fault). Use of probabilistic-based ground motions during evaluation of an entire system tends to overestimate pipeline damage because it is highly unlikely any single earthquake would result in equally high ground motions throughout the service area. Scenario earthquakes can be selected to represent probabilistic-based return periods.

Pipeline damage caused by shaking tends to be more severe in areas with soft soils, such as in alluvial valleys that amplify ground motions.

As noted previously, PGD can result from liquefaction/lateral spread, landslides, lurching, settlement, and fault rupture. PGD damage rates are high and typically apply to only a small

cantly larger than that caused by shaking. Quantification of the PGD is required for the analysis of pipelines. Input ground motions (either probabilistic- or scenario-based), liquefaction susceptibility, and depth to groundwater are used to estimate the probability of liquefaction. Liquefaction susceptibility mapping is some-

using the empirically based modified multiple linear regression analysis (MLR; Youd et al, 2002). The probability of landslide occurrence can be estimated based on slope, the type of geologic deposit, and groundwater conditions. PGD from lurching caused by intensely strong ground shaking in the vicinity of a fault rupture can be difficult to estimate, particularly over a large area. Seismologists, given the fault parameters, can estimate surface fault displacements.

Liquefaction probability should be mapped and overlain on the pipeline distribution system network using a geographic information system (GIS). This “relates” the two parameters (i.e., it ties a liquefaction hazard zone to every segment of pipe). A pipe-fragility relationship should then be applied to obtain an estimate of the

Pipeline damage is the leading cause of water system outage following earthquakes.

area, whereas shaking damage rates are relatively low but apply to large areas. Understanding the extent of PGD is important because the resulting level of damage is usually signifi-

cantly larger than that caused by shaking. Quantification of the PGD is required for the analysis of pipelines. Input ground motions (either probabilistic- or scenario-based), liquefaction susceptibility, and depth to groundwater are used to estimate the probability of liquefaction. Liquefaction susceptibility mapping is some-

TABLE 1 Performance of water systems in earthquakes*

| Type of Disaster | Year | Consequences | | | | Supply/Treatment | | | | | Tank | | Pipe | | |
|---|------|--------------------------------------|------|------------------------|-------------------------------|------------------------|------------------------|------------|------------------------------|---------------|-----------------|-------------------|------|------------------|-------------------|
| | | Fire Suppression/Lacked Water Supply | Fire | Used Alternate Supply† | Telephone CO Computer Cooling | Surface Supply Failure | Raw Water Transmission | WTP Damage | Well Casing/Equipment Damage | Loss of Power | Shell/Structure | Inlet/Outlet Pipe | PGD | Wave Propagation | Building Services |
| Earthquake | | | | | | | | | | | | | | | |
| San Francisco, Calif. | 1906 | 5 | 5 | 5 | NA | 2 | 5 | NA | NA | 1 | 1 | 1 | 5 | 3 | 5 |
| Kanto, Japan | 1923 | 5 | 5 | 5 | NA | 4 | 5 | 3 | 1 | 1 | 1 | 1 | 5‡ | 3‡ | 5 |
| Whittier, Calif. | 1987 | 3 | 1 | 3 | NA | 1 | 1 | 1 | 1 | 4 | 3 | 4 | 5‡ | 3‡ | 1 |
| Loma Prieta, Calif. (San Francisco, East Bay Municipal Utility District only) | 1989 | 4 | 4 | 1 | 1 | 1 | 3 | 1 | NA | 1 | 1 | NA | 5 | 3 | 3 |
| Landers/Big Bear, Calif. | 1992 | 5 | 1 | NA | NA | 1 | NA | NA | 1 | 3 | 3 | 4 | 5 | 5 | 1 |
| Northridge, Calif. | 1994 | 5 | 4 | 5 | 4 | 1 | 5 | 3 | NA | 4 | 3 | 5 | 5 | 5 | 1 |
| Kobe, Japan | 1995 | 5 | 5 | 3 | ‡ | 1 | 5 | 3 | NA | 3 | 1 | 2 | 5 | 5 | 5 |
| Other type of disaster | | | | | | | | | | | | | | | |
| Oakland Hills (Calif.) fire | 1991 | 3 | 5 | 3 | NA | NA | NA | 1 | NA | 4 | NA | NA | NA | NA | 5 |
| Des Moines (Iowa) flood | 1993 | 5 | 3 | 2 | 4 | 1 | 1 | 5 | NA | 4 | 1 | 1 | 2 | 1 | 1 |
| Average | | 4.4 | 3.7 | 3.4 | 3.0 | 1.5 | 3.6 | 2.4 | 1.0 | 2.8 | 1.8 | 2.6 | 4.6 | 3.5 | 3.0 |

Source: Ballantyne, 1997

CO—central office, NA—not applicable, PGD—permanent ground deformation (lateral spread, landslide, fault offset), WTP—water treatment plant

*Rankings in columns 3, 4, and 6–16 range from 1 (insignificant) to 5 (very significant)

†Rankings in column 5 range from 1 (used aggressively) to 5 (not used/not available)

‡Data unclear

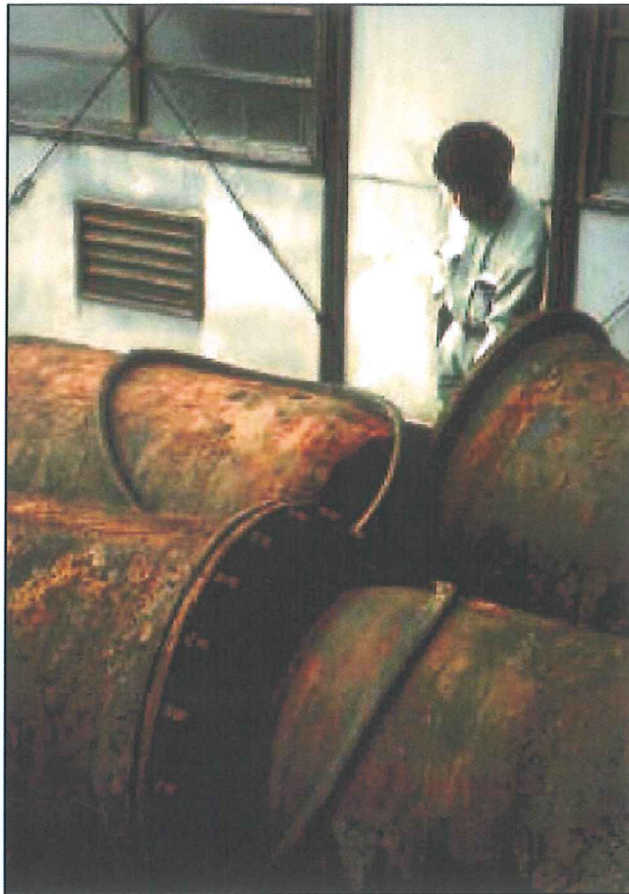
pipe failure rate, and the results should be plotted to show the most vulnerable pipelines. Figure 1 shows liquefaction probability in an example water utility service area overlain by the water distribution system pipe reliability (where reliability is the inverse of its vulnerability; EQE, 2000).

Commonly used pipe. The types of pipe material and joint types used must be understood before their expected performance can be evaluated. Material selection is often controlled by the cost of materials and the familiarity of operations and maintenance staff, design engineers, and local contractors with their use. Water purveyors also have their own preferences for pipe material for specific applications.

Generally, large-diameter transmission mains (i.e., larger than about 600 mm in diameter) are constructed of welded steel or concrete cylinder pipe. Smaller transmission mains may also be constructed of ductile-iron pipe. Ductile iron and polyvinyl chloride pipe (PVC) with bell-and-spigot joints are the materials of choice for most distribution piping in the United States. Pipe applications vary by utility and region. Some jurisdictions prefer ductile iron because it is perceived to be more reliable and easier to tap for building services. Others prefer PVC because it is resistant to corrosion and less expensive to use in construction. High-density polyethylene (HDPE) pipe is available, but it is not widely used because of historical material failure problems in service lines. AWWA has established standards for each of these pipe materials, however these standards do not address seismic design.

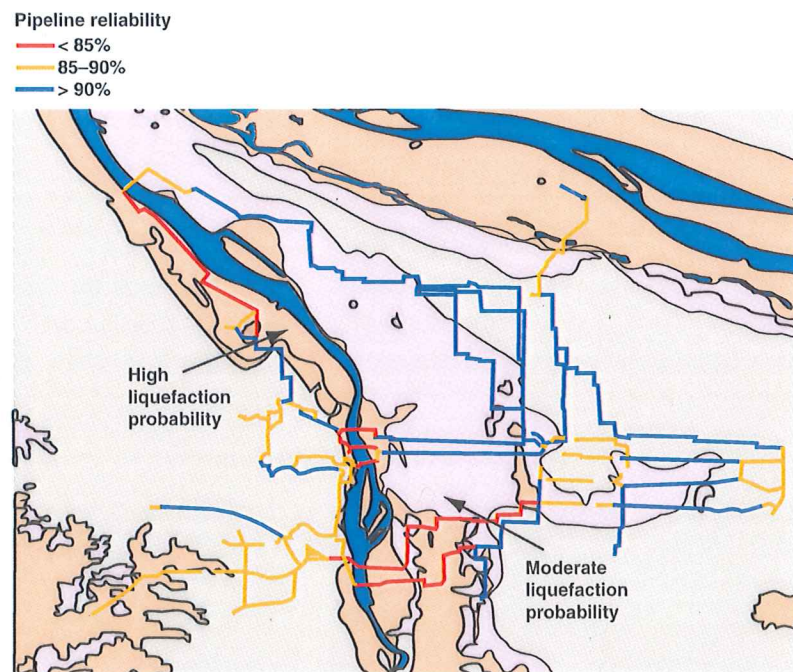
Welded steel and concrete cylinder pipe both use bell-and-spigot joints. These joints are sometimes welded, but not always. Welding is typically used to transfer thrust loads. Joints on pipe up to 600 mm in diameter are welded only on the exterior. On larger-diameter pipe, they are back-welded on the interior.

Ductile-iron pipe is available with bell-and-spigot push-on joints,



After the 1995 earthquake in Kobe, Japan, some ductile-iron pipe had "telescoped," i.e., the spigot end of the pipe was squeezed inside the pipe at the bell end, shortening its overall length.

FIGURE 1 Example of water system pipe fragility overlaid on liquefaction probability map



mechanical joints, or flanged joints. Mechanical designs and designs using wedges embedded in the gaskets are used to restrain joints. PVC pipe can also be restrained using similar designs. No restrained joints similar to the Japanese seismic joint, which allows longitudinal movement, are available in the United States.

Large inventories of asbestos-cement and cast-iron pipe remain in most water systems, but neither type of pipe is available or used for new pipe installations.

Pipe performance and damage mechanisms. Pipe vulnerability to earthquake shaking and PGD can be related to four parameters (Ballantyne, 1995):

- ruggedness—a function of material strength or ductility to resist shear and compression failures;
- bending—a function of either beam strength or material ductility to resist barrel-bending failures;

- joint flexibility—a function of the design of the joint and gasket to allow elongation, compression, and rotation; and

- joint restraint—a system that keeps joints from separating.

Joint flexibility and joint restraint could be considered to be diametrically opposed conditions, but the Japanese seismic joint provides both flexibility and restraint.

Table 2 scores the relative vulnerability of pipe using the four vulnerability parameters as well as the repair rates given in Table 3 for five pipe materials involved in three major earthquakes. The scoring was then totaled, and pipe vulnerability was grouped in accordance with those totals. Joint restraint is a key parameter when pipe is subjected to PGD.

The type of failure mechanism is dependent on the type of pipe and

the surrounding soils. Table 4 shows failure rates for each failure mode for five pipe materials in varying liquefaction conditions for the Kobe earthquake. In Kobe, the water department had replaced 80% of the pipe with ductile iron and another 10% with steel before the 1995 earthquake. The predominant failure mechanism was pulled joints in ductile-iron pipe (0.47 failures/km; Table 4). The system contained very little of the other types of pipe listed.

Primarily on the basis of empirical data, the American Lifelines Alliance developed a relationship for the expected number of pipe failures subjected to shaking and PGD hazards (G&E Engineering Systems, 2001). O'Rourke and Deyoe (2004) subsequently proposed a damage relationship for segmented pipe based on strain and applicable to both wave propagation (shaking) and PGD.

TABLE 2 Relative earthquake vulnerability of water pipe

| Material Type/Diameter | AWWA Standard | Joint Type | Ruggedness | Bending | Joint Flexibility | Restraint | Total |
|------------------------------------|---------------|-------------|------------|---------|-------------------|-----------|-------|
| Low vulnerability | | | | | | | |
| Ductile iron | C1xx Series | B&S, RG, R | 5 | 5 | 54 | 4 | 18 |
| Polyethylene | C906 | Fused | 4 | 5 | 5 | 5 | 19 |
| Steel | C2xx Series | Arc-welded | 5 | 5 | 4 | 5 | 19 |
| Steel | None | Riveted | 5 | 5 | 4 | 4 | 18 |
| Steel | C2xx Series | B&S, RG, R | 5 | 5 | 4 | 4 | 18 |
| Low/moderate vulnerability | | | | | | | |
| Concrete cylinder | C300, C303 | B&S, R | 3 | 4 | 4 | 3 | 14 |
| Ductile iron | C1xx Series | B&S, RG, UR | 5 | 5 | 4 | 1 | 15 |
| PVC | C900, C905 | B&S, R | 3 | 3 | 4 | 3 | 13 |
| Steel | C2xx | B&S, RG, UR | 5 | 5 | 4 | 1 | 15 |
| Moderate vulnerability | | | | | | | |
| AC > 8-in. diameter | C4xx Series | Coupled | 2 | 4 | 5 | 1 | 15 |
| Cast iron > 8-in. diameter | None | B&S, RG | 2 | 4 | 4 | 1 | 11 |
| PVC | C900, C905 | B&S, UR | 3 | 3 | 4 | 1 | 11 |
| Concrete cylinder | C300, C303 | B&S, UR | 3 | 4 | 4 | 1 | 12 |
| Moderate/high vulnerability | | | | | | | |
| AC ≤ 8-in. diameter | C4xx Series | Coupled | 2 | 1 | 5 | 1 | 9 |
| Cast iron ≤ 8-in. diameter | None | B&S, RG | 2 | 1 | 4 | 1 | 8 |
| Steel | None | Gas-welded | 3 | 3 | 1 | 2 | 9 |
| High vulnerability | | | | | | | |
| Cast iron | None | B&S, rigid | 2 | 2 | 1 | 1 | 6 |

Source: Ballantyne, 1995

AC—asbestos-cement, B&S—bell and spigot, PVC—polyvinyl chloride, RG—rubber gasket, R—restrained, UR—unrestrained

Design of new pipelines. Seismic resistance can be most readily built into a pipeline when it is new. New pipelines can be structurally analyzed or designed in accordance with a standard. In many cases, large-diameter transmission lines are structurally analyzed, but distribution piping is often designed in accordance with an off-the-shelf standard. Unfortunately, there are no widely recognized seismic pipe standards for water pipe.

ANALYTICAL METHODS

Analytical methods have been developed for the analysis of both continuous and segmented pipe (O'Rourke & Liu, 1999). Continuous pipe includes steel pipe with welded joints, HDPE pipe with

fused joints, and, to some degree, restrained joint pipe and concrete cylinder pipe with welded joints. Segmented pipe is nonrestrained bell-and-spigot pipe with elastomeric gaskets or leaded or mortared joints.

O'Rourke and Deyoe (2004) provide a method for analysis that calculates the differential movement along the pipe between the "high point" and "low point" on a progressing earthquake wave. This allows the engineer to calculate the stress and strain on the pipe barrel and joint. Application is complicated by the need for wave propagation speed, which is likely a function of the epicentral distance. However, there have been few failures of continuous steel pipe with

welded joints subjected to shaking. Such failures have occurred only in special cases: (1) in pipe with very poor gas welds and (2) under extra large ground strains (O'Rourke & Deyoe, 2004).

The vulnerability of segmented pipe can be assessed using the same general method presented by O'Rourke, except that instead of pipe strain, the relative movement across the joint is calculated. Unfortunately there is no engineering methodology that replicates observed damage. The designer must evaluate the capability of the pipe to expand and compress by evaluating the joint detail. In brittle pipe joints (e.g., leaded joints), this relative movement can cause the lead to crack and the joint to

TABLE 3 Summary of pipeline repairs for three recent earthquakes

| Earthquake and System Parameters | Ductile Iron | Cast Iron | PVC | Steel | Asbestos-Cement | Total/Net Rate |
|--|--------------|-----------|---------|---------|-----------------|----------------|
| Kobe/Ashiya/Nishinomiya* | | | | | | |
| Pipeline length— <i>km</i> | 1,874 | 405 | 232 | 30 | 24 | 2,565 |
| Percent of system | 73% | 16% | 9% | 1% | 1% | |
| Number of repairs | 915 | 611 | 331 | 14 | 43 | 1,914 |
| Repairs/km | 0.49 | 1.51 | 1.43 | 0.47 | 1.79 | 0.75 |
| Northridge/LADWP† distribution piping (< 24 in.) | | | | | | |
| Pipeline length— <i>km</i> (back-calculated) | 860 | 7,740 | 0 | 1,183 | 967 | 10,750 |
| Percent of system | 8% | 72% | 0% | 11% | 9% | |
| Number of repairs (back-calculated) | 28 | 673 | 0 | 196 | 28 | 935 |
| Repairs/km | 0.03 | 0.09 | NA | 0.17 | 0.03 | 0.09 |
| Loma Prieta‡/EBMUD§ | | | | | | |
| Pipeline length— <i>km</i> | 0 | 2,500 | No data | 1,300 | 1,700 | 5,600 |
| Percent of system | 0% | 45% | <2% | 23% | 30% | |
| Number of repairs | 0 | 52 | 2 | 46 | 13 | 113 |
| Repairs/km** | NA | 0.023 | 0.007 | 0.039 | 0.007 | 0.023 |
| Loma Prieta‡/Santa Cruz†† | | | | | | |
| Pipeline length— <i>km</i> | 75 | 150 | 50 | No data | 200 | 475 |
| Percent of system | 16% | 32% | 11% | No data | 42% | |
| Number of repairs | 1 | 47 | 0 | 3 | 13 | 64 |
| Repairs/km | 0.01 | 0.31 | 0 | No data | 0.07 | 0.13 |

EBMUD—East Bay Municipal Utility District, LADWP—Los Angeles Department of Water and Power, NA—not applicable, PGA—peak ground acceleration, PVC—polyvinyl chloride

*PGA of 40–80% gravity with significant liquefaction

†PGA of 50–90% gravity with minimal liquefaction

‡In the Loma Prieta earthquake, there was also extensive damage to the San Francisco Municipal Water Supply System. There were 69 cast-iron pipe failures in the Marina District (repair rate = 6 repairs/km). There were no failures of the 400 km of ductile-iron pipe, which comprised 20% of the entire system.

§PGA of 5–25% gravity with liquefaction along San Francisco Bay

**Repair rates as reported; not calculated from data in this table

††PGA as high as 60% gravity with liquefaction along San Lorenzo River

leak. For joints with elastomeric gaskets, the relative movements are small and can be accommodated by the joint when moderate earthquake ground motion occurs. However, in both the Northridge, Calif., and Kobe earthquakes, where large ground motions were

slides when the critical threshold is reached. In these cases, the pipe is displacing with the soil, so the analysis focuses on allowable pipe strain rather than stress. O'Rourke (1999) provides a simplified method. These analyses would be applicable for welded steel pipe being installed in

values; actual strength depends on the size of the fillet weld.

Historically, most steel pipe used in the water supply industry in the United States has not been butt-welded because designers believed it was too difficult or expensive to properly align the pipe. However, in the oil and natural gas industry (and in the water industry in Japan), steel pipe is butt-welded. The Los Angeles (Calif.) Department of Water and Power bid a steel pipeline construction project, requiring the contractor to either use butt straps for each joint (welding both in and out, i.e. four welds) or to butt weld the pipe. The contractor chose to butt weld the pipe. This demonstrates that the use of new construction techniques make butt welding of large diameter pipe feasible.

Concrete cylinder pipe also has some interesting issues. Steel pipe can make use of some of the pipe strength to resist longitudinal loads provided by the wall that is designed to resist pressure circumferentially. Concrete cylinder pipe uses wire or bars circumferentially wrapped around the "can" to resist internal pressure, with a steel bell-and-spigot joint welded to the thin-walled can. The pipe is very weak in tension and compression and thus is not recommended for use where PGD is expected.

Japanese design standards. The Japan Water Works Association has developed a standard for water pipe installed in areas subject to liquefac-

Pipeline damage caused by shaking tends to be more severe in areas with soft soils, such as in alluvial valleys that amplify ground motions.

experienced, many joints separated in areas where no liquefaction was found to have occurred.

PGD can cause significant loading on continuous pipe, and it can cause segmented pipe joints to pull out or to compress, either splitting the bell or telescoping the pipe. The potential for joint separation failures can easily be evaluated by considering the joint geometry and the expected movement of the surrounding soil. Several inches of soil movement along a pipe's axis can cause the joint to pull out.

A continuous pipe can be evaluated using a finite element model of the soil-pipe system. Slip between the pipe and soil is modeled using axial soil spring to replicate the interface between the pipe and soil. The soil initially compresses when loaded, but the soil-pipe interface

soils where PGD is expected. The parameters required to evaluate the pipe include:

- soil—soil spring/slider parameter, density, depth;
- pipe—diameter, wall thickness, steel material properties, joint detail;
- geometry—unanchored length (e.g., bends, valves, and so on).

Steel and concrete cylinder pipe. There has been significant research on the performance of welded steel joints, which are usually the weakest component of a pipe system. In general, bell-and-spigot joints welded just on the inside or outside develop about a third of the strength of the pipe barrel, those welded both inside and outside develop about two thirds of the strength of the pipe barrel, and butt-welded joints develop the full strength of the pipe barrel. These are typical

TABLE 4 Kobe water pipeline damage rates—failures/km

| Type of Failure | Average* | Pipe Material | | | | | Liquefaction | | |
|-----------------|----------|---------------|------|------|-------|------|--------------|------|------|
| | | DI | CI | PVC | Steel | AC | 0% | 50% | 100% |
| Barrel | 0.15 | 0.00 | 0.63 | 0.38 | 0.34 | 1.24 | 0.13 | 0.25 | 0.22 |
| Fitting | 0.06 | 0.00 | 0.31 | 0.17 | 0.03 | 0.04 | 0.04 | 0.17 | 0.08 |
| Pulled joint | 0.47 | 0.47 | 0.49 | 0.33 | 0.00 | 0.37 | 0.33 | 0.76 | 1.22 |
| Joint failure | 0.06 | 0.00 | 0.06 | 0.50 | 0.07 | 0.08 | 0.04 | 0.13 | 0.04 |
| Total | 0.74 | 0.47 | 1.49 | 1.38 | 0.44 | 1.73 | 0.54 | 1.31 | 1.56 |

No damage to specially designed seismic joint ductile-iron pipe

AC—astbestos-cement, CI—cast iron, DI—ductile iron, PVC—polyvinyl chloride

*Average computed on the basis of the total number of failures divided by the total length of pipe.

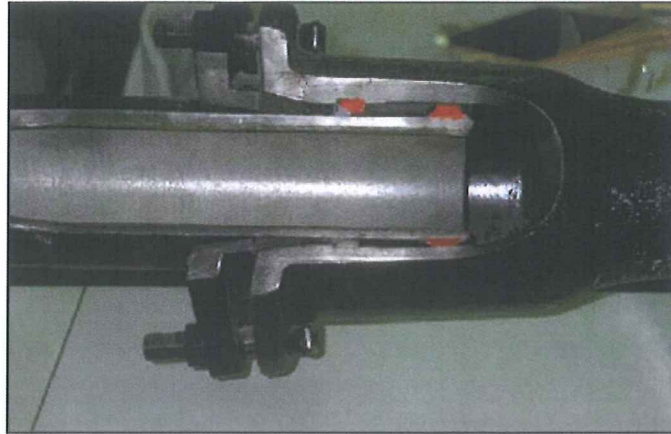
tion (JWWA, 1997). This standard was one of many water system standards developed as a result of the Kobe earthquake. Japan now requires that pipe be restrained and be able to accommodate 1% strain. Steel pipe and HDPE pipe can meet this standard if welded joints are used, depending on the ductility of the pipe. Ductile-iron pipe meets the standard by using a specially designed “seismic” joint (see the photograph on the right). The seismic joint allows the 1% longitudinal movement using a slip joint, which restrains the joint with a lock ring. In Kobe approximately 240 km of seismic joint pipe was in place in areas subject to the most severe liquefaction, and no failures occurred. In the United States, designers have used a combination of restrained joints and expansion sleeves to accomplish this same result.

Residential service lines. Residential services have performed poorly in many earthquakes. In the 1995 Kobe earthquake, there were 10,000 service line failures—eight times the number in distribution and transmission lines. Although service lines are small in diameter and their associated water loss is limited, when there are many service line failures, it becomes a major concern.

The best performance has been provided by polyethylene and copper service lines because they are ductile and can accommodate both wave propagation and moderate levels of PGD. Solvent welded-joint PVC and screwed-joint steel pipe are the poorest performers. The screwed joint provides no longitudinal flexibility. Also, the threads reduce the cross-sectional area of the pipe wall, and the threading process changes the material properties, making the pipe more vulnerable to corrosion.

RECOMMENDED PIPE SELECTION FOR DIFFERENT HAZARD CONDITIONS

There are no seismic-resistant pipeline standards widely used in the water industry in the United States.



The Japanese seismic joint allows extension and compression with restraint.

The design practices described here are often recommended to water purveyor clients. Three hazard conditions are considered.

Wave propagation: ground acceleration <math>< 40\% \times \text{gravity}</math>. This condition exists where there are nonliquefiable soils that are not subject to landslides and are not in fault zones (i.e., no PGD). Most populated areas of the United States fit into this category, even for earthquake ground motions that are expected once every 2,475 years (with the exception of areas such as the western United States and the midwestern New Madrid Fault Zone). Probabilistic ground motions can be found online for the entire United States. These ground motions must then be corrected to address site amplification.

zones, i.e., no PGD. This includes the highly seismic areas in the United States. For this condition, welded steel, restrained-joint ductile-iron, or HDPE pipe is recommended. Before the Kobe earthquake, it was believed that nonrestrained pipe joints would be adequate in areas where PGD was not expected. In Kobe, there were more than 600 pulled ductile-iron pipe joints in areas with no liquefaction. Therefore, use of restrained joints is now recommended, particularly for critical pipelines.

Concrete cylinder pipe is not included in the recommended list for this application because it is less ductile than steel. The effectiveness of restraints across joints is limited by the strength of the thin-walled steel can. PVC is not recommended

Extended periods of water outage have had significant effects on customers as well as community business operations.

For this condition, commonly used pipe materials such as nonrestrained joint ductile-iron, PVC, or concrete cylinder pipe are acceptable. Modern bell-and-spigot joints with elastomeric gaskets are adequate to accommodate pipe strain induced by wave passage.

Wave propagation: peak ground acceleration = This condition exists where there are nonliquefiable soils that are not subject to landslides and are not in fault

for this application; it is more brittle than ductile iron. The PVC pipe bell-and-spigot assembly is designed like a wedge, and it will split the bell when subjected to compressive strains. However, one purveyor had good success with PVC in the Northridge earthquake and recommends its use for seismic resistance. There has been only limited exposure of PVC pipe to earthquakes, so there is a limited empirical database on which to judge its performance.

Most of the PVC pipe exposed in the Kobe earthquake was small-diameter, typically < 75–100 mm. This may not be representative of larger PVC pipe performance.

PGD: > 5 cm expected. The PGD condition can exist anywhere the pipe is located where there are liquefiable soils, landslide zones, or fault zones. The liquefaction susceptibility has to be high enough so that the soil will liquefy during a design basis earthquake. For PGDs < 5 cm, use the design for wave propagation.

anchors include connections to buildings and vaults, tees or crosses, and bends.

- Minimize soil–pipe friction by wrapping the pipe in polyethylene. The angle of friction between the pipe and polyethylene is greatly reduced, allowing the pipe to slide through the soil and thus relieve pipe strain.

System mitigation:

- Provide valves around liquefiable areas so the area can be isolated from the undamaged parts of the system.

no means drives US replacement programs. In Japan, many cities replace as much as 5% of their water pipes annually, and earthquake mitigation is the deciding factor as to which pipes will be replaced.

System monitoring and control can be an effective way to maintain some level of postearthquake system functionality. Earthquake valves have been promoted for years as a method to isolate tanks after a quake. However, caution is advised before using these systems because immediate closure may disrupt water service even if system damage is small. Kobe used earthquake valves effectively in the 1995 quake, but they were only installed on one of a pair of tanks at each location. One tank was kept on line at all times.

System monitoring can be used more broadly to allow quick isolation of areas or pressure zones within the system that are expected to be heavily damaged. One utility has been considering installing supervisory control and data acquisition (SCADA) on pressure-regulating valves (PRVs) that feed a low-lying pressure zone vulnerable to liquefaction. In the event of an earthquake, the utility could quickly observe the flow through the PRVs serving that zone, and shut them off (via SCADA) if it was determined that the system could not keep up. Even the addition of manually operated isolation valves in key locations may be useful to help isolate vulnerable portions of the system. However, getting quick access to these valves may be problematic, considering transportation system damage, traffic congestion, and availability of personnel after an event.

It is critical to make provisions within emergency response plans to ensure that water will be available for fire suppression. Water utilities and fire departments must have a mutual understanding of the expected performance of the water system after an earthquake. Alternative water supplies (potentially non-potable supplies) should be investigated to evaluate their potential for

Understanding and mapping ground motions and liquefaction susceptibility are critical elements to consider when selecting appropriate pipe types to resist local earthquake hazards.

For this condition, welded steel, restrained-joint ductile-iron, or polyethylene pipe is recommended. Use of these pipe materials will enhance seismic performance, but they may not provide absolute assurance that the pipe will not fail. So, in addition to use of these materials, the following items should be considered:

PGD avoidance:

- Relocate the pipeline corridor outside liquefaction zone.

- Tunnel or use directional drilling to go under the liquefiable layer.

Geotechnical mitigation:

- Reduce liquefaction susceptibility by installing gravel columns, grouting, and so forth.

- Limit lateral spread by installing earth-retaining structures.

Pipe structural mitigation (for continuous pipe):

- Install expansion sleeves with stops along the pipeline to relieve pipe strain.

- Minimize anchors and/or provide flexibility where anchors are required. Anchors tie the pipe to the surrounding soil, limiting its capability to slide through the soil to relieve pipe strain. Examples of

- For transmission lines, provide connections on either side of the liquefaction or landslide area to allow quick installation of temporary piping.

SYSTEM MITIGATION STRATEGY

Postearthquake system operation can be improved using three general approaches: (1) pipeline replacement, (2) monitoring and control systems, and (3) emergency response. Pipeline replacement is an expensive option that could probably only be justified if it were to occur over a long time frame and if it were integrated with other asset-management priorities. The design recommendations discussed in this article are applicable to new pipelines and to pipelines being replaced. So which pipelines should be replaced for earthquake mitigation? Run a system hydraulic model to identify critical pipelines that are required to maintain overall system functionality. It is interesting to compare the strategies used in the United States and Japan. In the United States, many pipeline replacement programs replace between 0 and 2% of their inventory annually. Although earthquake vulnerability may be one of the parameters considered, it by

use in postearthquake fire suppression. Several communities (e.g., San Francisco, Calif., and Vancouver, B.C., Canada) have installed sophisticated dedicated fire protection systems, but even basic systems relying on dry hydrants with intakes on rivers or lakes and/or a system of pumps and hoses can be crucial if the potable water system fails.

LIFE CYCLE COST ANALYSIS

Chang (2003) has evaluated the life cycle cost of pipeline replacement in the Portland, Ore., water system. The analysis takes into account operating, maintenance, repair, earthquake repair, and postearthquake business interruption costs. Societal losses from earthquakes are found to outweigh utility agency losses by a factor of 100. Chang's analysis does not take into account the cost associated with fire following an earthquake. The author ultimately concludes that replacement of water pipelines cannot be justified based on earthquake damage, including business interruptions.

CONCLUSION

Historically, pipelines have been the weakest link in water systems subjected to earthquakes, but their continued performance is critical to

provide water for fire suppression. Understanding and mapping ground motions and liquefaction susceptibility are critical elements to consider when selecting appropriate pipe types to resist local earthquake hazards. New pipe types currently being installed in the United States are resistant to moderate earthquake ground motions. Restrained-joint ductile-iron, welded steel, or polyethylene pipe should be used to resist large ground motions and in areas subject to liquefaction. Special consideration should be given to the design of welded joints used on steel pipe.

Water system pipeline replacement for earthquake mitigation is an expensive alternative. It may be appropriate for a long-term strategy when integrated with other asset management pipeline-replacement priorities. In the short term, system monitoring and control and emergency response may offer the best solutions.

ABOUT THE AUTHOR



Donald Ballantyne is a senior consultant with MMI Engineering, 33530 1st Way South, Ste. 102, Federal Way, WA

98003. Ballantyne received a BS degree from Rensselaer Polytechnic Institute (Troy, N.Y.) and an MS degree from SUNY @ Buffalo (Amherst, N.Y.), both in the field of civil engineering. He has conducted more than 65 hazard assessments of water and wastewater utilities in major cities and regional metropolitan areas, including Seattle, Wash.; Portland, Ore.; Vancouver, B.C., Canada; San Francisco, Calif.; and Mekorot, the national water supply system for Israel. He has conducted postearthquake reconnaissance of eleven major earthquakes, including Haiti, Peru, India, Sumatra (Sri Lanka tsunamis), Turkey, Japan, and Nisqually, Northridge, and Loma Prieta in the United States. He is a 30-year member of AWWA, a past director of the Earthquake Engineering Institute, and past chair of the American Society of Civil Engineer's Technical Council on Lifeline Earthquake Engineering Executive Committee.

JOURNAL AWWA welcomes comments and feedback at journal@awwa.org.

REFERENCES

Ballantyne, D.B., 1994. *Minimizing Earthquake Damage: A Guide for Water Utilities*. AWWA, Denver.

Ballantyne, D.B., 1995. Relative Earthquake Vulnerability of Water Pipe. Proc. 1995 AWWA Annual Conf., Anaheim, Calif., June 18–22.

Ballantyne, D.B., 1997. Performance of Water Systems in Historic Earthquakes, Section 3. *Reliability and Restoration of Water Supply Systems for Fire Suppression and Drinking Following Earthquakes* (D.B. Ballantyne and C.B. Crouse, editors). National Institute of Standards and Technology, Gaithersburg, Md.

Ballantyne, D. & Heubach, W., 2003. Comparison of Mitigation Alternatives for Water Distribution Pipelines Installed in

Liquefiable Soils. Proc. ASCE TCLEE 6th US Conference on Lifeline Earthquake Engineering. Long Beach, Calif.

Chang, S.E., 2003. Evaluating Disaster Mitigations: Methodology for Urban Infrastructure Systems. *Natural Hazards Rev.*, 4:4:186.

EQE International, 2000. Confidential system vulnerability assessment.

G&E Engineering Systems, 2001. Seismic Fragility Formulations for Water Systems. Prepared for the American Lifelines Alliance. www.americanlifelinesalliance.org (accessed April, 2001).

JWWA (Japan Water Works Association), 1997. *Seismic Design and Construction Guidelines for Water Supply Facilities*. JWWA, Tokyo.

O'Rourke, M.J. & Liu, X., 1999. Response of Buried Pipelines Subject to Earthquake Effects. Monograph No. 3, Multidisciplinary Center for Earthquake Engineering Research. Buffalo, N.Y.

O'Rourke, M. & Deyoe, E., 2004. Seismic Damage to Segmented Buried Pipe. *Earthquake Spectra*, 20:4:1167.

O'Rourke, M., 2009. Wave Propagation Damage to Continuous Pipe. Proc. Technical Council on Lifeline Earthquake Engineering. Lifeline Earthquake Engineering in a Multihazard Environment, Oakland, Calif.

Youd, T.L.; Hansen, C.M.; & Bartlett, S.F., 2002. Revised MLR Equations for Predicting Lateral Spread Displacement. *Jour. Geotechnical & Geoenvironmental Engrg.*, 128:12:1007.

Donald B. Ballantyne

Principal



Education

B.S. Civil Engineering
Rensselaer Polytechnic Institute, 1974

M.S. Civil/Sanitary Engineering
SUNY at Buffalo, 1977

Registration

California — Civil Engineer
License No. 34088

New York — Civil Engineer
License No. 056494-1

Oregon — Civil Engineer
License No. 18322PE

Washington — Civil Engineer
License No. 23237

Professional Affiliations

American Water Works Association: Member, 1982

American Society of Civil Engineers : Past Chair, Technical Council on Lifeline Earthquake Engineering

Earthquake Engineering Research Institute: Past Director; Past Member Spectra Editorial Board

Don Ballantyne has particular expertise in -hazard risk management of infrastructure systems. He has evaluated and/or designed upgrades for over 70 systems in the U.S. He has designed pipelines, pump stations, and treatment plants, and has a broad-based understanding of system operation requirements.

He has studied the water distribution systems for the cities such as Seattle and Portland, considering the pipe materials, pipe embedment, pipe failures, and the damage mechanisms leading to those failures. He was the resident engineer for the installation of 80 miles of pipe, and early in his career, worked locating pipe breaks in water distribution systems. He has conducted several pipeline research projects funded by the American Water Works Research Foundation including one addressing the economic impacts of internal corrosion, and a second on performance of the Seattle water system in the 2001 Nisqually Earthquake.

Professional History

Degenkolb Engineers, San Francisco, CA and Tacoma WA, Principal, 2011 to present

MMI Engineering, Federal Way, WA, Senior Consultant, October 2007 to 2011

EQE International Consulting/ABS Consulting, Seattle, Washington, VP/Director, 1995 - 2007

Dames & Moore, Seattle, Washington, Associate, 1994-1995

Kennedy/Jenks, Federal Way, WA & San Francisco, CA, Senior Consultant, 1980-1994

EQSI, Rockville, Maryland, Project Engineer, 1979-1980

E.R. Cotton Associates, Gowanda, New York, Project Engineer, 1974-1979

Degenkolb Engineers

235 Montgomery Street
San Francisco, California 94104-4207

www.degenkolb.com

500
SUITE

415

392.6952 phone
554.0782 fax

Donald B. Ballantyne

Relevant Experience

City of Los Angeles, Independent Review of Material Section for Water Mains

Los Angeles, California

Reported for the Board of water and Power Commissioners, City of Los Angeles, Department of Water and Power. Provided comparison of pipeline seismic performance of pipeline systems/materials for LADWP's pipeline replacement program.

Seismic Vulnerability Assessment of Water and Sewage Facilities

City of Lake Oswego, Oregon

Evaluated water treatment plant and Tryon Creek wastewater treatment plant, pump stations, pipelines and water reservoir. Prioritized system component vulnerability and criticality.

City of Portland Water Bureau, Multi-Hazard System Vulnerability Assessment

Portland, Oregon

Quantified the risk to their water system for a wide range of hazards including earthquake, intense storm, and terrorism. The project included hazard quantification, assessment of the vulnerability of the system and system components, and identification of the consequences of to the system. Focused on the system backbone including the watershed, dams and reservoirs, 85 miles of large diameter conduits, terminal reservoirs, and selected distribution pump stations and tanks.

Water System Seismic Vulnerability Assessment

Oregon City, Oregon/West-Yost

Conducted seismic assessment quantifying shaking and liquefaction hazards for operating- and design-basis earthquakes. Evaluated reservoirs, pump stations, and PRV vaults. Estimated likely performance of system pipelines. Summarized expected performance for the 2 levels of earthquakes, and recommended short, medium, and long-term improvements.

Portland Bureau of Waterworks, Groundwater Pump Station Improvements

Portland, Oregon

Evaluated and designed seismic upgrades for 2 MG tank and large diameter site piping. The Groundwater Pump Station relies on a 2 MG reservoir to collect groundwater, and provide water for suction on the 100 MGD pump station. The steel reservoir is on liquefiable soil, and is potentially vulnerable to earthquake ground motion. Developed 5 upgrade alternatives. Looked at upgrading the existing reservoir, moving the reservoir to an alternate site to allow ground improvement, raising the reservoir, and constructing one of several new reservoir alternatives.

Donald B. Ballantyne

Relevant Experience

WRF and Seattle Public Utilities, Performance of Water Supply Systems during 2001 Nisqually Earthquake

Various Locations

Developed mitigation strategies to mitigate the effects of pipeline damage following earthquakes, documented “lessons learned” in the Nisqually Earthquake, and documented pipeline damage data from the Nisqually Earthquake, and other Puget Sound earthquakes that have impacted Puget Sound area water systems.

Washington Wastewater System, Seismic Risk Assessment of the King County

Seattle, Washington

The system is the regional wholesale wastewater collection and treatment agency serving Seattle and the surrounding cities. The project evaluated the risk of all pipeline segments submerged, buried under water, or founded in liquefiable soils for three levels of earthquake hazards. The vulnerability due to wave propagation and permanent ground deformation addressed. The consequence of failure was considered taking into account approximately 20 parameters. The sewers were ranked by risk to focus a detailed evaluation. Schematic mitigation solutions were prepared for selected sewers.

Clearview Consortium, Clearview Pipeline Project

Snohomish County, Washington

Seismic consultant to project team with the following responsibilities: recommended seismic design criteria for pipeline, reservoir and pump station, pipeline material and joint design for seismic resistance, equipment and piping anchorage and bracing in the pump stations, and reservoir connections.

Portland Water Bureau, Design, Inspection & Maintenance of Water Pipes Installations on Host Bridges

Portland, Oregon

Prepared report sections on pipe material, restraint, and flexibility required for seismic performance. Developed discussion on prioritization of needs/risk assessment based on function of line on bridge within the overall system.

River Crossing Seismic Assessment

Richmond, British Columbia

Evaluated the seismic vulnerability of three Fraser River pipeline crossings, considering the expected permanent ground deformation and the ability of the pipelines to accommodate the expected movement. Also identified mitigation strategies to provide water following earthquakes.

City of San Francisco/Olivia Chen Consultants, Earthquake Vulnerability Assessment of San Francisco Zoo Infrastructure Design

San Francisco, California

Quantified earthquake hazards including shaking and liquefaction/lateral spread primarily from the San Andreas Fault. Recommended three seismic resistant material/design systems for pressure piping. Evaluated sewers vulnerability and recommended approaches to mitigate flotation and lateral movement.

*Relevant Experience Projects listed above have been performed with firms other than Degenkolb Engineers.

Donald B. Ballantyne

Relevant Experience

Publications and Presentations

Ballantyne, Donald (2012) "Pipeline damage Mechanisms and Material Selection in an Earthquake Environment", Presentation to the Water Research Foundation Workshop, Los Angeles, California, March.

Ballantyne, Donald (2010), "Seismic Assessment and Design of Pipelines" Webinar, ASCE Continuing Education Program, May.

Ballantyne, Donald (2010) "Seismic Vulnerability Assessment and Design of Pipelines", Journal of the American Water Works Association, Denver, Colorado, May

Ballantyne, Donald (2005) "Earthquake Impacts on Pipelines, Analysis, and Mitigation Approaches", Presented at the Pacific Northwest Section of the American Water Works Association Annual Conference, May.

Ballantyne, Donald and William Heubach (2003), "Comparison of Mitigation Alternatives for Water Distribution Pipelines Installed in Liquefiable Soils", Advancing Mitigation Technologies and Disaster Response for Lifeline Systems, Proceedings of the Sixth US Conference and Workshop on Lifeline Earthquake Engineering, James Beavers, Editor, August.

Ballantyne, Donald (2000) "Use of Geotechnical Information for Pipeline System Analysis" Lifeline Geotechnical Engineering, Proceedings of the 14th Annual Vancouver Geotechnical Society Symposium, Vancouver BC, May 26.

Ballantyne, Donald (1997) "Seismic Vulnerability Assessment and Design of Water Pipelines in the United States" Proceedings of the 4th International Symposium on Water Pipe Systems, Kobe Japan, November.

Ballantyne, Donald (1995) "Relative Earthquake Vulnerability of Water Pipe", Proceedings of the American Water Works Association Annual Conference, Anaheim, California, AWWA, Denver, Colorado, June.