Clean Water Services
East Basin 2019 Master Plan Project

Technical Memorandum 16
GEOTECHNICAL SEISMIC HAZARDS ASSESSMENT

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Technical Memorandum 16

GEOTECHNICAL SEISMIC HAZARDS ASSESSMENT

16.1 Introduction

Clean Water Services (District) is currently conducting a resiliency study for the East Basin service area. A key required component of the study is understanding both the seismic hazards and resiliency of the system. The Owner has contracted Carollo Engineers, Inc. (Carollo) to provide professional services for the resiliency study. Carollo has retained McMillen Jacobs Associates (McMillen Jacobs) to conduct a seismic hazards assessment. The primary purpose of this task is to broadly identify the seismic hazard potentials, namely the strong ground shaking potential and seismic permanent ground deformation (PGD) in the East Basin service area. This task includes creating seismic hazard maps. This task also included a focused study of the seismic hazards at the Durham Advanced Wastewater Treatment Facility (AWWTF), as well as associated seismic hazard maps.

This memorandum presents the results of our evaluation. The following tasks were completed in accordance with our scope of work:

1. Review of available local and geological information.
2. Review of Oregon Department of Geology and Mineral Industries (DOGAMI) seismic hazard maps for a magnitude 9.0 Cascadia Subduction Zone (CSZ) event.
3. Review of available geotechnical boring and well log information to verify DOGAMI seismic hazard maps.
4. Develop estimates of strong ground shaking, liquefaction-induced settlement, lateral spreading displacement, seismic landslide slope instability, and develop maps illustrating these hazards in relation to the East Basin service area and the Durham AWWTF.
5. Conduct a limit equilibrium slope stability analysis of the southern slope of the Durham AWWTF.
6. Develop this memorandum and associated seismic hazard maps summarizing the results of our evaluations.

In the following sections, we present the results of the data review, seismic hazards evaluation, and a summary of geotechnical hazards in East Basin service area and at the Durham AWWTF. Figures 16.1 through 16.5 provide estimated seismic hazards to the District’s East Basin service area. Figures 16.6 through 16.9 provide estimated seismic hazards to the Durham AWWTF and Figures 16.10 through 16.13 provide results of slope stability analyses at the Durham AWWTF.
### 16.2 Data Review

McMillen Jacobs reviewed background information and existing geotechnical data from various previous projects within the District’s service area. Existing geotechnical data sources consisted mainly of geotechnical borings advanced for various public projects such as highways, bridges, schools, pipelines, reservoirs, and at the Durham AWWTF. Sources also included well logs and subsurface information from several private projects. The liquefaction potential and estimated liquefaction induced settlement was calculated for 154 of the existing geotechnical explorations in order to provide a broad geographic range of seismic PGD estimates.

### 16.3 Geologic and Seismic Setting

#### 16.3.1 Geologic Setting

The District’s East Basin service area (including the Durham AWWTF) is located predominantly in Washington County at the northern end of the Willamette Valley in northwestern Oregon. The service area is approximately 30 square miles in size, and relatively flat sloping generally gently down to the southeast.

Geologically, the District’s service area lies within the Tualatin Basin, a structural depression created by complex folding and faulting of the basement rocks which consist of a sequence of middle Miocene age (17 to 6 million years ago) lava flows of the Columbia River Basalt Group. An extensive sequence of sediments have since accumulated in the basin and overly the basalt basement rocks (Trimble, 1963; Tolan and Beeson, 1984). The Tertiary sedimentary units include up to 1,300 feet of the Sandy River Mudstone, overlain by 100 to 350 feet of sandstone and conglomerate of the Troutdale Formation (Pratt et al., 2001).

These consolidated sediments are overlain by unconsolidated sediments consisting primarily of catastrophic flood sediments deposited near the end of the last ice age, between 15,000 and 12,000 years ago (Mullineaux et al., 1978; Waitt, 1987; Allen et al., 2009). Forty or more catastrophic floods occurred at intervals over several decades on the Columbia River system. The flood waters swept across the Tualatin Basin and deposited sediments, termed the Missoula Flood Deposits, ranging in size from clay to cobbles. The deposits generally consist of silt, sand, and gravel and range in thickness from a few feet to more than 200 feet.

More recently, since the deposition of the Missoula Flood Deposits, alluvial deposits have accumulated along the several creeks and rivers in the project area (specifically Fanno Creek, Beaverton Creek, the Tualatin River, and their tributaries). These young alluvial deposits consist primarily of reworked Missoula Flood Deposits and eroded material from the surrounding highlands and are present generally as soft silts and clays.

Surface geology in the area is dominated by volcanic rocks in the highland areas such as Bull and Cooper Mountains, Missoula Flood Deposits in the lower lying flatland areas, and alluvial deposits along the banks of rivers and streams. A geologic map of the project area is provided in Figure 16.1.
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

LEGEND

- Durham AWWTP
- CWS Pipes

Geology
- Fine Grained Sediments
- Mixed Grained Sediments
- Coarse Grained Sediments
- Sedimentary Rocks
- Volcanic Rock

NOTES:
GEOLOGY ESTIMATES SHOWN ARE BASED ON DATA FROM EXISTING BORINGS AND DOGAMI OGDC-6. AREAS OUTSIDE OF EXISTING BORINGS HAVE NOT BEEN VERIFIED.
16.3.2 Seismic Setting

The Pacific Northwest is located near an active tectonic plate boundary. Off the northwest coast the Juan de Fuca oceanic plate is subducting beneath the North American crustal plate. This tectonic regime has resulted in seismicity in the project area occurring from three primary sources:

- Shallow crustal faults within the North American plate.
- CSZ intraplate faults within the subducting Juan de Fuca plate.
- CSZ megathrust events generated along the boundary between the subducting Juan de Fuca plate and the overriding North American plate.

Among these three sources, CSZ megathrust events are considered as having the most hazard potential due to the anticipated magnitude and duration of associated ground shaking. Recent studies indicate that the CSZ can potentially generate large earthquakes with magnitudes ranging from 8.0 to 9.2 depending on rupture length. The recurrence intervals for CSZ events are estimated at approximately 500 years for the mega-magnitude full rupture events (magnitude 9.0 to 9.2) and 200 to 300 years for the large-magnitude partial rupture events (magnitude 8.0 to 8.5). Additionally, current research indicates a probability of future occurrence because the region is “past due” based on historic and prehistoric recurrence intervals documented in ocean sediments. For example, over the next 50 years, the CSZ earthquake has an estimated probability of occurrence off the Oregon Coast on the order of 16 to 22 percent (Goldfinger et. al., 2016).

In 2013, the State of Oregon developed the Oregon Resilience Plan (ORP, 2013) to prepare the state for the magnitude 9.0 CSZ event. We understand that this earthquake scenario is selected as the seismic source in the District’s seismic hazard study.

16.4 Subsurface Conditions

The subsurface within the project area is dominated by the following geologic units:

- Alluvial Deposits: This unit consists of sediments that are variable in grain size, ranging from clay to gravel, but is generally soft clay and silt and loose sand. This material has been deposited by relatively recent stream action, and locally the soil is highly dependent upon the velocity of water that has deposited it. This unit is generally susceptible to liquefaction and lateral spreading, especially when adjacent to existing waterways.
- Fine-Grained Missoula Flood Deposits: This unit consists of sediments that are variable in grain size, ranging from clay to gravel, but is generally loose sand and medium stiff silt. Scattered gravel lenses and weakly cemented sandy zones are present. This unit is generally susceptible to liquefaction and lateral spreading, especially when adjacent to existing waterways.
- Coarse-Grained Missoula Flood Deposits: This unit consists of sediments that are variable in grain size, ranging from silt to cobbles, but is generally dense, poorly graded gravel with sand. Scattered sand beds up to 5 feet in thickness are present. This unit is generally not susceptible to liquefaction and lateral spreading, except in isolated loose sand lenses below the groundwater table.
- Sedimentary Rocks: This unit consists mainly of Oligocene and Miocene aged marine sandstone and is not susceptible to liquefaction and lateral spreading.
• Volcanic Rocks: This unit consists mainly of Miocene aged basalt of the Columbia River Basalt Group and is not susceptible to liquefaction and lateral spreading.
• Hillsboro Formation: This unit consists mainly of very soft to hard clay with some sand and gravel. This unit is not susceptible to liquefaction and lateral spreading.

16.5 Geotechnical Seismic Hazards

Seismic hazards include strong ground shaking, liquefaction settlement, lateral spreading, and seismic-induced landslides. These hazards have the potential to damage facilities (i.e., pipelines, lift stations, treatment plant structures) through either permanent ground deformation or intense shaking. Our analysis of these seismic hazards is based on information provided from existing geotechnical explorations, historic well logs, DOGAMI hazard maps created for the ORP (Bauer et al., 2018), and our knowledge of the geotechnical conditions of the area. In our seismic analyses we assumed a magnitude 9.0 earthquake and a peak ground acceleration of 0.20 g to represent the effects of a magnitude 9.0 (M9) CSZ seismic event in the project area (based on DOGAMI hazard maps).

Geotechnical information contained in logs and reports studied for this project were analyzed for potential seismic hazards and compared to seismic hazards mapped by DOGAMI. Where appropriate, DOGAMI mapped hazards were modified and improved to incorporate results of the analysis of local geotechnical information.

16.5.1 Ground Shaking (Peak Ground Velocity)

To assess the hazard potential of ground shaking in the project area we reviewed the peak ground velocity (PGV) map published by DOGAMI for the ORP in the event of a M9 CSZ earthquake (Bauer et al., 2018).

The estimated ground shaking intensity (PGV) depends on earthquake magnitude, distance to fault rupture, and the subsurface materials present at the site. Generally, in the East Basin service area the PGV values are estimated to range between 7 and 19 inches per second with higher velocities in low lying areas along streams and rivers and lower velocities in areas with shallow bedrock such as Bull Mountain. At the Durham AWWTF the PGV values are estimated to range between 10 and 19 inches per second. The PGV hazard map for the East Basin service area is shown in Figure 16.2, and for the Durham AWWTF in Figure 16.6.

Figures 16.2 through 16.10 are shown at the end of Section 16.5.

16.5.2 Liquefaction

Liquefaction is a phenomenon affecting saturated, granular soils in which cyclic, rapid shearing from an earthquake results in a drastic loss of shear strength and a transformation from a granular solid mass to a viscous, heavy fluid mass. The results of soil liquefaction include loss of shear strength, loss of soil materials through sand boils, flotation of buried chambers/pipes, and post liquefaction settlement.

To evaluate the hazard potential of soil liquefaction in the project area, we reviewed liquefaction hazard maps published by DOGAMI for the ORP, modified as discussed in Section 5.0, in the event of a M9 CSZ earthquake. Where geotechnical data was available, we conducted site specific analyses based on the subsurface conditions shown in previous geotechnical explorations listed in Section 2 using the latest standard penetration testing (SPT)-based liquefaction susceptibility and settlement assessment procedures (Boulanger and Idriss, 2014;
Idriss and Boulanger, 2008). Based on our evaluation, several areas within the East Basin service area are subject to liquefaction hazards, especially in low lying areas along Tualatin River and its tributaries such as Fanno Creek. It is possible that greater than 6 inches of liquefaction induced settlement could occur. At the Durham AWWTF liquefaction settlement is not expected to exceed 3 inches within the footprint of the facility. The East Basin service area liquefaction hazard map is shown in Figure 16.3 and the Durham AWWTF liquefaction hazard map is shown in Figure 16.7, with the hazard quantified by estimated liquefaction induced settlement.

16.5.3 Lateral Spreading

Liquefaction can result in progressive horizontal deformation of the ground known as lateral spreading. The lateral movement of liquefied soil breaks the non-liquefied soil crust into blocks that progressively move downslope or toward a free face in response to earthquake generated ground accelerations. Seismic movement incrementally pushes these blocks downslope as seismic accelerations overcome the strength of the liquefied soil column. The potential for and magnitude of lateral spreading depend on the liquefaction potential of the soil, the magnitude and duration of earthquake ground accelerations, the site topography, and the post-liquefaction strength of the soil.

To assess the hazard potential of lateral spreading in the project area, we reviewed a lateral spreading hazard map published by DOGAMI for the ORP, modified as discussed in Section 5.0, in the event of a M9 CSZ earthquake. The primary zones of lateral spreading hazard in the East Basin service area correspond to slopes around waterways. This is due to the combination of generally steep slopes along the river and creek banks and generally soft soils around the waterways. Lateral spreading PGD up to 4 feet may occur in these areas. At the Durham AWWTF lateral spreading hazard is generally low for the treatment plant area, but the hazard level is generally high for the outfall alignment south of the plant. The East Basin service area lateral spreading hazard map is shown in Figure 16.4 and the Durham AWWTF lateral spreading hazard map is shown in Figure 16.8 with the hazard quantified by estimated lateral spreading induced PGD.

16.5.4 Seismic Landslides

Earthquake induced landslides can occur on slopes due to the inertial force from an earthquake adding load to a slope. The ground movement due to landslides can be extremely large and damaging to pipelines and other structures. To assess the hazard potential of landslides in the project area, we reviewed a landslide hazard map published by DOGAMI for the Portland Metro area, and modified it based on reviewed geotechnical data.

Generally, the seismic landslide hazard for the study area is low due to its relative flatness. However, seismic landslide hazard is present in isolated areas where steeper slopes are present such as Bull Mountain, Cooper Mountain, and hills at the north end of the service area near Highway 26. Seismic landslide PGD up to 4 feet may occur in these areas. There is not a significant seismic landslide hazard risk at the Durham AWWTF. The seismic landslide hazard map of the service area is shown in Figure 16.5 and the seismic landslide hazard map of the Durham AWWTF is shown in Figure 16.10, with the hazard quantified by estimated seismic landslide induced PGD. Historic mapped landslides are also shown.
LEGEND

- Durham AWWTP
- CWS Pipes

Estimated Peak Ground Velocity

- 7 - 10 in/sec
- 10 - 14 in/sec
- 14 - 19 in/sec

NOTES:
PEAK GROUND VELOCITY ESTIMATES SHOWN ARE BASED ON DATA FROM EXISTING BORINGS AND DOGAMI OPEN FILE REPORT O-18-02.
AREAS OUTSIDE OF EXISTING BORINGS HAVE NOT BEEN VERIFIED.
NOTES:
LIQUEFACTION SETTLEMENT ESTIMATES SHOWN ARE BASED ON DATA FROM EXISTING BORINGS AND DOGAMI OPEN FILE REPORT O-13-06.
AREAS OUTSIDE OF EXISTING BORINGS HAVE NOT BEEN VERIFIED.
NOTES:
LIQUEFACTION LATERAL SPREADING ESTIMATES SHOWN ARE BASED ON DATA FROM EXISTING BORINGS AND DOGAMI OPEN FILE REPORT O-18-02.
AREAS OUTSIDE OF EXISTING BORINGS HAVE NOT BEEN VERIFIED.
LEGEND

- Durham AWWTP
- CWS Pipes

**Estimated Seismic Landslide PGD**

- None
- 0 - 2 ft
- 2 - 10 ft
- > 10 ft
- Mapped Landslide Deposits

**NOTES:**

Seismic landslide estimates shown are based on data from existing borings and DOGAMI Open File Report O-18-02. Areas outside of existing borings have not been verified.

**EAST BASIN SEISMIC RESILIENCY**

WASHINGTON COUNTY, OREGON

SEISMIC HAZARDS TECHNICAL MEMORANDUM

SEISMIC LANDSLIDE MAP

McMILLEN JACOBS ASSOCIATES

OCT 2020

FIGURE 16.5
LEGEND

Geology
- Fine Grained Sediments
- Mixed Grained Sediments
- Coarse Grained Sediments

NOTES:
GEOLOGY ESTIMATES SHOWN ARE BASED ON DATA FROM EXISTING BORINGS AND DOGAMI OGDC-6.
AREAS OUTSIDE OF EXISTING BORINGS HAVE NOT BEEN VERIFIED.
LEGEND

CWS Pipes

Estimated Peak Ground Velocity

- 10 - 14 in/sec
- 14 - 19 in/sec

NOTES:
PEAK GROUND VELOCITY ESTIMATES SHOWN ARE BASED ON DATA FROM EXISTING BORINGS AND DOGAMI OPEN FILE REPORT O-18-02.
AREAS OUTSIDE OF EXISTING BORINGS HAVE NOT BEEN VERIFIED.
NOTES:
LIQUEFACTION SETTLEMENT ESTIMATES SHOWN ARE BASED ON DATA FROM EXISTING BORINGS AND
DOGAMI OPEN FILE REPORT O-13-06.
AREAS OUTSIDE OF EXISTING BORINGS HAVE NOT BEEN VERIFIED.
NOTES: LIQUEFACTION LATERAL SPREADING ESTIMATES SHOWN ARE BASED ON DATA FROM EXISTING BORINGS AND DOGAMI OPEN FILE REPORT 0-18-02. AREAS OUTSIDE OF EXISTING BORINGS HAVE NOT BEEN VERIFIED.
LEGEND

Analyzed Slope

CWS Pipes

NOTES:

FIGURE 16.10
16.6 Durham AWWTF Seismic Slope Stability

The Durham AWWTF site slopes down to the south towards the Tualatin River. A limit equilibrium slope stability analysis was conducted on this existing slope at three different locations to identify the stability of the slope and its likelihood of failure and movement. The following sections provide a discussion of the methodology and summarize the results.

16.6.1 Methodology

Limit equilibrium slope stability analyses were performed with the computer software program SLIDE 2018 (RocScience, 2018) using the Spencer and Morgenstern-Price method. The limit equilibrium approach approximates a factor of safety (FOS) against failure for a given two-dimensional cross section by comparing the resisting forces (i.e. shear strength of the soil) to driving forces (i.e. mass of the soil and seismic forces) along a proposed failure surface. This calculation is repeated for several thousand possible surfaces. The surface with the lowest FOS is the critical failure surface. A slope stability evaluation was performed on three slope cross sections at the Durham AWWTF southern slope: (1) approximately 150 feet west of SW 85th Ave (Slope A); (2) on the southern slope approximately 150 feet east of SW 85th Ave (Slope B); and (3) on the north bank of the Tualatin River at the outfall pipe location (Slope C). The analyzed slope locations are shown in Figure 16.10. There is minimal existing geotechnical data at the Slope C location and assumptions regarding soil properties and depths had to be made.

The existing slope was evaluated under long-term static conditions and three seismic cases. The following items discuss the three seismic cases:

- “Seismic (Pseudostatic)”: One half of the peak ground acceleration (PGA) is applied to the slope (i.e. 0.10 g) and peak soil strength parameters are used. This represents the case where soil has not liquefied, but the slope is subjected to seismic loading.
- “Liquefaction Post-seismic” – Where liquefiable soils are present the slope is analyzed using estimated residual shear strength parameters with no horizontal acceleration. This type of hazard, also called “flow failure” applies to a condition where the fully liquefied soils are failing under gravity after the strong earthquake shaking.
- “Liquefaction with horizontal acceleration coefficient” – Similar to post-seismic scenario except one half of the peak ground acceleration (0.10 g) is applied. This is a “worst-case scenario” and represents the case where the soil has fully liquefied while strong ground shaking is ongoing. This is applicable to long-duration (subduction zone) earthquakes and is representative of a condition after approximately 45 to 60 seconds of shaking.

Generally minimum recommended factors of safety are 1.5 for long term (static) scenarios and 1.1 for seismic scenarios. Limit equilibrium methods provide an estimate of the slope stability in terms of FOS only. If the minimum FOS is met, the slope displacements are considered small enough to not affect structure foundations. To estimate the magnitude of slope displacement methods of Youd et al. (2002) were used, which estimate lateral spreading displacement. Material properties for soils were estimated based on available subsurface explorations and our experience locally with similar soils.
16.6.2 Slope Stability Results

The results of the slope stability analyses are provided in Table 16.1, and graphical results of the “Post-seismic with horizontal acceleration coefficient” (the worst-case scenario) analyses are shown in Figures 16.11 to 16.13.

Table 16.1  Durham AWWTF Slope Stability Analysis Results

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<th>Slope</th>
<th>Factor of Safety</th>
<th>Estimated Lateral Spreading Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static</td>
<td>Pseudo-Static</td>
</tr>
<tr>
<td>Slope A</td>
<td>1.94</td>
<td>1.50</td>
</tr>
<tr>
<td>Slope B</td>
<td>3.16</td>
<td>2.07</td>
</tr>
<tr>
<td>Slope C</td>
<td>1.15</td>
<td>0.94</td>
</tr>
</tbody>
</table>

These results indicate that Slope A and Slope B are generally stable under both static and seismic conditions. Slope C is considered unstable under seismic condition and only marginally stable under static condition.
NOTES:
1. MFD: MISSOULA FLOOD DEPOSITS
2. HF: HILLSBORO FORMATION
3. ANALYSIS CASE REPRESENTS POST SEISMIC SOIL STRENGTHS WITH A SEISMIC LOADING COEFFICIENT
NOTES:
1. MFD: MISSOULA FLOOD DEPOSITS
2. HF: HILLSBORO FORMATION
3. ANALYSIS CASE REPRESENTS POST SEISMIC SOIL STRENGTHS WITH A SEISMIC LOADING COEFFICIENT 1.27
NOTES:
1. MFD: MISSOULA FLOOD DEPOSITS
2. HF: HILLSBORO FORMATION
3. ANALYSIS CASE REPRESENTS POST SEISMIC SOIL STRENGTHS WITH A SEISMIC LOADING COEFFICIENT
16.7 Conclusions

16.7.1 East Basin System

The majority of the District’s East Basin pipeline system is located within the seismic PGD hazard zones. Exceptions to this occur where piping is located outside of a seismic hazard zone. Examples include, Bull Mountain and the northeast of the project area at the base of the Portland Hills (West Hills). Pipelines along creeks and waterways (Beaverton Creek, Fanno Creek, Tualatin River) and in the low-lying areas of Beaverton and Sherwood are most susceptible to liquefaction induced PGDs. Liquefaction-induced settlement of more than 6 inches is expected in these areas. Along the banks of waterways, greater than 4 feet of lateral spreading PGD is expected.

The most seismically susceptible areas are where pipelines are located near or cross existing waterways. In these areas, large magnitude lateral displacements and liquefaction-induced settlement (specifically differential settlement) have the potential to severely damage pipelines and appurtenances.

Due to the extent of the facilities located in seismic hazard zones, it is not feasible to improve all existing pipelines at risk of failure. However, all new or improved pipelines should be designed to address seismic hazards either by relocating facilities outside the hazard zone or through designing the facilities to survive the CSZ seismic event. Cost estimates for CIP purposes should include costs associated with addressing the seismic hazards in new facilities.

16.7.2 Durham AWWTF

The majority of the Durham AWWTF is located in a relatively low seismic hazard area. Liquefaction induced settlements are not expected to exceed 3 inches. At this magnitude differential settlement has the potential to damage pipeline connections as well as crack and displace buildings. However, catastrophic damage in a seismic event is not expected for the majority of the Durham AWWTF, since most of the treatment facilities are supported on mat foundations with can tolerate most of the differential settlement. However, it is recommended that structures should be evaluated to determine if improvements are needed to meet life safety standards.

Near the southern border of the facility property, where the ground surface begins to slope downward to the south towards the Tualatin River, some soil layers under this slope have the potential to liquefy. Therefore reducing the strength and stability of the slope. However, our preliminary slope stability analyses indicate that the majority of the slope will likely still be stable with some minor deformations limited to the crest of the slope. Where the facility outfall pipe meets the Tualatin River, the soil conditions are significantly weaker. During a CSZ earthquake 2 to 3 feet of permanent ground deformation is expected at this location, likely resulting in significant damage to the outfall pipe. Therefore, it is recommended that improvements be implemented within the planning period to reduce damage to the outfall during the CSZ event.

16.8 Limitations

This Seismic Hazards Technical Memorandum has been prepared for the District’s East Basin Seismic Resiliency Study, located in Washington County, Oregon. This report contains a compilation of information from previous studies, projects, and published literature. The professional judgements and characterizations presented herein are based on this information.
McMillen Jacobs Associates is not responsible for errors and omissions that might appear in studies reported by others.

The scope of our geotechnical services has not included an environmental evaluation regarding the presence or absence of hazardous or toxic materials in the soil, surface water, groundwater, or air, on or below the site.

This report has been completed within the limitations of the Carollo, Inc. approved scope of work, schedule and budget. The services rendered have been performed in a manner consistent with the level of care and skill ordinarily exercised by members of the profession currently practicing under similar conditions in the same area. McMillen Jacobs Associates is not responsible for the use of this report for anything other than the District’s East Basin Seismic Resiliency Study.

16.9 References


Tolan, T.L., and Beeson, M.H., 1984, Exploring the Neogene history of the Columbia River: Discussion and geologic field trip guide to the Columbia River Gorge, Oregon Department of Geology and Mineral Industries, Volume 46, Number 8, August 1984.

