# Technical Memorandum

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| Date: | April 24, 2024 |
| Project: | Chehalis River Basin Flood Damage Reduction Project |
| To: | Chehalis Basin Flood Control Zone District |
| From: | HDR Engineering, Inc. |
| Subject: | **Seismic Hazards for Design** |

## 1.0 Introduction

As a part of recommended measures to reduce damage to communities of the Chehalis River Basin during major flood events, identified as part of the Chehalis River Basin Flood Damage Reduction Project, the Chehalis Basin Flood Control Zone District (District) is proposing a Flood Retention Expandable (FRE) structure located on the Chehalis River, south of the town of Pe Ell, Washington (WA).

This technical memorandum describes the seismic design hazards and setting associated with the proposed FRE structure.

## 2.0 Seismic Design Hazards

The most important safety concern of concrete dams subjected to earthquakes is the potential for cracking, which can lead to significant damage or potential instability from sliding or overturning. Sliding could occur on an existing plane of weakness in the dam foundation, at the foundation-dam interface, or along RCC lift surfaces within the dam. Although some major concrete dams have experienced strong ground motion with some damage, in general, well designed and constructed concrete dams show significant resilience to seismic loading. There has been only one major concrete dam failure in recent times as a result of earthquake-induced ground motions. This failure was in Taiwan, where the dam was constructed directly on an active fault that experienced about 30 feet of differential vertical displacement during the earthquake. In general, instability of gravity dams caused by excessive cracking of the concrete is most likely to occur in the upper half of the dam.

Development of a dam cross-section that includes appropriate defensive design measures is required to address safety and earthquake performance concerns. Defensive measures for concrete dams might include the following:

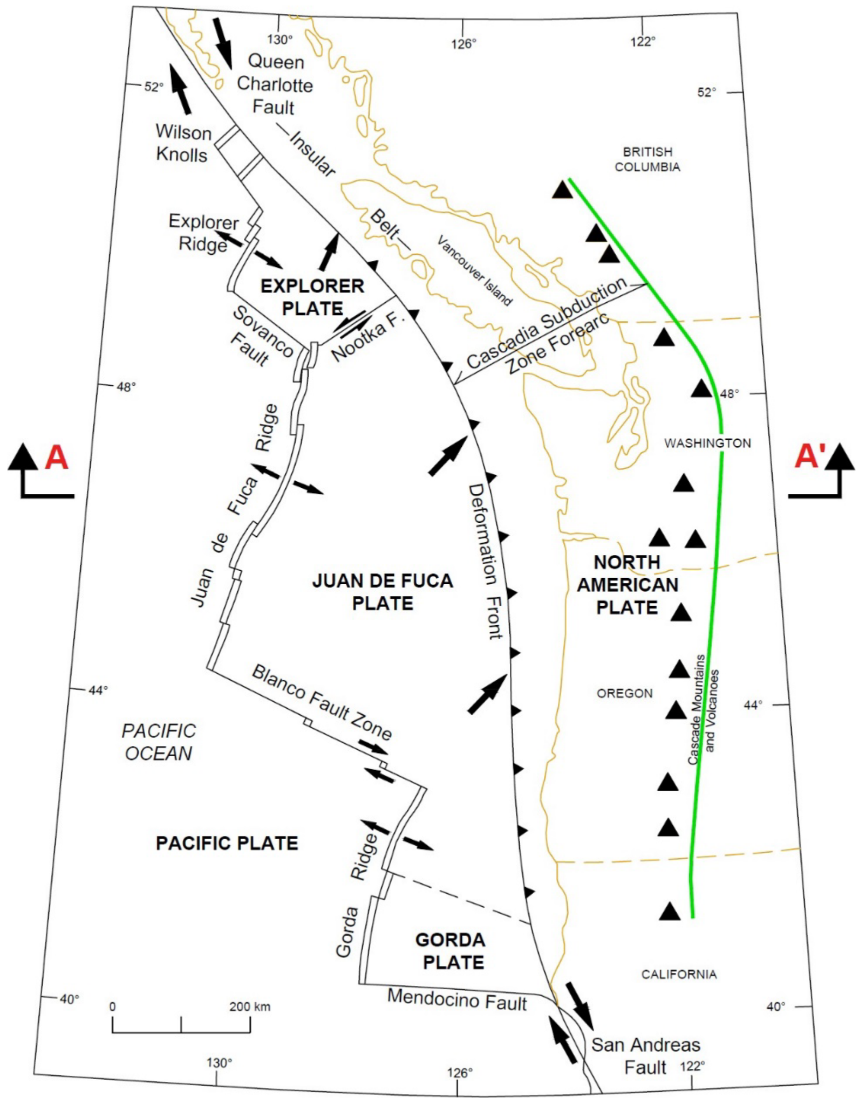
- Adequate dam and foundation seepage control and drainage is typically the first line of defense against dam and/or foundation instability, in part because it is the most economical.

- Typical upstream and downstream slopes may be modified as needed to meet tensile stress and sliding stability design criteria. Use of a chimney section with a curved transition to the downstream slope of the dam can reduce tensile stresses in downstream dam face in the upper portion of the dam. The upstream face of the dam can be sloped to reduce hydrodynamic forces on the dam and tensile stresses that can develop at the upstream heel.
- RCC mixes, design provisions, and construction procedures may be implemented to achieve uniformity of the concrete materials and adequate direct tensile and shear strength without causing excessive thermal cracking problems.
- Identify an appropriate excavation objective that when combined with the other defensive measures, it results in an economical configuration. Similarly, the excavation profile along the axis of the dam should have minimal geometric irregularities and gradual variations in structural stiffness. Over-excavation and use of backfill concrete and shaping blocks in foundation defect areas can be effective measures to improve seismic performance in critical areas.
- Effective quality control during construction to achieve desired foundation preparation, strength of the concrete, and bonding of the dam to the foundation. Appropriate cleaning, preparation, and treatment of lift surfaces to provide a good bond for both seepage control and seismic performance within the body of the dam.
- Vertical contraction joints and crack inducers can be incorporated into the design to control cracking and accommodate small differential displacements in the dam profile.

## 2.1 Proposed FRE Structure Seismic Hazard Setting

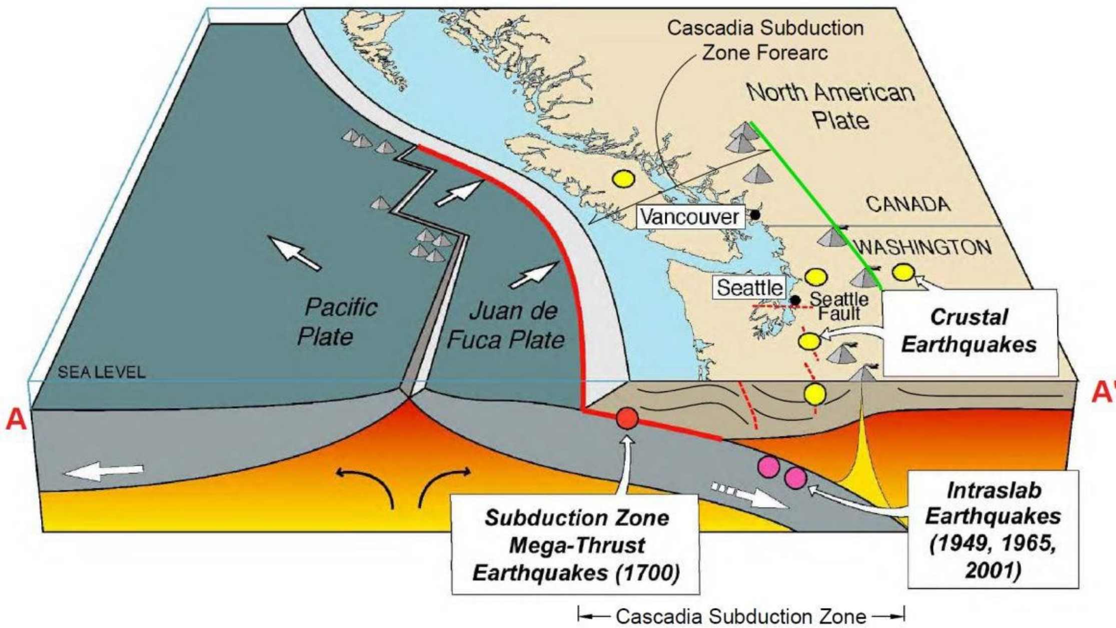
Proposed Project setting and hazards are described in more detail in the Phase 1 Site Characterization TM (HDR and S&W 2015). Figure 2-1 shows the northern Cascadia forearc positioned within two tectonic convergence regimes that deform western Washington: east-west contraction across the CSZ and north-south shortening from the northward migration of forearc blocks. The combined effect of the two produces complex and diverse deformation within the northern edge of the Cascadia forearc that can trigger large, damaging earthquakes from multiple seismogenic sources in the western Washington region (Figure 2-2).

**Figure 2-1. Plate Boundaries**




Source: HDR (2017)

**Figure 2-2. Typical Geologic Cross-section**

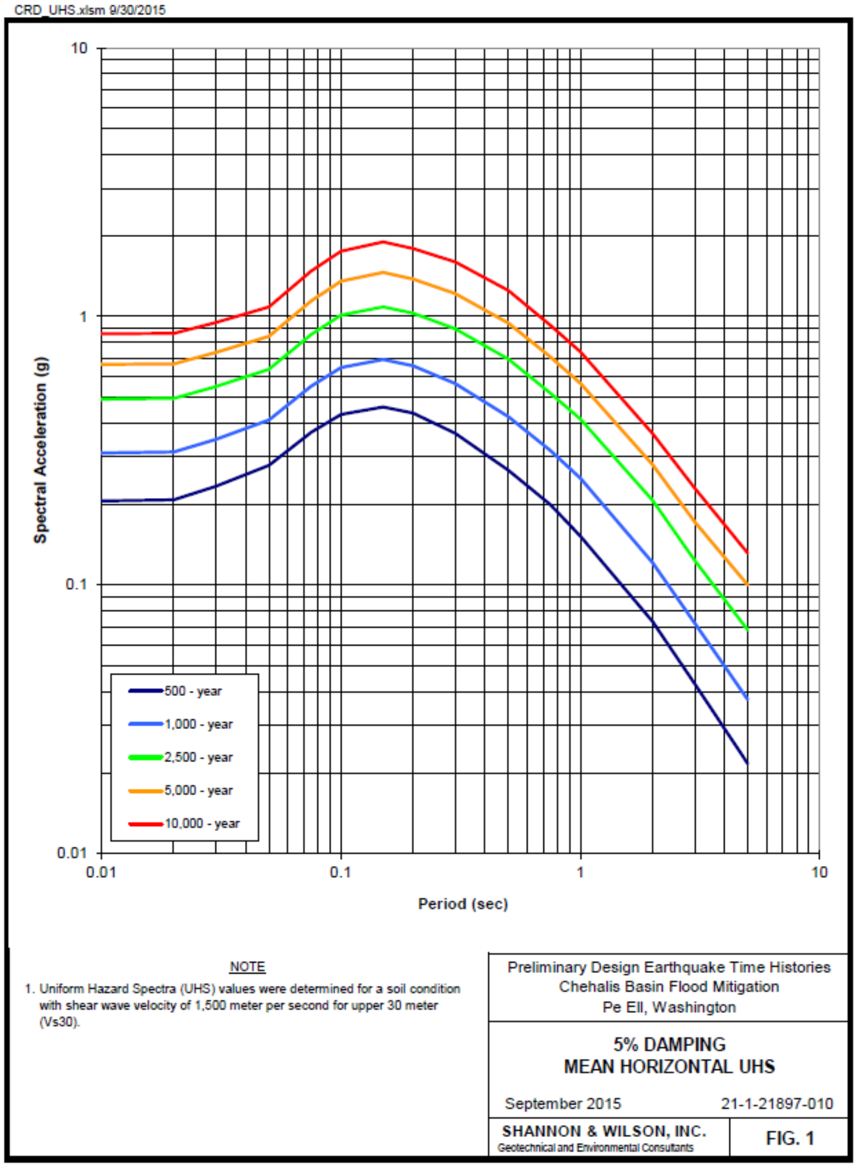



Source: HDR (2017)

### 2.1.1 Seismic Hazards

The horizontal uniform hazard spectra from the PSHA for estimated 500-, 1,000-, 2,500-, 5,000-, and 10,000-year return periods were developed and plotted. The uniform hazard spectra represent the sum of the hazards from various regional seismic sources included in the seismic source characterization model for the FRE site (S&W 2015). Figure 2-3 illustrates the estimated hazard curves from the PSHA for horizontal ground motion versus mean annual rate of exceedance or return periods, which, based on current knowledge, indicate the CSZ interface is the dominant contributor to the ground motion hazard at the site for 500- to 10,000-year return periods.

**Figure 2-3. Horizontal Uniform Hazard Spectra**




Source: S&W (2015)

A deterministic seismic hazard analysis was completed to estimate the ground motions from a specific seismogenic source at the site regardless of the rate at which earthquakes are generated from the source. In a deterministic seismic hazard analysis, the various seismic parameters (e.g., fault type, rupture dimensions, and maximum magnitude) for each potential earthquake source are evaluated, and an MCE is determined for that source. Using the distance between the site and the source, the ground motions at the site for a given MCE were estimated, and the MCE source that produces the largest (strongest) ground motions at the site produces the Controlling MCE.

The PSHA results were used to identify and characterize earthquake sources that produce the MCE, locations of potential fault rupture, and the source mechanisms to estimate deterministic ground motions (i.e., spectra). Uncertainties in seismic source characterization are reflected in logic tree weights of the PSHA. However, in the deterministic approach, the MCE can be identified by selecting the most likely or best estimate for each source parameter (i.e., fault type, location, geometry, maximum magnitude, and source-to-site distance). The source parameters given the highest weight in PSHA are considered the most likely in defining the MCE for the deterministic analysis.

The potential MCEs evaluated as part of the most recent deterministic study are as follows:

- Moment magnitude (megawatt [Mw]) 8.9 CSZ interface earthquakes at source-to-site distances of 71 kilometers (km) and mean-plus-one standard deviation ground motions because of the relatively short recurrence interval (i.e., about 500 years) for these events
- Mw 7.5 CSZ intraslab earthquakes directly beneath the site at a distance of 43 km
- Mw 7.1 Olympia Fault events at a distance of 48 km from the site
- Mw 6.9 Doty fault events at a distance of 13 km from the site

Thirteen time history sets were developed (39 individual time histories) for use in the HDR (2017) conceptual design. Each time history set is composed of three time histories, two orthogonal horizontal components, and one vertical component.

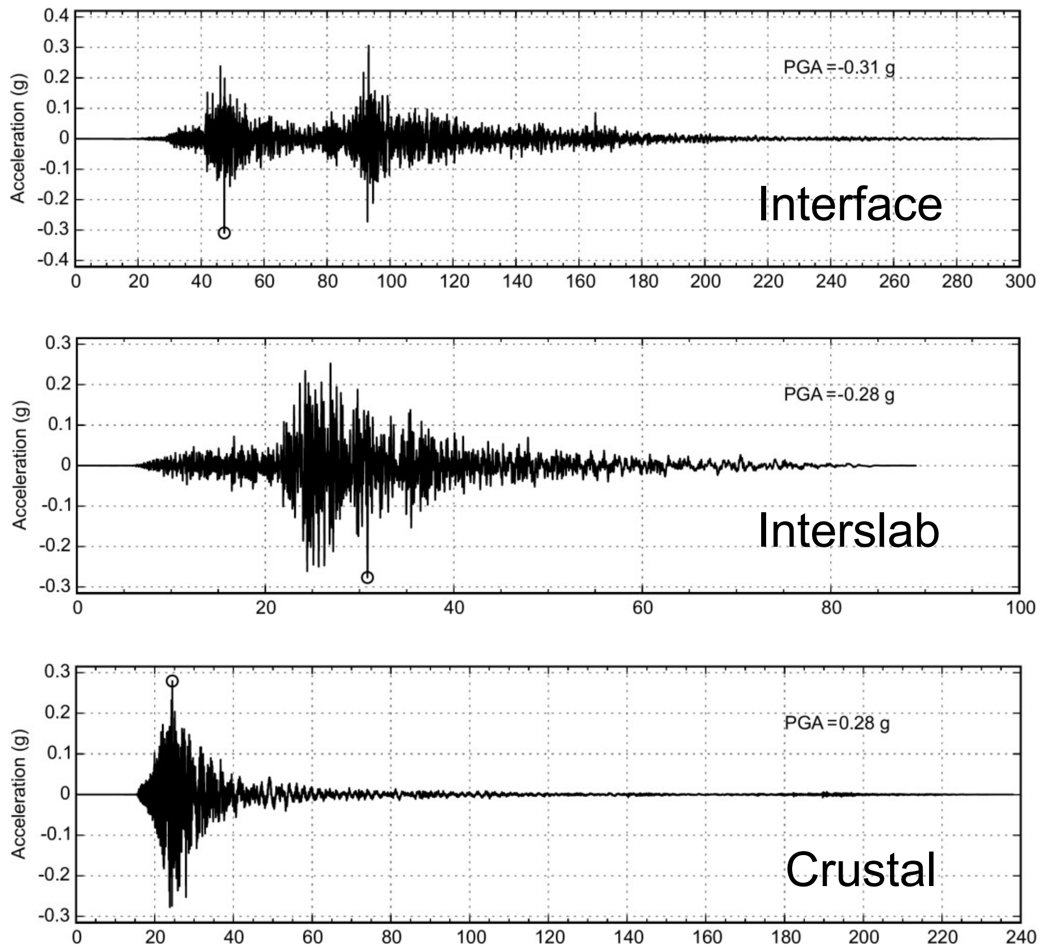
Specifically, time history sets were developed for the following:

- Ten sets corresponding to probabilistic ground motions with an estimated 2,500-year return period
  - Five sets matched to conditional mean spectra conditioned at a 0.2-second period
  - Five sets matched to conditional mean spectra conditioned at a 1.0-second period
- Scaling factors for the 10 probabilistic 2,500-year ground motions to scale them to other return periods ranging from 500 to 10,000 years
- Three sets corresponding to deterministic MCE ground motions for the following sources:
  - CSZ Mw 8.9 interface event (one set)
  - CSZ Mw 7.5 intraslab event (one set)
  - Shallow crustal Mw 6.9 Doty fault event (one set)

Figure 2-4 shows examples of the interface, interslab, and crustal event time histories of horizontal ground motions. Similar to the HDR (2017) conceptual design, the FRE structure was analyzed using one of the time histories that was conservatively chosen because it has the highest peak ground acceleration (PGA), and the most excursions close to the PGA (reference structural report in Revised Project Description Report for additional information).

Figure 2-4 shows example ground motions relative to the earthquake hazards at the FRE site, the duration of strong shaking is substantially different for different hazards. A period of strong shaking of 140 to 180 seconds may occur for a CSZ event, while the corresponding duration of strong shaking may be 50 to 60 seconds for an interslab event and 20 to 30 seconds for a crustal event. The duration of shaking is directly tied to the length of fault rupture and corresponding event magnitude.

**Figure 2-4. Time Histories**




### 2.1.2 Doty Fault Length Effect on Seismic Hazard

During the 2015 earthquake source assessment and corresponding site ground motion hazard development, the deterministic and probabilistic ground motions were developed using a Doty fault length of approximately 50 km. The Doty fault structure is visible on existing aeromagnetic and gravity anomaly datasets. Based on these datasets, researchers at the U.S. Geological Survey (USGS) and Washington Department of Natural Resources (WDNR) have questioned whether the fault might extend farther west than currently mapped, to near the Washington coast.

At the time of the 2015 seismic hazard assessment, the USGS had recently acquired a new high-resolution aeromagnetic dataset of the area and will use that, along with newly acquired LiDAR data, to closely analyze the fault length and geometry of the Doty fault in the future. Additionally, researchers at the USGS and WDNR were planning field campaigns to identify active structures and potential recurrence rates along the Doty fault zone.

If the Doty fault extends farther west, it would be capable of producing larger-magnitude earthquakes. As described in the 2015 ground motion hazard study, the maximum magnitude of Mw 6.9 was estimated for a 50-km-long Doty fault. If the fault length increased to 100 km, the corresponding maximum magnitude would increase to about Mw 7.2. Extending the fault farther west would change the nearest site-to-source distance; for either a 50- or 100-km-long fault, the site-to-source distance would remain 13 km.

A preliminary assessment was made in 2015 of the potential impact to the site ground motion hazard should the future USGS/WDNR studies support the hypothesis that the Doty fault is longer and capable of generating larger earthquakes. For the deterministic motions, the increased Doty fault length/magnitude ground motions would still be lower than the CSZ interface, which would remain the controlling deterministic ground motion hazard source. Probabilistic motions could increase by a few percent if the future USGS/WDNR studies support a longer, active Doty fault.

The WDNR (2021) completed and published the in-depth investigation of the existing Doty fault to determine its length and activity level. This study provides an updated understanding of potential seismic activity around the proposed FRE facility associated with the Doty crustal fault system. In 2022, HDR performed a high-level review of the report to identify if the information could potentially affect the proposed location and design of the FRE facility. Below are the major findings from the review (HDR 2022).

- The MCE event from the Doty fault has increased from a moment magnitude M6.9 to M7.3. There also appear to be some updates to estimated slip rates for the Doty fault. These updates would affect the contribution of the crustal fault hazard slightly from the seismic hazard characterization provided by S&W (2015). Therefore, the site-specific hazard evaluation should be updated to incorporate the new Doty fault characterization information.
- The overall length of the Doty fault including the possible rupture length has increased as a result of the new M7.3 estimate. The increased fault length appears mostly as a northwestern extension moving away from the FRE site.
- Because there is no new information suggesting a fault hazard traversing the FRE site, there is no new fault rupture concern for the FRE foundation.

Based on the review, it was recommended that the site-specific seismic hazard analysis be updated including ground motion time histories for use in the structural analyses of the facility when the design proceeds to the full preliminary design level.

## 3.0 References

HDR Engineering, Inc. (HDR)

2017 Combined Dam and Fish Passage Conceptual Design Report. June 2017.

2018 Combined Dam and Fish Passage Supplemental Design Report FRE Dam Alternative Report. September 2018.

HDR Engineering, Inc. and Shannon & Wilson, Inc. (HDR and S&W)

2015 Phase 1 Site Characterization Technical Memorandum, Report Prepared for the State of Washington Office of Financial Management and the Chehalis Basin Work Group. September 2015.

2022 Dam Safety Standards and Seismic Fault Study Review Technical Memo, Chehalis River Basin Flood Damage Reduction Project. February 23, 2022.

Shannon & Wilson (S&W)

2015 Preliminary Design Earthquake Time Histories, Chehalis Basin Flood Mitigation, Pe Ell, Washington, September 30, 2015.

Washington Department of Natural Resources (WDNR)

2021 Geologic and Geophysical Assessment of Tectonic Uplift and Fault Activity in the Doty and Willapa Hills, Southwest Washington: Final Report. June 30, 2021.

## 4.0 Acronyms/Abbreviations

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| HDR | HDR Engineering, Inc. |
| RCC | roller-compacted concrete |
| Project | Chehalis River Basin Flood Damage Reduction project |
| FRE | Flood Retention Expandable (FRE) |
| Mw | megawatt |
| km | kilometer(s) |
| PGA | peak ground acceleration |
| RPDR | Revised Project Description Report |
| USGS | U.S. Geological Survey |
| WDNR | Washington Department of Natural Resources |