Coast & Harbor Engineering
A Division of Hatch Mott MacDonald

Technical Memorandum

Westway and Imperium Terminal Services Expansion Projects EIS's Tsunami Impact Modeling and Analysis

1. Introduction

This technical memorandum presents the results of analysis and numerical modeling of tsunami wave generation and propagation for the expansions projects proposed by Westway and Imperium Terminal Services Expansion Projects Environmental Impact Statements (EIS's) in Grays Harbor, Washington. The facilities are located on the north banks of the Chehalis River in the upland area of Terminals 1 and 2, as shown in the aerial photograph in Figure 1.

The analysis and numerical modeling included simulation of tsunami wave generation at the Cascadia Subduction Zone (CSZ), tsunami wave propagation toward the project site, and evaluation of possible inundation of these two facilities. The objectives of the modeling and analysis were as follows:

- Estimate elevation of inundation in the project area during the design tsunami event.
- Determine possible forces on oil tank structures from the tsunami wave during the design earthquake event.

The current tsunami modeling study (presented herein) incorporated lessons learned from recent earthquake events, specifically the 2011 Tohoku, Japan earthquake and the new Cascadia Subduction Zone (CSZ) rupture scenarios, developed and published by the Department of Geology and Mineral Industries (DOGAMI) in 2011 (Witter *et al.*, 2011). In addition, the modeling study incorporated further measures in anticipation of an update to the American Society of Civil Engineers Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10) to be released in 2016. This update will include a chapter on 'Tsunami Loads and Effects.'

Figure 1. Location of proposed Westway and Imperium Terminal Services Expansion Projects EIS's in Grays Harbor

2. Tsunami Modeling Methodology and Input Data

2.1. Modeling Inputs and Methodology

Prior to conducting the numerical modeling, CHE prepared the tsunami modeling methodology for this project. For this purpose, CHE prepared and issued the technical memorandum *Grays Harbor Tsunami Hydrodynamic Modeling Methodology* (CHE, 2014). The modeling methodology described in this document is consistent with past CHE project experiences that were conducted in coordination with DOGAMI and Federal Emergency Regulatory Commission (FERC). The following is a list of major modeling input parameters and modeling results evaluation procedures that were coordinated by this technical memorandum. Some of these parameters and procedures are further discussed in detail in the present technical memorandum.

- FERC's revised seismic design criterion (2007) requires that the seismic source used to generate a design tsunami event be consistent with a Safe Shutdown Earthquake (SSE) with a return period of 2,475 years. As documented in CHE's 2014 technical memorandum, DOGAMI recommended using their rupture Scenario L1 to best represent the 2,475-year hazard level design criteria outlined in the revised FERC seismic design criteria. Therefore, the earthquake source for this tsunami modeling effort meets FERC's criteria (See Section 2.2 for more details).
- Tsunami hydrodynamic modeling was conducted for three rupture scenarios for CSZ (also referenced as the seismic source for modeling): L1, L2, and L3 that were developed by DOGAMI. It was found that Scenario L1 is the most critical

event (Zhang, 2012) and produces the largest tsunami wave, compared to Scenarios L2 and L3. Therefore, this technical memorandum describes the results of only one modeling event: L1 (See Section 2.2).

- The model bathymetry was adjusted (i.e., raised at the areas of uplift and lowered at the areas of subsidence including the project site) before the start of the simulation to account for the L1 rupture scenario. The earthquake was modeled as a 10-sec seafloor deformation sequence, resulting in an initial surface slope and acceleration field that drives the subsequent fluid motion. Modeling was conducted using the 2-D version of the three-dimensional (3-D) hydrodynamic model SELFE (Zhang & Baptista, 2008). See Section 2.2 for more details.
- The initial, prior to earthquake, water surface elevation for the entire modeling grid was assigned to be at Mean High Water (MHW) elevation. The Aberdeen, WA NOAA Station database was used to define the MHW elevation for the modeling grid. Based on this database, MHW elevation is +7.82′ (+2.384 m) NAVD88 (See Table 1 below).
- As required by FERC, a safety factor of 1.3 was applied to the results of tsunami numerical modeling to further increase water surface elevations (WSEL) referenced to MHW in the project area. The factor is intended to account for uncertainties in the modeling.
- Initial water surface elevation will be raised an additional 0.75 feet (0.229 m) to incorporate the possible sea level rise by 2037, as provided by ICF International (ICF).
- The following scenarios were selected for modeling in coordination with ICF:
    - Scenario 1: Assuming both Westway Terminals LLC and Imperium Terminals Services tanks are constructed without incorporating sea level rise; and
    - Scenario 2: Assuming both Westway Terminals LLC and Imperium Terminals Services tanks are constructed with incorporating sea level rise.

Figure 2 shows a conceptual diagram that schematically demonstrates changes (modifications) in ground and water surface elevations with regard to all factors discussed above, including the safety factor. It should be noted that Figure 2 demonstrates the concept at the project site where subsidence occurs.

Table 1. NOAA Tidal Datums for Aberdeen, Washington

Aberdeen, WA TIDAL DATUMS[1]		
	Elevations	
Datum	**(feet-MLLW)**	**(feet-NAVD88)**
MEAN HIGHER HIGH WATER (MHHW)	10.11	8.52
MEAN HIGH WATER (MHW)	9.41	7.82
MEAN SEA LEVEL (MSL)	5.60	4.01
MEAN TIDE LEVEL (MTL)	5.44	3.85
NATIONAL GEODETIC VERTICAL DATUM (NGVD29)	4.88	3.29
NORTH AMERICAN VERTICAL DATUM-1988 (NAVD88)	1.59	0.00
MEAN LOW WATER (MLW)	1.47	-0.12
MEAN LOWER LOW WATER (MLLW)	0.00	-1.59
Notes: [1]Datums are from NOAA National Ocean Service website for Station 9441187 Aberdeen, WA accessed on 11/12/2014. Time Datum Analysis Period: 01/01/1983-04/30/1991 Tidal Epoch: 1983-2001		

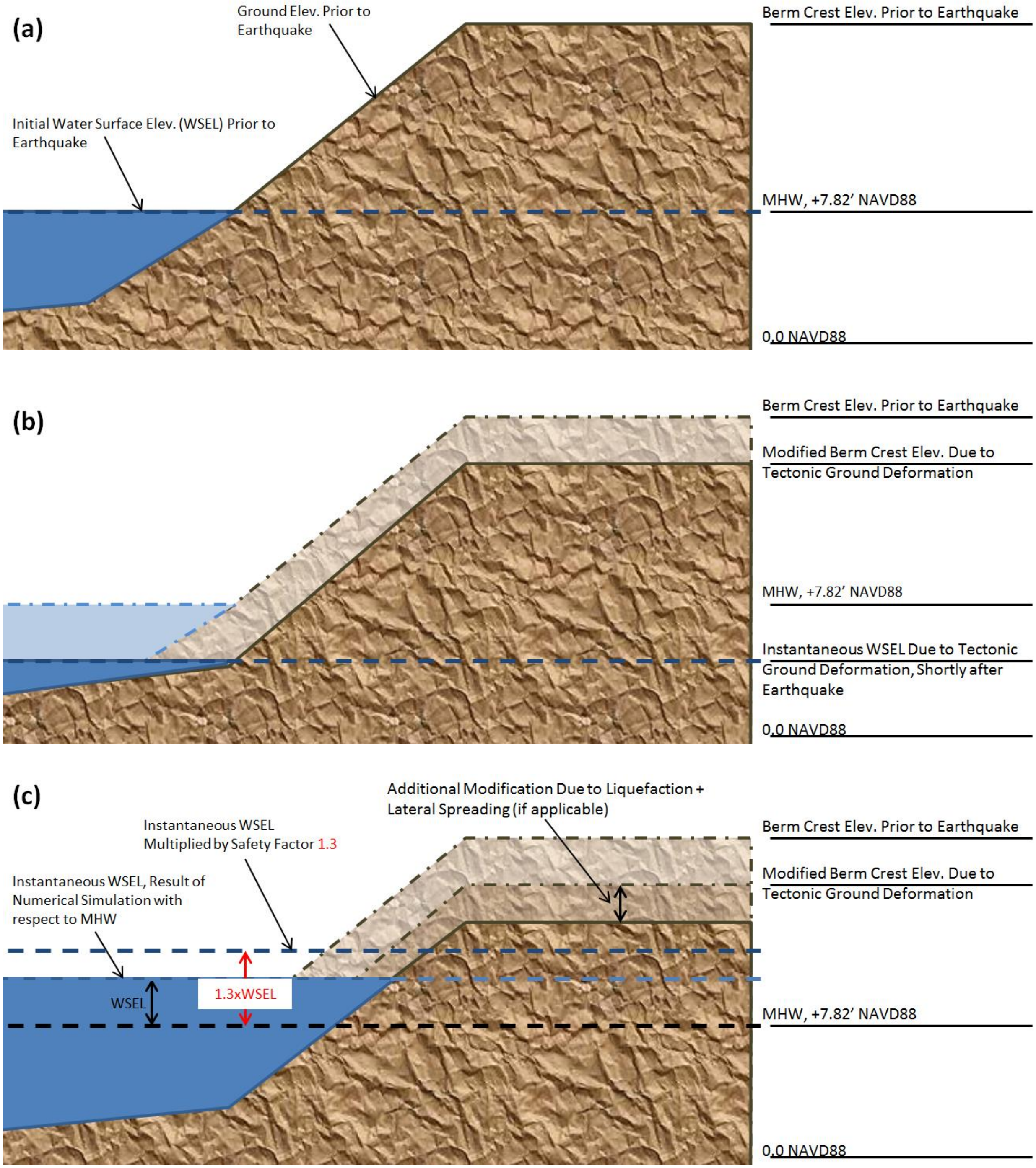

Figure 2. Schematic representation of elevations and implementation of safety factor required by FERC: (a) ground and water surface elevation (WSEL) prior to earthquake and tsunami; (b) ground and instantaneous (snapshot of) WSEL, result of numerical modeling shortly after Earthquake; and (c) maximum results of WSEL tsunami hydrodynamic modeling, adjusted by a safety factor of 1.3; incorporating liquefaction settlement and lateral spreading (if applicable). It should be noted that the hydrodynamic model determines response of water to the input land elevation deformations due to Earthquake.

2.2. Earthquake Source Model

The earthquake source model utilized for this study was based on DOGAMI's most recent study and official publication. DOGAMI has studied and developed 15 rupture scenarios for the Cascadia Subduction Zone (CSZ), recommended to be used in tsunami inundation studies (see Witter *et al.*, 2011 for more details). Among these 15 rupture scenarios, Scenarios L1, L2, and L3 represent events with three occurrences in 10,000 years, with L1 being the largest event. As documented in the CHE's 2013 memorandum, DOGAMI recommended using their rupture Scenario L1 to best represent the 2,475-year FERC criteria.

FERC requires the seismic source for generation of a tsunami event be consistent with the seismic source for the Safe Shutdown Earthquake (SSE) that has a return period of 2,475 years (FERC, 2007). As discussed above, rupture Scenario L1 developed by DOGAMI is estimated to correspond to a 3,333-year return period event that satisfies FERC criteria. Therefore, this event was used for tsunami wave generation for the Westway and Imperium Terminal Services Expansion Projects EIS's. CSZ dislocation maps corresponding to rupture scenario L1 (as well as other scenarios) were produced by DOGAMI and were purchased by CHE to be used as input for the numerical modeling.

Figure 3 shows vertical tectonic ground deformation for Scenario L1. Scenario L1 includes a subsidence of approximately 2.93 m (9.61 ft) at the project site. This subsidence was accounted for in the modeling effort by lowering the project site and the surrounding area by 9.61 ft.

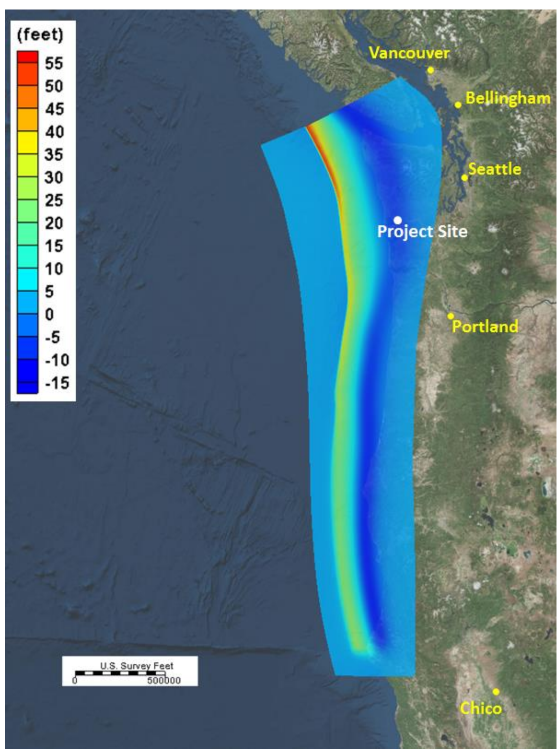

Figure 3. Tectonic vertical ground deformation in feet for CSZ rupture Scenario L1 (Witter *et al.*, 2011)

3. Tsunami Hydrodynamic Model and Modeling Grid

3.1. SELFE Model

Tsunami modeling was conducted using the hydrodynamic numerical model SELFE (Zhang and Baptista, 2008). SELFE is a three dimensional (3-D), unstructured-grid, fully nonlinear, semi-implicit Eulerian-Lagrangian finite element model. SELFE is capable of simulating tsunami wave generation in the open coast and propagation of the tsunami wave through river embayment to the project site. The SELFE model is currently being used by DOGAMI for developing inundation and evacuation maps for the entire coast of Oregon.

3.2. Numerical Modeling Grid and Bathymetry

An unstructured triangular grid was developed specifically for the present numerical modeling effort. The triangular grid extends approximately 200 miles offshore of the project site. The grid varies in resolution between approximately 4 miles at the offshore boundary to 32 ft at the project site, with a total of 645,590 calculation nodes. Figure 4 shows three views of the modeling grid.

Model bathymetry/topography data for numerical modeling was composed from:

- Bathymetry data provided by the Scripps Institute of Oceanography Global Grid (2009).
- Astoria V2 DEM provided by NOAA (2012).
- LiDAR data provided by FEMA (2010).
- Existing and Design Grading at the project site provided by the client.
- Bathymetry data used in the previous tsunami modeling study for the project site (Zhang, 2008 & 2012).
- Offshore bathymetry used in the recent tsunami modeling studies conducted by DOGAMI (Zhang, 2012).

Figure 5 shows a compiled bathymetry dataset representing the extent of the domain that was used for tsunami modeling in the study. Figures 6 and 7 show a close-up of local bathymetry and topography for Grays Harbor and in the vicinity of the project site, respectively.

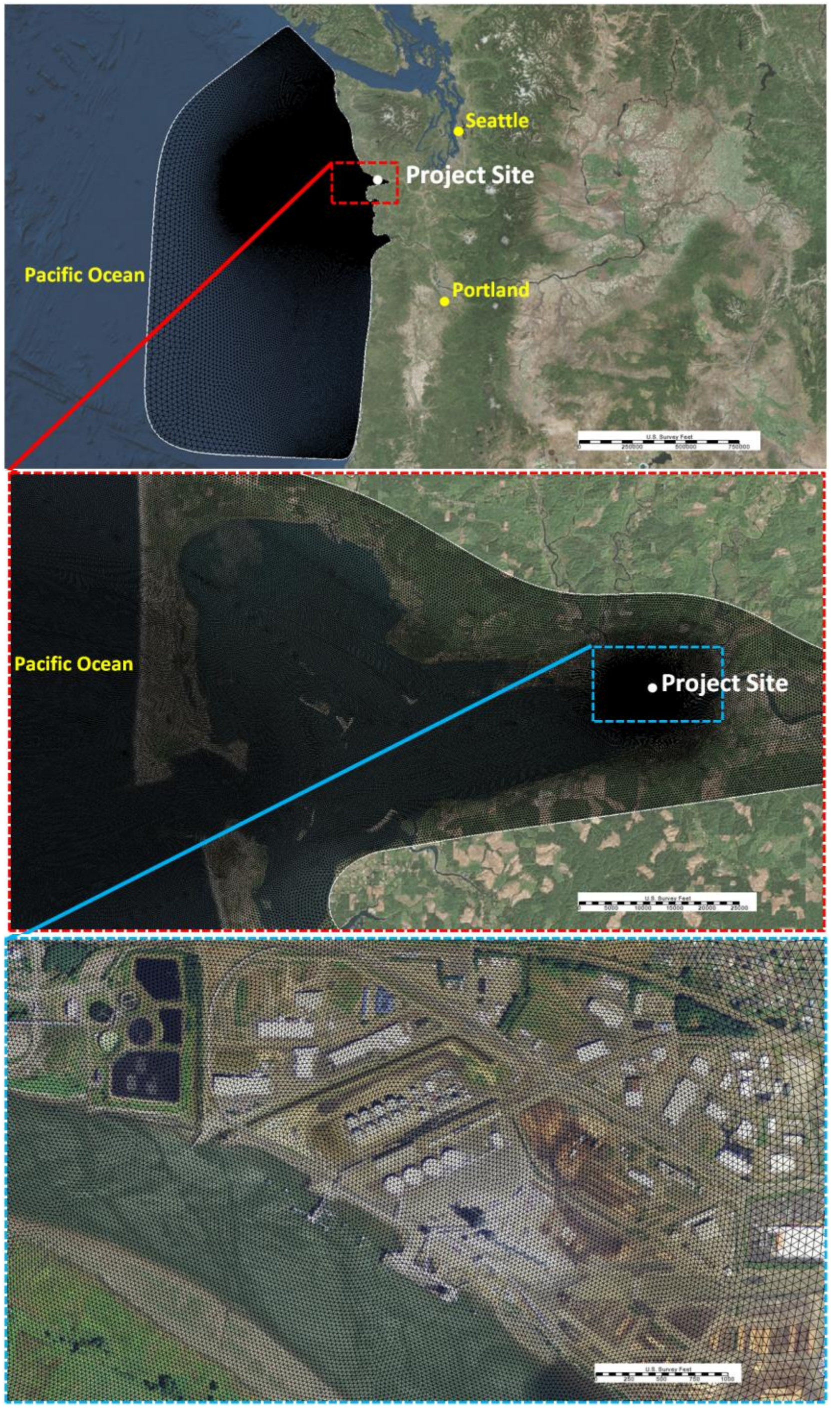

Figure 4. Three views of modeling grid extending approximately 200 miles offshore of project site

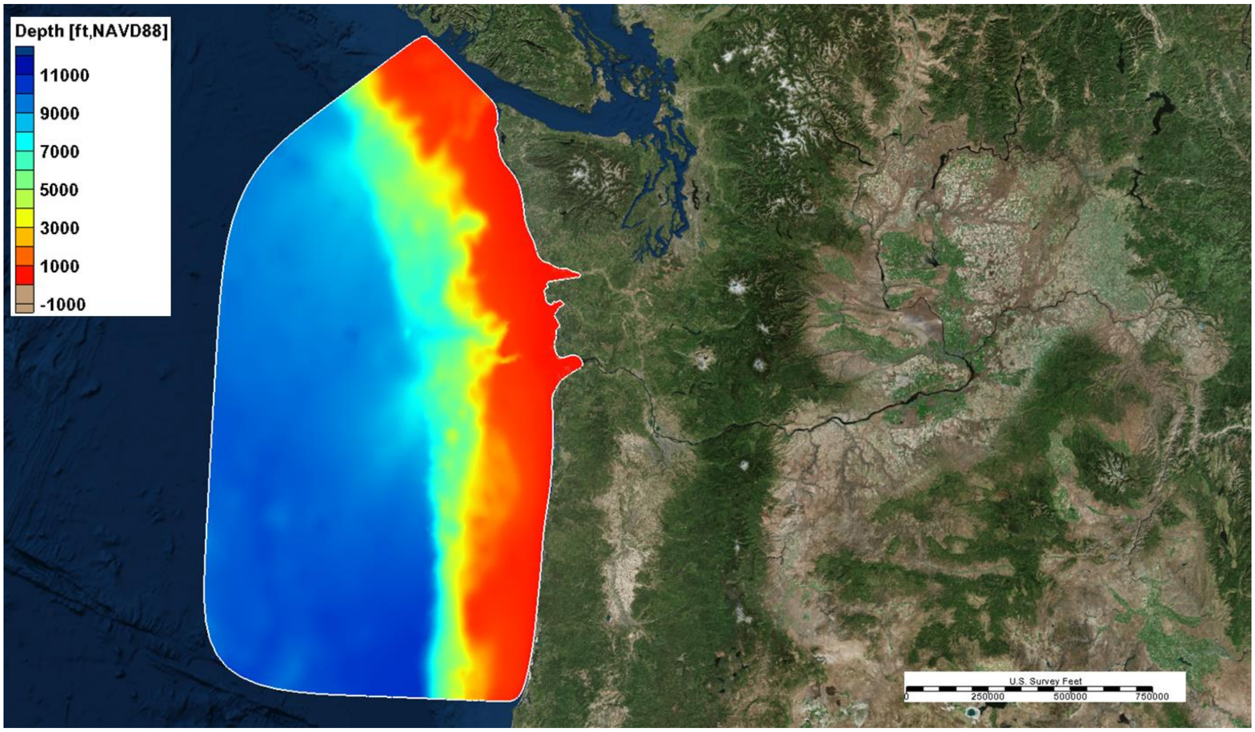

Figure 5. Model bathymetry for entire modeling grid used in numerical modeling

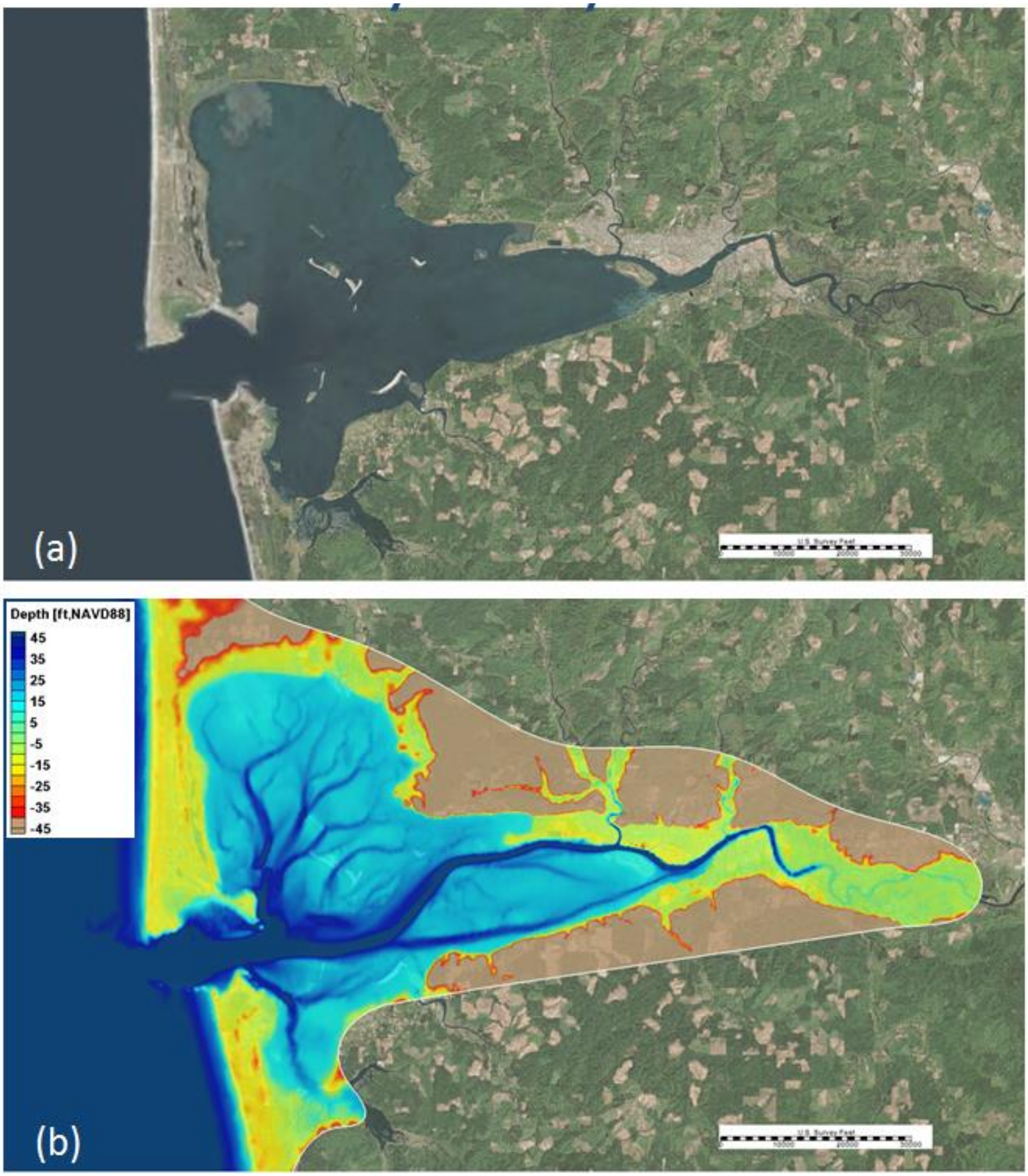

Figure 6. (a) Aerial imagery of Grays Harbor; (b) model bathymetry of Grays Harbor superimposed on aerial image used in numerical modeling

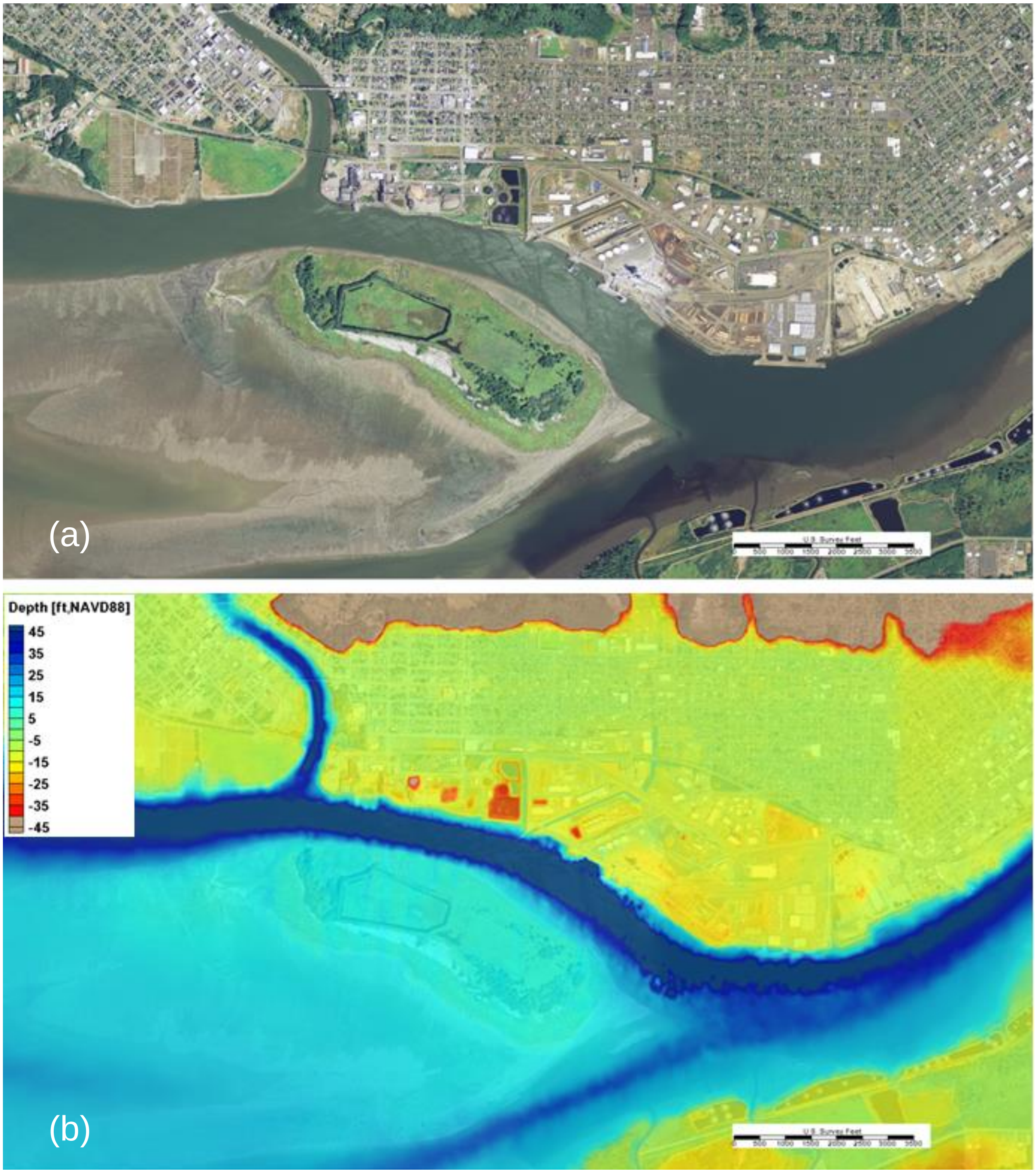

Figure 7. (a) Aerial imagery of Grays Harbor and Aberdeen; (b) model bathymetry of superimposed on aerial image used in numerical modeling

3.3. Tsunami Modeling Results

Figure 8 shows the extent of tsunami inundation (red line) in Grays Harbor and in the project vicinity. As discussed in Section 2.1, water surface elevations (the results of numerical modeling) were increased by a safety factor of 1.3 to account for uncertainties in overtopping of the berm predicted by the model. An adjustment was conducted by increasing tsunami surface elevation at each node of the model (tsunami elevation referenced to MHW elevation[1]), multiplied by the 1.3 safety factor. For example, if the modeling results at a specific point indicate tsunami water surface elevation to be at elevation +5.0 ft, referenced to MHW (or +12.82 ft referenced to NAVD88), the adjusted water surface elevation was computed to be:

= +5.0 ft, referenced to MHW × 1.3 (safety factor)

= +6.5 ft, referenced to MHW (or +14.32 ft referenced to NAVD88).

In order to satisfy no-overtopping criteria for these facilities, the post-earthquake berm crest elevation (after tectonic subduction, liquefaction settlement, and lateral spreading) should be equal to or higher than the water elevation shown in the figure. For this purpose, the maximum adjusted water surface elevations were extracted from the model along the berm, and are shown in Figure 9 and tabulated in Table 2. It should be noted that proper design of berm crest elevation to prevent overtopping requires an iterative exercise with adjustments in berm height.

Figure 8. Extent of tsunami inundation shown by red line along with modeling boundary shown by white line for (a) Grays Harbor; and (b) project vicinity

[1] All modeling results in terms of water surface elevation are referenced to NAVD88 elevation.

Figure 9 shows a plan view of the adjusted water surface elevations in the vicinity of the project site at the instant of maximum inundation for Scenario in color format 1. Red color corresponds to higher water surface elevations. The figure shows that water surface elevations generated by tsunami vary in the vicinity of the project site and are typically higher closer to the shoreline. The figure shows that both Imperium Terminals LLC and Westway Terminals Services would experience overtopping except for the high-elevation hill in the Imperium Terminals LLC site.

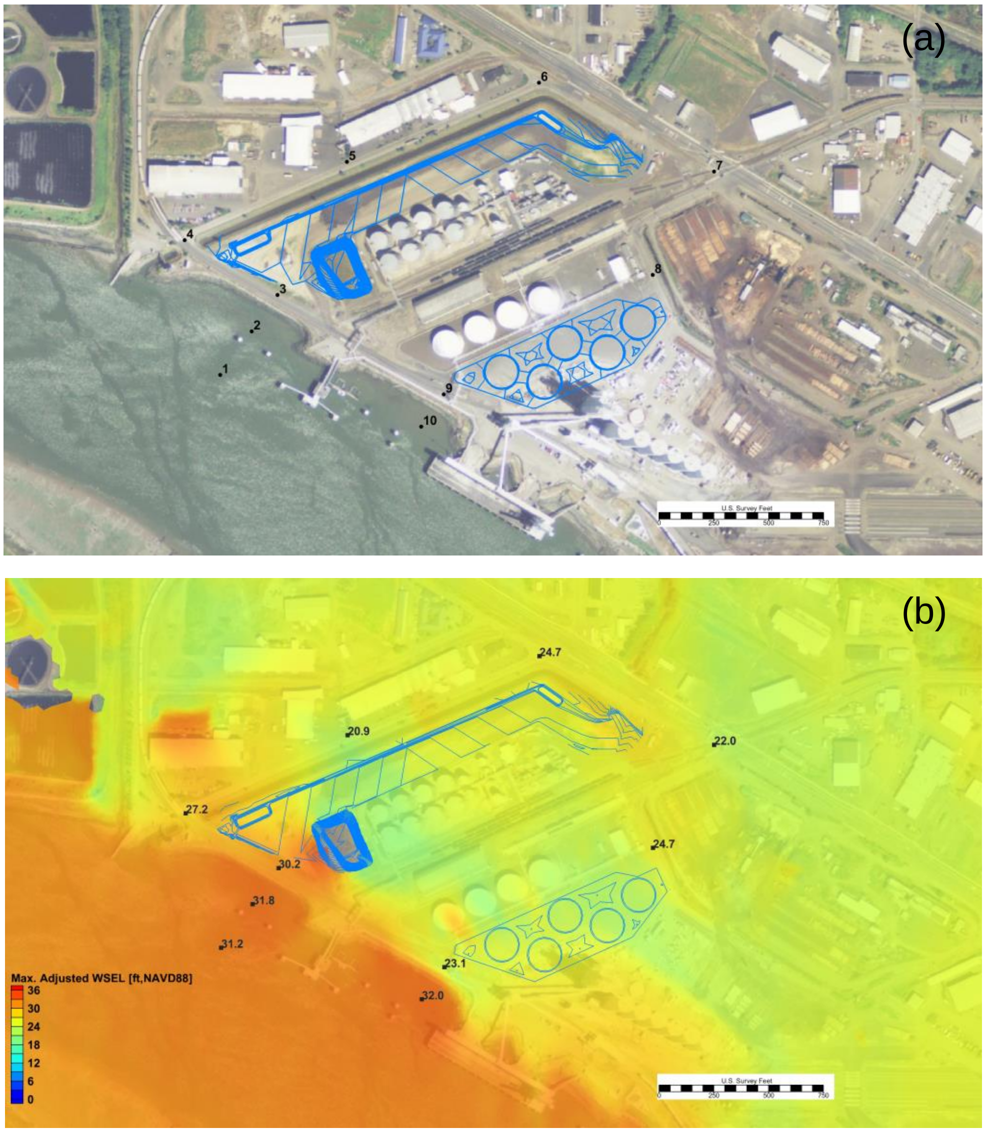

Figure 9. (a) Extraction points; and (b) maximum adjusted water surface elevations in project vicinity overlaid on aerial image for Scenario 1

Table 2. Results of Tsunami Hydrodynamic Modeling Extracted along Berm in terms of Adjusted Maximum WSEL for Scenarios 1 and 2

Pt #	Easting	Northing	Ground Elevation (ft,NAVD88)		Adjusted Maximum Water Surface Elevation (ft,NAVD88)	
	(UTM Zone 10, mNAD83)	(UTM Zone 10, mNAD83)	Prior to Earthquake	After Earthquake	Scenario 1	Scenario 2
1	434,681.5	5,201,756.1	-15.7	-18.6	31.1	32.1
2	434,725.3	5,201,816.6	-8.6	-11.5	31.8	32.7
3	434,761.2	5,201,867.1	3.9	1.0	30.2	31.1
4	434,632.2	5,201,943.3	4.6	1.6	27.2	28.2
5	434,857.6	5,202,052.1	4.9	1.9	20.9	23.3
6	435,124.5	5,202,162.0	4.3	1.4	24.7	25.6
7	435,367.8	5,202,038.6	4.5	1.6	22.0	23.3
8	435,282.6	5,201,895.1	2.9	0.0	24.7	26.4
9	434,992.2	5,201,729.1	4.2	1.2	23.1	23.9
10	434,960.8	5,201,684.3	-14.6	-17.5	32.0	32.9

Figures 10 and 11 demonstrate the extracted time history of adjusted water surface elevations and depth-averaged velocity respectively for point 1, offshore of the project site.

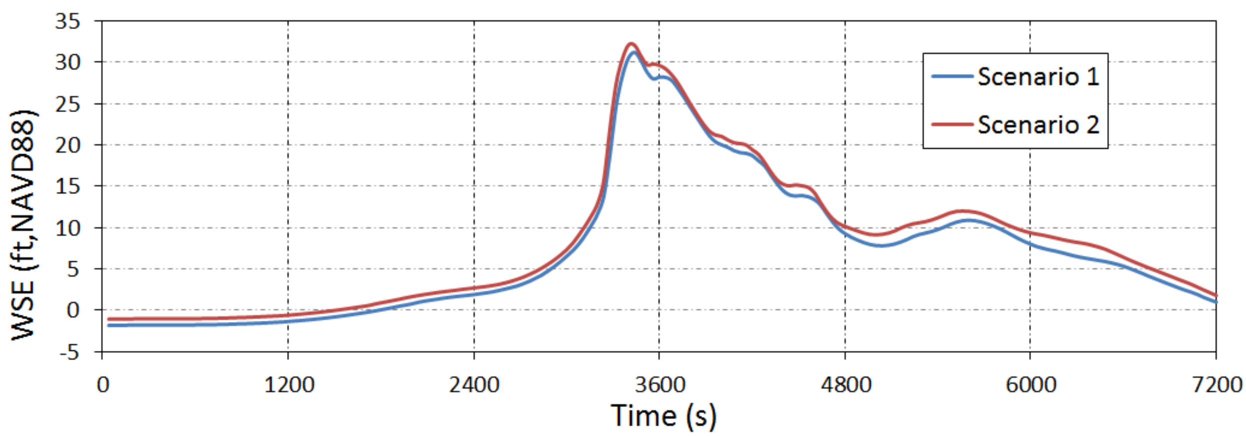

Figure 10. Time history of adjusted water surface elevations at extraction point 1 for Scenarios 1 and 2

The figure shows that water gradually starts to return after the rapid drop due to the earthquake. The tsunami wave arrives approximately at 3200 seconds past the earthquake and tsunami wave generation. The consequent waves are smaller than the first wave. It is also shown that accounting for Sea Level Rise (Scenario 2) results in slightly higher water surface elevations and larger velocities.

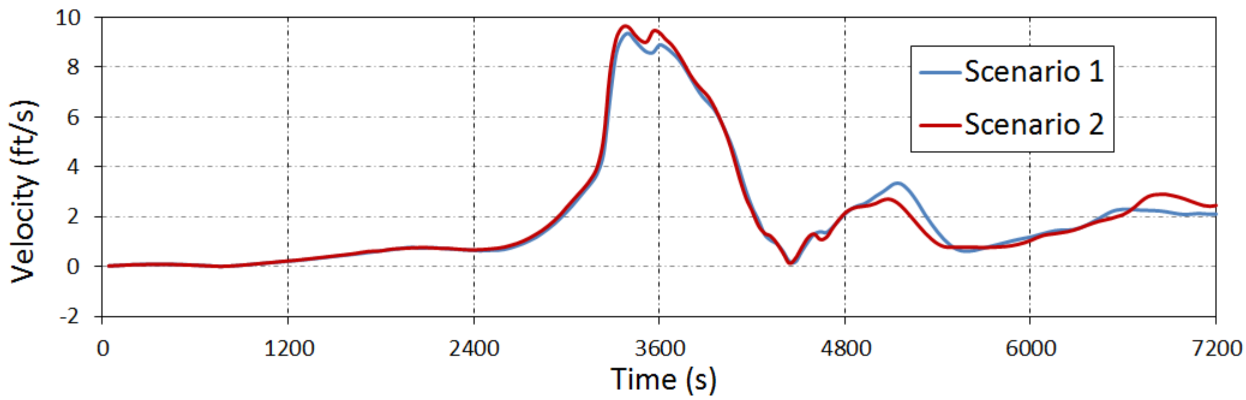

Figure 11. Time history of depth-averaged velocity by design tsunami event at extraction point 1 for Scenarios 1 and 2

3 Tsunami Force Calculations

Tsunami wave exerts forces on structures (obstacles to the flow) upon impact. Depending on the type of the structure and tsunami flow, the tsunami force can be comprised of the following components: (1) hydrostatic force; (2) buoyant force; (3) hydrodynamic force; (4) uplift force; (5) additional gravity loads from retained water on elevated floors. It should be noted that depending on the type of the structure, some of these components are not applicable. Force distribution for hydrostatic and hydrodynamic components is demonstrated in Fig. 12.

Calculation of tsunami forces herein is conducted according to FEMA P646 (2012)[2]. Results of force calculation for each tsunami force component are listed in Tables 3 and 4 for Westway Terminals LLC and Imperium Terminal Services Facilities, respectively. Calculation of floating debris impact force has been conducted assuming lumber or a wood log – oriented longitudinally as debris.

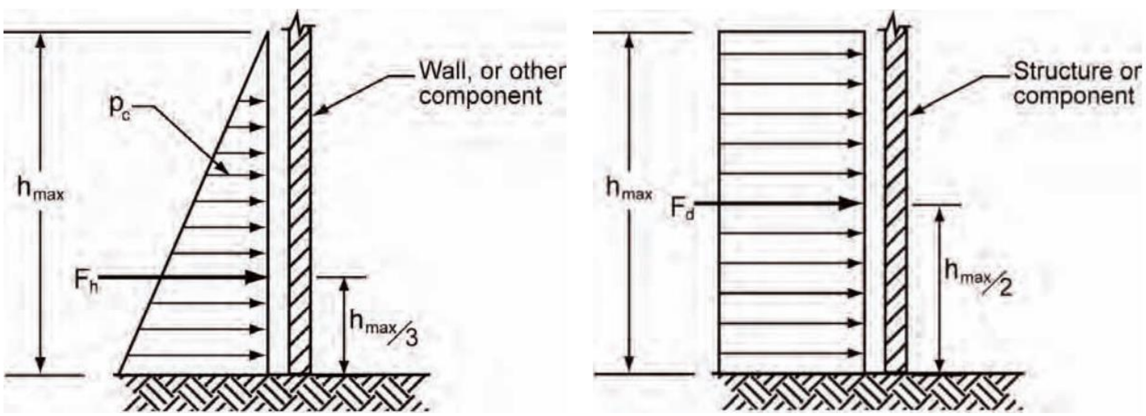

Figure 12. Force distribution and location of resultant force for tsunami Hydrostatic (left) and Hydrodynamic (right) force components (FEMA 2012).

[2] Please note that calculation of design runup elevation herein is conducted according to methodology described in Sections 2.1 and 3.3. This methodology has been previously approved by FERC and DOGAMI.

Table 3. Tsunami force calculations according to FEMA P646 (2012) for two scenarios: with and without Sea Level Rise for Westway Terminals LLC Facility

	Parameter	Symbol	Scenario 1	Scenario 2	Unit
Constants	Gravitational Acceleration	g	32.2	32.2	ft/s^2
	fluid density including sediments	ρ_s	2.3	2.3	$slugs/ft^3$
Inputs	Tank breadth (width)	b	150.0	150.0	ft
	Tank height	h_w	64.0	64.0	ft
	maximum water height above base	h_{max}	20.6	21.2	ft
	maximum momentum flux	$(hu^2)_{max}$	6130.6	6610.9	ft^3/s^2
	maximum runup	R	17.1	17.5	ft
	design runup elevation[2]	R^*	20.6	21.2	ft
	Drag Coefficient	C_d	2.0	2.0	-
	Hydrodynamic Mass Coefficient	C_m	0.0	0.0	-
	maximum flow velocity	u_{max}	19.0	19.5	ft/s
	mass of debris	m	30.8	30.8	slugs
	effective stiffness of debris	k	1.7E+05	1.7E+05	lbf/ft
Calculations	Hydrostatic Force	F_h	2,386	2,533	Kips
	Hydrodynamic Force	F_d	2,143	2,311	Kips
	Impulsive Force	F_s	3,214	3,466	Kips
	Floating Debris Impact Force	F_i	56	57	Kips
	Damming Force	F_{dm}	2,143	2,311	Kips

Table 4. Tsunami force calculations according to FEMA P646 (2012) for two scenarios: with and without Sea Level Rise for Imperium Terminal Services Facility

	Parameter	Symbol	Scenario 1	Scenario 2	Unit
Constants	Gravitational Acceleration	g	32.2	32.2	ft/s^2
	fluid density including sediments	ρ_s	2.3	2.3	slugs/ft^3
Inputs	Tank breadth (width)	b	95.0	95.0	ft
	Tank height	h_w	65.0	65.0	ft
	maximum water height above base	h_{max}	25.5	26.4	ft
	maximum momentum flux	$(hu^2)_{max}$	4184.8	4598.0	ft^3/s^2
	maximum runup	R	20.7	21.4	ft
	design runup elevation	$R*$	25.5	26.4	ft
	Drag Coefficient	C_d	2.0	2.0	-
	Hydrodynamic Mass Coefficient	C_m	0.0	0.0	-
	maximum flow velocity	u_{max}	18.4	16.0	ft/s
	mass of debris	m	30.8	30.8	slugs
	effective stiffness of debris	k	1.7E+05	1.7E+05	lbf/ft
Calculations	Hydrostatic Force	F_h	2,320	2,490	Kips
	Hydrodynamic Force	F_d	926	1,018	Kips
	Impulsive Force	F_s	1,389	1,527	Kips
	Floating Debris Impact Force	F_i	54	47	Kips
	Damming Force	F_{dm}	926	1,018	Kips

4 Summary and Conclusions

Numerical simulation of tsunami generation and inundation was conducted to assess potential impacts and overtopping at the Westway Terminals LLC and Imperium Terminal Services Facilities. It was found that the berm surrounding the Westway Terminals LLC and Imperium Terminal Services will be overtopped.

Analysis also resulted in computation of tsunami forces on the tanks of the Westway Terminals LLC and Imperium Terminal Services Facilities. The forces are presented in Tables 3 and 4 and should be accounted in the structural design of the project.

It is shown that accounting for Sea Level Rise (Scenario 2) results in slightly higher water surface elevations, larger velocities and tsunami forces.

5 References

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