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DESIGN OF A TSUNAMI VERTICAL EVACUATION REFUGE ON THE WASHINGTON COAST

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ABSTRACT: Due to its ability to generate both intense seismic ground shaking and a subsequent tsunami, the Cascadia Subduction Zone presents a unique geologic risk to coastal residents in the Pacific Northwest. The proximity of the subduction zone to the coasts of Vancouver Island, Washington, and Oregon results in tsunami arrival times of thirty minutes or less. For some locations in Washington, residents lack access to natural high ground to safely evacuate within this time. In order to help address this risk, the community of Westport, Washington recently approved construction of a replacement elementary school with integrated tsunami vertical evacuation refuge. Scheduled for completion in early 2016, this facility will provide students, faculty, staff, and the public access to a rooftop safe refuge designed for the maximum considered tsunami. The lateral force-resisting system in the safe refuge consists of concrete walls to resist seismic and tsunami inundation forces while having inherent ductility and toughness for impact loads. A steel-framed roof is supported on beams and columns proportioned to prevent progressive collapse for extreme impact forces. Foundation piles were designed to resist both earthquake-induced liquefaction and tsunami-induced scour and lateral forces.

1. Introduction

The 1,000 km long Cascadia Subduction Zone (CSZ) presents a unique hazard to coastal communities in both Canada and the United States. The close proximity of the fault to the coast means that some communities may have as little as thirty minutes of available evacuation time before a CSZ-induced tsunami reaches shore. For some communities, this is not enough time for horizontal evacuation to high ground and other options must be considered.

In 2013, voters in Westport, Washington decided to invest in the safety of their school children by funding the first tsunami vertical evacuation refuge in the country (Doughton, S. 2013). As shown in Figure 1, the safe refuge will be located on a rooftop of the replacement elementary school and is designed to house over 1,000 occupants; including the approximately 700 students, faculty, and staff who make up the school campus. The safe refuge is located at an elevation of 16.2 m above sea level (8.5 m above adjacent grade) and was designed using tsunami-resistant building code provisions slated to be adopted in the US later this decade.

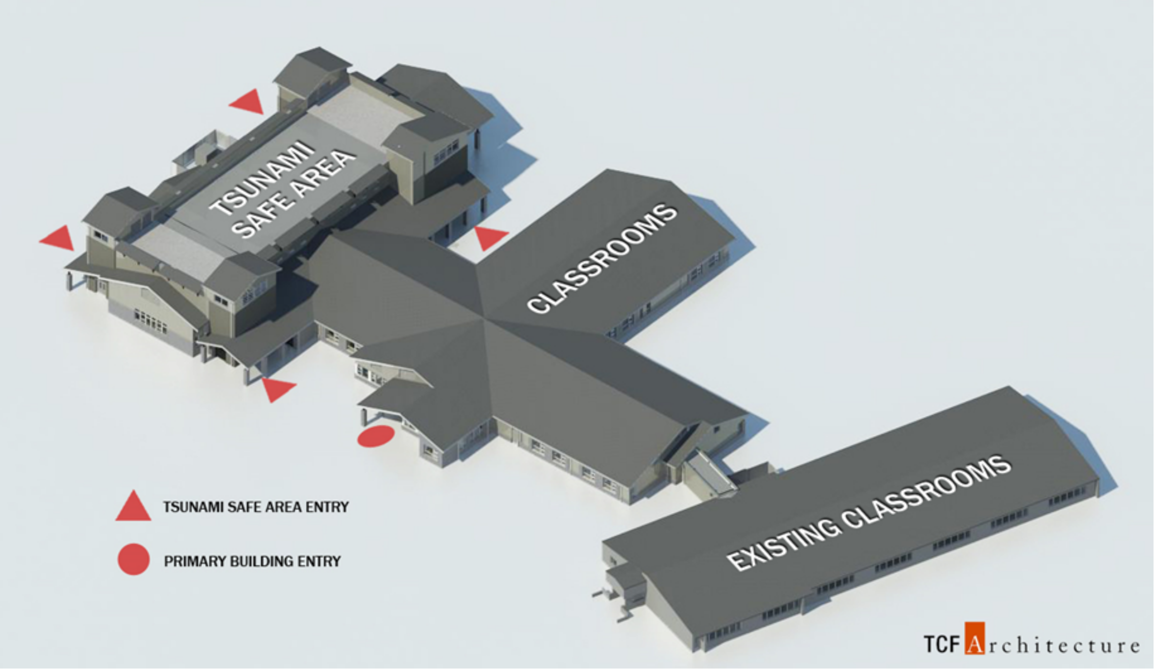

Fig. 1 – Ocosta Replacement Elementary School Rendering (courtesy TCF Architecture). North is at upper left

2. Project Background

The groundwork for the Ocosta Elementary School project began with Project Safe Haven in 2011 (Freitag, B. et al). As mapped by the Washington Department of Natural Resources, the school campus (along with much of the Westport peninsula, see Figure 2) is within a known tsunami hazard zone (Walsh, T. 2000). The school is aware of this hazard and has regular evacuation drills where the school population moves to the second story of the adjacent high school. This 1980's-built facility was not designed to resist tsunami forces nor does the elevation of the second floor necessarily meet current minimum elevation requirements for safe refuge.

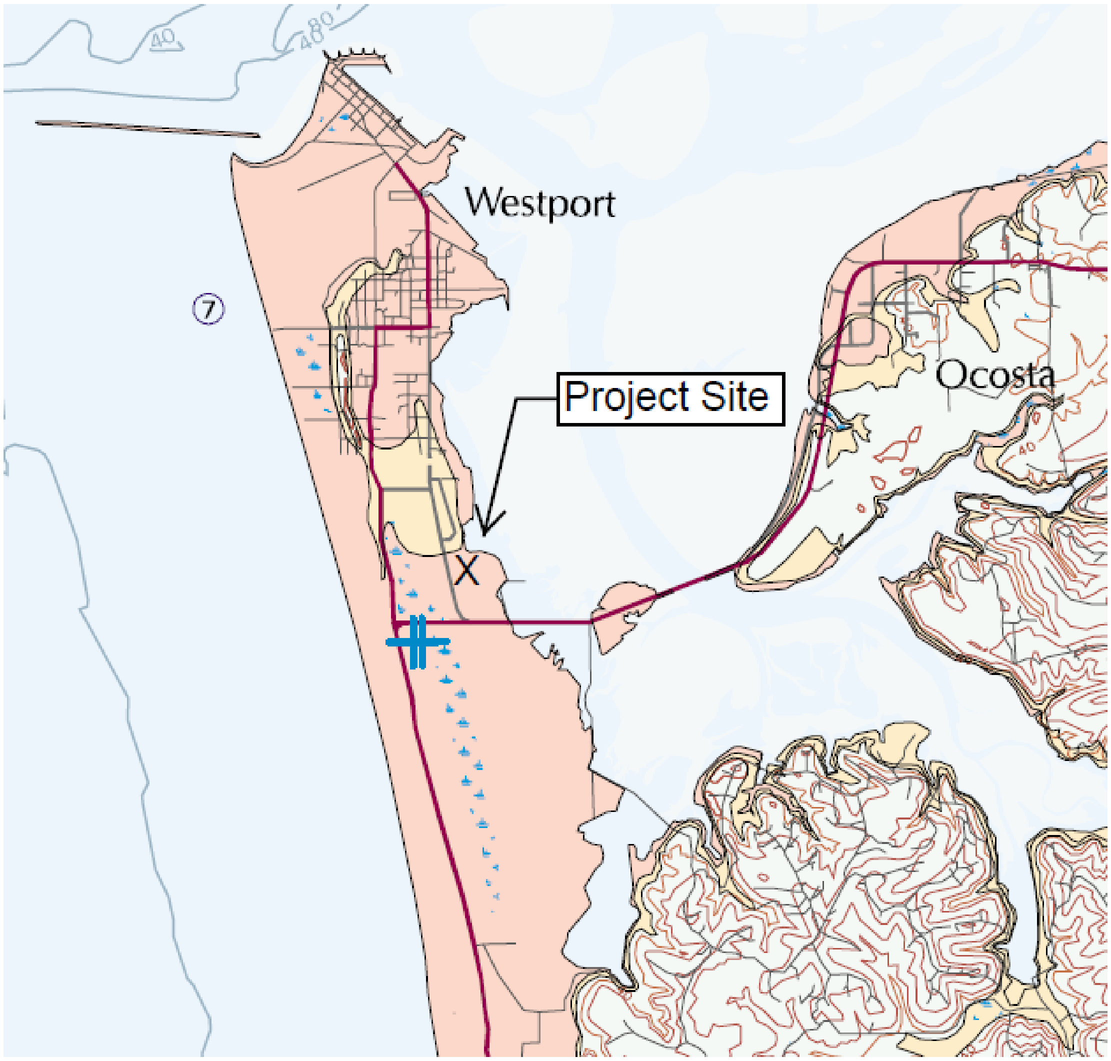

Fig. 2 – Project Site within the WA DNR Mapped Tsunami Hazard Zone

Although the hazard posed by a CSZ-induced tsunami has been known for decades, Project Safe Haven was the catalyst for actively engaging local communities in mitigation-related discussions. These discussions intentionally brought together local leaders such as politicians, school administrators, and emergency managers along with the general public. When talks of a replacement elementary school for Westport began in 2012, these leaders were able to successfully integrate the scientific information presented during Project Safe Haven into the plans for the new building. Widespread community support of this building was confirmed in April 2013 when 70% of voters approved the bonds necessary for constructing the new school, a notable accomplishment considering previous bond measures (without the safe refuge component) all had failed to gain voter approval.

3. Tsunami-Resistant Design Code Status in the United States

Tsunami-resistant design has yet to be formally incorporated into US building codes. However, in 2008 the Federal Emergency Management Agency published P-646 (FEMA, 2008) as a document which could eventually be developed into a design standard. This document was updated with a second edition published in 2012 (FEMA, 2012). The first edition of P-646 was included as an optional reference in the 2012 International Building Code (ICC, 2012) although this was not officially adopted in Washington State.

Over the past several years a committee within the American Society of Civil Engineers (ASCE) has been building upon the FEMA work by developing design provisions for inclusion in the 2016 version of the ASCE 7 Standard: Minimum Design Loads for Buildings and Other Structures. (http://www.asce.org/structural-engineering/news/20140123-new-chapter-on-tsunami-design-in-asce-7-16/). ASCE 7-16 will be referenced by the 2018 IBC meaning that certain buildings in the western U.S., Hawaii, and Alaska will be required to be designed for tsunami loads and effects once those states adopt the 2018 IBC.

3.1. Design Tsunami Definition & Site-Specific Inundation Modeling

FEMA P-646 and ASCE 7-16 both define a Maximum Considered Tsunami (MCT) to be used for structural design purposes. This is similar to the definition of a Maximum Considered Earthquake (MCE) in that it is based on an event with a 2% probability of exceedance in 50 years or one with a nominal 2,500-year return period.

For many coastal locations, the CSZ represents both the design earthquake and design tsunami. From a performance-based design standpoint, this means that a vertical evacuation structure must be designed to resist the MCE and have remaining strength to resist a subsequent MCT.

In order to accurately capture site effects and determine design parameters, ASCE 7-16 will require a site-specific tsunami inundation analysis for all vertical evacuation structures. This is similar to site-specific seismic hazard analysis which is typically performed for higher risk category buildings or those with higher seismic performance expectations.

For the Ocosta Elementary School project, the site-specific inundation modeling work was completed by a University of Washington team led by Frank Gonzalez using GeoClaw, a benchmarked modeling software (Gonzalez, F. et al, 2013). This software utilizes a detailed three-dimensional digital elevation model of the adjacent topography and offshore bathymetry near the building site as an initial input. The software then uses wave propagation and conservation law equations to compute an inundation time history beginning with the initial modeled fault rupture. For the Ocosta project, a series of sensitivity analyses were performed to account for variables such as scour-induced erosion, sea level rise, and co-seismic coastal subsidence.

As its output, GeoClaw can provide a range of values useful for design. As shown in Figures 3 & 4, these range from flow depth, flow velocity, and inundation arrival time at the subject location. Model results indicate that the maximum depth is approximately 1.5 m and the maximum velocity is 1.2 m/s. Including safety factors and minimum design values from ASCE 7-16, the safe refuge was designed for 4.4m flow depth and 3.0 m/s velocity.

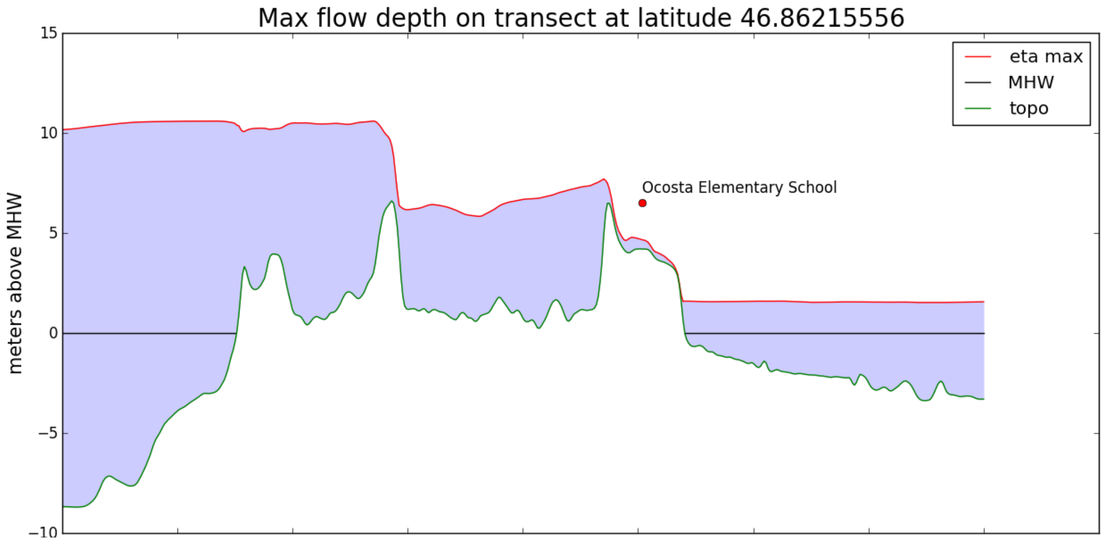

Fig. 3 – West-East Transect Showing Inundation Results

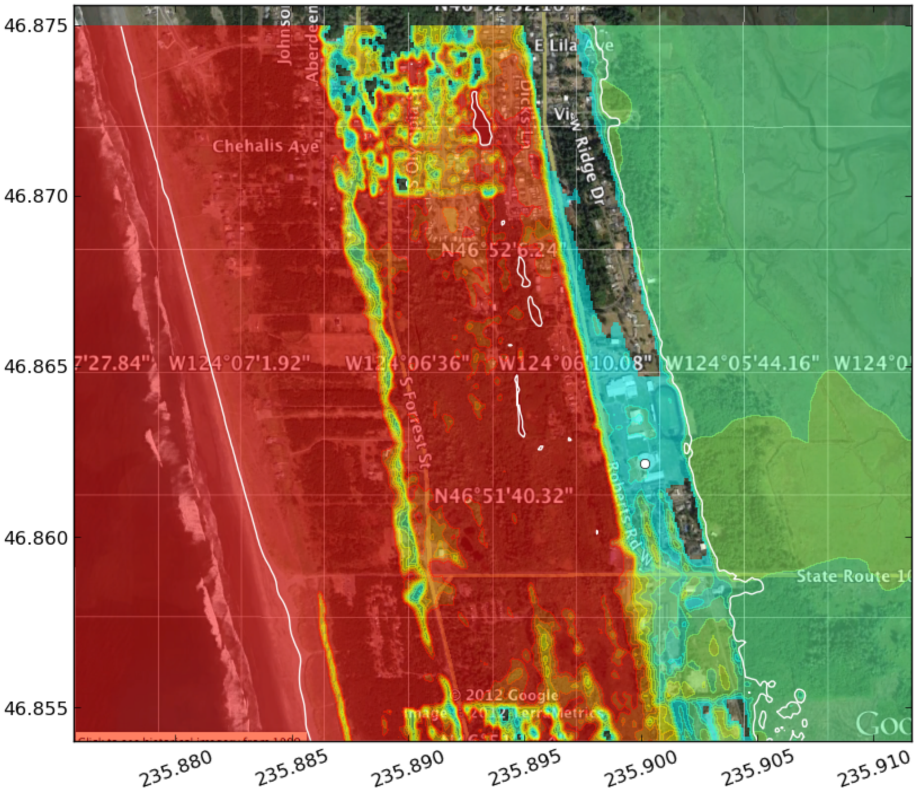

Fig. 4 – Inundation Depth Result Overlaid on Satellite Image of Site

4. Building Design Features

As shown in Figure 1, the tsunami safe refuge will be located on the roof of the northernmost wing of the replacement elementary school. To the south of this will be a new one-story classroom wing which will then connect to an existing classroom building at the southernmost end of the site. Neither classroom wing was designed as a safe refuge; however they are seismically-separate from the safe refuge.

4.1. Functional Considerations

The design team was led by TCF Architecture in Tacoma, WA and one of the initial design challenges was to integrate the tsunami safe refuge into a functional elementary school. The northern wing will house the cafeteria, music room, and gymnasium and, due to the interior height requirements for the gym, this made a logical choice for the safe refuge.

Access to the roof will occur via the four stair towers located at the building corners. Building code requirements do not specifically address this type of ingress situation but each tower will have two pairs of doors. The ingress doors will open into the stairwell and the egress doors will open out of the stairwell. Overall stair sizing was based on the area and capacity (1,000 people) of the safe refuge.

The safe refuge is intended to be accessible at any time and several active and passive security measures are provided to ensure the doors can be opened event in the event of a power outage. In order to maintain security at the school, all of the stairwell doors open to the outside. This prevents someone from accessing the stairs and then making it inside of the school.

Safe refuge occupants are intended to remain for only a short period of time until the inundation recedes. Therefore only limited emergency supplies will be provided by the school and there are no provisions for power, running water, or toilets on the rooftop safe refuge.

4.2. Performance-Based Design Requirements

Due to the fact that the safe refuge structure must first resist the MCE before being subjected to the MCT, performance-based design was utilized for both the foundations and superstructure design. The foundation piles were designed to resist post-liquefaction down drag forces and therefore have reduced capacities available to resist the subsequent inundation forces. Pile ultimate capacities were reduced by the liquefaction down drag forces when considering tsunami loading conditions and pile lengths were selected to avoid a 15m deep liquefiable soil layer so as to minimize the effects of down drag.

For the superstructure design, ASCE 7-16 will not require that post-earthquake damage to the structural system be explicitly considered. The expectation is that a properly-designed structure has sufficient reserve capacity to resist both a design earthquake and then tsunami forces. For the Ocosta project, shear walls and foundations were proportioned to have moderate demand to capacity ratios so as to limit the likelihood of significant damage and deterioration during the earthquake.

4.3. Tsunami-Induced Scour Effects

As observed in past tsunami events, sandy or loose soils can experience significant scouring which can result in exposure or undermining of foundation elements. Depending on flow depth calculated for the site, ASCE 7-16 will require that foundations be designed for up to 3.7 m of scour depth. Foundations must also be designed for an initial flow cycle at 80% of MCT depths and then a subsequent flow cycle at 100% of MCT. The result is that the initial flow cycle will cause scour (and corresponding weakening of pile foundations) and the effects of the subsequent cycle must be resisted by the remaining pile capacities. As scour occurs at the building perimeter, this was accounted for by reducing the stiffness of these piles in the mathematical model. This increases the forces on the non-scoured piles which was a critical loading condition for some piles. A 30 cm thick structural slab on grade was used at the first floor of the safe refuge building to serve as a horizontal diaphragm to distribute forces to the interior, non-scoured piles.

4.4. Foundation System

A geotechnical investigation of the site revealed the presence of two near-surface liquefiable soil layers; the first at 6 m deep and the second beginning at 15 m deep. This, combined with the potential for tsunami-induced scour, led to the decision to use a pile foundation system. As shown in Figure 5, a series of 60 cm diameter auger-cast grout piles were used to support the safe refuge while 45 cm diameter piles were used to support the classroom wing. All pile depths were selected to avoid the deeper liquefiable layer and, as required by code, all piles are interconnected with pile caps and grade beams.

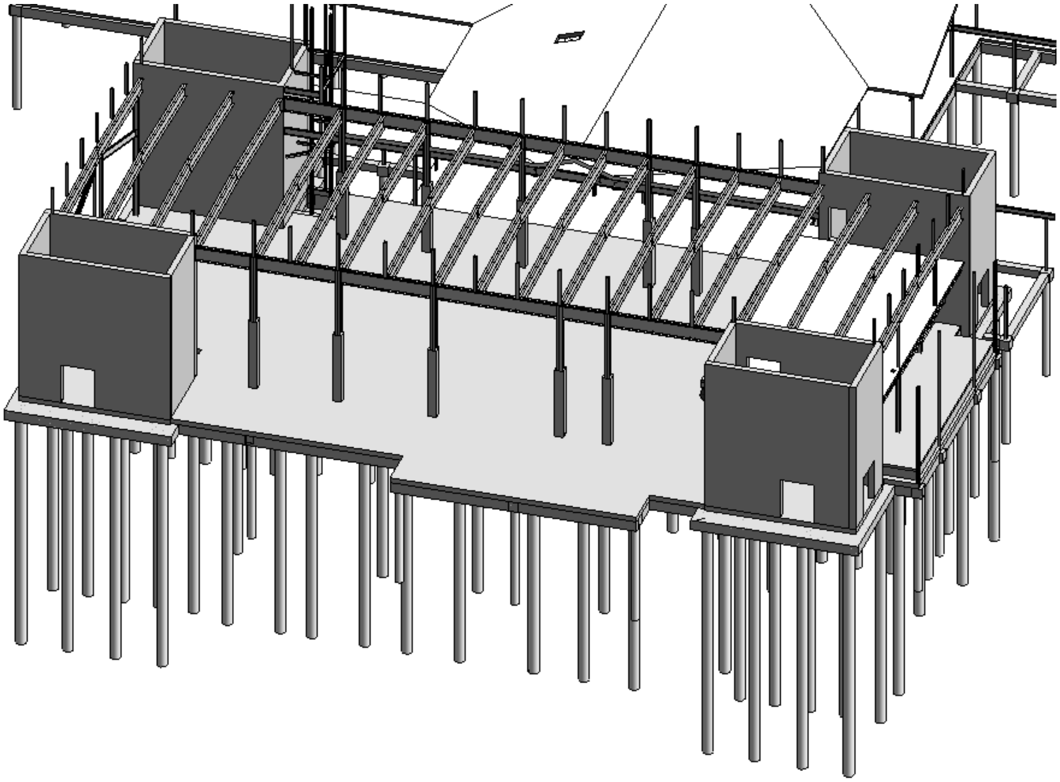

Fig. 5 – Activity Wing Structural System Schematic

4.5. Structural System

The structure of the safe refuge consists of a concrete over metal deck roof slab supported by structural steel beams and columns. Reinforced concrete shear walls at the four corner stair towers provide lateral resistance and also resist various tsunami load effects. The classroom wing is seismically-separate and its structure consists of a metal roof deck supported by steel open-web joists and structural steel girders and columns. Steel special concentric braced frames provide lateral resistance in the classroom wing and this portion of the building is not designed to resist tsunami loads and effects.

Concrete shear walls were selected for the safe refuge structure due to the observed favorable performance of concrete structures in other recent tsunami events. The concrete walls have an inherent combination of mass, strength, and ductility that provides resistance to inundation and impact forces while maintaining residual capacity if moderately damaged. As mentioned above, access and exiting requirements necessitated the four stairwells and enclosing each tower with 36 cm thick concrete walls was sufficient to resist the design loads.

In order to validate the design, a range of tsunami-induced load cases and combinations from ASCE 7-16 were considered. These load cases included hydrostatic forces where water levels vary on opposite side of an element, hydrodynamic forces that are generated from the flowing water, and impact forces which are imparted by carried debris. Tsunami load combinations in ASCE 7-16 includes likely combinations of inundation flow and velocity states which were either observed in past events or validated through experimental research.

4.6. Hydrostatic Forces

Hydrostatic forces are generated when water level varies on opposite sides of an element. During a tsunami, this can occur in buildings because the water elevation on the outside of the building increases faster than the water level inside of the building. In past tsunami events, buildings on shallow foundations or with inadequate pile anchorage have become buoyant and toppled due to this effect combined with hydrodynamic forces.

The safe refuge structure was designed to resist buoyancy effect by assuming the water level is at its maximum outside of the building and the interior of the building is not yet inundated. Large uplift forces are developed from the 4.4 m of differential water depth and these forces were resisted through skin friction on the auger-cast grout piles.

The concrete stair walls were the only elements explicitly designed for unbalanced hydrostatic forces as the doors may be able to resist these forces without failing. It was assumed that the metal stud-framed perimeter walls would fail at this water level and allow water to flow inside of the building. Failure of these metal stud walls would not be detrimental to the overall performance of the building.

4.7. Hydrodynamic Forces

The flow of water during a tsunami results in hydrodynamic forces which are applied to both the exposed exterior surfaces of the building and to individual building elements assuming that the flowing water eventually penetrates the exterior envelope. The orientation of the safe refuge was such that the narrow dimension faces west towards the coast and the resultant overall hydrodynamic forces were equal to approximately 25% of the seismic base shear. Therefore, hydrodynamic forces did not control the overall design of the lateral system, however, when scour effects were considered on the peripheral piles these forces did increase the demands on selected interior piles and controlled their design.

Hydrodynamic drag forces on individual elements such as columns, stair towers, and wall piers imparts unit forces higher than the drag forces for the overall building. The forces on individual elements do not need to be applied concurrently with the overall hydrodynamic forces. In general, these individual element forces did not control the design of elements that were otherwise designed for impact force resistance.

4.8. Impact Forces

Impact forces and effects presented several design challenges. ASCE 7-16 will require consideration of debris impact from logs, vehicles, ships, and containers. Each impact type has specific analysis or loading requirements. Since the project site is not within a port or container yard influence area, the impact forces considered the design were those due to wood logs, vehicles, and submerged tumbling boulders.

Of these three, the wood log impact generates the highest demands on the structure and is likely to result in non-linear component response. A work-energy method was used to evaluate the steel gravity columns to verify their adequacy. In addition, the steel wide-flange columns are concrete-encased to further protect against impact and local damage to the flanges.

Passenger vehicles experience deformation upon impact which reduces the magnitude of the imparted force on the building structure. The submerged tumbling boulder impact does result in higher forces than vehicles do but it is still significantly less than the wood log impact force.

4.9. Alternative Performance-Based Criteria

Due to the potential for high local element demands in a tsunami, ASCE 7-16 will also allow for nonlinear analysis procedures for evaluating component demands. Acceptance criteria are typically taken from published standards for the seismic retrofit of existing structures. For the design of the safe refuge, only the impact forces are expected to result in inelastic response for the concrete walls and steel gravity columns.

Design for these extraordinary impact loads was performed by checking the residual structural capacity per ASCE 7-10 Section 2.5.2.2 (ASCE, 2010). The concrete shear walls were evaluated by determining if failure of an individual pier or wall segment would result in collapse of the wall. The steel gravity columns supporting the safe refuge roof were evaluated by designing moment-resisting beam-column connections at the roof level such that the loss of an individual column would not result in collapse of the roof structure. The low roof areas and mechanical mezzanine in the safe refuge building were detailed such that their failure or partial collapse would not induce failure of the roof structure.

5. Conclusions

The tsunami safe refuge at the Ocosta, Washington school campus was designed using tsunami loads and effects requirements contained in the upcoming ASCE 7-16 standard. A site-specific inundation model was performed to determine flow depth and velocity at the site for design purposes. The foundation and superstructure was designed for the maximum considered earthquake followed by the maximum considered tsunami. Once open in early 2016, it will provide a vertical evacuation refuge for over 1,000 students, faculty, staff, and neighboring residents in the event of a Cascadia Subduction Zone tsunami.

6. Acknowledgements

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