

Tsunami Vertical Evacuation Structures (TVES)

Bringing High Ground to a Location Near You!



The ground shakes and a magnitude 9 earthquake originating from the Aleutian Trench Subduction Zone *Drops* people to their knees. They *Cover* and *Hold* until the shaking subsides. Taking the shaking itself as their tsunami warning, coastal people immediately start to evacuate to higher ground knowing they may have only 15 to 30 minutes before the first tsunami wave. But in some areas high ground may be several miles away. Even where it is closer, children, the elderly, and the physically challenged, may not be able to reach safety in time. Fortunately, Tsunami Vertical Evacuation Structures (TVES) can make “high ground” closer.



Drop-Cover-Hold on
...until shaking stops
...then move quickly
to high ground!

Objectives

This four-part activity provides participants an opportunity to learn about Tsunami Vertical Evacuation Structures (TVES) and to be able to apply and interpret their learning. Student Worksheets include:

- Part A:** Participants discover basic concepts about Vertical Evacuation location and structural design by answering questions using background resources.
- Part B:** Given a specific city, participants determine appropriate locations for TVES using a Tsunami Inundation Map and City Street maps.
- Part C:** Participant groups design and then construct berm (artificial high ground created from soil) and tower models for the sites selected in Part B.
- Part D:** Participants present their models to an audience explaining how their site was chosen, the type of structure selected, and how the model was designed and built as the best solution for vertical tsunami evacuation.

References for Alaska Tsunami Info:

Tsunami Mitigation in Alaska:
<https://ready.alaska.gov/Plans/Mitigation/Tsunamis>
Alaska tsunami Inundation Maps:
<http://earthquake.alaska.edu/tsunamis/atom>

NGSS Science Standards

- From Molecules to Organisms—Structures and Processes: MS-LS1-8
- Ecosystems—Interactions, Energy, and Dynamics: MS-LS2-1, HS-LS2-1, MS-LS2-4, HS-LS2-7, HS-LS2-8
- Motion and Stability—Forces and Interactions: HS-PS2-1, MS-PS2-2
- Energy: MS-PS3-1, HS-PS3-2, HS-PS3-2, MS-PS3-5
- Waves and Their Applications in Technologies for Information Transfer: MS-PS4-1, MS-PS4-2
- Earth’s Systems MS-ESS2-2, HS-ESS2-2, MS-ESS2-3
- Earth and Human Activity: HS-ESS3-1, MS-ESS3-2
- Engineering Design: MS-ETS1-1, HS-ETS1-1, HS-ETS1-3

This activity was prepared by Bonnie Magura, retired teacher Portland Public Schools, education consultant. With assistance from Roger Groom and his 8th grade class at Mount Tabor Middle School, Portland OR.

Teacher Notes

The purpose of the activity is to provide students/participants an opportunity to learn about vertical evacuation and to learn about the components of vertical evacuation towers and berms by building a model. The model suggests a safe elevation of 25' however, the elevation changes a great deal by location along the Alaska coastlines. The teacher/presenter may wish to create an accurate safe height for their specific area.

This activity was developed using an actual study in developed in 2011 by the University of Washington under a funding by the National Tsunami Hazard Mitigation Program. The report titled "Project Safe Haven" was a critical reference for developing the activity. Though teachers will want to use a site that is specific to a study area in Alaska, it is useful to see how a similar areas without access to natural high ground was studied in Pacific, Grays Harbor and Clallam Counties of Washington State.

These solutions include proposing the locations and types of safe haven structures that should be designed to withstand forces of magnitude 9.1 Cascadia Subduction Zone earthquake and the resulting tsunami waves. Project Safe Haven explored the use of four different types of vertical evacuation structures, including towers, berms, tower-berm combinations, and buildings (such as fire stations and parking garages)

Background Resource for Parts A–D

Part A: Learning About Tsunami Vertical Evacuation Structures

Source A: Washington Emergency Management Division; Project Safe Haven: Tsunami Vertical Evacuation on the Washington Coast for Pacific County. Download pages from:
www.mil.wa.gov/uploads/pdf/emergency-management/final-report-2016-11-21-16.pdf

Source B: FEMA (Federal Emergency Management Agency) P646 Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (Publication 176 pages). Download pages from:
<http://www.fema.gov/library/viewRecord.do?id=3463>

Tsunami Vertical Evacuation Video—Well worth watching!!!

An excellent FEMA video on TVES spells out all the forces acting on a building during a tsunami:

- Hydrostatic force
- Buoyant (vertical force)
- Hydrodynamic drag force (fluid density & building geometry are used to calculate)
- Debris impact forces (floating debris such as building materials, vehicles, etc.)
- Debris Dams alter the forces.

As well as describing the needs of a structure to withstand the strong forces:

- Open systems
- Ductile systems
- Redundant systems
- Foundation systems.



<https://www.fema.gov/media-library/assets/videos/79474>

Background Resources for use with Part A

Modeling a Subduction Zone Earthquake Hazard Scenario

To analyze the effects of a worst-case scenario tsunami, Project Safe Haven, on the Washington coast, used a modeled subduction zone earthquake hazard scenario¹. Additional information from the Cascade Region Earthquake Workgroup² was combined with the model. The scenario is a local Cascadia subduction zone magnitude 9.1 earthquake. An earthquake of this size occurs off the Washington coast every 300-500 years, on average, with the last taking place in January 1700 AD.

A local subduction zone earthquake in this area will:

- Originate approximately 80 miles off of the Pacific Northwest coast.
- Likely cause six feet of land subsidence (dropping of the land) along the coast.
- Have shaking that lasts four or more minutes.
- Create a tsunami that will reach the coast approximately 20–40 minutes³ after shaking stops.

If the tsunami wave model for a given region suggests about half an hour is available for evacuation, only 25 minutes of that time (after the ground stops shaking) will be left after people reorient themselves following the earthquake and prepare to evacuate. The earthquake will cause extensive destruction to local infrastructure and buildings and will result in tremendous debris on roadways and other property. For example, people at most locations on the Long Beach and Tokeland peninsulas in Washington will only be able to evacuate on foot. As an additional margin of safety, the estimated on-foot evacuation time was reduced to 15 minutes, to take into account the physical and emotional turmoil people experience during and after a major earthquake.

According to the model, the primary tsunami wave in this area is approximately 22 feet⁴ at the western shore, with some variation depending upon local ocean floor and land differences. Several other tsunami waves will likely follow the initial wave, and the danger of repeated waves will last throughout one entire tide cycle, 12 hours, after the earthquake. The 2010 Chilean earthquake (magnitude 8.8) produced at least three significant tsunami waves. Of the three, the third wave was the largest and most destructive⁵.

Vertical Evacuation – What Is It?

After a tsunami warning from an earthquake you can feel, residents of the affected area typically evacuate horizontally, on streets, usually on foot. A horizontal evacuation strategy is appropriate when communities have natural high ground that is easily accessible. The traditional advice is, “go uphill or inland.” However, if a community has little or no natural high ground, horizontal evacuation may not be an option. A different strategy is necessary. A vertical evacuation strategy provides engineered high ground in communities that lack natural high ground, in order to provide safety from multiple tsunami waves that may come and go for as long as 24 hours after the earthquake⁶.

Types of Vertical Evacuation Structures

In order to accommodate vertical evacuation, there are three potential options: berms, towers, and buildings. These generalized designs take into consideration the forces of both the earthquake vibration (anticipated to reach up to 1G, defined as 100% of the force of gravity) and the immense sideways forces of a tsunami.

Implications for Tsunami-Resistant Design

How the building survives depends on the construction type and tsunami height. While observations from past tsunamis show that certain types of construction are largely destroyed by high-velocity water flow, there is much evidence that well-designed structures can survive the initial tsunami inundation.

Data from historical tsunamis, the 2004 Indian Ocean Tsunami, and supporting evidence from extreme storm surge flooding associated with Hurricane Katrina result in the following implications for tsunami-resistant vertical evacuation design⁷:

- The structures should be well-engineered reinforced concrete or steel frame structures.
- The structures need to withstand the local earthquake and then the tsunami.
- They should be located away from the wave breaking zone, so not right on the beach or too close to shore.
- Impact forces and debris in the water need to be considered because the debris can cause water to back up and flood the structure.
- When elevated floor levels are subject to inundation, trapped air below can cause uplifting forces on the building.
- Erosion around the foundations must be considered.

(Continued on page 5)

¹ Developed in part by Priest and others, 1997; and Walsh and others, 2000

² CREW, 2005

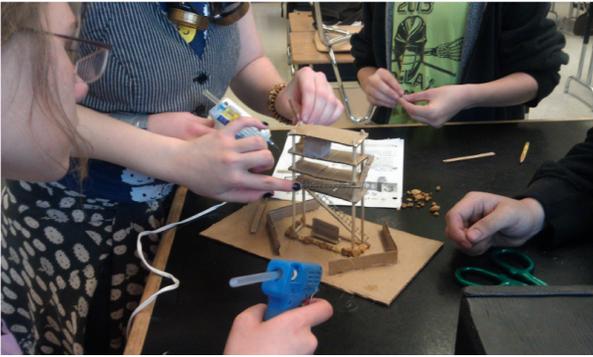
³ Exact arrival times vary along the coast depending largely on the distance to the plate boundary and the intervening water depth.

⁴ National Geodetic Vertical Datum — NGVD

⁵ Warren and Vergara, 2010

⁶ FEMA P646: Guidelines for Design of Structures for Vertical Evacuation from Tsunamis

Photographs of student projects



Photograph shows students working collaboratively on their structures in the classroom.

Vertical-evacuation berms and towers made in Roger Groom's Mount Tabor Middle School science class. Students were expected to explain all the requirements and how the structure meets those requirements. They were also asked to describe how the structure could be used by community when not actively needed for evacuation. Students included community garden, park, basketball court, etc.

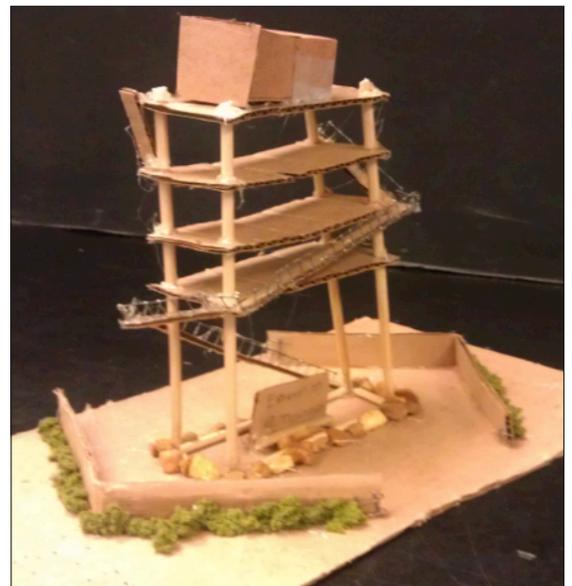


Left: Example of a student-constructed vertical evacuation berm with rock gabions to prevent ocean erosion, is large enough to hold 240 people, and can be used as a park during the year.

Below: berm-tower combination.



Towers: Three examples of a student-constructed vertical evacuation towers



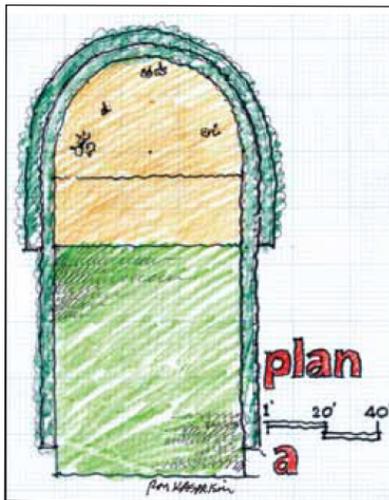
(Continued from page 3)

Berms

Berms are engineered artificial high ground created from soil. They have a large footprint on the landscape, giving the appearance of a man-made hill. A berm can range in size from 1,000 square feet for 100 people up to 100,000 square feet for 10,000 people.

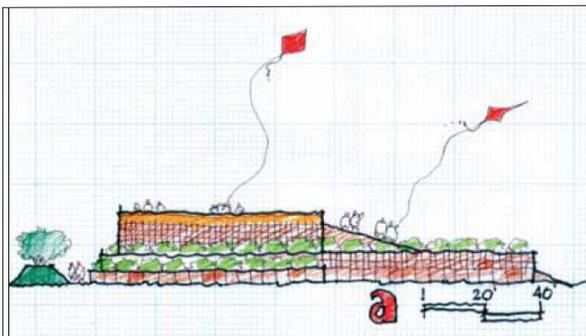
A berm has three component parts (see figures below):

1. A rounded front portion and gabion mound. Wire gabions are wire mesh baskets filled with rock. “Grouted” gabions use cement to fill or partially fill the spaces between rocks. Gabions are used to help prevent erosion by breaking the impact force of the incoming tsunami.
2. An elevated safe haven area, where ‘safe haven’ is the area above inundation level.
3. An access ramp, at a 1:4 slope. This means that for every 1 unit of vertical gain, you need 4 units of horizontal distance. This makes it easier to move upwards for individuals with limited mobility.



Berm design plans.
Left: Plan (map) view.

There are many variations based on local need and budgets that can add recreational facilities, landscaping and weather protection.
See examples in Source A



Side view of upper plan-view image.

Advantages to berms include the following⁸:

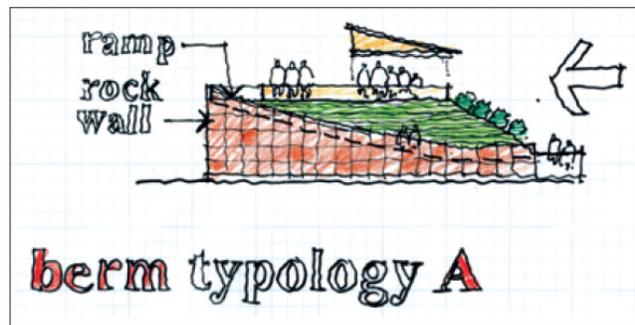
- They have easy access for many people, including those with limited mobility.
- They allow people to follow their natural instinct to evacuate to high ground.
- They eliminate fear of entering a structure that may not be safe.
- The basic berm structure can be modified to enhance its visual appearance and use.

Towers

A tsunami evacuation tower can take the form of a simple elevated platform above the projected tsunami wave-height, or something like a lighthouse, that has a ramp or stairs leading to an elevation above projected wave height. A 500 square foot tower can accommodate 50 people and a 1,000 square foot tower can accommodate 100 people.

The design consists of a foundation with a four-legged base with deep vertical supports stabilized by grade beams. Grade beams are strong support structures placed between vertical columns below or at ground level. These supports, placed in the same direction as the incoming tsunami wave, follow the level of the ground and provide stronger sideways stability against the forces of floodwaters. This type of foundation is necessary to make sure the structure remains safe for occupation while still being able to withstand the immense lateral forces from the tsunami.

An enclosed structure is made primarily of wood and can be sized in order to provide the required safe haven area. Two access options are available; the first is a breakaway stair system designed for daily use and to access the safe haven area following a major earthquake. In the case of a tsunami, however, the stair system would breakaway freely from the structure. Following the tsunami event evacuees would use a retractable staircase to leave the tower.



Side view of different berm.

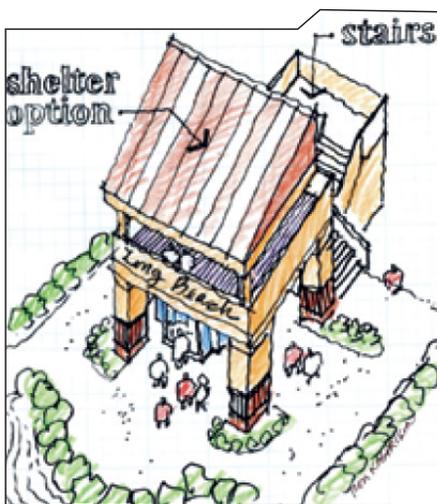
Figures from Project Safe Haven: Tsunami Vertical Evacuation on the Washington Coast

⁷ Source B Page 28 – 29 (For “Source” see page 2 this document)

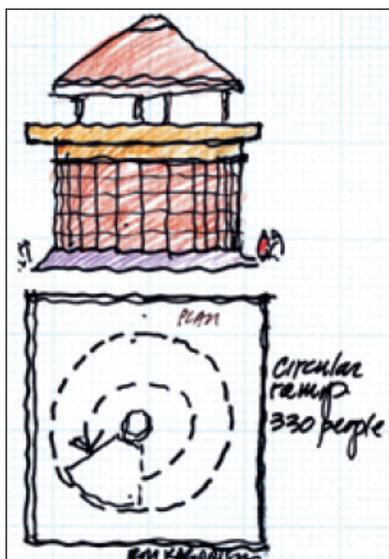
⁸ Source A, pages 10 and 33



Tower design plan, side view



Tower design



Tower design

Advantages to towers include the following⁹:

- They are economical, so more towers could be distributed through the affected areas to increase accessibility and availability.
- They have a small footprint so wouldn't require as much land on which to build.
- They can be multifunctional, and can have a wide variety of designs like the ones below:

Berm/Tower Combinations

There are a number of design alternatives that offer combinations of towers and berms. Ramp-berms can provide access to tower structures if space permits, increasing access capabilities for physically challenged persons. Combinations also can reduce the overall footprint for a large berm structure¹⁰.

Additional Considerations

Shelters, non-motorized winches (lifting mechanisms), and other climate protection features are optional things and can serve as community amenities for everyday use. Bathroom facilities and storage facilities for basic supplies such as water, medical supplies, and tarps are additional options to be considered¹¹.

Tsunami Vertical Evacuation Refuges and Mobility Impaired Access

It is important to communicate that the proposed vertical evacuation structures are "refuges" (short term safe havens) and not "shelters" (places designed for longer-term housing for the displaced). According to FEMA P646, vertical evacuation refuges are not necessarily required to meet American Disability Act (ADA) requirements when they operate as a refuge. However, for day-to-day uses, vertical evacuation refuges should consider the needs of disabled occupants to the extent possible and the extent required by law, in the event of an emergency evacuation.



Berm/Tower design

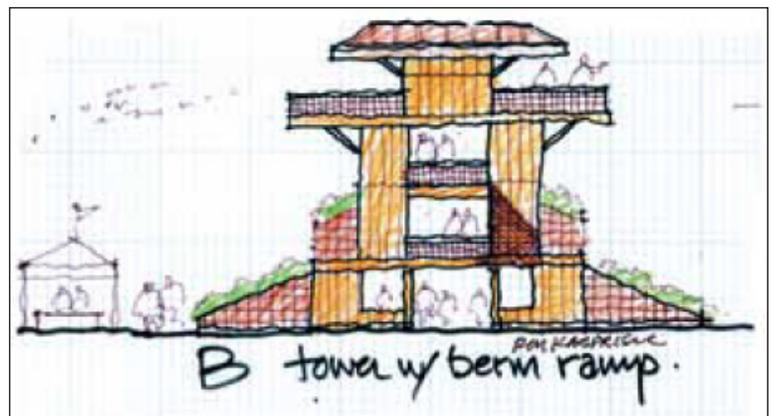
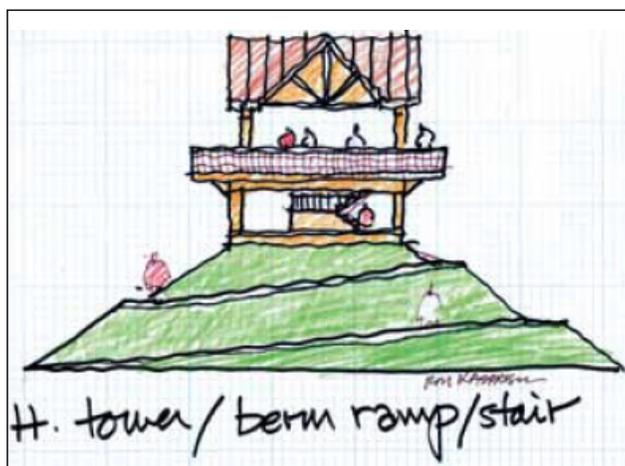
⁹ Source A, Page 11

During a tsunami evacuation, following a local earthquake, disabled evacuees may need additional assistance getting into refuge areas in vertical evacuation structures. Accessibility should be planned to the greatest extent possible. In later stages of structure development additional accessibility features may be added into the existing designs. Ultimately, compliance with ADA may vary by structure type, function and whether or not the detailed building plans call for long-term sheltering options as opposed to a short-term safe area for refuge¹².

Location and Spacing of Structures

It is important to think about the time it would take for people to reach a refuge. To determine the maximum spacing of TVES, critical things are expected wave arrival time after the earthquake and walking capability of the surrounding community. Once maximum spacing is determined, size must be considered, and population size becomes important. If the population is large, structures need to be large enough and close enough to fit everyone needing evacuation.

The average, healthy person can walk at about 4 mph. Age, health, or disability, however, can slow a person to about 2 mph. Assuming a 2-hour warning time associated with distant tsunamis, most people will have adequate time to drive to existing high ground. If people need to evacuate on foot, vertical evacuation structures would need to be located a maximum of 4 miles from any given starting point, or approximately 8 miles between structures. However, assuming a 30-minute warning time, structures would need to be located a maximum of 1 mile from any given starting point, or 2 miles between structures. Again, with larger populations and size considerations, they may need to be even closer. Terrain should also be taken into consideration when determining the distance between structures.



Square Footage for Short-Term Refuge from Tsunamis

For short-term refuge in TVES, the minimum time expected to be in the structure should be between 8 to 12 hours. Because tsunami events can include several waves, there are recommendations that suggest evacuees should remain in a tsunami refuge until the second high tide after the first tsunami wave, which could occur up to 24 hours later. In addition, debris and hazardous materials may surround the TVES after the event, making the ability to immediately leave the TVES difficult.

The recommended minimum square footage per person for a tsunami refuge is 10 square feet per person. This will give evacuees room to sit down without feeling overly crowded for a relatively short period of time, but would not be considered appropriate for longer stays that included sleeping arrangements.

Elevation Considerations

In order to be safe, the refuge area must be well above the predicted maximum tsunami inundation level. Finding the right height should consider the uncertainty of estimating tsunami run-up, splashing of the waves, and anxiety of evacuees. So, wave run-up is assumed to be 30% higher than simulations, models, or tsunami maps. Then, because of the number of people involved, it is recommended to have an additional one-story height (10 feet or 3 meters) above the 30% margin (See figure below).

The recommended minimum elevation for a tsunami refuge area is, therefore, the maximum tsunami runup elevation anticipated at the site, plus 30%, plus 10 feet (3 meters).¹³

¹⁰ Source A, pages 10 and 33

¹¹ Source A, pages 33-34

¹² Source A pages 57-58

Recommended Tsunami Inundation Safe Elevation example using FEMA guidelines*

- 1) Hypothetical Wave Inundation height = 9'
- 2) Uncertainty of Predicted Values (30% of 9') = 3'
- 3) Margin of Safety = 10'

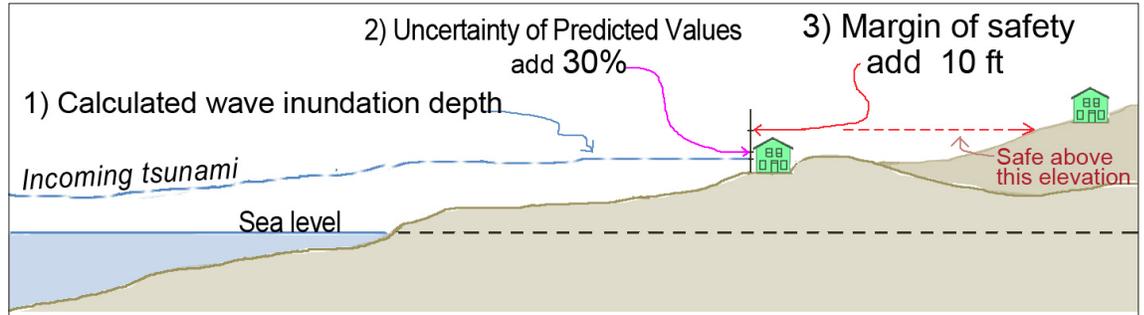
$$9 + 3 + 10$$

Total of the 3 factors = 22'

That means, if you were standing at a ground elevation of 16 feet above sea level, you would need to find higher ground or refuge at a minimum of 6 feet higher than you are standing.

The equation is:

$$22' - 16' = 6'$$



* Co-seismic subsidence is factored into computer models predicting tsunami wave inundation height.

¹³ Source A, page 60

Part B: Background Tips & Information—Siting for Tsunami Vertical Evacuation Structures (TVES)

Source B: FEMA (Federal Emergency Management Agency) P646 *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis* (Publication 176 pages) <http://www.fema.gov/library/viewRecord.do?id=3463>

If possible, attain detailed street maps that indicate not just streets, but also parks, hospitals, schools, etc. The more detail students/participants have about the available space, the better. The teacher/presenter may want to ‘touch-up’ the street maps to show the demarcation of tsunami safe zones.

Alternatively, if teachers/presenters have access to computers, **GoogleEarth** is an amazing resource to accompany this portion of the Vertical Evacuation activity. Locate the city/town in question, zoom in to the scale that is needed, and students/participants can visually scan for places that could accommodate vertical evacuation structures. They can ‘pin’ those locations and rename the pin with labels for the towers/berms, including the size and number of people each structure can accommodate.

They can also use Measurement Tool (Tools > Ruler) to measure distances either in a line or a path. This will enable students/participants to calculate travel times and evacuation routes to the TVES.

Part C: Background Information—Design and Build a Berm or a Vertical Evacuation Tower

When designing the structure to meet the given criteria of size and height, it will be very beneficial to do an example together to review the mathematics of scaling, i.e. 1 inch = 10 ft. The teacher/presenter must review how to calculate area and how much area is needed to accommodate a certain number of people given that each person needs 10 ft². (3.16’ x 3.16’)

Furthermore, when building a berm, make sure to review the 1:4 ratio for the slope of the ramp.

Photographs of finished student projects are on Pages 5, 7, and 8 of this document show examples of berms (p. 5) towers (p. 7) and combo tower-berms (p. 8) that were built according to the specifications.

Question B3 (Page SW-3) Tourism reference numbers*

- **Oregon** inundation zone: residents = 63,000; average daily state park visitors = 54,000
- **Washington** inundation zone: residents = 43,740; average daily state park visitors = 17,000

See Page 51 of *The Oregon Resilience Plan*: www.oregon.gov/oem/Documents/Oregon_Resilience_Plan_Final.pdf

The population could be more than 5x higher for many Oregon communities in peak summer and, at least double in Washington. There would be big local variation. These numbers do not include Olympic National Park visitors or Wildlife Refuges.

Students/teachers may inquire with their local chamber of commerce or visitor’s bureau for peak visitation numbers or use some estimation from the numbersvxxv above.

Many of the parks will have their own numbers for visitor attendance.

Part D: Background Information—Presentation of TVES to a Public Gathering

Video clips of students doing short presentations about how their buildings met the criteria of the building component of the TVES Activity can be seen on YouTube: <http://youtu.be/4gjdhnkBYuA>

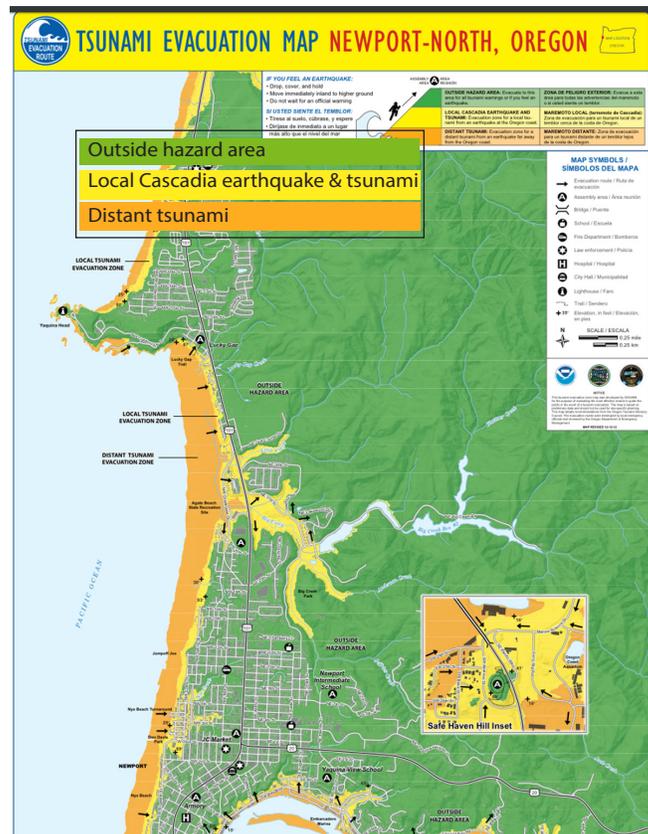
Part B:

Siting for Vertical Evacuation Structures

Using the Tsunami Evacuation Map and city street maps, decide where vertical evacuation structures should be placed.

1. Identify places where people are clustered within the tsunami zone. (ex. schools, shopping and business areas)
2. Identify areas where there is no viable high ground for evacuation from a tsunami within a mile from the places you identified in Number 1 above.
3. How many people will need to use TVES including high tourist months?
4. Identify specific locations (provide cross streets or proximity) for TVES sites that people will be able to reach in 15 minutes. Identify possible sites for both towers and berms and estimate the number of people the structure needs to contain.

Name _____



Map of Newport-North, Oregon Tsunami Inundation Zones. Download this or other evacuation brochures for Oregon towns: www.oregongeology.org/tsuclearinghouse/pubs-evacbro.htm

Type	Location (cross streets)	Current Use	Capacity Needed

Part C: Design and Build a Berm or a Vertical Evacuation Tower for the site

Create 2 teams in your group. Each team will design and build either a tower or a berm TVES using the materials provided. Use rough draft paper to sketch out ideas for your structure.

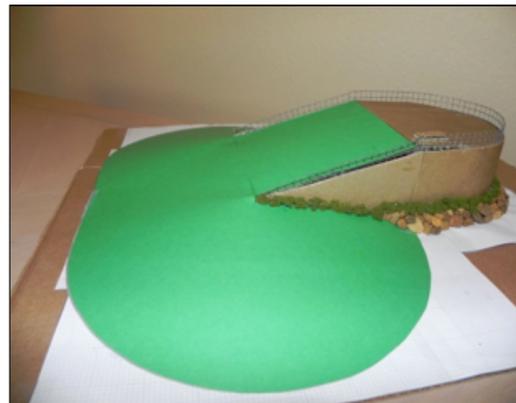
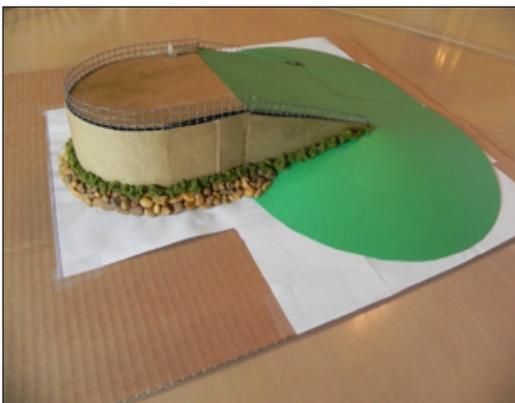
Instructions for Designing & Building a Model Berm

- 1) Provide “refuge” space for at least 200 people.
- 2) Create a plan for your structure on graph paper showing both bird’s eye and side view drawn to scale. Scale is 1” = 10’.
- 3) Include all measurements demonstrating how the required number of people will be accommodated on the structure. $10 \text{ ft}^2 (1 \text{ m}^3) \text{ per person} \times 200 = 2,000 \text{ ft}^2$.
- 4) The ramped slope of the ground to reach safe elevation is a 1:4 ratio (The 25’ safe elevation requires a 100 foot ramp.)
- 5) Minimum berm height is 2.5’ = 25’. A protective shelter is optional.
- 6) Create a storage space for emergency supplies.

Materials for a Berm:

- Tsunami Inundation Map and City Street Maps
- ¼” graph paper
- Cardboard
- Angular aquarium gravel
- Glue Gun and glue sticks
- Glue
- Tape
- Scissors
- Ruler
- Construction paper
- Window or metal screen

See **Background Resources** for design examples. Here is a sample model from two views:



Instructions for Designing and Building a Model Tower

1. Provide “refuge” space for at least 200 people.
2. Create a plan for your structure on graph paper showing both a bird’s eye and side view drawn to scale. Scale is 1” = 10’
3. Include all measurements demonstrating how the required number of people will be accommodated on the structure. $10 \text{ ft}^2 (1 \text{ m}^3) \text{ per person} \times 200 = 2,000 \text{ ft}^2$.
4. Minimum first floor finished height is $2.5'' = 25'$. If applicable, a second safe floor is $1'' = 10'$ above the first floor. Protective roofing is optional.
Example: 100 people per floor = 1,000 sq. ft. ($40' \times 25'$) per floor. Stairs are outside the floor space.
5. Create a storage space for emergency supplies.
6. Show staircases for the VE Tower.
7. Supporting columns should be 15–20 feet apart. Grade beams are optional.

Materials for Tower:

- Extra Thick Bamboo Skewers
- $\frac{1}{4}''$ graph paper
- ruler
- Glue Gun and glue sticks
- Glue
- Cardboard
- Scissors
- Spaghetti

Optional Gabion Materials:

- Angular aquarium gravel
- Window or metal screen for wire gabions

Optional Grade Beam* Materials:

- Balsa wood or craft sticks

** Grade beams are structural elements placed between vertical columns at grade or below grade to provide increased lateral stability against the forces of flood waters. Grade beams follow the surface level of the ground and are placed in the same direction as the incoming water.*



Part D: Presentation of the Vertical Evacuation Structures to a Public Gathering

Use a map to show where the structures are located.

Show the area served by the tower and the berm TVES.

How many people can the tower and the berm TVES each accommodate?

What are the dimensions of each structure?

Describe at least 3 structural hazards you considered and accommodated in your designs.

Describe any unique features (protective barriers, or storage areas).

How can the structures be used for other purposes other than a TVES?