16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 4635
Registration Code: S-C1464445013

THE DESIGN OF STRUCTURAL FOUNDATIONS FOR TSUNAMIS IN ASCE 7-16 CHAPTER 6: TSUNAMI LOADS AND EFFECTS

C. Petroff (1), S. Tonkin (2), M. Francis (3)

(1) Hydraulic Engineer, LP4 associates LLC, cpetroff@lp4associates.com
(2) Coastal Engineer, Moffatt & Nichol, stonkin@brightwave.com
(3) Principal Geotechnical Engineer, AECOM, mathew.francis@aecom.com

Abstract

The design of structural foundations for tsunamis is a complex process that must account for the effects of erosion and local scour. As unsteady and violent tsunami flow propagates over the ground, it causes transient loads and reduced soil strength. Foundation design provisions must consider the cumulative effects of hydraulic processes (e.g., shoreward overland and overtopping flows, flow concentration, and downwash); geotechnical processes associated with the flow (elevated pore pressures, uplift forces on soil grains, and loss of shear strength in submerged soils); and residual soil liquefaction from near-field earthquake events. The new ASCE 7 provisions for Tsunami Loads and Effects address foundation design criteria by combining current methods in geotechnical engineering and sediment transport with observations of scour and foundation failures from recent large magnitude tsunamis. The provisions specify not only the evaluation of potential scour from tsunamis but also the design of tsunami countermeasures to both structures and sites. Structural countermeasures such as tsunami barriers as well as foundation countermeasures (pavements, revetments, geotextiles and ground improvements) are considered.

Keywords: tsunami; foundation design; pore pressure; scour; erosion.

1 Introduction

While coastal structures are usually designed to withstand storm wave attack, the extreme flow height, velocity and duration of tsunamis can lead to sustained severe hydraulic forcing, overtopping, and failure of either the seaward or the landward side of structures. As documented in recent tsunami events, structural loading is often exacerbated by the scouring of foundations and foundation failure during the tsunami, which in turn often progresses to failure of the entire structure. Collectively, failures of structural foundations have lengthy and costly effects inhibiting rapid recovery of a region after a tsunami.

Tsunami scour differs from steady flow scour and typical wind wave scour in that tsunamis create sustained periods of high water accompanied by unidirectional flow both onshore and offshore. In addition to the unsteady flow from each tsunami wave or bore, previous tsunami pulses can elevate the pore pressure near structures and reduce the ability of soils to withstand scour from successive inflows and outwash.

Typical foundation failure mechanisms that have been observed during post-tsunami surveys include

- lateral sliding due to sustained unidirectional flow during a tsunami with the added effects of any unbalanced lateral soil pressures caused by general erosion or local scour;
- uplift or flotation from buoyancy forces;
- soil piping caused by excess seepage stresses reducing the strength and integrity of the soil fabric;
- slope instability caused by saturation and pore-pressure softening effects of inundation; and
- loss of bearing capacity where soil strength properties may be affected by sustained pore pressures, or where soil is removed by local scour or general erosion.

These mechanisms can work in combination and can be affected by the time-history of loading from the tsunami as well as by soil conditions, such as liquefaction, that are caused by earthquake activity.

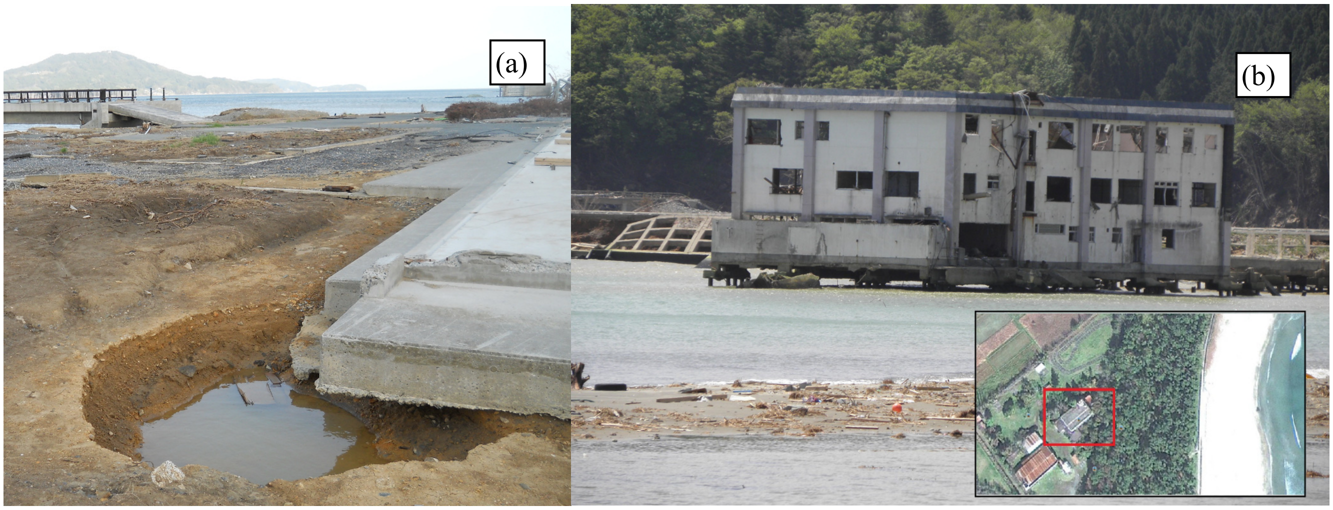

Fig. 1 (a). Local scour around building corner at Rikuzentakata after 2011 Tohoku tsunami. (Photo courtesy B. Jones). (b) General erosion in combination with subsidence of a pile-supported structure at Kiozumi Beach, Japan after 2011 Tohoku tsunami. Before the tsunami the building was separated by over 120 meters (400 feet) of wooded area from the beach. (Photo courtesy L. Ewing).

2 Overview of Provisions

The new ASCE 7 provisions [1] include performance objectives for foundation design for tsunamis as well as tsunami inundation zone maps to be used in siting studies. The provisions incorporate many observations and analysis of foundation performance during the Tohoku (2011), Chile (2010) and Indian Ocean (2004) tsunamis. They are aimed primarily at Risk Category 4 and other critical facilities, but are useful as well for protection of lower risk category structures. The provisions specify that design of structural foundations and tsunami barriers consider changes in the site surface and in-situ soil properties during the tsunami. In addition to the site response and geologic site hazard considerations, design analysis should also consider both topographic changes caused by scour and erosion, and the effects of the surroundings, which can shield or concentrate flow as well as dissipate energy at structure or its foundation. In cases where either site conditions or flow conditions are complex, numerical modeling is recommended. Countermeasures, such as barriers, berms, geotextile reinforcements, or ground improvements can be designed to protect the foundations and their vicinity and to relieve them of direct loading.

2.1 Load and resistance factors

Because of the variability and the inherently nonlinear behavior of soil materials, soil loading analysis incorporates geotechnical judgment in selecting a nominal strength for soils that underlie a foundation. A limit state is assumed to exist along some failure surface, and the resultant loads from an equilibrium analysis are compared to a reduced nominal strength for the soil. This approach is commonly called limit equilibrium analysis. To ensure that the assumed failure does not occur, a resistance factor is applied to the nominal strength.

$$\text{Applied Load} \leq \phi \text{ Resistance} \qquad (1)$$

The inverse of the resistance factor is often called a “factor of safety” in the recognized soils literature and is the approach traditionally used in geotechnical engineering. The new ASCE 7 provisions consider a common minimum value of 1.33 for factor of safety as applicable to the analytical methods and practices for typical foundations, berms, geotextiles, and slope applications. A factor of safety for uplift of 1.5 has been adapted from the design of water retention structures [2], which allows a credit for the uplift resistance of piles and anchors since traditional water retention structures often rely solely on gravity for stability. Accordingly, a single uniform resistance factor of 0.67 (1/1.5) is applied, which covers both cases and allows the combined effects of the tsunami on the foundation to be consistently evaluated.

For foundations subject to tsunami flows and inundation, the weight of the structure and the soils that overlie the foundation act together with the foundation elements to resist uplift (Eq. 2).

$$0.9D + F_{\text{tsu}} \leq \phi R \tag{2}$$

where D = Counteracting downward weight of the structure
F_{tsu} = Net maximum uplift
R = Upward design load resisting capacity
ϕ = Resistance factor, = 0.67.

Fig. 2. Effects of uplift: overturned building in Onagawa Japan after 2011 Tohoku tsunami. Although supported by pile groups, the foundation was not sufficient to resist earthquake shaking followed by hydrodynamic and buoyancy uplift and overturning forces during the tsunami. (Photo courtesy L. Ewing).

2.2 Foundation loads and effects

The provisions describe specific loads that apply to a foundation, together with considerations (loss of strength, scour, and erosion) that affect the structural design.

2.2.1 Uplift and underseepage forces

Tsunami loads on a foundation include uplift and underseepage forces as well as lateral loading by the wave. The new ASCE provisions call for uplift and underseepage forces to be considered when the soil is expected to be saturated before the tsunami, or when soil saturation is anticipated to during or after a series of tsunami waves. As with the loading of other structure components in the provisions, the buoyant forces are determined from the water depth assuming density of seawater plus a 10% increase for potential suspended particles and debris. Underseepage forces are addressed by traditional seepage gradient analysis and geomechanical modeling for critical gradients leading to piping and boiling conditions.

2.2.2 Loss of strength

The resistance of a foundation to tsunami forces can be decreased by soil softening through mechanisms such as seismic shaking, piping, pore pressure softening, and scour. Shaking effects are evaluated under the seismic load section. Piping effects on strength loss, while not well-documented in the field, can be addressed within the existing procedures given for filtration design of facing and armoring. This paper focuses on the two strength loss mechanisms addressed directly in the ASCE 7 provisions: pore pressure softening and scour.

Pore pressure softening is a mechanism whereby increased pore-water pressure is generated during rapid tsunami loading and is released during drawdown. This increased pore-water pressure can soften the ground and decrease its effective shear strength. The differences between standard seismic liquefaction and pore pressure softening are illustrated schematically in Fig. 3.

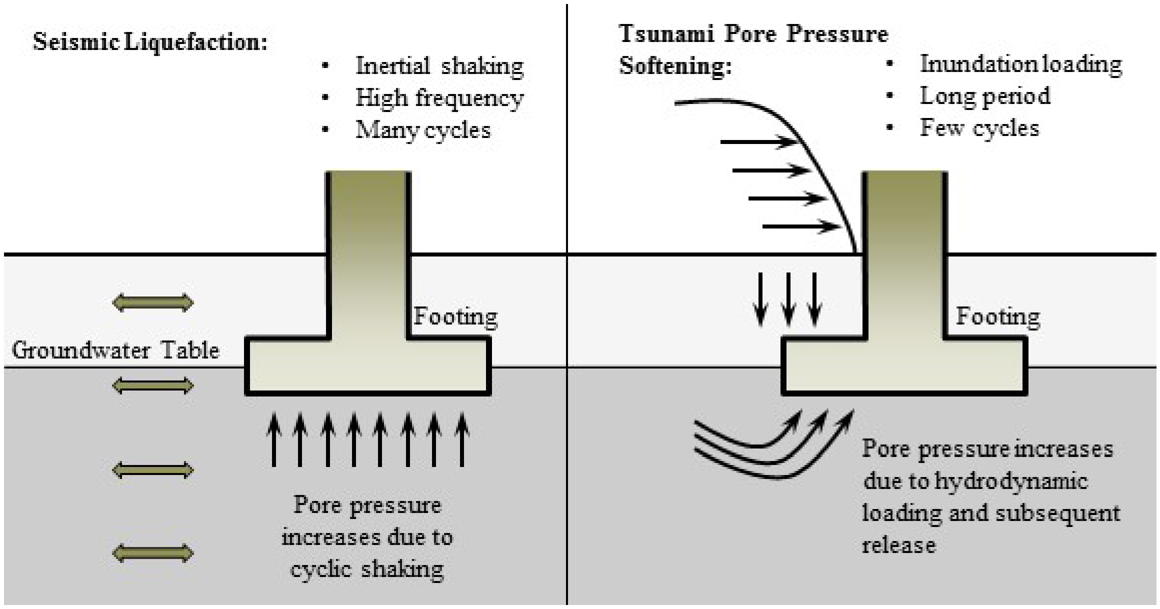

Fig. 3 – Schematic diagram showing differences between seismic liquefaction and tsunami-induced pore pressure softening, from ASCE 7 [1].

The new ASCE provisions call for pore-pressure softening to be considered in foundation design, together with the other mechanisms listed here; however, the analysis method is not specified. The ideal method is scale modeling of soil-structure-fluid interactions; however, the model scale must be relatively large (typically 1:5 for geotechnical investigations) and such modeling is costly. A second analysis method is detailed numerical modeling of soil-structure-fluid interactions.

A third method, described in the Commentary, extends theoretical descriptions and field observations of tsunami-induced scour to estimate the loss of strength due to pore pressure softening. This method makes use of a scour enhancement parameter Λ, which approximates the fraction of the weight of soil grains supported by the excess pore water pressure [3]. Equivalently, Λ can be considered a measure of the loss of confinement. The loss of shear strength can be presumed proportional to the fractional loss of confinement, so that the shear strength is multiplied by a factor $1 - \Lambda$ to incorporate the effects of pore pressure softening. The parameter Λ is given in Eq. 3:

$$\Lambda = \min\left[0.5, \frac{2}{\pi} \cdot \frac{h_{\max} \gamma_s}{\gamma_b \sqrt{c_V T_{\text{draw}}}}\right] \tag{3}$$

In this equation:

$h_{\max}$ is the maximum inundation depth;
γ_b is the buoyant weight density of the soils (the difference between the bulk weight density of the saturated soil skeleton and the weight density of the pore water);
γ_s is the fluid weight density for tsunami loads;
c_V is the consolidation coefficient of the soil; and
T_{draw} is the drawdown timescale of the tsunami.

The consolidation coefficient c_V is a standard geotechnical parameter. However, using standard values of this parameter would lead to the conclusion that loss of strength is substantially greater in finer soils. Field observations of damage due to tsunamis so not support this. Therefore, the method limits the value of c_V for fines as follows [3, 4, 5]:

- Gravel: approximately 1 to 100 m^2/s (10 ft^2/s to 1,000 ft^2/s);
- Sand: approximately 0.01 to 0.1 m^2/s (0.1 ft^2/s to 1 ft^2/s);
- Finer materials: approximately 0.01 m^2/s (0.1 ft^2/s).

Based on theoretical considerations described in the commentary and field observations of scour, the loss of strength can be considered uniform down to a depth of 1.2 times the maximum inundation depth. The corresponding increased active and decreased passive earth pressures in this zone should be evaluated during design analysis.

2.2.3 Scour and erosion

The resistance of a foundation structure to tsunami loads can be further decreased by scour and general (wide-area) erosion, which lower the ground around the foundation. The depth and horizontal extent of scour and erosion are driven by the structure and flow geometry. The provisions identify four classes of geometry with corresponding analysis considerations:

- Sustained flow shear scour, in which tsunami flow accelerates around the structure, leading to increased shear stresses and scour;
- Plunging scour, in which the flow overtops an obstacle;
- General site erosion, occurring over a broad area; and
- Channelized scour, which occurs when flow is concentrated in channels newly formed during tsunami inundation and drawdown.

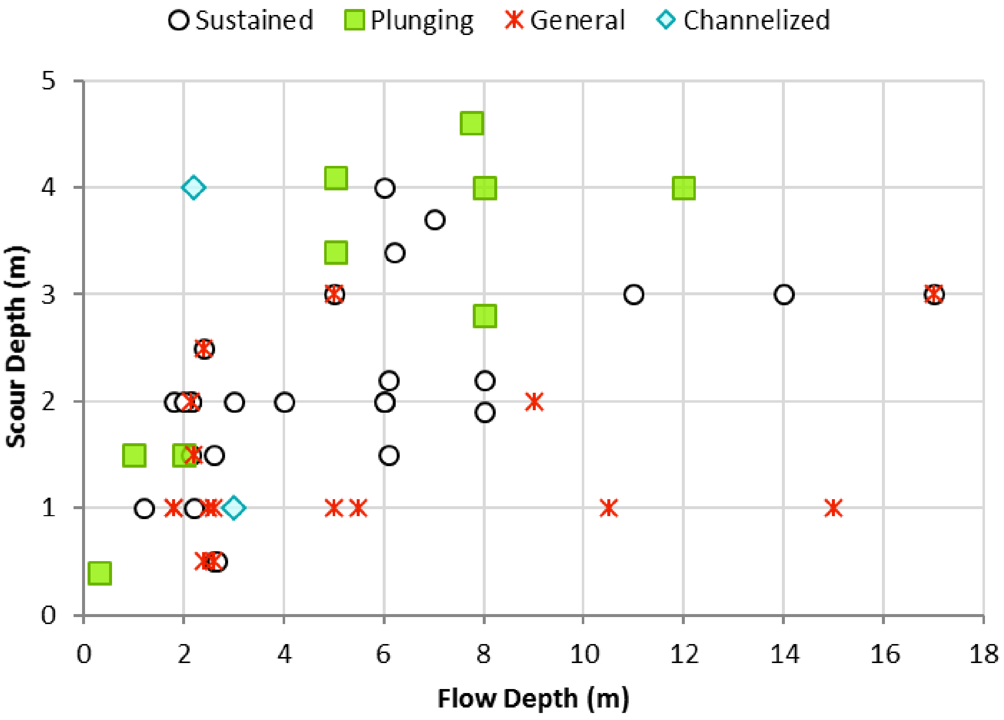

Fig. 4 – Scour observations from Sumatra and Tohoku tsunamis [5, 6, 7].

Fig. 4 shows the observed variation in scour depth and its relation to flow depth for a number of sites impacted by the Tohoku and Sumatra tsunamis. For sustained flow shear and plunging scour, there is a clear correlation between flow depth (tsunami wave height at the structure) and scour depth. For general erosion, this correlation is largely absent – and observed scour has not exceeded 3 m (10 ft). The small number (two) of channelized scour observations means it is difficult to draw a general conclusion.

As with loss of strength, the new ASCE provisions do not specify analysis methods for scour and general erosion. However, they do provide general considerations and suggest acceptable methods for use.

2.2.3.1 Sustained flow shear scour

Sustained flow shear scour describes the effects of sustained flow around structures and including building corner piles. Sustained flow shear can be greatly enhanced by pore pressure softening, and it is required that this be included in any analysis for tsunami design. Physical model tests, numerical modeling, and empirical methods are all acceptable for analysis of sustained flow shear.

The new ASCE provisions also provide a simple method for estimating scour depth, based on the empirical observations shown above. Fig. 5 plots the scour observations for sustained flow shear only, together with an envelope for the observations [8]. This envelope is provided as an acceptable analysis method for sustained flow shear scour in the new ASCE provisions:

$$D_s = \begin{cases} 1.2h_{\max}, & h_{\max} < 3.05\ \text{m (10 ft)} \\ 3.66\ \text{m (12 ft)}, & h_{\max} \geq 3.05\ \text{m (10 ft)} \end{cases} \tag{4}$$

where:

D_s is the scour depth;

$h_{\max}$ is the maximum inundation depth.

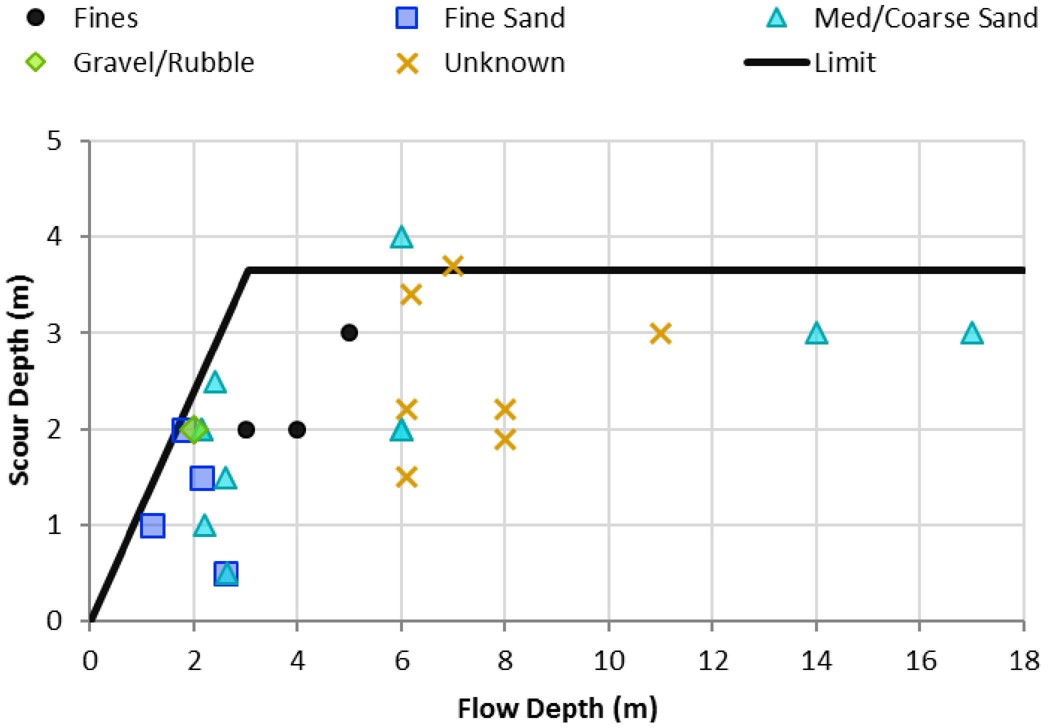

Fig. 5 – Scour observations from Sumatra and Tohoku tsunamis [5, 6, 7]: Sustained flow shear for different grain sizes. Figure is based upon [8].

The linear functional form in Eq. 4 is consistent with the upper limit of observational data in Figure 5, based on the model of [3], as shown in [8]. However, the observations further show no obvious correlation between scour depth and soil type (grain size). This runs counter to most scale model studies and theoretical analysis of scour under tsunami conditions; the reason for this discrepancy is unknown at this time. Based on observation, a single design envelope is provided for all soil type in the provisions, subject to possible future revision.

2.2.3.2 Plunging scour

Plunging scour is caused by tsunami flow over an overtopped structure. Plunging scour does not appear to be enhanced by pore pressure softening. It is caused by water falling down onto the soil, and the resulting complex hydrodynamic and soil mechanics are incorporated into existing empirical plunging scour methods.

As for the scour modes discussed above, the new ASCE provisions do not specify analysis methods for plunging tsunami scour. However, a well-established plunging scour formula [9] is adequate to describe field observations of plunging scour. Fig. 6 provides a comparison of the predictions and field observations; the straight line represents perfect predictions

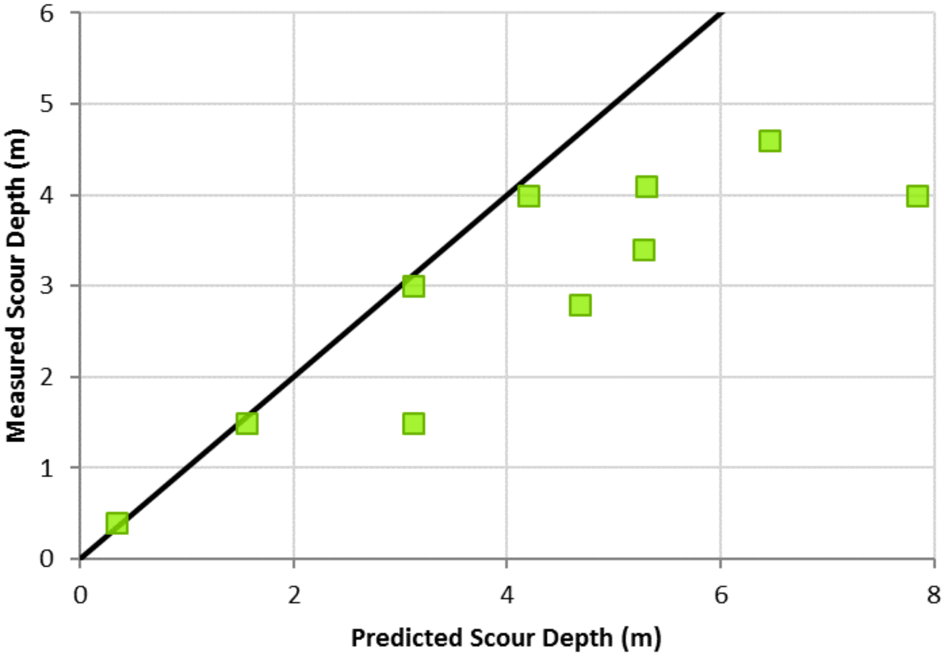

Fig. 6 – Comparison of field observations and calculations for plunging scour. Figure is based upon [8].

2.2.3.3 General site erosion

Standard literature and models describing flood-induced general erosion do not include the effects of pore pressure softening. Pore-pressure softening can increase the depth of general site erosion, as described in Yeh and Li [10].

As with the loss of strength, the effect of pore pressure softening on erosion and during drawdown may be evaluated using physical scale modeling or numerical modeling of soil-structure-fluid interactions. Alternatively, the increase in general site erosion during drawdown may conservatively be evaluated by multiplying the buoyant specific weight γ_b of the sediment or the critical shear stress by a factor $1 - \Lambda$, where Λ is the scour enhancement parameter described shown above. An example of general scour across an entire area is shown in Figure 1b.

2.2.3.4 Channelized scour

Some of the deepest scour observed in field investigations of tsunami damage has been created in channels newly formed during tsunami inundation and drawdown (channelized scour). Analysis of channelized scour need not include enhancement caused by pore-pressure softening: it typically forms over a relatively long period of time, after the tsunami waves have passed and the water slowly drains back to sea. However, it does require detailed site-specific modeling of tsunami flows to determine the most likely drainage paths.

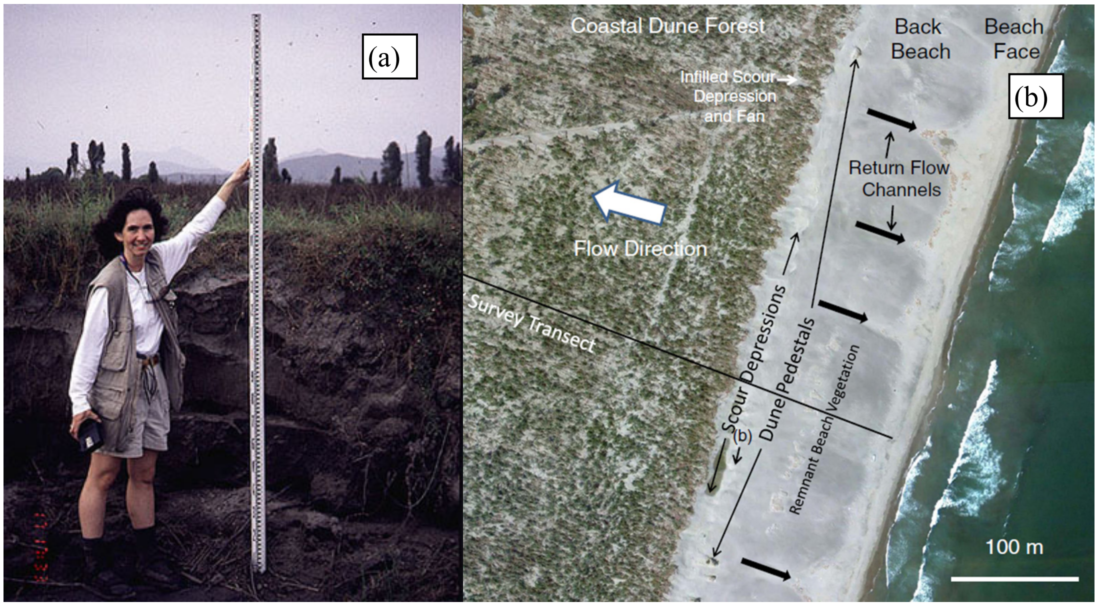

Fig. 7. (a) Channelized scour caused by outwash from 1996 Chimbote Peru tsunami. (Photo courtesy C. Petroff). (b) Aerial view of channelized scour, Sendai, Japan following the Tohoku tsunami, from Richmond et al [11].

2.2.4 Countermeasures

The severity of tsunami loading may require the use of both local foundation countermeasures and site protection countermeasures, such as structural barriers located exterior to buildings. The type of selected countermeasures, their strength, and the extent of protection are dependent upon the performance objectives of the structure to be protected and the extent of protection achievable by countermeasures. For most sites, a rational alternatives evaluation incorporating the severity of loading, local construction costs and site features can identify the optimal protection method or blend of methods.

2.2.4.1 Tsunami barriers

Tsunami barriers are used as an external perimeter structural countermeasure and can be designed to completely block tsunami flow or to act as a partial barrier allowing for overtopping.

Fig. 8. Fudai Village tsunami barrier, Fudai, Japan. The houses on the left side of the photograph were completely protected by the barrier during the Tohoku tsunami event. (Photo courtesy Y. Tanaka).

Design criteria include barrier height and footprint, barrier strength, stability, slope erosion protection, toe scour protection, and geotechnical stability requirements. The following are some of the considerations for layout of tsunami barriers:

- The setback distance of the barrier from the structure perimeter should provide adequate access around the protected structure, and should be large enough to minimize hydrodynamic loading of the structure in the event of overtopping.
- The radius of curvature for corners and alignment changes should minimize flow separation, with a minimum radius of curvature equal to at least half the maximum inundation depth.
- Barriers designed for overtopping or partial protection from inundation should be configured to protect the structure from flow based on an approach angle of ±22.5 degrees from the shoreline which model studies show to be the zone of significant loading attack [12].

2.2.4.2 Revetments and facing systems

Facing materials for coastal structures and reinforced earth systems are critical to prevent raveling of surface protection followed by erosion of substrate (see Fig. 1). Facing systems together with their anchorages need to be sufficiently strong to resist uplift and displacement during tsunami inundation.

Fig. 9. Raveling of landward slope protection facing on overtopped seawall at Noda, Japan in Tohoku tsunami. Concrete panels that protected the slope are scattered in the foreground. The loss of the facing system allowed soil erosion and collapse of the seawall as seen on the right side of the photograph. (Photo courtesy B. Jones).

The new ASCE provisions highlight the following alternatives for facing systems as part of tsunami design, based upon well-established methods, applying high velocity tsunami conditions:

- Vegetative facing for general erosion and scour resistance where tsunami flow velocities are less than 3.81 m/s (12.5 ft/s).
- Geotextile filter layers, including primary filter protection of countermeasures using a composite grid assuming high contact stresses and high-energy wave action including soil retention, permeability, clogging resistance, and survivability.
- Mattresses providing adequate flexibility and including energy dissipation characteristics.
- Concrete facing containing adequate anchorage to the reinforced earth system under design inundation flows.

- Stone armoring and riprap. Armor sizing in areas of high Froude number ($\Im \geq 0.5$) should take into account the high-velocity turbulent flows associated with tsunamis and the height of the incoming waves. In areas of low Froude number, the tsunami acts more as current flow, and stone sizing may be treated accordingly using standard steady flow methods.
- Edges shall be embedded to maintain edge stability under design inundation flows.

2.2.4.3 Pavements for roadways and scour protection: creating a protective slab-on-grade.

In general, one can expect exterior slab-on-grade to be uplifted during the initial stages of a tsunami so that the predictions of local, sustained flow and plunging scour are based on native soil characteristics. In certain critical cases, the design of stable slabs-on-grade may be desirable or required. This design under tsunami loading relies on recognizing the potential for scour at slab edges and ensuring the stability of slab sections and substrates. At slab edges, grade changes often result in rapid changes in flow speed and depth, which can carry away material and substrate, while large-scale pressure fluctuations in high-speed flows over pavers or concrete slab sections can pry sections loose and cause further damage.

Fig. 10. (a) Roadway damage at Dichato, Chile after 2010 Maule earthquake and tsunami. (Photo courtesy C. Petroff). (b) Hasaki Port, Japan, pavement scour, Tohoku earthquake and tsunami. (Photo courtesy M. Francis).

Guidance for protective slab-on-grade design is drawn from roadway design in the coastal environment [13] as well as from best practices in the design of spillways and lined open channels [14]. Protective slabs on grade used as a counter-measure need to have the strength necessary to resist shear forces from sustained high flows, uplift pressures from flow acceleration at upstream and downstream slab edges, seepage flow gradients, pressure fluctuations, pore pressure increases; and erosion of substrate at upstream, downstream, and flow parallel slab edges, as well as transitions between slab sections.

2.2.4.4 Geotextiles and reinforced earth systems.

Geotextiles increase foundation stability and erosion resistance under tsunami loading by providing internal reinforcement to confined the soil mass and anchor facing vegetation or armoring. A wide variety of high-strength and low-strength geotextiles are available and can be used as long as the expected tsunami loads are within manufacturers' installed strength allowances as supported by documented load testing. Analysis conditions for bearing capacity, uplift, lateral pressure, internal stability, and slope stability should be verified using applicable resistance factors for the installation. These systems can be effective for creating protective reinforcement to traditional shallow footings, slabs on grade, small retaining walls, and berms, as well as to larger structures such as mechanically stabilized earth walls as used in the transportation industry. They are more particularly cost effective in lower tsunami loadings such as less than 2 m (6 ft) flow depths.

Fig. 11. Installation of geotube geotextile technology for coastal armoring [15].

The new ASCE7 provisions allow use of the following reinforced earth systems:

- geotextile tubes constructed of high-strength fabrics capable of achieving full tensile strength when subject to the design tsunami loads,
- geogrid earth and slope reinforcement systems that include facing protection and adequate protection against general erosion and scour with a maximum lift thickness of 0.3 m (1 ft) and
- geocell earth and slope reinforcement erosion protection systems. If no facing is used, the design of these systems should include an analysis to determine anticipated performance against general erosion and scour.

2.2.5 Ground improvements

Soil–cement ground improvement is effective for foundations exposed to high-velocity turbulent flows such as tsunamis because it provides both strength and erosion resistance to the improved soil mass. Deep soil mixing and jet grouting are widely used for bridge scour and foundations for levees, dikes, and coastal structures; and can be applied in a variety of geometries and design strengths for particular tsunami loading conditions. Soil–cement ground improvement countermeasures should be designed to provide non-erodible scour protection and at minimum should provide a well-blended soil–cement reinforcement mass with cured strength of at least 0.69 MPa (100 psi) average unconfined compressive strength.

3 Conclusions

Foundation stability is critical to assuring building resilience and in reducing the costs of losses community wide during a tsunami. The new ASCE7 Tsunami Loads and Effects provisions specify improved better-validated procedures than have been available in the past for tsunami foundation design. The provisions lay out a means of integrating the building structure, the foundation and the siting designs to achieve resilience – that is, more cost effective protection or rapid recovery of core critical functions. The ASCE7 foundation provisions take into account additive effects of various failure mechanisms by considering both steady flow and transient flow effects. By using a combination of field observations from recent damaging tsunamis, references from reviewed literature and common geotechnical design practice, the provisions:

- recommend design loading using a load resistance factor based on foundation design practice;
- develop scour relations for sustained flow shear scour and plunging scour, from field data and from hydraulics literature; and
- adapt foundation countermeasures for use in tsunami design and specify structural countermeasure design criteria.

The process of developing the provisions highlighted some knowledge gaps for foundation design in the case of tsunamis. Some of these gaps were resolved during the committee work, but others persist as challenges for future research and field investigation. Pore pressure softening remains an area that requires further investigation as prototype scale testing is difficult to conduct and the transient nature of this phenomenon is not currently amenable to collection of data after a tsunami event. Although since the 2011 Tohoku tsunami, much progress has been made on observed trends in plunging scour and sustained flow shear scour, current data and methods are not able to derive simple design relations for general erosion and channelized scour. Estimates for these types of scour are best made using detailed numerical modelling, if site data is available.

Future refinements of tsunami foundation design will rely on examining more field data and detailed modeling of different types of scour from tsunamis. Prototype scale testing may be of great help in understanding complex phenomena such as pore pressure softening and the performance of countermeasure investments. As foundations are designed and constructed under the new ASCE 7 load standard, careful analysis and monitoring of their performance under tsunami loads can provide much needed insight into improving and optimizing the design procedures.

4 References

[1] ASCE 7-16 (2016): Minimum Design Loads for Buildings and Other Structures. ASCE, Reston, VA.

[2] U.S. Army Corps of Engineers (2005): Stability Analysis of Concrete Structures, EM 1110-2-2100.

[3] Tonkin SP, Yeh H, Kato F, Sato S (2003): Tsunami scour around a cylinder. *Journal of Fluid Mechanics*, 496, 165–192.

[4] Hicher P-Y (1996): Elastic properties of soils. *Journal of. Geotechnical Engineering*, 122, 641–648.

[5] Francis M (2008): Tsunami inundation scour of roadways, bridges and foundations: Observations and technical guidance from the Great Sumatra Andaman tsunami, *EERI/FEMA NEHRP 2006 Professional Fellowship Report*.

[6] Bricker, J, Francis, M, Nakayama, A (2012): Scour depths of coastal structures due to the 2011 Tohoku Tsunami. *Journal of Hydraulic Research*, 50(6), 637-641.

[7] Chock G, Robertson I, Kriebel D, Francis, M, Nistor, I (2013): Performance of Structures under Tsunami Loads, Tohoku Japan Earthquake and Tsunami of 2011, ASCE, Reston, VA.

[8] Tonkin SP, Francis M, Bricker JD (2013): Limits on coastal scour depths due to tsunami, *International Efforts in Lifeline Earthquake Engineering, TCLEE Monograph 38*, ASCE, Reston, VA.

[9] Fahlbusch FE (1994): Scour in rock riverbeds downstream of large dams. *The International Journal of Hydropower and Dams*, IAHR, 1, pp. 30-32.

[10] Yeh H, Li W (2008): Tsunami Scour and Sedimentation. *Proceedings 4th Intl. Conf. on Scour and Erosion*, Tokyo, Japan, 95-106.

[11] Richmond B, Szczuciński W, Chagué-Goff C, Goto K, Sugawara D, Witter R, Tappin D, Jaffe B, Fujino S, Nishimura Y, Goff J (2012): Erosion, deposition and landscape change on the Sendai coastal plain, Japan, resulting from the March 11, 2011 Tohoku-oki tsunami. *Sedimentary Geology*, 282, 27-39.

[12] Thomas S, Killian J, Bridges K (2015): Influence of Macroroughness on Tsunami Loading of Coastal Structures. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 141(1), 04014028-1-14, ASCE, Reston VA.

[13] Douglass S, Krolak J (2008): Highways in the coastal environment. *Hydraulic Engineering Circular 25, FHWANHI-07-09.,* Federal Highway Administration, Washington, DC, 2nd edition.

[14] Clopper P, Chen HY (1998) Minimizing embankment damage during overtopping flow. *FHWA-RD-88-181.* Federal Highway Administration.

[15] "Grande Isle Geotube Construction" by Team New Orleans, US Army Corps of Engineers is licensed under CC BY 2.0