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ESTIMATION OF SEISMICALLY-INDUCED POTENTIAL TSUNAMI PENETRATION ONTO COASTAL TERRAINS

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Abstract

This paper presents a methodology of estimating the inland incursion of tsunamis generated offshore by earthquakes by adapting prognostic equations of wind wave run-up to the earthquakes' long-period characteristics. Tsunami height is estimated from site-specific historical events. The methodology takes account the nearshore depths, backshore topography, tidal range, and tsunami approach direction. Two project applications are discussed; one involving site development planning for a coastal resort whereas the other involving tsunami evacuation zone assessment for a prospective seaport site.
Keywords: *Tsunami, run-up, earthquake, planning, site development*

1 Introduction

This paper presents a methodology of quantifying tsunami potential penetration on the backshore. The method is based on an adaptation of prognostic wind-wave equations to predict the tsunami-wave movement, considering the characteristics and water surface movement of earthquake-induced tsunamis. The methodology takes into account the effects of bottom topography, nearshore wave transformations, and tide levels that results in the hindcast of the inland penetration of a historical tsunami. The methodology has been applied to a residential development project in the Philippines, in which the highest elevations that both historical and design tsunami events were to be determined to guide in-site development planning for civil works and permanent structures. In another project, the methodology was used to evaluate the relative suitability of prospective sites for a seaport partly on the basis of inland extent of a potential tsunami occurrence and the availability of backshore spaces to host tsunami evacuation. A brief discussion of earthquake-induced tsunamis and available data on Philippine tsunamis are presented in the first sections of this paper. Applicable wave transformation equations and tsunami run-up relations are next presented. Finally, the project applications are shown.

2 Nature and characteristics of tsunamis

Tsunamis are surface water waves generated by displacements of large volumes of the earth's surface water. Tsunami-generating (or tsunamigenic) events include earthquake-induced ocean floor displacements, volcanic eruptions, submarine landslides, and more recently, nuclear explosions. The displacement of the overlying water creates surface waves that travel over large distances. Tsunamis are generated by volcanic activity or landslides affect mainly the areas near the source, while those that are generated by tectonic uplifting may travel across ocean basins and cause damage to areas far from the generating source.

Detailed discussion of tsunami generation and propagation is available in Murty (1977)

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Figure 1: Inland houses destroyed by Moro Gulf tsunami, August 16, 1976 (from Pararas-Carayannis, 1976)

and Camfield (1980). In general, the large tsunamis that travel transoceanic distances are typically generated by tectonic activity associated with shallow-focus earthquakes (Iida, 1970). In terms of faultline type, dip-slip faults cause large vertical tectonic displacements that induce larger tsunamis, as against the strike-slip faults that typically induce earthquakes with high ground accelerations. Tsunamis that are generated by unipolar disturbances are stronger than due to bipolar disturbances. A unipolar disturbance, for example, is the uplifting of a large part of the sea bed without subsidence in adjacent areas. From such disturbance, stable forms of surface waves called "soliton" evolve (Hammack and Segur, 1974), which can travel very long distances without dispersion.

Tsunamis are characterized by a long period, i.e. long time for two successive wave crests to pass a fixed location. Their periods are of the order of 5 minutes to one hour, depending on the nature and location of the generating event. Due to the dependence of the wavelength (the distance between successive high points, or crests, of a wave), the wavelength of tsunamis is long. In the deep oceans, this wavelength is of the order of hundred kilometers and about a few kilometers in the coastal area.

Like any surface water wave, tsunamis undergo transformations as they encounter changes in the sea bottom topography (bathymetry) on their travel toward the coast. Tsunamis undergo initial reflection as they reach the seaward edge of the continental shelf and are reflected a second time as they encroach on the nearshore slope. Within the continental shelf itself, the tsunami direction is altered by depth refraction, such that they reach the shore at a more perpendicular direction. They also induce secondary waves called edge waves within the nearshore zone due to their inherent long period and oblique approach direction which can, in turn, induce other nearshore processes, such as the formation of caustics and the trapping of waves. Also, tsunamis interact with coastal structures mainly through diffraction, reflection, energy damping, and wave breaking.

In the absence of coastal structures, the propagation of tsunamis toward the coastal area is governed mainly by refraction and wave breaking. Energy damping by seabed friction is usually inconsequential in dissipating tsunami energy. The initial reflection by the continental shelf may be significant but this is typically neglected in wave run-up computations unless the shelf data, like slope, depth and location, are available. Through this depth refraction process, coastal areas are not directly along the initial tsunami path from the generator can experience significant damage, even though they are physically very distant from the source.

3 Earthquake-induced tsunamis

The Philippines is located along the boundaries of the Pacific Ocean which are seismically active areas, thus has a high potential for generating tsunamis. Figure 2 shows the Philippine seismicity map for one decade, including the magnitude (size of circles) and depths (color scale) of earthquakes, as well as the location of the active faults and trenches. It is well known that the country is in an earthquake-dotted region of the world.

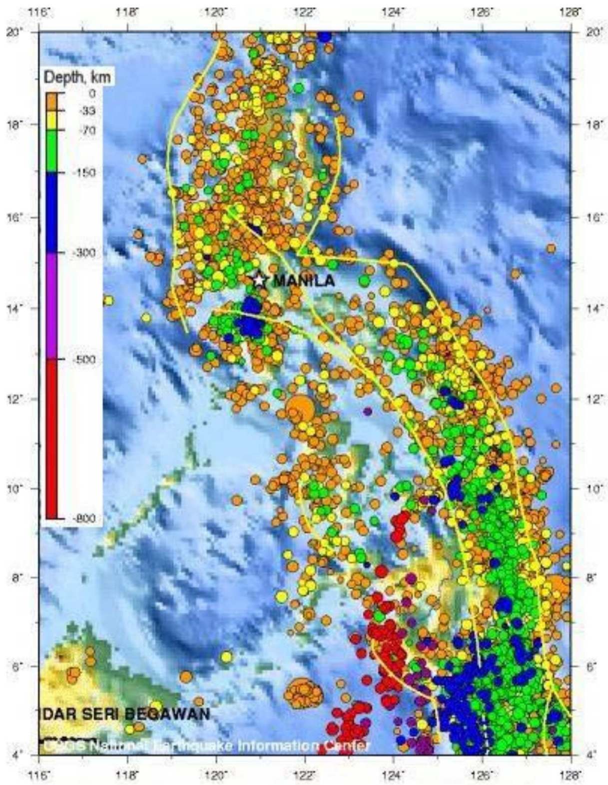


Figure 2: Philippine seismicity map 1901-2001, location of trenches (from PHIVOLCS)

Table 1 lists the tsunami events that originated within Philippine waters in the last 40 years based on the database in the US NGDC (see References). The magnitude of the earthquake event that generated the tsunamis and the maximum observed height of the induced run-up on coastlines are also shown. The most recent strong tsunamigenic event as of this time occurred in 2002 with an maximum run-up of 3 meters observed along 3 locations in Mindanao. The strongest tsunamigenic earthquake occurred in August 1976 in Moro Gulf with a magnitude of 8.1 which also led to the highest run-up of 8.5 meters in the immediate coastline in Cotabato, and also reached distant coastlines in Japan.

Table 2 shows the tsunami run-up observations at various Philippine coastlines in the last 40 years. The highest run-up events were associated with the 1976 and 1994 earthquakes. The 1994 earthquake was generated in a bay and induced high run-ups at adjacent coastlines from various directions from the source. Moro Gulf,

Table 1: Tsunami events in the Philippines

Yr/Mo/Day	Max Tsunami Height (m)	Source Region	Earthquake Magnitude
1970/01/10	0.06	Philippine Trench	7.6
1970/04/07		Philippine Sea	7.3
1970/09/30		Philippine Trench	5.3
1972/12/02	0.5	Mindanao Is.	7.4
1973/03/17	1.3	Quezon	7
1975/10/31	4	Philippine Trench	7.2
1976/08/16	8.5	Moro Gulf	8.1
1978/06/14	0.03	Mindanao Is.	6.9
1982/01/11	0.1	Philippines	7.1
1983/08/17	0.1	Luzon Is.	6.6
1988/06/24	1.03	north of Luzon Is.	5.4
1990/05/--	0.1	Camiguin Is.	
1992/05/17	0.1	Philippines	7.3
1994/11/14	7.3	Philippine Is.	7.1
1995/04/21	0.2	Samar	7.2
2002/03/05	3	Mindanao Is.	7.5

Source: US NGDC database (see References)

on the West of Mindanao Island, is a known tsunami generator, while many coasts in the island are known to be vulnerable to tsunamis generated both locally and from foreign waters. For example, Davao in southern Mindanao is susceptible to tsunamis generated in Davao trench, but the most recent 13-cm run-up observation in 2009 was caused by a tsunami in Indonesian waters.

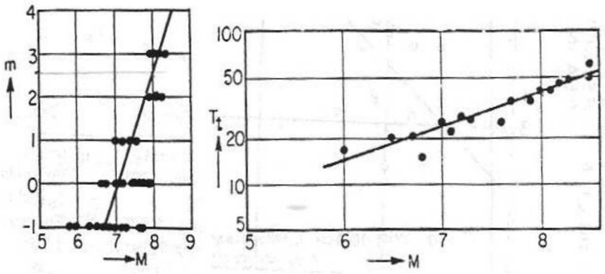
Not all earthquakes that occur offshore generate tsunamis. Earthquakes of high magnitude that occur offshore with shallow focus (depths of about 40 km or less) are known to induce significant tsunami waves. Such seismicallygenerated tsunamis have value of wave period, the time for two consecutive tsunami crests to pass a fixed point in the water, that are much longer than wind-generated surface waves. Iida (1963) studied historical data of tsunamis in Japan and

Table 2: Recent tsunami run-up observations

Yr/Mo/Day	Runup Location (runup in meter)
1970/04/17	Dingalan Bay (*)
1970/09/30	Bataan Is. (*)
1973/03/17	Caluag(1.3), Quezon (1.3)
1975/10/31	Legaspi (0.2), Manila (4.0), Samar Is. (*)
1976/08/16	Alicia (4.43), Bongo Is. (4.3), Jolo Is. (3.0), Lebak (3.4), Moro Gulf (4.48), Pagadian (4.3), Resa Bay (3.0), Linek, Cotabato (8.5), Malabang (6.0)
1982/01/11	Legaspi (0.1)
1983/08/17	Luzon Is. (0.1), Paoay, Ilocos Norte (*)
1994/11/14	Baco (3.3), Baco Is. (7.3), Balete (2.2), Brgy. Sawang, Lobo (3.8), Baruyan (2.4), Baruyan River (0.5), Calapan (2.6), Charico (2.1), Ibaba (1.8), Puerto Galera (*), Lagadla Rin (3.4), Lobo (2.6), Malaylay (3.2), Mindoro (*), Pachuka (2.2), Pampisan (2.2), Verde Is. (3.6), Villaflor (2.3), Wawa (4.0), Wawa Is. (3.5), Legaspi (0.2)
2002/03/05	Kiamba, Sarangani (3.0), Maitum, Sarangani (3.0), Palimbang, Sultan Kudarat (3.0)
2007/08/15	Davao (0.01)
2008/11/16	Davao (*)
2009/02/11	Davao (0.13)

Source: US NGDC database; *Not available.

concluded that the magnitude m of a tsunami is proportional to the magnitude (on Richter scale) M of the causative earthquake (Figure 3). Tsunami magnitude is defined as the logarithm of the maximum run-up height of the tsunami wave (Iida, 1963). The maximum period T t of the tsunami wave was also found to be logarithmically proportional to the earthquake magnitude, as shown in Figure 3. The tsunami period is an important parameter in the estimation of the extent of inland incursion of a historical tsunami, as discussed below.



(a) (b)

Figure 3: (a) Relationship between earthquake magnitude M and tsunami magnitude m (b) Relationship between period of a tsunami T t and earthquake magnitude M (from Iida, 1963)

4 Tsunami hazard assessment

The large wavelength of tsunamis is one cause of concern for the potential damage that can be brought by a tsunami to a coastal area. Since the wave steepness (ratio of the wave height to the wavelength) of tsunamis is very low, tsunamis propagate to the shore largely without breaking. For tsunamis that do break, the breaking location is close to the shore, which induces high dynamic forces on coastal structures. Wave breaking is a hydrodynamic process that naturally dissipates much of the energy of incoming waves. Without breaking, tsunami energy can only be damped by seabed friction, but usually insignificantly. Furthermore, when compared with wind waves, which typically have periods of 4 to 15 seconds (including typhoon-induced storm waves), tsunamis exert much higher dynamic pressures than wind waves of the same height on the surfaces that buffet them. These two prominent characteristics of tsunamis are the bases for the potential damage associated with them.

In the deeper offshore areas, the larger depths allow the tsunami waves to propagate without breaking until very close to the shore. However, this transformation is hastened by a steeply sloping coast, such as a revetment or seawall, that quickly turns the tsunami crests into turbulent flumes that entrain air, bottom sediments, and debris into the flow. This entrainment of solids into the high-momentum flow adds to the potentially catastrophic damage of tsunamis on the inland areas. The highest point on the coastal interface that the transforming tsunami impinges inland provides a measure of such potential damage.

In this paper, tsunami hazard is quantified by computing the potential run-up of tsunami waves on a given coastal terrain. Two-dimensionality of the run-up process is assumed and consequently the terrain can be represented by a series of composite slopes that locally contains the run-up point of the tsunami. The terrain is obtained from the combination site bathymetry (bottom contours) and the shore topography. The coastal slope is a series of plane slopes that are each idealized as being smooth and solid (Figure 4). The vertical profile of the composite slope thus provides the local depths and bottom slopes required in predicting the transformation of tsunamis on the coastal terrain.

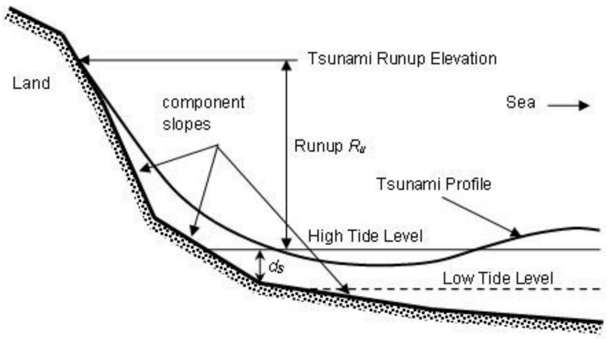


Figure 4: Definition sketch of tsunami run-up on a coastal terrain

The tsunami parameters required for the computations include the tsunami height H or tsunami amplitude, wave period T, and its source location. The height of a tsunami is normally obtained from historical data at the nearest observation station to the site, or by hindcasting based on run-up observations at various known locations. Information on the tsunami source can be obtained from a seismicity map (see Figure 2).

The tide level is another important input parameter. At a location where the normal tidal range is almost equal to the tsunami height, a tsunami occurring at low tidal stage may not be noticed, but a nominal tsunami coinciding with high tide may be considered as a major tsunami. The tide level also affects the toe depth d_S in front of the composite slopes which may govern the breaking of tsunamis. Tide data from annual tide tables published by mapping agencies, such as NAMRIA in the Philippines, can be used to determine the tidal range.

5 Potential tsunami incursion

Since tsunamis are surface water waves, they follow the same governing equations of wave motion once they have considerably moved out of the generation area. In trans-oceanic tsunami propagation in the deep oceans, tsunamis may still be influenced by geostropic forces, that is, forces induced by the earth's rotation or the so-called Coriolis effect. However, in the smaller spatial scale of the continental shelf, their motion is determined by essentially the same governing equations of free surface waves, except that their inherent periods are long. In view of this, the transformation of tsunamis is governed by equations for the typical surface water waves. The bending transformation of tsunami waves are based on the refraction equation:

$$\frac{\partial(k\sin\theta)}{\partial x} - \frac{\partial(k\cos\theta)}{\partial y} = 0 \qquad (1)$$

where x, y are the horizontal coordinates, θ is the angle of the wave ray with the bottom contours (wave direction), and k is the wave number, or $k = 2\pi/L$, in which L is the wavelength. The wavelength and wave period are related by the dispersion equation:

$$L = \frac{gT^2}{2\pi}\tanh\frac{2\pi d}{L} \qquad (2)$$

where g is the gravity acceleration, T is the tsunami period and d is the local depth. Eq.(2) is used to determine the tsunami wavelength for known period and depth, while the refraction equation is typically used to determine the tsunami direction θ at the project site.

The height of a tsunami will increase as it approaches shallow waters. The change of tsunami height can be computed from the shoaling equation. However, tsunamis may break at a critical depth as they propagate toward shore. Wave breaking thus effectively imposes a limit to the maximum height that a tsunami will attain. Such condition is expressed through a wave breaking equation, which has various functional forms depending on the range the surf-similarity parameter ξ_0,

$$\xi_0 = \frac{\tan\beta}{\sqrt{H_0/L_0}} \tag{3}$$

where H_0 and L_0 are respectively the deepwater tsunami height and wavelength. β is the angle of slope from the horizontal for a single-slope terrain. For composite slopes, β is the effective slope of a fictitious line from a seaward location to the tsunami run-up point. For non-breaking waves, this seaward location is the first slope junction seaward of the shoreline, where the depth is d_S (Figure 3). For breaking waves, this seaward point is at the location of the breaking point. For tsunamis, the following breaking condition of Le Mehaute and Kho (1967) is appropriate in view of its long period and reflection characteristic on plane slopes:

$$\frac{H_b}{H_0'} = 0.76(\tan\beta)^{1/7}\left(\frac{H_0'}{L_0}\right)^{-1/4} \tag{4}$$

where H o ′ is the unrefracted deepwater wave height.

The most critical part of tsunami incursion computation is the determination of the run-up height R u (see Figure 3). For this purpose, predictive formulas based on both theory and empirical data for wind waves can be used. The Coastal Engineering Manual (USACE, 2004) predicts the wave run-up as a function of the significant wave height H s and the deepwater wave steepness as follows:

$$\begin{aligned} \tfrac{R_u}{H_s} &= 1.6\xi_0 && \text{if } _{\text{¸}}0 \leq 2.5 \\ \tfrac{R_u}{H_s} &= -0.2\xi_0 + 4.5 && if\, \xi_0 > 2.5 \end{aligned} \tag{5}$$

Due to the higher wavelength of tsunami waves, run-up computations for most historical tsunamis will take the second form in Eq.(5). The Shore Protection Manual (SPM) (CERC, 1984) adopts the semi-empirical formula of Goda (1970), which expresses wave run-up in terms of H_0', the toe depth d_S, wave period T, and effective bottom slope β, as follows

$$\frac{R_u}{H_0'} = f\left(d_S, \cot\beta, \frac{H_0'}{gT^2}\right) \tag{6}$$

Eq.(6) is resented in the SPM as nomograms which can be converted to numerical relations. Miche (1951) theoretically developed a formula based on partial standing non-breaking waves, which shows the wave run-up to be inversely related to the bottom slope:

$$\frac{R_u}{H_0} = \sqrt{\frac{\pi}{2\beta}} \tag{7}$$

Eq.(7) has been recommended in the engineering manual for Japanese ports and harbors (OCDIJ, 1991).

6 Site development planning for coastal engineering project

The foregoing methodology has been applied to the calculation of tsunami incursion at the site of a proposed mixed residential-resort development in Davao Province, Mindanao. The project site lies along Davao Gulf which is not frequently hit by typhoons. The susceptibility of the site to tsunami incursion is established from the knowledge of historical earthquake occurrences in Mindanao and specific data for Davao which indicate that the project site is located in a tectonically active region. An engineering geological report (AMH, 2007) describes the nature and locations of tsunami generators in the area, including nearsource generators in Davao Gulf and far-source generators in Indonesia. The report also reveals the proximity of the site to reverse-fault type of earthquake generators in Davao Gulf, which established its proneness to tsunami events. A tsunami incursion map was necessary during the site development planning stage to determine the susceptibility of proposed infrastructures such as roads and retaining structures to tsunami hazards, also to determine where permanent structures can be safely built. A nearshore bathymetric survey covering an offshore area of roughly 1.7 kilometers alongshore by 200 meters cross-shore was commissioned, which revealed that the longshore variations in bathymetry are not significant.

Tables of local tsunami events (similar to Table 1) and tsunami run-up observations were prepared from the NGDC database that indicated a maximum historical offshore tsunami height of 0.80 m. The most recent tsunamigenic event in 2002 produced a smaller offshore wave height of 0.45 m, coming from a more proximate source to the project site.

Figure 4 shows a photo of the project site prior to development, revealing the gentle beach slope at low tide. Figure 5 shows the combined bathymetry and topography of the project site, as well as the transect lines used to estimate the tsunami run-up. These transects are selected to produce the potentially highest run-up elevations, that is, mild foreshore slopes on recessed points along the coastline. The other input data are:

- Offshore wave height, H_0 = 0.8 m
- Wave steepness in deep water, H_0/L_0 = 0.0024
- Wave direction in deep water, θ_0 = 74 degrees
- Water levels from Mean Lower Low Water (MLLW) to Mean Higher High Water (MHHW)

Figure 5: Photo of project coastline

Tide levels MLLW and MHHW, taken from the nearest tide station, are considered since the water surface at low tides may intersect a mild bed slope, possibly leading to higher run-up than that at high tide. Low tides may also yield a higher depth d_S which leads to a non-breaking tsunami and consequently higher run-up. The wave direction θ_0 is assumed for a tsunamigenic event originating from the south of project site where the nearsource tsunami generator is known to exist.

The period of the earthquake-induced tsunami was estimated directly from the earthquake magnitude. With a near-source tsunami generator at Davao Gulf, the tsunami event table for the area suggests a historically high earthquake magnitude of 7.9. For purposes of evaluating potential tsunami incursion, an earthquake magnitude of 8.1 is used for which a period of 40 seconds is appropriate (see Figure 3b). A near-source tsunami generated close to the site is thus characterized by a deepwater wave steepness H_0/L_0 of 0.0024, which is beyond the range of typical surface waves. This steepness results in a non-breaking tsunami at the foreshore.

Table 3: Computed run-up elevations for historical and potential tsunami heights

Trans.	Runup Elev. (m)		Trans.	Runup Elev. (m)	
	H_o = 0.8m	H_o = 0.45m		H_o = 0.8 m	H_o = 0.45 m
1	7.57	4.30	9	6.30	5.49
2	7.60	4.32	10	7.03	5.81
3	7.37	6.80	11	7.74	5.95
4	8.70	6.94	12	7.02	5.46
5	7.66	4.95	13	8.24	5.67
6	6.60	4.98	14	6.77	4.64
7	7.20	6.97	15	6.27	4.87
8	5.44	3.73	16	6.87	4.16

A computer program was developed for the numerical implementation of run-up computations based on the foregoing methodology. For this site, 32 transects were used and the tidal stage is varied with steps of 0.5 meter. A spline is then connected through the computed run-up points for each transect. The run-up elevations are shown in Table 3 for the first 16 transects, and the resulting tsunami incursion maps are plotted in Figure 6 for the historical and potential tsunami heights of 80 and 45 cm, respectively. It is seen that incursion limits are farthest inland at water level MHHW for this site, and the results tend to confirm that tsunami run-up is highest at high tides. They also indicate that tsunami run-up through coastal gullies is higher, but smaller through coastal terraces and cliffs, mainly due to their steep slopes.

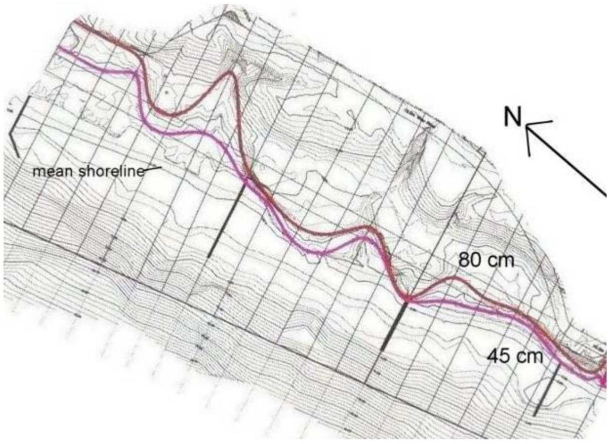


Figure 6: Computed incursion limit for offshore tsunami heights of 80 cm and45 cm

It should be noted that tsunami incursion maps are not single-event indicators, that is, they envelope curves that result from critical events that do not occur simultaneously. Also, the maps represent potential run-up values since the following factors were neglected: (a) surface frictional resistance of coastal slopes (b) permeability of seabed and coastal slope (c) wave reflection from continental shelf and shore, and (d) three-dimensionality of tsunami run-up process.

7 Prospective site evaluation considering tsunami evacuation

A second application of the methodology involves the assessment of a prospective site for a port in Batangas, a suburban area south of Manila. The site was previously used as a recreational beach. The site is characterized by a steep foreshore, almost flat backshore, and hilly inland just several meters from the national roads. The surrounding bay of the site is known to be tsunami-prone, with far-field generators associated with a trench in South China Sea and near-field source just within the seas around the site. As part of the appraisal study, the siting of an inland area within a 200 meter long coastline that can be used for evacuation of personnel and critical port materials was to be carried out.

Figure 7 shows a view of the backshore with the hills on the background. The digital elevation model (bottom) reveals the terrain and the wide tidal incursion on the flat backshore, revealing a likely narrow dry area during a tsunami event.

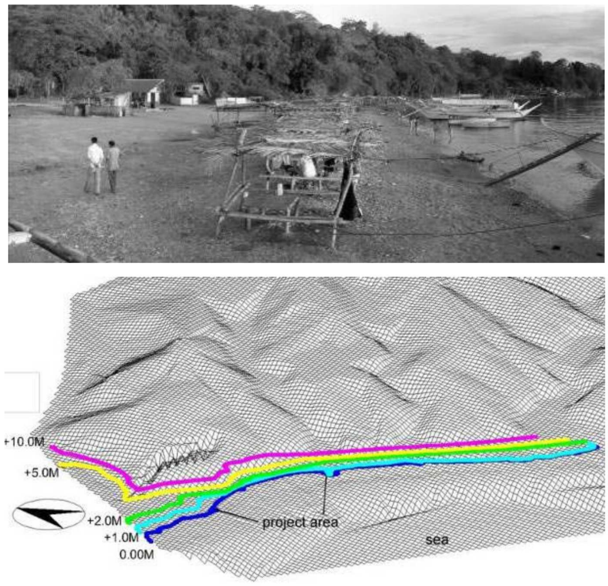


Figure 7: (top) Photo of project area; (bottom) nearshore and inland topography

Earthquake characterization was carried out to determine the offshore tsunami parameters. It was found that the strongest historical tsunami event has a near-field tsunami height of just 8.2 cm and wave period of 25 seconds, while a potential tsunami has height of 30 cm and period of 35 seconds.

Figure 8 shows the computed incursion limits of the two cases, with red and blue curves corresponding respectively to low and high tides. For the historical event (top figure), the more critical incursion occurs at high tide (blue curve). For a potential tsunami, however, the farthest inland movement happens at low tide (red line). Also, the incursion limit at high tide moves substantially inland within the flat reach of the backshore, leaving a narrow potential evacuation area in the backshore. The results of this study segment were used as basis to recommend a separate but adjacent site for the tsunami evacuation zone or to include an evacuation zone in the site development plan.

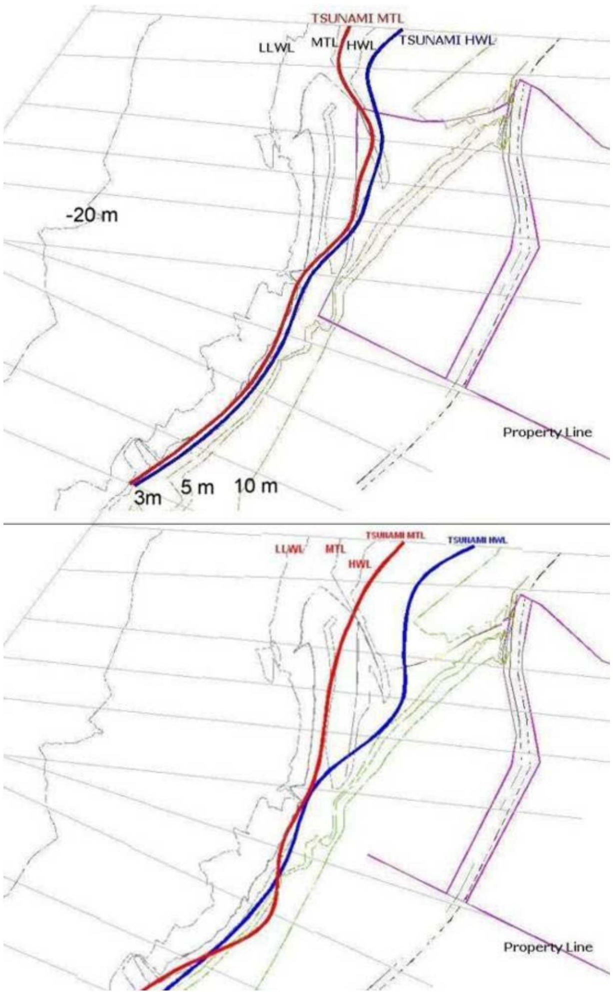


Figure 8: Computed incursion limits for: (top) historical tsunami, and (bottom) potential tsunami events

8 Conclusions

This paper presents a methodology of quantifying earthquake-induced tsunami hazard on a coastal terrain. The method is based on adapting wave transformation and run-up equations for windinduced waves to tsunamis considering their long period characteristics. The methodology accounts for the earthquake magnitude and offshore height of the induced tsunami, nearshore depths, backshore topography, and tide levels. While the approach has limitations, it can be applied to estimate the potential run-up elevation of a tsunami event with known offshore conditions to obtain the inland incursion map.

Through two project applications of the method, it is shown that a quantitative method of evaluating the inland penetration of tsunamis is imperative in planning and appraising development activities, especially in historically vulnerable coastal areas.

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