THE WAVE FORMS AND DIRECTIVITY OF A TSUNAMI GENERATED
BY AN EARTHQUAKE AND A LANDSLIDE.

S. I. IWASAKI
National Research Institute for Earth Science and Disaster Prevention,
3–1 Tennodai Tsukuba Ibaraki 305 JAPAN

ABSTRACT

Using a realistic topography of an ocean, differences in wave forms and directivities
of tsunamis generated by earthquakes and landslides are investigated through
numerical simulations. The ocean is composed of a shelf, shelf slope and bottom regions.
Tsunami sources are located on the shelf slope and the bottom region. The length of the
tsunami source is 100 km and the width is 50 km. For the earthquake, uniform vertical
deformation of 1 m is assumed to jerk instantaneously. For the landslide, solid slab with
50 m thickness is assumed to be moved in off-shore direction with the uniform velocity.
The boundary condition on the coastline is solid and elsewhere are open boundaries.
The linear long wave simulation model is used.

Tsunamis generated by landslides show strong directivities compared with those
generated by earthquakes. But, in the range less than $3\pi/8$ from the direction of the
minor axis of tsunami sources, the variation of the directivity coefficients are almost the
same regardless of differences in the generation mechanisms, generating regions and the
ocean topographies. The ratios of the amplitude of the first crest (trough) to trough
(crest) of the waves are roughly unity for the tsunamis generated by earthquakes. But
those for the landslides, the ratios are varied from unity to 1/5 depend on the azimuths
of the observing points.
1. INTRODUCTION

The two great tsunamis, the Sanriku in 1896 and the Aleutian in 1946, were extraordinary. The tsunami run-up heights observed at coasts were so large in spite of the moderate magnitudes of the earthquakes which generated the tsunamis. The reasons are not fully clear. Slow-earthquake is one of the explanations (Kanamori, 1972). But, landslide is also one of the possibilities. It is well known that landslides generate tsunamis. Recently several large scale landslide traces were found near the Sanriku coast (Honza et al., 1978). And, it was discovered that one of these landslides would have a potential to generate a large tsunami (Iwasaki et al., 1996). Sometimes landslides are triggered by earthquakes. In the Grand Bank earthquake in 1929, a turbidity current was generated and set off tsunami (Heezen and Ewing, 1952). At the time of the Nihonkai-Chubu earthquake in 1983 and Hokkaido Nansei-Oki earthquake in 1993, it was reported that the arrivals of the initial wave of these two tsunamis were observed earlier at several coasts than the expected times. These were explained due to the pre-slips or landslides (Shuto et al., 1993 and 1994). In the Flores island tsunamis in 1992 there exist clear pictures of evidence of landslide trace and this landslide affected the tsunami characteristics locally (Imamura et al., 1993). Nakamura and Arai (1996) reported extraordinary fast arrival of the tsunami at the several coasts along the Okhotsk sea at the time of the Hokkaido Toho-Oki earthquake in 1994 and these waves were generated at the other places, apart from the main shock about 200 km. From the seismicity near this region, they concluded that a landslide is the most probable cause of the fast arrivals.

It is quite possible that landslides generate tsunamis or that landslides triggered by earthquakes affect the tsunami characteristics. It is important to know the difference of the characteristics between tsunamis generated by landslides and tectonic movements to prorate that portion of the tsunamis generated by landslides and that by earthquakes. For tsunamis generated by tectonic movements, Kajiura (1970) discussed the energy and directivity of the wave qualitatively considering various source models in an ocean of constant depth. But, for landslides, this type of study has not been done. In this paper, using the numerical simulation methods, the differences of the directivity and wave forms of tsunamis generated by landslides and tectonic movements are investigated in an realistic ocean model.

2. The MODEL

The schematic view of the model is shown in Fig.1. The Cartesian co-ordinate system
is used with the origin at the center of the coast. The left figure is a plan view of the model and the right is the vertical profile of the ocean. The depth and the length of the continental shelf is 200 m and 100 km, respectively. The slope of the shelf slope is 1/30 and the length is 120 km. The depth of the ocean bottom is 4200 m and the length is 230 km. Tsunami source is located on the shelf slope and the bottom region. The area of tsunami source is 100 km long and 50 km wide. For the earthquake, it is assumed that uniform vertical deformation of 1 m jerked instantaneously. For the landslide, a rectangular slab with thickness 50 m is slid down in the off-shore direction (y-direction) with the uniform velocity. The duration of the landslide is 4000 sec. Three cases of landslide simulations are made by changing the uniform sliding velocity as 5 m/s, 10 m/s and 20 m/s.

Fig.1 A schematic view of the model.

3. NUMERICAL SIMULATIONS

Under the linear long wave approximation, the basic equations are

\[ \frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0, \]
\[
\frac{\delta M}{\delta t} + gd \frac{\delta \eta}{\delta x} = 0, \quad (2)
\]
\[
\frac{\delta N}{\delta t} + gd \frac{\delta \eta}{\delta y} = 0, \quad (3)
\]

Where
\( \eta \): surface water level,
\( M, N \): discharge fluxes in x, y directions,
\( d \): water depth and
\( g \): gravity constant.

Since, the ocean bottom deformation is assumed to be an instantaneous jerk, it is converted to the water surface maintaining its shape as the initial condition of the simulation for the tsunami generated by the tectonic movements. For the landslide, the distinguishing point is the source movement. The generating mass moves horizontally and generates successive tsunamis. According to Iwasaki et al. (1996), the procedure is as follows. The initial wave form of the tsunami due to the landslide is calculated by an analytical method. Then, the initial wave form is transferred to numerical simulation program as the initial condition. The wave form of the next time step produced by the continuing landslide is again calculated analytically. The results of the second step are added to the numerical simulation results of the former step. The routine continues to the end of the movement of the landslide.

As an analytical solution, Kajiura (1963) presented a time dependent Green's function in an ocean of constant depth under the long wave approximation. Using this, the tsunami wave form due to the landslide is given by

\[
\eta_A = \frac{V_h}{\pi} \Delta t \{ \tanh^{-1}(\frac{\zeta_0}{2d}) \tan^{-1}(\frac{x-d}{2d}) - \tanh^{-1}(\frac{x+d}{2d}) \}.
\]  

(4)
Fig. 2 Perspective views of tsunami generated by the landslide. Landslide location is on the shelf slope and the horizontal sliding velocity is 10 m/s.
Fig. 3 Perspective views of tsunami generated by the earthquake. The uniform vertical deformation of 1 m is jerked instantaneously on the shelf slope.
Fig. 4 A same figure as Fig. 2, but, the landslide location is on the bottom.
Fig. 5 A same figure as Fig. 3, but, the earthquake location is on the bottom.
Tsunami is generated at the front and rear side of the landslide. The above solution is valid only for a constant depth ocean. However, the solution decays very rapidly with the distance. So, this solution was used as the initial and successive tsunami wave forms due to landslide even in the sloping region as the water depth is locally constant.

4. THE RESULTS

Fig. 2, 3, 4 and 5 are perspective views of tsunamis generated by landslides for the case of the sliding velocity being 10 m/s and earthquake. The vertical scale is in m and the horizontal scale is in km. The time measured from the onset of landslide and earthquake are shown in the upper side of each figure. Here, SLOPE means tsunami source is located on the shelf slope, BOTTOM means the source located on the bottom region and E means that this is the tsunami generated by an earthquake.

Differences of wave forms due to the generating region locations are not clear from the perspective views. For the earthquake, up to 8 min. the directivity is not changed drastically for both cases. Rather small peaks exist in the directions of the major and minor axis directions of tsunami sources. After 10 minutes from the onset of the earthquakes, on–shore side wave height enlarges because the water depth became shallow. For the landslides, both for the tsunami source located on the shelf slope and the bottom, the difference of wave heights shows strong directivity even at 3 minutes from the onset of landslides. Due to the successive tsunami generations, small peaks and troughs are shown in the region after the first wave propagates to outside.

Fig. 6 Observing points arrangement.
Fig. 7. Tsunami wave forms as a function of the time. Tsunami sources are located on the shelf slope.
Fig. 8 A same figure as Fig. 7, but, tsunami sources are located on the bottom.
Several observing points were picked up to see the time dependence of waveforms. Fig. 6 shows the observing points arrangement. The points were located at a distance of 100 km from the center of the tsunami source. The azimuths were measured in a counterclockwise manner and off-shore direction of the minor axis of the tsunami source is selected as $\theta = 0$.

Fig. 7 and 8 shows tsunami waveforms as a function of time. The vertical scale is in m and the horizontal scale is in second. For most of the observing points, the waves are composed of a single crest and trough. The waveforms due to earthquake and landslide are quite similar, in particular, at $\theta = 0$ and $\theta = \pi / 2$. But, the sign is converted for $\theta = \pi / 2$. The duration of the first elevated (or, depressed) portion in each wave is roughly related to the length of the tsunami source projected in the direction of the observing point. Significant differences of waveforms due to the differences of generation mechanisms are restricted less than $\pi / 8$ from the directions of the major axis of the tsunami source. The ratios of the first crest (trough) to trough (crest) are roughly unity in case of earthquakes but the ratios vary from unity to $1/5$ in case of landslides. The differences due to the location of the tsunami source are significant at $\theta = 3\pi / 4$, $\theta = 7\pi / 8$ and $\theta = \pi / 2$, these are the directions of the rear side of the landslides movements. This is because the differences of superpositions of successive wave trains of a tsunami. That is, in the direction of the front side, the position of the first wave crest and that of the second one are more closer than those in the direction of the rear side and this tendency is emphasized in case of the tsunami source is on the shelf slope.

Directivity coefficients are calculated for the earthquake and three cases of landslides. The total flux of gravity wave energy $E_f$ for the unit width, transmitted in the peculiar direction can be computed approximately by following the formula, because the wave can be considered as a progressive after leaving the tsunami source.

$$E_f = pg \int_0^\infty \eta^2 c dt$$  \hspace{1cm} (5)

where

$\rho$ denotes the density of the water and $c$ denotes the phase velocity.

The directivity coefficient $Q$ is defined as
Fig. 9 Directivity coefficients as a function of azimuth of the observing point in case of tsunami sources are located on the shelf slope. Kajiura's (1970) solution is also shown in comparison.
Fig. 10 A same figure as Fig. 9, but, tsunami sources are located on the bottom.
\[ Q = \frac{E_f}{E_{f\text{max}}}. \]  

(6)

where, \( E_{f\text{max}} \) is the maximum value of \( E_f \) for each cases.

Fig. 9 and 10 shows the directivity coefficients \( Q \) as a function of \( \theta \) in case of tsunami source located on the shelf slope and the bottom, respectively. In these figures Kajiura's (1970) result is also shown for the comparison. He calculated the directivity coefficients in the range of \( 0 < \theta < \pi/2 \) for the tectonic movement by earthquake in an ocean of constant depth. Since, the ocean in his model was constant depth, his results can be extended in the range of \( \pi/2 < \theta < \pi \) assuming the symmetry relative to \( \theta = \pi/2 \). In his case, the distance of the observing points from the center position of the tsunami source were 200 km whereas it is 100 km in the present study. The ratios of the maximum value to the minimum value of \( Q \) in each cases are calculated and shown in Table.1

<table>
<thead>
<tr>
<th>locations mechanisms</th>
<th>shelf slope on-shore</th>
<th>shelf slope off-shore</th>
<th>bottom on-shore</th>
<th>bottom off-shore</th>
</tr>
</thead>
<tbody>
<tr>
<td>landslide: ( V_H = 5 ) m/s</td>
<td>0.0359</td>
<td>0.0256</td>
<td>0.00830</td>
<td>0.00878</td>
</tr>
<tr>
<td>landslide: ( V_H = 10 ) m/s</td>
<td>0.0370</td>
<td>0.0295</td>
<td>0.0100</td>
<td>0.0117</td>
</tr>
<tr>
<td>landslide: ( V_H = 20 ) m/s</td>
<td>0.0366</td>
<td>0.0374</td>
<td>0.0120</td>
<td>0.0174</td>
</tr>
<tr>
<td>earthquake</td>
<td>0.278</td>
<td>0.247</td>
<td>0.266</td>
<td>0.262</td>
</tr>
</tbody>
</table>

Table 1. The ratios of the maximum to the minimum values of \( Q \).

The variation of directivity coefficients are large in case of landslides compared with those in case of earthquakes, in particular, in case of the tsunami source located on the bottom region. For the earthquakes, the variations of \( Q \) are significant in the range \( 0 < \theta < \pi/4 \) and \( 3\pi/4 < \theta < \pi \), while in the range \( \pi/4 < \theta < 3\pi/4 \), the values are almost constant.

The variations of \( Q \) are almost symmetric relative to the direction of the major axis
of tsunami source \((\theta = \pi/2)\) for the case of the source located on the bottom region, but, for the case of the source located on the shelf slope, there exist somewhat differences of the variation of \(Q\) in the ranges \(0 < \theta < \pi/2\) and \(\pi/2 < \theta < \pi\). The total energy flux propagating in the on-shore direction is a little bit large compared with that to the off-shore direction. The most significant characteristics is the variations of the directivity coefficient being almost the same from \(\theta = 0\) to \(\theta = 3\pi/8\) regardless of the differences of the generation mechanisms, the generating regions and the ocean topography. The discrepancy of the variation of the directivity coefficients due to the difference of the generation mechanisms are obvious from \(\theta = \pi/4\) for the tsunami source located in the shelf slope and from \(\theta = 3\pi/8\) for that in the bottom region.

5. CONCLUDING REMARKS

In the present paper, the differences of wave forms and directivities of tsunamis due to the differences of generation mechanisms and generation regions for a realistic ocean topography are discussed through the numerical simulations. Following conclusions are found.

(1) Differences of generation mechanisms:

\* wave forms of tsunamis generated by tectonic movements and landslides are quite similar in the direction of the minor axis of tsunami sources.

\* the variations of the directivities coefficient are large for tsunamis generated by landslides compared with those for tectonic movements.

(2) Differences due to the generation regions.

\* wave forms are quite similar near the directions of minor axis of tsunami sources, but, the slight differences exist near the major axis of tsunami sources.

\* Variations of directivity coefficients are large for tsunamis generated by landslides on the bottom compared with those on the shelf slope. On the contrary, for tsunamis generated by earthquakes, this tendency is reversed.

The most significant characteristics is that the wave forms and the variations of directivity coefficients are almost the same in the range less than \(3\pi/8\) from the direction of the minor axis of tsunami sources regardless the differences of generation mechanisms, generation regions and the ocean topographies. It suggests strongly that if the azimuths of the observing points are distributed in a narrow region, it is difficult to know what potion of a tsunami was generated by an earthquake and what portion by landslide.
ACKNOWLEDGEMENT

The simulation program used in the present study was originally developed at the Tohoku University under the TIME (Tsunami Inundation Model Exchange) project and modified by the author. Thanks are also extended to Ms. S. Kashimura for assistances in the various phases of this study.

REFERENCES


