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Simulation of Historical Tsunamis in the Taiwan Region

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ABSTRACT

A well-developed numerical tsunami computation technique was applied to simulate historical tsunamis of the 1604 to 1978 period in the Taiwan region. The observed tsunami for the November 14, 1986 Hualien earthquake was examined to test the reliability of the numerical technique. Based on the occurrence of historical tsunamis, the Taiwan area is divided into five areas, namely Keelung, Hualien, Taitung, Tainan and Hsinchu. Due to the less than complete understanding of historical tsunami earthquakes, a simulation of historical tsunami in each area was made by considering the focal mechanisms of recent earthquakes in the vicinity. The empirical relationship of the moment magnitude and fault dimension was utilized for the computation of the synthetic tsunamis to obtain the relation between Mw and the maximum tsunami amplitudes of the first tsunami wave. The earthquake magnitude which was responsible for generating disaster tsunamis were then estimated. The obtained earthquake magnitudes from these simulations are comparable to those reported in historical literature. In addition to enhancing the understanding of the possible causes of historical tsunamis, the simulations made in this study also provide important information regarding the characteristics of tsunami waveforms in different regions. This information provide useful insight for the purposes of establishing tsunami warnings.

(Key words: Historical tsunamis, Numerical tsunami technique, Earthquake magnitude)

1. INTRODUCTION

A tsunami is considered a kind of gravity wave mainly caused by a large scale disturbance such as an earthquake (the 1960 Chilean Tsunami), landslide (the 1975 Alaskan Tsunami) or a volcanic eruption (the 1883 Indonesian Tsunami). Among these, the tsunamis caused by earthquakes are more frequent. A tsunami generally results from the vertical crustal deformation of the sea-floor during an earthquake. It propagates with the velocity $v = \sqrt{gd}$ for actual bathymetry, where g is the gravitational acceleration and d is the water depth.

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Table 1. Historical tsunami earthquakes in the Taiwan region from 1604 to 1978.

Date (yr/mon/day)		Location (°E)	(°N)	Magnitude [1](M)	[2](m)	Remarks
1604/12/29	Hsinchu	119.5°	25°	8.0	0~1	
1661/01/08	Tainan	120.1°	23°	6.0	1	Great Taiwan-Anpin Tsunami
1754/04/-	Danshui	121.4°	25.3°	<6	1	Some houses damaged
1867/12/18	Keelung	121.7°	25.5°	6.0	2	Several hundred people drowned
1917/05/06	Hualien	121.6°	23.2°	5.8	-1	Keelung 100cm.period 26 min.
1966/03/13	Hualien	122.6°	24.1°	7.5	-1	Moderate tsunami killed 7 people.
1978/07/23	Taitung	121.5°	22.3°	7.4	0~1	Hualienkang minor tsunami.

[1]Earthquake

[2]Tsunami

Recently, efforts have been made by seismologists to develop the relationship between earthquakes and tsunamis. Hwang *et al.* (1970, 1972a,b) obtained a numerical model of generation and trans-oceanic propagation of tsunamis using hydrodynamic equation in a spherical coordinate system. Kanamori (1975) obtained the relationship between tsunami magnitude and earthquake magnitude. Later, Abe (1980) used numerical modeling to study tsunamis. The synthetic tsunami waveforms computed numerically were in satisfactory agreement with the observed tsunamis at tide-gauge stations. Satake (1987, 1989) developed an inversion of tsunami waveforms to dtermine the mechanism of the earthquake. Building upon these developments, Ma *et al.* (1993) inverted the tsunami waveforms to obtain the vertical sea-floor deformation during the 1989 Loma Prieta and 1906 San Francisco earthquakes and to understand the origins of the observed tsunamis.

Taiwan is located in the Circum-Pacific Ocean Belt where many large offshore earthquakes occur. Although Taiwan has not been damaged recently by large tsunamis, the historical literature shows that the island of Taiwan was destroyed by large tsunamis and caused tremendous damages. Tsunami generation in the China region (including Taiwan) from 1831 BC to 1980 AD were compiled by Zhou *et al.* (1985) and show that Taiwan was attacked by tsunamis during the period of 1604~1978 as listed in Table 1, where the dates, locations and the magnitudes of the earthquakes and tsunamis are listed. Figure 1, showing the distribution of tsunamigenic earthquakes, indicates those earthquakes which generated tsunamis (Kanamori, 1972). These are different from a tsunami earthquake which indicate the earthquake generating abnormally large tsunamis in relation to the earthquake size, such as the1992 Nicaragua earthquake (Kikuchi and Kanamori, 1993).

The historical literature shows that the areas of Keelung, Hualien, Taitung, Tainan and Hsinchu have all been damaged by tsunamis associated with local earthquakes. This implies that the tsunamis in the Taiwan region have mainly resulted from local earthquakes.

In this study, an investigation is made into the possible origins of the historically disasterous

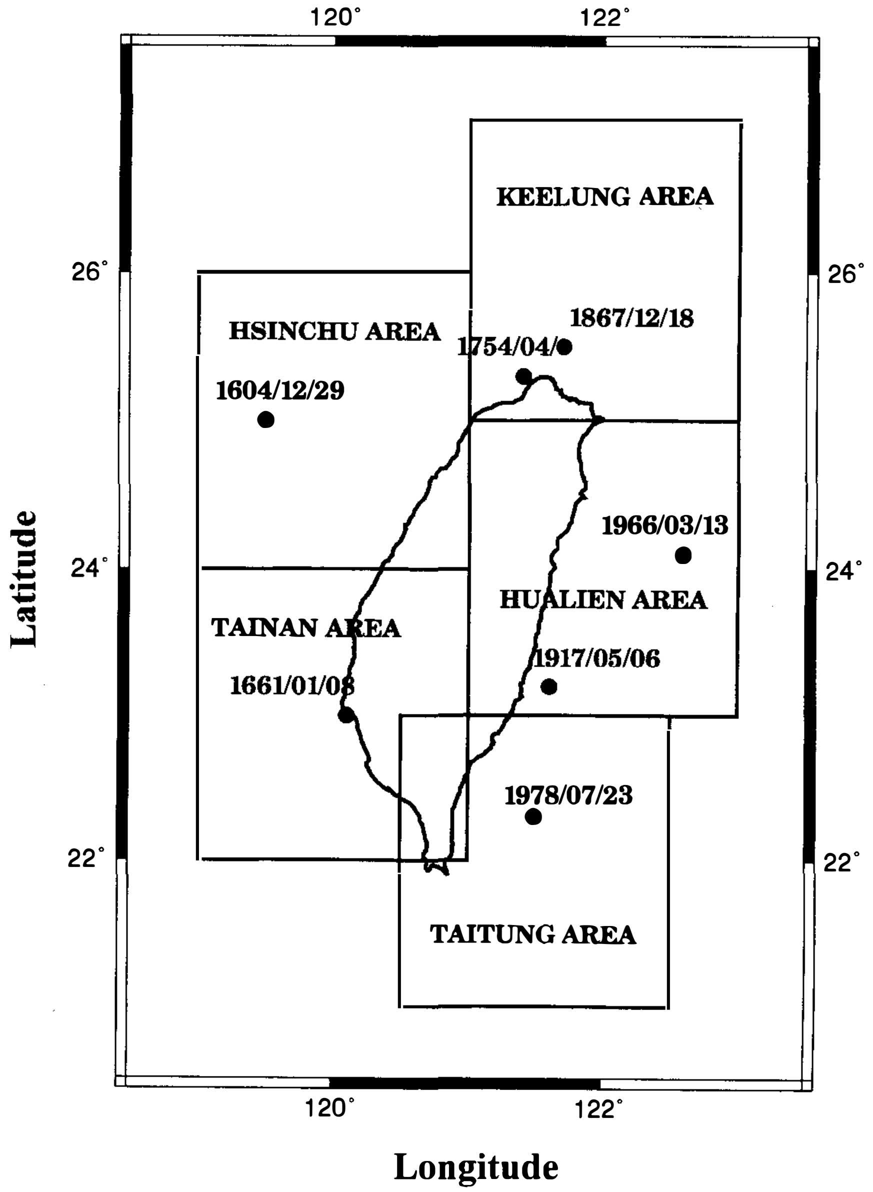

Fig.1. Distribution of the tsunamigenic earthquakes from 1604 to 1978. Five areas are designated.

tsunamis. From the simulation of synthetic tsunamis, the possible magnitudes which are responsible for historically disasterous tsunamis are estimated. The period of the tsunamis and the corresponding travel velocity in each area are also estimated. This information will be useful for tsunami warning evaluation in the Taiwan region.

2. METHODOLOGY

Tsunami waveforms have been computed either analytically for a uniform depth (Takahashi, 1942; Kajiura, 1963) or numerically for actual topography (Aida, 1978; Satake,1985) before.

Detailed descriptions of the basic equations of motion for tsunami computations can be seen in Ma (1993). Ignoring the Corioli's force and frictional force into consideration, the equation of motion can be considered a linear one (Murty, 1977):

$$\frac{\partial v}{\partial t} = -g\nabla h; \tag{1}$$

and the equation of continuity is:

$$\frac{\partial(d+h)}{\partial t} = -\nabla\{(d+h)v\}, \tag{2}$$

where v is the flow rate obtained by integrating the velocity vertically from the bottom to the water surface; h is the water level elevation relative to still water; d is the water depth prior to source displacement; and g is gravitational acceleration. The finite-difference method was applied to compute tsunami waveforms for actual bathymetry. Since the source process of the earthquake taken only in few seconds which is very short compared with the tsunami propagation in minutes, water surface is considered to have simultaneous deformation as sea bottom during an earthquake. Therefore, the vertical sea-floor deformation during the earthquake is considered the initial condition for a tsunami calculation. The time step of 2 sec was used to satisfy the stability condition of the finite-difference computations. The grid size of the bathymetry data for tsunami propagation is 0.5 minute (about 0.8 km).

Simulations of the synthetic tsunamis were calculated according to the following procedures. The vertical sea-floor deformation, as the initial condition, was first calculated from the earthquake source parameters and the geometry of the fault (Okada, 1985). For historical earthquakes whose source parameters and geometry are unknown, the mechanism of a recent earthquake in its nearby area was taken as as the reference. This reference earthquake was selected on the basis of its size and can be considered as representative earthquake in that area. Since the size of the reference earthquake might not have been large enough to produce tsunamis, the empirical equation derived by Wells and Coppersmith (1994) for the relationships of moment magnitude, rupture length and width were used to upgrade the size (geometry) of the earthquake.

From the definition of the geometry and mechanism of the fault, the vertical ground deformation could be obtained, and the tsunami amplitude at the certain grid point could be calculated using the finite-difference technique for the integrated long-wave equation. In considering an disasterous tsunami, the run-up effect close to the coast had to be considered. These calculation were for a synthetic tsunami at tide-gauge and did not consider the non-linear effect near the coast.

The non-linear effect for shallow water is normally difficult to model. Satake (1995) recently compared synthetic tsunamis from the non-linear water wave equation simulation and the linear equation for different grid sizes. He concluded that the non-linear effect could be reduced for a fine grid size. Imamura *et al.* (1993) and Togashi (1981) had previously suggested that the run-up effect also depended upon the near offshore topography and coastal structure. It can be stated that, in general, the tsunami amplitude for the run-up is about 3~5 times larger than that at tide-gauge (Satake, 1995). For this study, the description in the literature of historical tsunamis as compiled by Hsu (1995), was used as reference to discuss the possible amplification factor and the ratio of run-up height to tide-gauge height in each region. The results in this study show that the amplification factor was 5 in most regions in Taiwan. For eastern Taiwan, a smaller amplification factor was obtained. In the simulations here, the synthetic tsunamis were calculated for various magnitudes with a 0.5 increment in magnitude for M6.5~8.5, and the maximum tsunami height for certain stations was obtained for each magnitude. The relationships between tsunami heights and magnitudes were thus obtained to estimate the tsunami magnitudes which were responsible for disaster tsunami generation.

3. METHODS

On the basis of the occurrence of historical tsunamis, Taiwan is classified into five areas: Keelung, Hualien, Taitung, Tainan and Hsinchu, as shown in Figure 1. For the area where two tsunamigenic earthquakes occurred, the more devastating one was selected for simulation. Figure 2 shows the distribution of tide-gauge stations in the Taiwan region. For convenience, the name of the closest station of CWBSN (Central Wether Bureau Seismographic Network) was used in its abbreviated form. It has to be kept in mind, however, that the actual stations used were not those of the CWBSN. The present tide-gauge stations running in Taiwan were designed to detect tidal variations with a sampling rate of every six minutes. The six-minute interval data in fact, however, are not accurate enough for a tsunami study. Since the historical data are not available, in this study, the tsunami were simulated at certain tide-gauge stations to discuss the relation between tsunami height and earthquake magnitude. No comparison of observed and synthetic tsunamis was actually made here for each of the five areas, except for one. In 1986, a rare observed tsunami was recorded at the Hualien tide-gauge station as shown in Figure 3(b). This observed tsunami was adopted and digitized by Hsu and Chen (1994). This rare recorded tsunami data, therefore, provides us a good opportunity to test the reliability of the synthetic results here. In this study, the recent tsunami excited by the November 14, 1986 Hualien earthquake (Ms=7.3) was first used as an example to test the reliability of the synthetic results. Accordingly, the tsunami height at a certain selected tide-gauge station could then be taken and used in the calculation to understand the characteristics of tsunamis in each area.

4. RESULTS

November 14, 1986 Hualien Earthquake

The November 14, 1986 earthquake occurred offshore of the Hualien area. Figure 3(a) shows the location of the earthquake. Another earthquake with similar magnitude occurred in the following May but inland. Although these two earthquakes caused some damage in Taiwan, the offshore November event produced tsunamis which were recorded by the Hualien tide-gauge station (HWA). Consequently, for the tsunami simulation study, only the November event was focused upon. The mechanisms of the earthquake were done using local polarity data (Chen and Wang, 1988) and teleseismic data (Huang and Kanamori, 1989), which both showed a similar mechanism with a thrust faulting mechanism as shown in Figure 3(a). Figure

3(b) shows the observed tsunami waveform at tide-gauge station HWA.

Figure 3(a), showing the vertical ground deformation using the mechanism as determined by Hwang *et al.* (1989), indicates that the maximum sea-floor deformation caused by the earthquake was 64.17 cm. The deformation offshore was responsible for the tsunami generation. Since the tide-gauge station was within the deformation area, the tsunami was excited about the same time as the occurence of the earthquake. Figure 3(b) compares the synthetic tsunami with that observed at HWA. The synthetic tsunami explains the arrival time, period and the amplitude of the first arrival. The average period of the observed tsunami was about

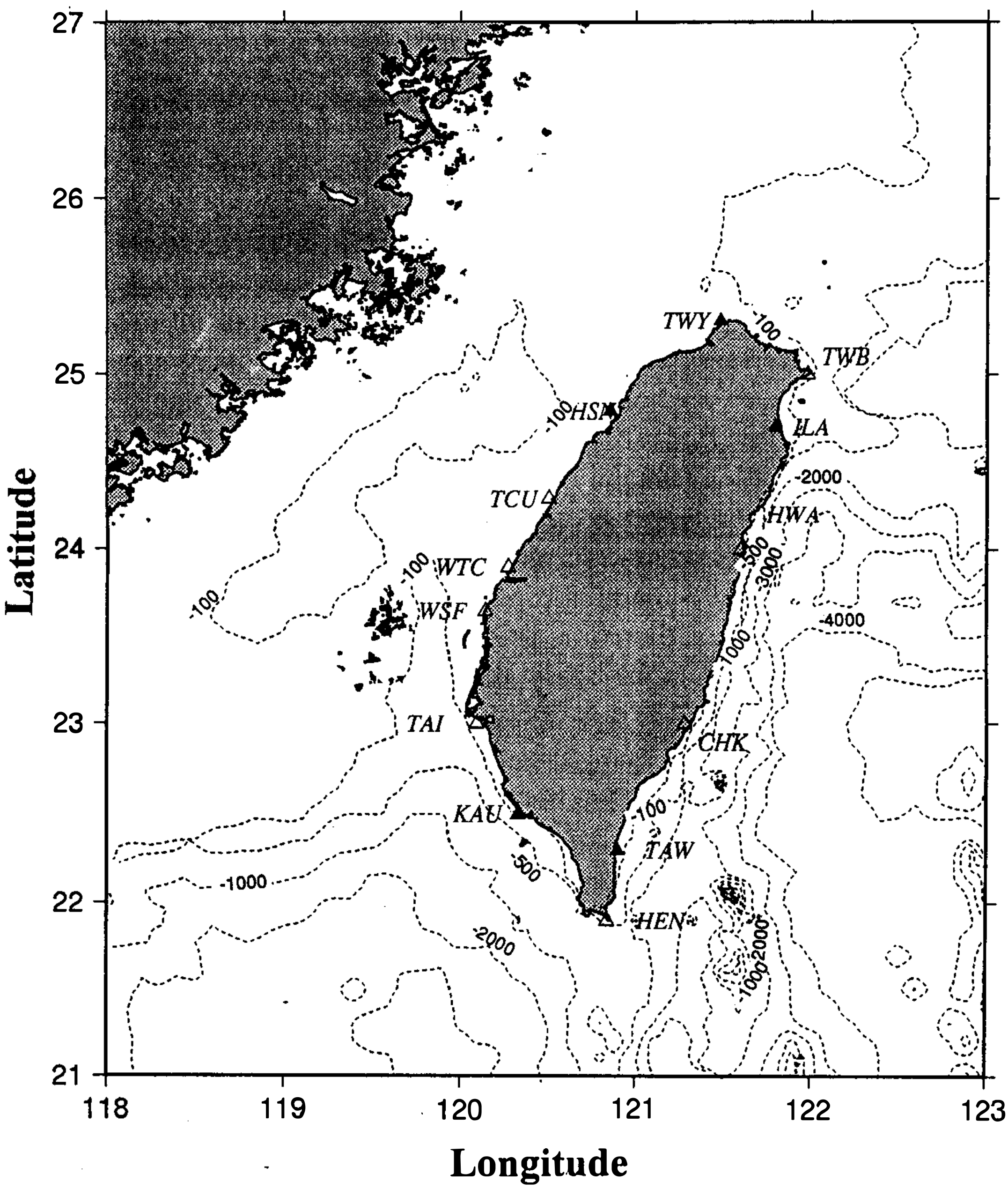

Fig.2. Distribution of tide-gauge stations (open triangles) in the Taiwan region. The solid triangles indicate the stations used in these simulations. The contours indicate the water depth in meters.

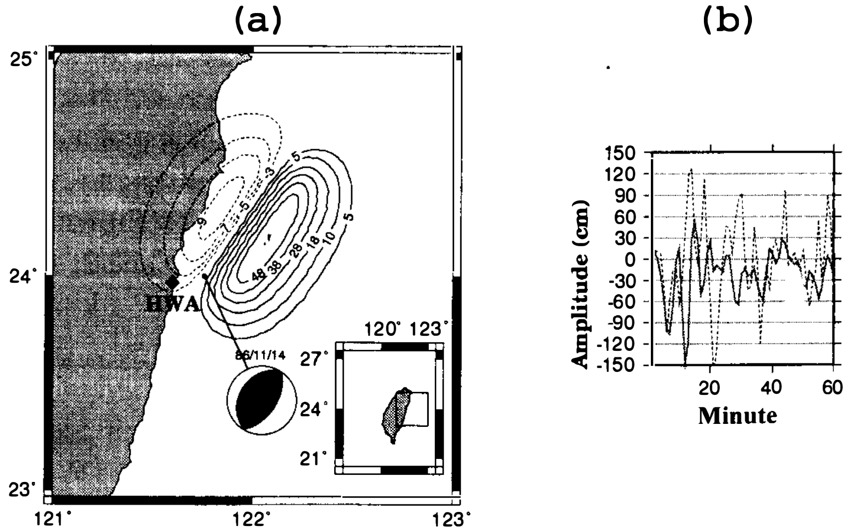

Fig.3. (a) Location, focal mechanism and accompanying vertical sea-floor deformation for the 1986/11/14 earthquake. The numbers on the contour lines indicate the deformation in cm. Solid and dashed lines indicate the upward and downward motions. (b) Comparison of the observed (solid line) and synthetic (dashed line) tsunamis at the HWA tide-gauge station.

10~20 minutes in general. The relatively short 10-minute period at HWA might have been a result of the bathymetry or the near source effect (Lamb, 1932). In most synthetic tsunami calculations, usually only the first cycle of the waveform is simulated, since the latter phases might be caused by reflection from the coast (Kajiura, 1963; Ma, 1993). The well-fitting of the synthetic tsunami here suggests that the synthetic tsunami simulation in the Taiwan region is reliable. This technique can readily be adopted for the simulation of historical tsunamis whose observed tsunami waveforms are not available.

Keelung Area - August 18, 1867 Keelung Tsunamigenic Earthquake

The 1867 Keelung event is reported to have been the largest tsunamigenic earthquake in the Taiwan region, causing several hundred fatalities and tremendous damage in the Keelung and Taipei areas (Zhou *et al.*, 1985). Since there was no seismological observatory in Taiwan at that time, the location and mechanism of the earthquake are unclear. Whereas Tsai (1985), on the basis of descriptions from the literature, concluded that the location of the earthquake is at the longitude of 121.7°E and latitude of 25.3°N. Zhou *et al.*(1985) concluded it was at the longitude of 121.7°E and latitude of 25.5°N.

This earthquake is considered particular in that only a few other events have occurred in that area since seismological observations first began in Taiwan. This implies that the repeat time of large earthquakes in this region is long. However, should a large earthquake actually occur, it might give rise to tsunamis as large as those of 1867. Therefore, it is valuable to understand what size of earthquake would produce disasterous tsunamis.

Since there are many unknowns about this earthquake, the simulation here was more difficult to model. The most representative earthquake in that area was selected for the historical tsunami simulation. To do so, events occurring in the area of latitude: 25°N to 27°N and longitude: 121°E to 123°E for the time period of 1973~1993 were considered. The mechanism of the July 3, 1988 earthquake (ML=5.06) occurring at 25.158°N and 121.568°E was finally selected since it was the largest and one of the most widely studied ones. The mechanism determined by Cheng (1994) is a normal faulting mechanism as shown in Figure 3(a) with fault plane 1: strike=135°, dip=52° and rake=-90°; and with fault plane 2: strike=315°, dip=38° and rake=-90°. The depth and mechanism of the earthquake were adopted for the Keelung tsunami simulation.

The empirical relationship of the seismic moment and dimension of the fault derived by Wells and Coppersmith (1994) were applied to determine the approximated dimensions of the earthquake for certain magnitudes. The synthetic tsunamis at stations of TWY (in Taipei County) and TWB (in Keelung County) for various magnitudes were calculated. The area and the stations for the tsunami calculations are shown in Figure 4(a). The sea-floor deformation associated with the earthquake is shown in Figure 4(b). It shows a subsidence toward to the land and an uplift toward to the sea, which is consistent with the description of Tsai (1985). Figure 4(c) demonstrates the synthetic tsunamis thus calculated for a magnitude of 7.0 for station TWY. The maximum tsunami height (peak to peak amplitude of the first period) was then estimated from the simulated tsunami. Figure 4(d) shows the relation of maximum tsunami height versus various magnitudes from M6.5~8.0. According to Hsu (1996), the tsunami magnitude of M=7 for the 1867 event produced a tsunami run-up height of 4 ~ 6 m. From Figure 4(d), it was estimated that the tsunami height at the tide-gauge was about 70 cm for M=7. If the tsunami run-up height of 4 m had been considered, the amplification factor would have been about 5 which is comparable to common observations. Since the run-up height might vary according to the area, the amplification factor was only considered as an estimation. However, when the amplification of 5 was considered, the tsunami height of 40 cm could be considered as the tsunami warning height which might cause tsunami hazard due to the run-up effect at the coast. According to Figure 4(d), an earthquake with a magnitude of 6.9 is considered a potential generating tsunami hazard earthquake in the Keelung area. In addition to the 1867 event, historical literature shows that the 1917 Keelung earthquake also produced minor tsunamis. Hsu (1996) described the period of the observed tsunami as about 26 minutes. This period is comparable to the synthetic tsunamis for the 1867 event as shown in Figure 4(c). Since the period of a tsunami is more related to local bathymetry, the observed period should stand as the characteristic period of the tsunami in this region. Again, the similarity between the observation and synthetic periods suggests the reliability of the numerical simulation.

Hsinchu Area - December 29, 1604 Hsinchu Tsunamigenic Earthquake

The region for the tsunami calculation for the Hsinchu area is shown in Figure 5(a). The synthetic tsunamis at the stations of HSN in Hsinchu County and TCU in Taichung County were computed. Similar to the 1867 Keelung earthquake, the mechanism and dimensions of the earthquake were not well determined. An earthquake of M_L=5.2 occurring on January 8, 1989 at the depth of 31 km, latitude of 24.706°N and longitude of 120.334°E was selected as the representative earthquake in this area. The Hsinchu area is also less of a seismicity region in Taiwan. The most devastating earthquake in this area was the 1935 Hsinchu-Taichung (M=7.1) earthquake which caused a surface ruptures of 20 km, known as the Shihtan and Tuntzuchio Faults (Huang and Yeh, 1992). Since this earthquake was inland, no tsunami was generated. It was, however, the 1604.Hsinchu tsunamigenic earthquake which drew attention to the possibility of earthquake hazards in this area.

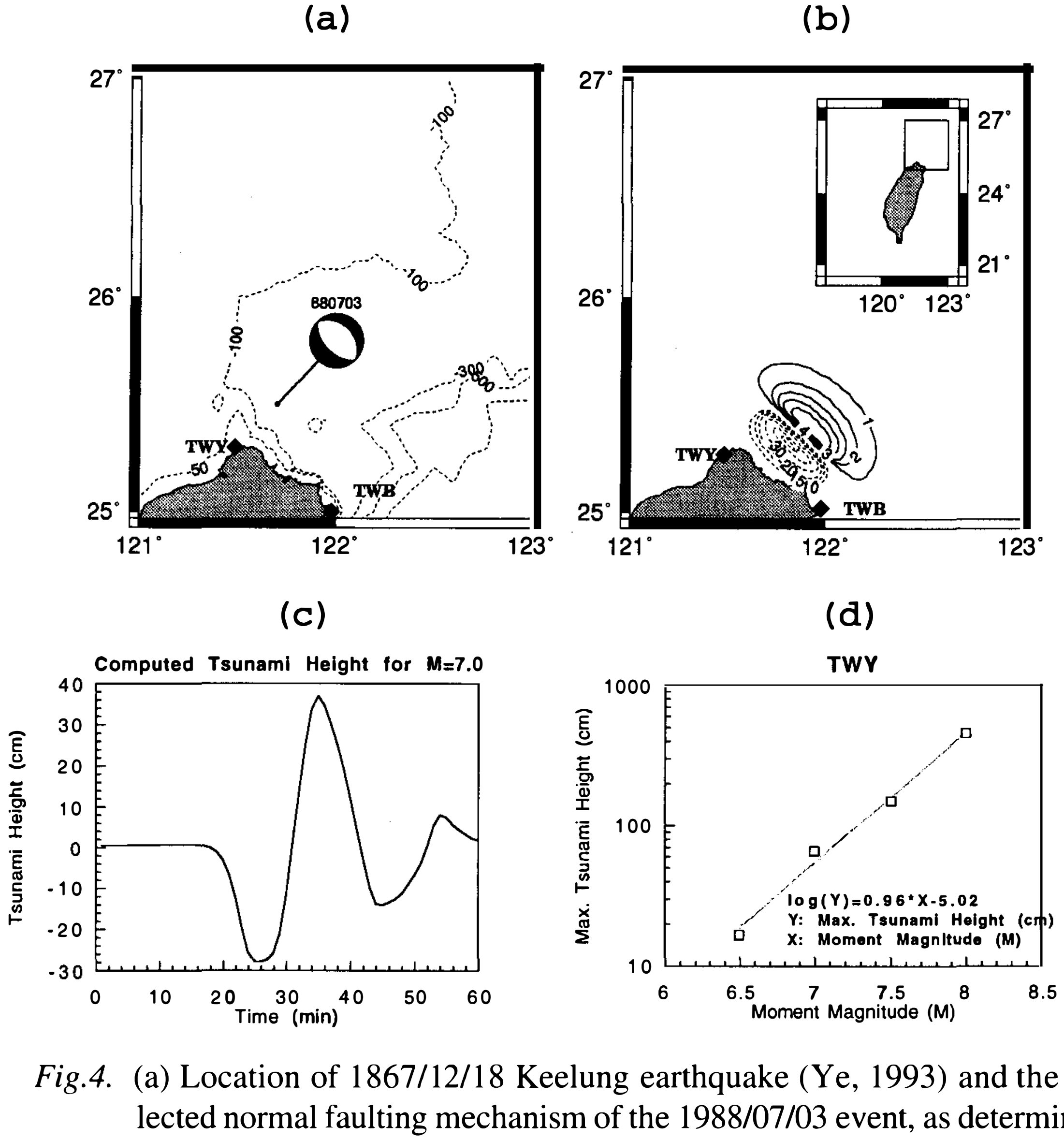

Fig.4. (a) Location of 1867/12/18 Keelung earthquake (Ye, 1993) and the selected normal faulting mechanism of the 1988/07/03 event, as determined by Cheng (1994). The diamond symbols indicate the locations of the tide gauge stations in the Keelung area. The dashed lines indicate the bathymetry in the area in m. (b) Vertical sea-floor deformation for mechanism of strike: 135°, dip: 52° and rake: -90° for Mw=7.0. The numbers on the contour lines indicate the deformation in cm. The solid and dashed lines indicate the uplift and subsidence. (c) Synthetic tsunamis at station TWY. (d) Synthetic maximum tsunami height versus moment magnitude for the TWY station.

The mechanism of the representative earthquake, determined by Cheng (1994), (Figure 5(a)) is a thrust faulting mechanism with plane 1: strike=60°, dip=60° and rake=90°; and plane 2: strike=240°, dip=30° and rake=90°. The location of the historical Hsinchu earthquake at the latitude of 25°N and longitude of 119°E, as determined by Ye (1993), was used for the tsunami simulation study. The sea-floor deformation associated with the simulation for the magnitude of 7.5 is shown in Figure 5(b). The synthetic tsunami for this Mw=7.5 earthquake at station HSN is shown in Figure 5(c). Figure 5(d) shows the relation of tsunami height versus various other magnitudes. Since there is no description in the literature about the observed tsunamis, it is difficult to estimate the amplification factor in this area. If the same amplification of 5 as assumed in the Keelung region is considered, the generation of a tsunami height of 40 cm at tide-gauge HSN requires a magnitude of Mw=7.5.

Tainan Area - January 8, 1661 Tainan Tsunamigenic Earthquake

The area for this simulation is shown in Figure 6(a). An earthquake with M_L=6.2 occurring on January 7, 1977 at the depth of 5.0 km, latitude of 21.81°N and longitude of 120.248°E was selected as the representative earthquake. The mechanism of the earthquake with plane 1: strike=194°, dip=29° and rake=-62°; planes: strike=343°, dip=65° and rake=-105° was determined by Dziewonski *et al.* (1987). The location of the historical Tainan earthquake (Table 1) and the mechanism were used to simulate the synthetic tsunami at station KAU in Kaohsiung County. The sea-floor deformation and the synthetic tsunami at station KAU (Mw=7.5) are shown in Figures 6(b) and 6(c), respectively. In the present study, secondary sources of tsunamis, such as landslides triggered by the earthquake, were not considered. For the M=6.4 1661 event, the tsunami run-up height was 1~2 m according to the compilation of Hsu (1996). According to Figure 6(d), the tsunami height at the tide-gauge was about 20 cm for M=6.4. The amplification factor is also 5 if a run-up height of 1 m is considered. The run-up height of 2 m might be resulted from reflected waves or secondary sources such as landslides triggered by this earthquake. Therefore, the disaster accompanying this earthquake may have been brought on by the secondary sources, since the run-up height of only 1 m should not have caused damage. Such results focus attention on arouse interest in the secondary sources of tsunamis in this region.

The areas simulated above are regions of relatively lower seismicity in Taiwan. In contrast, the two areas which follow belong to regions of high seismicity. The tsunami simulations of these two areas were estimated using their individual location and mechanism.

Taitung Area - July 23 , 1978 Taitung Tsunamigenic Earthquake

The July 23, 1978 Taitung earthquake (ML=6.3) occurred at the depth of 6.1 km, latitude of 22.35°N and longitude of 121.33°E according to the catalog of Taiwan Teleseismometer Seismographic Network (TTSN). Figure 7(a) shows the location of the earthquake and the area of tsunami simulation. The seismic moment and mechanism determined by Pezzopane *et al.* (1989) was 4.6~8.6x1026 dyne-cm (Mw=7.1~7.3) and strike=355°, dip=42° and rake=62° for plane 1; and strike=211°, dip=54° and rake=113° for plane 2 as shown in Figure 7(a).

Following the empirical relationship developed by Wells and Coppersmith (1994), the tsunami waveforms computed for various magnitudes were calculated based on the mechanisms and locations above. Figures 7(b) and 7(c) show the sea-floor deformation associated with the earthquake(Mw=7.1) and the synthetic tsunami waveform at TAW. Since there was no observed tsunamis in this region, it is not easy to estimate the exact amplification factor. If an amplification factor of 5 is again taken, the earthquake magnitude corresponding to the disaster tsunami is about 6.6. To generate the tsunami height of 40 cm at tide-gauge TAW accord-

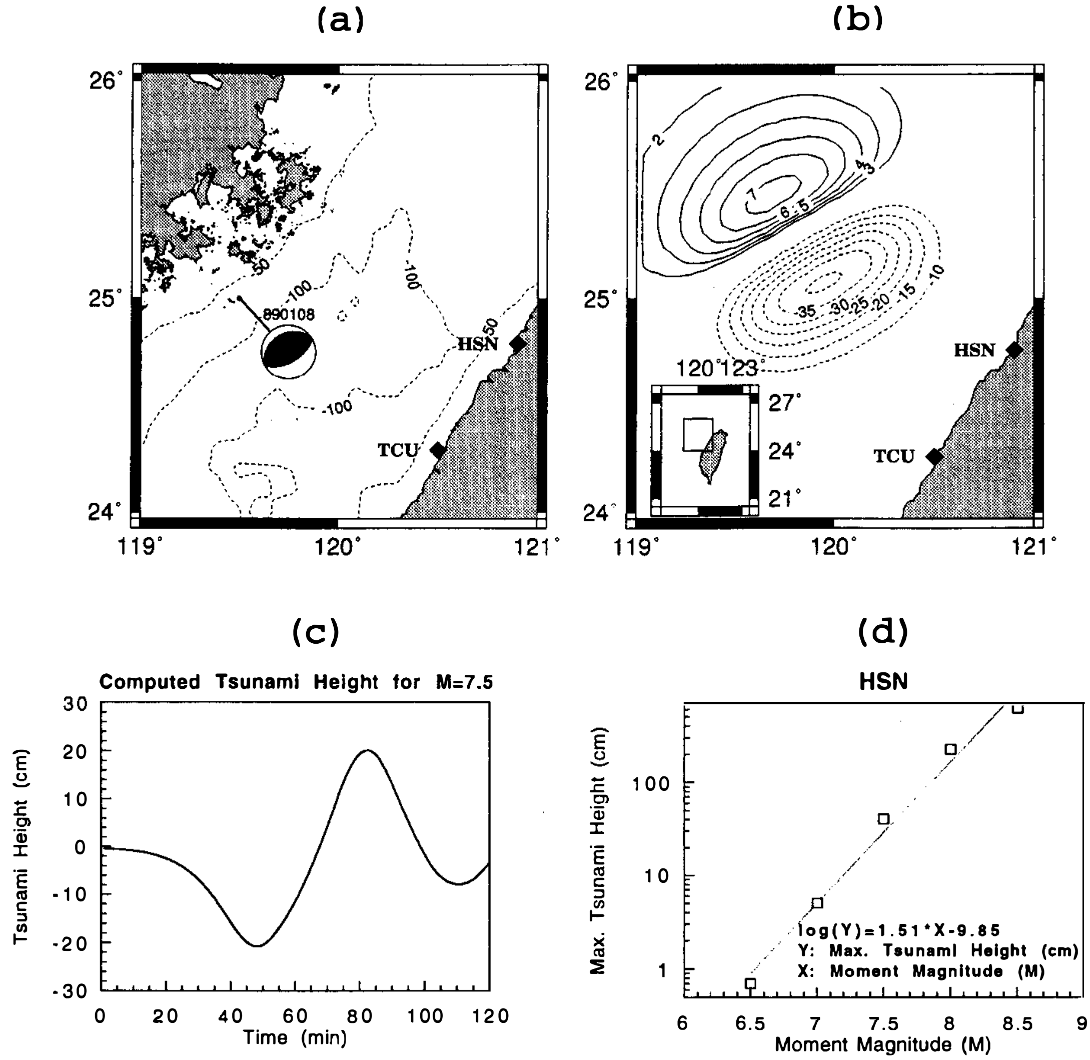

Fig.5. (a) Location of the 1604//12/29 Hsinchu earthquake (Ye,1993) and the selected earthquake of 1989/01/08. The diamond symbols indicate the locations of the tide gauge stations in this area. The dash lines indicate the bathymetry in m. (b) Vertical sea-floor deformation for mechanism of strike: 240°, dip: 30° and rake: 90° at Mw=7.5. The numbers on the contour lines indicate the deformation in cm. The solid and dashed lines indicate the uplift and subsidence. (c) Synthetic tsunami at station HSN. (d) Synthetic maximum tsunami height versus moment magnitude for the HSN station.

ing to Figure 7(d), the magnitude of 6.6 was required. Since the magnitude of this earthquake was only 6.3, according to Figure 7(d), the tsunami height should have been about 20 cm, which might have been too small to be noticed in tsunami observation. Therefore, no tsunami information was reported in Hsu (1996).

Hualien Area - March 12, 1966 Hualien Tsunamigenic Earthquake

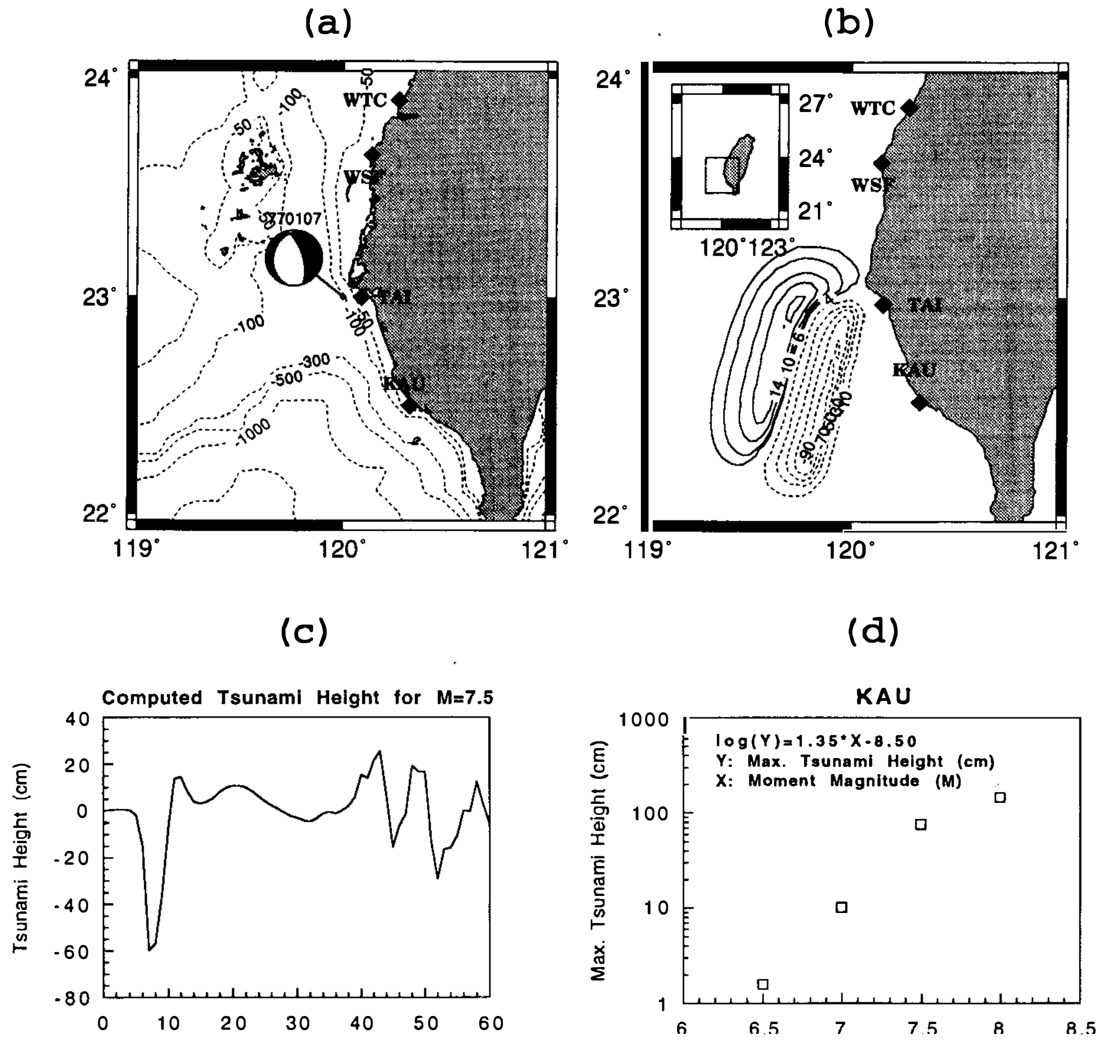

Fig.6. (a) Location of 1661/08/08 Tainan earthquake (Ye,1993) and the selected earthquake of 1977/01/07. The diamond symbols indicate the locations of the tide gauge stations in this area. The dashed lines indicate the bathymetry in m. (b) Vertical sea-floor deformation for mechanism of strike: 194°, dip: 29° and rake: -62° at Mw=7.5. The numbers on the contour lines indicate the deformation in cm. The solid and dashed lines indicate the uplift and subsidence. (c) The synthetic tsunamis at station KAU. (d) The synthetic maximum tsunami height versus moment magnitude for the KAU station.

Although earthquakes of magnitude 6 or higher occur very frequently in this area, not very often is there a tsunamigenic. The 1966 Hualien earthquake (M=7.5) occurred at the depth of 22 km, latitude of 24.2N and longitude of 122.6E as shown in Figure 8(a) and generated disasterous tsunamis as listed in Table 1. The seismic moment of 4.86x1027 dyne-cm and mechanism with plane 1: strike=130°, dip=76° and rake=18°; and plane 2: strike=36°, dip=73° and rake=165° (Figure 8(a)), as determined by Pezzopane *et al.* (1989), were used for the tsunami simulation in this area. The sea-floor deformation and the synthetic tsunami at station ILA(Mw=8.0) are shown in Figure 8(b) and 8(c), respectively. The ILA tide-gauge station

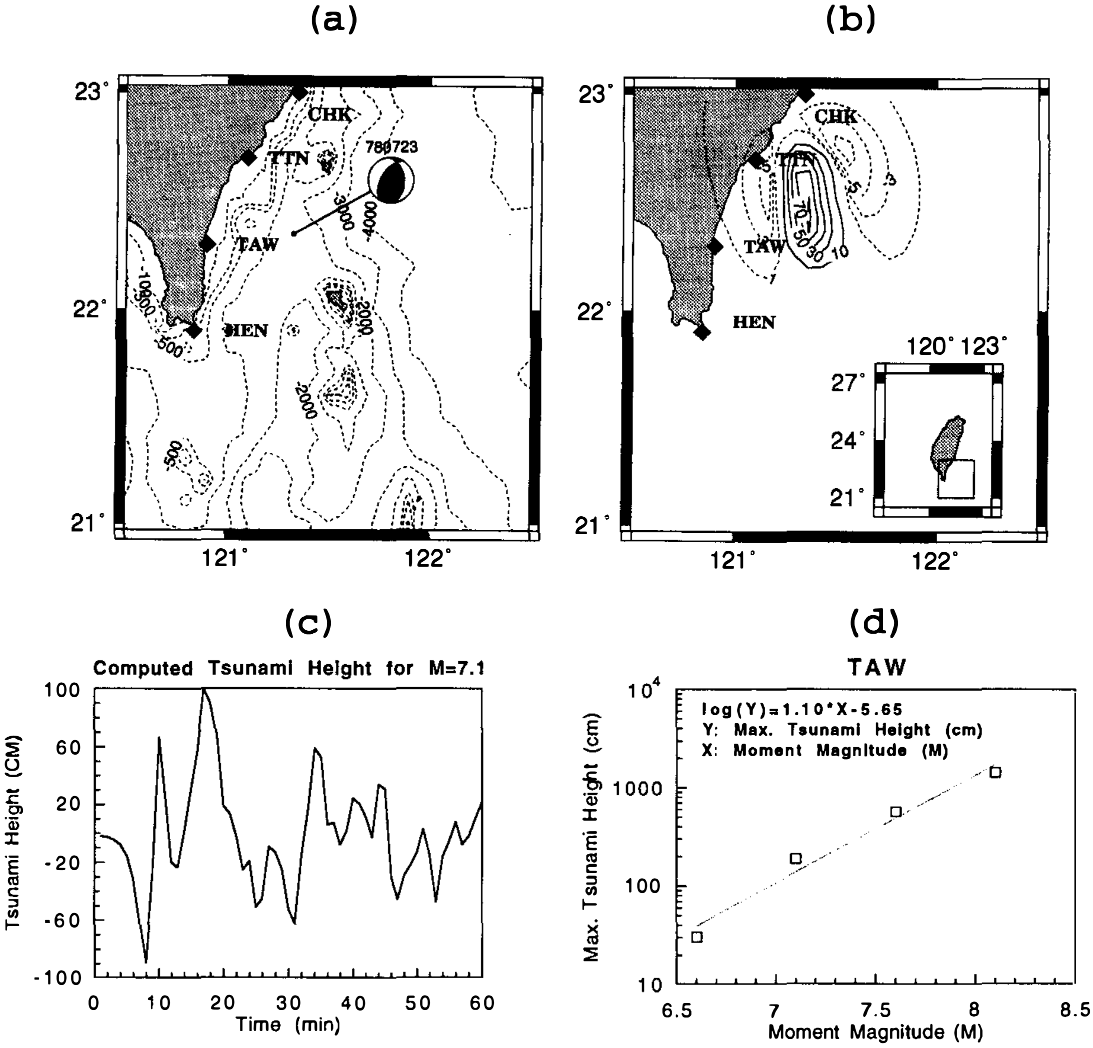

Fig.7. (a) Location and mechanism of the 1978/07/23 earthquake. The diamond symbols indicate the locations of the tide gauge stations in this area. The dashed lines indicate the bathymetry in m. (b) Vertical sea-floor deformation for mechanism of strike: 355°, dip: 42° and rake: 62° at Mw=7.1. The numbers on the contour lines indicate the deformation in cm. The solid and dashed lines indicate the uplift and subsidence. (c) Synthetic tsunamis at station TAW. (d) Synthetic maximum tsunami height versus moment magnitude for the TAW station.

showing a tsunami height of 20 cm for an event of magnitude 7.5 is presented in Figure 8(d). Considering the observed tsunami run-up height of about 50 cm (Hsu, 1996), the amplification factor is about 2, which is relatively small when compared with the commonly observed 3~5. This small amplification might be associated with the local topography. If such a small amplification is considered, the least magnitude of the tsunamigenic earthquake in this region is about 8.2. One fact which should be noted is that this earthquake was a strike-slip event. If a dip-slip event had occurred, instead, there would have been more potential to generate tsunamis, and the least magnitude of 8.2 estimated in this study might have been reduced.

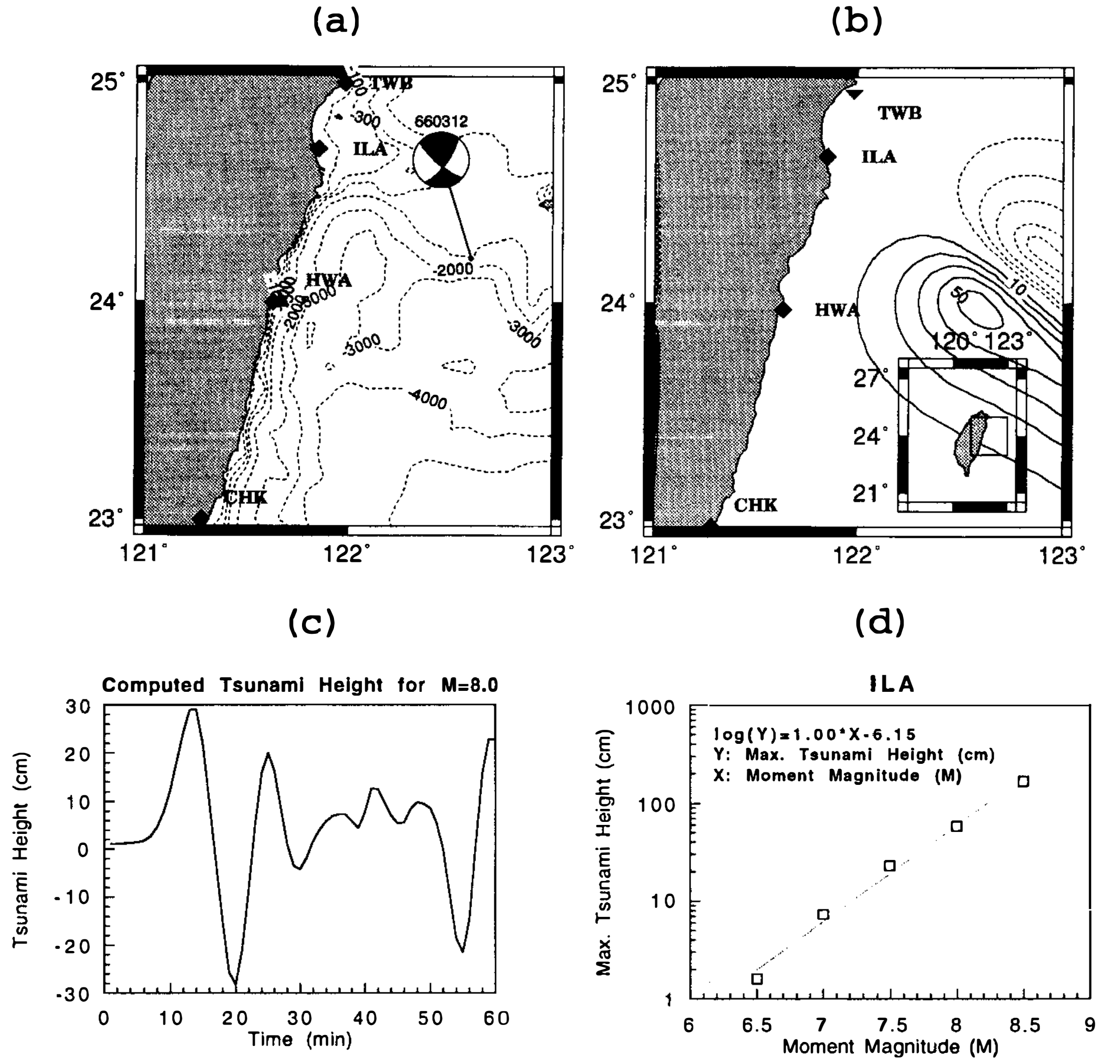

Fig.8. (a) Location and mechanism of the 1966/03/12 earthquake. The diamond symbols indicate the locations of the tide gauge stations in this area. The dashed lines indicate the bathymetry in m. (b) Vertical sea-floor deformation for mechanism of strike: 130°, dip: 76° and rake: 18° at Mw=8.0. The numbers on the contour lines indicate the deformation in cm. The solid and dash lines indicate the uplift and subsidence. (c) Synthetic tsunamis at station ILA. (d) Synthetic maximum tsunami height versus moment magnitude for the ILA station.

Table 2. Water depth, focal depth, mechanism and required minimal magnitudes in the five areas.

Area	Date (yr/mon/day)	Average depth	Focal depth	Type of fault motion	Minimal magnitudes required in this study	
Keelung	1867/12/18	100 m	5.31 km	dip-slip	6.9*	7.2**
Hsinchu	1604/12/29	100 m	31 km	dip-slip	8.0*	7.5**
Tainan	1661/01/08	100 m	5 km	dip-slip	7.4*	7.5**
Taitung	1978/07/23	2000 m	6.1 km	dip-slip	6.8*	7.6**
Hualien	1966/03/12	2000 m	22 km	dip-slip	7.8*	7.9**

* Based on plane 1 of focal mechanism
** Based on plane 2 of focal mechanism

5. DISCUSSION

With the amplification factor of 5 assumed, the magnitudes of earthquakes producing the tsunami height of 40 cm in each area were estimated and are listed in Table 2. The average water depth where the earthquakes occurred, focal depth and the type of fault motion are also listed in Table 2. Unlike the Hualien area which had a strike-slip fault motion, most of the earthquakes had dip slip mechanisms which are comparable to the mechanisms of most tsunamigenic earthquakes. The focal depth of 31 km in the Hsinchu area is relatively deep compared with most tsunamigenic earthquakes. This implies that when shallower focal depth earthquakes occur, the magnitudes of disasterous tsunami earthquake could be smaller than those obtained in either of the Hsinchu and Hualien areas. Since the present study focused on the simulation of historical tsunamis, tsunami hazard evaluation are not addressed here. However, for a tsunami hazard evaluation, the tsunami height corresponding to the shallower focal depths or different mechanisms, especially for the Hualien area, should be considered.

Table 3 lists the magnitudes of the disasterous tsunami earthquakes we obtained along with the magnitudes of historical tsunamigenic earthquakes. The comparison is satisfactory with the only discrepancy being with the 1661 Tainan earthquake tsunami, where the magnitude of the simulated disasterous tsunami was Mw7.4~7.5 but was M6.0 according to historical records. One possible explanation for this is that the earthquake magnitude in the historical record was underestimated or the observed tsunamis were caused by secondary sources. The 1661 Tainan tsunamigenic earthquake with a magnitude of M=6.0 was relatively too small to have caused large tsunamis. Abe (1981) studied 80 tsunamigenic earthquakes in the northwestern Pacific, and his results showed that tsunamigenic earthquakes usually have magnitudes greater than 6.5 and, most are even greater than 6.8.

The average velocity, period and wavelength of the tsunamis for the five areas are listed in Table 4. They were estimated from its travel distance and first arrival time of tsunami waves. The difference in bathymetry for the west (about 100 m) and the east coast (at least 2000 m depth) gave rise to the differences in the period and velocity of the tsunamis. The

Table 3. Comparison of the magnitudes from historical records and the obtained magnitudes in this study.

Area	Date (yr/mon/day)	Magnitudes on the historical records	Minimal magnitudes required for simulation	
Keelung	1867/12/18	7.0 [1]	6.9*	7.2**
Hsinchu	1604/12/29	8.0 [2]	8.0*	7.5**
Tainan	1661/01/08	6.0 [2]	7.4*	7.5**
Taitung	1978/07/23	7.0 [3]	6.8*	6.6**
Hualien	1966/03/12	7.8 [3]	7.8*	7.9**

[1] Tsai (1985)
[2] Ye *et al.* (1993)
[3] Pezzopane *et al.* (1989)

* Based on plane 1 of focal mechanism
** Based on plane 2 of focal mechanism

propagating velocity on the east coast was about five times faster than that on the west coast. This finding implies that tsunami warnings are more necessary for the east coast than that for the west. However, the smaller amplification factor of 2 in the Hualien region, as estimated from the 1966 event reduces the tsunami hazard potential on the east coast. The tsunami velocities obtained in this study could be taken as references for a tsunami warning system.

6. CONCLUSIONS

Due to a lack of understanding of historical tsunami earthquakes, a representative earthquake which is considered to represent the earthquake mechanism in each of 5 tectonic regions was selected to simulate historical tsunami. Through the calculations made for various magnitudes, the magnitudes responsible for the historical disaster tsunamis are comparable to the magnitudes listed in historical literature. From the comparison of limited observations and synthetic tsunamis, an estimated amplification factor of 5 was obtained in most regions. The amplification factor is smaller in Hualien regions, due to the local topography there. The small amplification factor, in fact, reduced the tsunami hazard in that region. However, from nu-

Table 4. Average velocities, periods and wavelengths of the simulated tsunamis for the selected stations in each area.

Area	Station	Average velocity (m/sec)	Period (min)	Average wavelength (km)
Keelung	TWY	32.3	24	46.56
Hsinchu	HSN	33	85	168.3
Tainan	KAU	37.1	20	44.6
Taitung	TAW	126.67	8	60.8
Hualien	ILA	194.45	13	151.67

merical simulations, it has shown that the Taiwan region indeed present great potential for tsunamigentic earthquake. The simulation for an historical tsunami provides us the understanding of the possible mechanisms of tsunami generation in the Taiwan region. The characteristics of the bathymetry in eastern and western Taiwan seem to result in the different tsunami periods and velocities. In short, the parameters of tsunami waveform could be used to establish a tsunami warning system in the future.

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REFERENCES

Abe, K. and H. Kanamori, 1980: Magnitude of great shallow earthquakes from 1953-1977. *Tectonophysics*, **62**, 191-203.

Abe, K., 1981: Physical size of tsunamigenic earthquakes of the northwestern Pacific. *Phys. Earth Planet. Inter.*, **27**, 194-205.

Aida, I., 1978: Reliability of a tsunami source model derived from fault parameters. *J. Phys. Earth*, **26**, 57-73.

Chen, K. C. and J. H. Wang, 1988: A study on the aftershocks and focal mechanisms of two 1986 earthquakes in Hualien, Taiwan. *Proc. Geol. Soc. China*, **3**, 65-72.

Cheng, S. N, 1994: The study of stress distribution in and around Taiwan, PhD Thesis, National Central University (in Chinese).

Dziewonski, A. M., E. J. E. Franzen and J. H. Woodhouse, 1987: Global seismicity of 1977: Centroid-moment tensor solutions for 471 earthquakes. *Phys. Earth Planet. Inter.*, **45**, 11-36.

Hsu, M. K.: Tsunamis in Taiwan and its near-by regions. *ACTA Oceanogr. Taiwanica,* **35**, 1-16 (in Chinese).

Hsu, M. K. and C. H. Chen, 1994: Numerical tsunami simulation in the Taiwan region. Research Report of the Central Weather Bureau, Taipei, Taiwan, R.O.C., No.447, 301-419 (in Chinese).

Huang, B. S. and Y. T. Yeh, 1992: Fault geometry and slip distribution of the April 21, 1935 Hsinchu-Taicheng, Taiwan earthquake. *Tectonophysics*, **210**, 77-90.

Hwang, L. S., D. Divoky and A. Yuen, 1970: Amchitka tsunami study. Tetra Tech. Inc., Pasadena, Calif. Rep. TC-177, 84pp.

Hwang, L. S., H. L. Butler and D. Divoky, 1972a: A Tsunami model: generation and open-sea characteristics. *Bull. Seism. Soc. Am.*, **62**, 1579-1596.

Hwang, L. S., H. L. Butler and D. Divoky, 1972b: Tsunami generation and propagation. 13th Int. Conf. on Coastal Eng., 10-14 July, Vancouver, B.C., 397-400.

Hwang, L. S. and H. Kanamori, 1989: Teleseismic and strong-motion source spectra from two earthquakes in eastern Taiwan. *Bull. Seism. Soc. Am.*, **79**, 935-944.

Imamura, F., N. Shuto, B. H. Choi and H. J. Lee, 1993: Visualization of the Nicaraguan Tsunami in September, 1992. Proc. of the IUGG/IOC International Tsunami Symposium, 23-27 August, Wakayama, Japan, 647-656.

Kajiura, K., 1963: The leading wave of a tsunami. *Bull. Earthq. Res. Inst. Univ. Tokyo*, **41**, 535-571.

Kanamori, H., 1972: Mechanism of tsunami earthquakes. *Phys. Earth Planet. Inter.*, **6**, 346-359.

Kanamori, H. and D. L. Anderson, 1975: Theoretical basis of some empirical relations in seismology. *Bull. Seism. Soc. Am.*, **65**, 1073-1093.

Kikuchi, M. and H. Kanamori, 1993: The 1992 Nicaragua earthquake: a slow tsunami earthquake associated with subducted sediments. *Nature*, **361**, 714-716.

Lamb, H., 1932: Hydrodynamics. Cambridge University Press, Cambridge, 738pp.

Ma, K. F., 1993: Part I: The origin of tsunamis excited by local earthquakes. Ph. D. Thesis, California Institute of Technology, 219pp.

Murty, T. S., 1977: Seismic sea waves-tsunamis. *Bull. Fish. Res. Board Canada*, **198**, 1-337.

Okada, Y., 1985: Surface deformation due to shear and tensile faults in a half-space. *Bull Seism. Soc. Am.*, **75**, 1135-1154.

Pezzopane, S. K. and S. G. Wesnousky, 1989: Large earthquakes and crustal deformation near Taiwan. *J. Geophys. Res.*, **97**, 11749-11759.

Satake, K., 1985: The mechanism of the 1983 Japan sea earthquake as inferred from long-period surface waves and tsunamis. *Phys. Earth Planet. Inter.*, **37**, 249-260.

Satake, K. 1987: Inversion of tsunami waveforms for the estimation of a fault heterogeneity: method and numerical experiments. *J. Phys. Earth*, **35**, 241-254.

Satake, K. 1989: Inversion of tsunami waveforms for the estimation of hetergeneous fault motion of large submarine earthquakes: the 1968 Tokachi-Oki and 1983 Japan Sea earthquakes. *J. Geophys. Res.*, **94**, 5627-5636.

Satake, K., and Y. Tanioka, 1995: Generation and propagation characteristics of the 1993 Hokkaido Nansei-oki earthquake tsunamis. *PAGEOPH*, **144**, 803-822.

Takahashi, R., 1942: On seismic sea waves caused by deformation of the sea bottom. *Bull. Earthq. Res. Inst. Univ. Tokyo*, **20**, 377-400 (in Japanese).

Togashi. H., 1981: Study on tsunami run-up and countermeasure. PhD Thesis, Tokohu University, 281pp.

Tsai, Y. B., 1985: A study of disastrous earthquakes in Taiwan, 1683-1895. *Bull. Inst. Earth Sci., Academia Sinica*, **5**, 1-44.

Wells, D. L. and K. J. Coppersmith, 1994: New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bull. Seism. Soc. Am.*, **84**, 974-1002.

Ye, L., X. Wang and C. Bao, 1993: Tsunami in the China seas and its warning service. Proc. IUGG/IOC International Tsunami Symposium, 23-27 August, 771-778.

Zhou, Q. and W. M. Adams, 1985: Tsunamigentic earthquakes in China 1831 B.C.-1980 A.D.. International Tsunami Symposium, Victoria, BC. Canada, 543-550.