Paper:

Characteristics and Mitigation Measures for Tsunamis Generated Along the Nankai Trough

Fumihiko Imamura*[ ]and Kentaro Imai**

*Disaster Control Research Center, Tohoku University, Sendai 980-8579, Japan
E-mail: imamura@tsunami2.civil.tohoku.ac.jp
**Earthquake Research Institute, The University of Tokyo, Yayoi, Bunkyo 113-0032, Tokyo, Japan
E-mail: imai@eri.u-tokyo.ac.jp

[Received December 27, 2008; accepted February 14, 2009]

Historical information related to tsunamis generated in the Nankai Trough was compiled to examine their frequency and associated destruction. Types of damage in a wide area throughout western Japan from Boso to Kyushu, Susaki, Kochi, and Osaka were selected to elucidate tsunami behavior and damage to areas where multiple damage to facilities was reported, such as that to floated ships, bridge destruction, and road blockage by strong current and floating materials such as destroyed house and ships. After reviewing the tsunami physics and damage from recent events including that related to 2004 Sumatra, suggestions are offered to mitigate future disasters.

Keywords: tsunami damage, Nankai Trough, mitigation

1. Introduction

The Nankai Trough, where the Philippines Sea plate is subducting under the Eurasian plate, accumulates stress at its boundary, which is very near the Japanese archipelago. This is a highly active seismic area, generating earthquakes and tsunamis repeatedly with an estimated return period of 100-150 years. Earthquakes are generated under the sea in the trough. Strong quakes with remarkably long components of seismic waves attack land areas, thereby imparting damage to buildings and structures and causing soil liquefaction. The ensuing tsunamis reach coastal areas within 10 min following an earthquake, widely affecting the region, which includes Shikoku and the Kii Peninsula. Earthquakes propagating from the Nankai Trough cause multiple disasters through strong ground tremors, liquefaction, landslides, and tsunamis in populated and industrial areas along the coast of central Japan.

Figure 1 depicts the positions of faults that have been reported for the Nankai Trough since 1300 A.D., suggesting typical patterns of fault segments, which are called simultaneously linked or co-movement events, releasing energy from its three major sections: Tokai, Tonankai, and Nankai. Propagation patterns of strong ground motion and tsunamis are inferred to be influenced by the fault rupture sequence, indicating that the types of damage and countermeasures should vary. **Fig. 2** portrays the distribution of tsunami heights for the 1707 joint Tonankai and Nankai tsunamis, the 1994 Tonankai tsunami only, and the 1946 Nankai tsunami only, suggesting a similarity between Boso and Kyushu, but a difference from the Kii Peninsula.

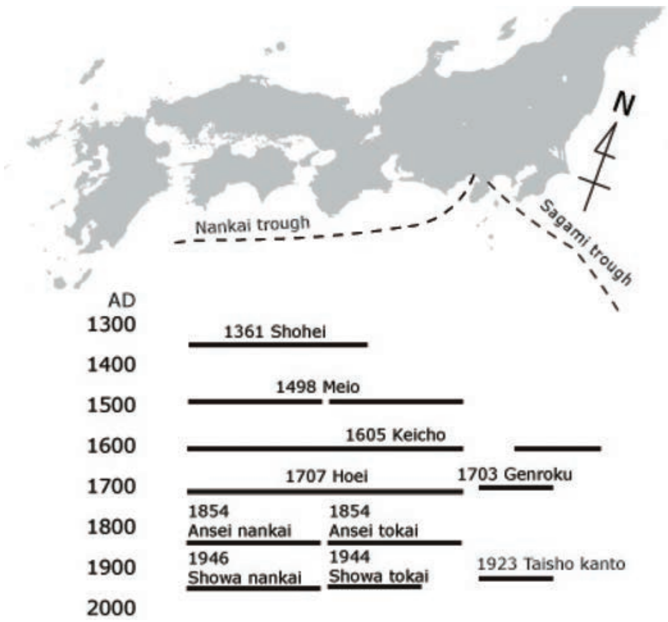

Fig. 1. Positions of faults of historical earthquakes preceding tsunamis in the Nankai Trough [11].

A estimation of the government's Central Disaster Prevention Council suggests 8,600 deaths if quakes hit the Tonankai and Nankai regions simultaneously [1], that estimation should be minimum based on the present methodology considering the past damage pattern. Furthermore, the death toll from a tsunami following a Tokai earthquake would reach 2,200. However, that number might probably be reducible from 2,200 to 700 if people were evacuated quickly [1]. Presently, the government is promoting a program to make buildings more quake-resistant and to enhance countermeasures for tsunami damage reduction by producing hazard maps and performing evacuation drills. Nevertheless, preparedness and prevention activities remain insufficient.

Countermeasures of two types exist for tsunami mitigation. The first anti-tsunami effort is to verify whether reinforced embankments and sea walls are constructed suf-

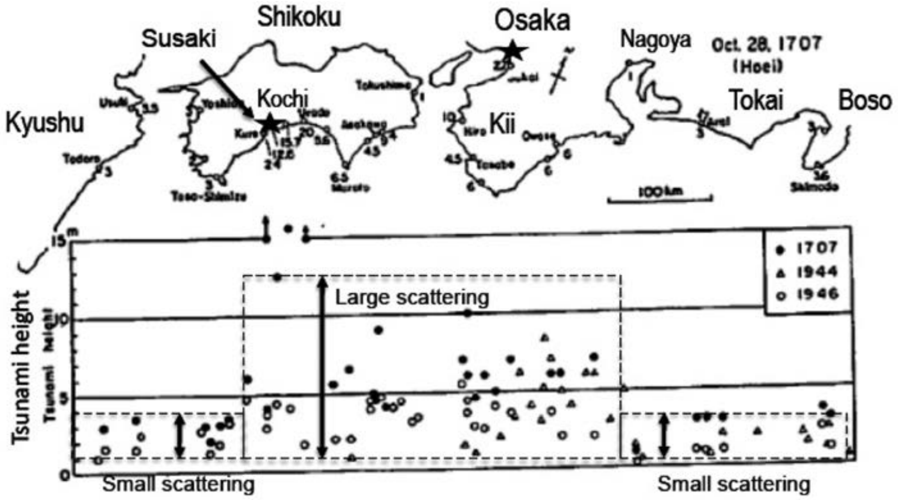

Fig. 2. Tsunami height distribution of the 1707 Hoei tsunami; comparison with the 1944 and 1946 tsunamis (referred from Hatori, 1974 [4]).

ficiently high to protect against a tsunami. Moreover, because the tsunami is expected to inundate land areas, people should be evacuated to a safe place before the tsunami attacks. It is necessary to prepare “tsunami hazard maps”, showing in detail how far the waves would advance beyond shorelines. Based on these maps, specific evacuation plans should be drawn up and designed. As a second measure, it is important to maintain an effective information system for dissemination of warnings to all people. The government plans to install wireless hot lines in all cities, towns, and villages in fiscal 2005. The national average for prefecture-wide coverage by disaster-prevention radio networks is 68%. In the 23 prefectures that are likely to be affected by the Tokai and Tonankai quakes, coverage was 39-100%. In 10 prefectures, it was below the national average.

This paper presents summaries of historical tsunamis propagating from the Nankai Trough and their damage based on historical documents and records dating from 600 A.D. or more recently [2]. That information is expected to be useful to infer scenarios about the fault process sequence. Considering also tsunami-induced damage of new types from recent events including the 2004 Indian Ocean tsunami, we can better discuss the damage that is likely to be caused by a tsunami in the future. Thereby, we can propose better methods of damage prediction. Hazards and damage inferred from each scenario should be compiled on a map, called a regional disaster map. Moreover, this paper presents discussion of tsunami feature due to a large scale earthquake, map-making methods, with participation of related members and residents in community-based workshops.

2. Tsunami Damage at Shikoku and Osaka Described in Historical Documents

Table 1 portrays tsunami heights recorded in documents produced during 684-1946 A.D. [2, 3]. All tsunamis propagating from the Nankai Trough are estimated to have been stronger than Tsunami Magnitude 3, indicating a large tsunami with heavy related coastal damage. The 1854 Ansei tsunami and the 1944 Showa tsunami were recorded as around 10 cm in Honolulu, Hawaii, and in San Francisco, and in San Diego in the United States [2], which indicates that a tsunami propagating from an earthquake in the Nankai Trough would affect not only Japan but also other Pacific Ocean areas. Consequently, tsunami mitigation measures should be conducted internationally to reduce tsunami damage. Especially, it is important that tsunami information of arrival times and tsunami heights that are estimated and observed in Japan be shared because tsunami propagation affects all Pacific coastal areas after attacking Japan. The representative tsunami height reported by Hatori (1974) [4] was 15.7 m at Usa, Kochi, for the 1707 Hoei tsunami, 9 m at Kata and Ninoki-jima, Mie, for the 1854 Tokai tsunami, and 12 m at Kure, Kochi, for the 1854 Nankai tsunami, as presented in **Fig. 2** [4]. Large tsunami heights were recorded in front of the tsunami source areas, especially at the gulf coast in the minor axis direction of the source. Energy concentration at the bottom of the bay is considerable and wave height amplification is dominant when the natural frequency period coincides with the tsunami period.

Representative tsunami damage at two locations for three tsunami events – 1707, 1854, and 1946 tsunamis – is introduced herein: Susaki Kochi [5], as depicted in **Fig. 3**, and Osaka [6], as shown in **Figs. 4** and **5**.

2.1. Tsunami Damage at Susaki, Kochi

Table 2 shows the damage and maximum tsunami heights at Susaki, Kochi by tsunamis [5]. The detail description are arranged in the following chapters.

2.1.1. The 1707 Hoei Tsunami

The tsunami reached at least 7-8 m at Susaki. A bridge at Horikawa was destroyed by the earthquake and the tsunami attacks, thereby cutting off evacuation routes and dooming many victims. Furthermore, no damage was imparted to houses at Ikenouchi, inland of Susaki, although

Table 1. Historical tsunamis propagating from the Nankai Trough [2, 3].

Year	Period	Estimated Magnitude	Tsunami Magnitude (m)	Damage	Description
684	Hakuo13	M8.4 (8.25)	3		This is the first event documented in Japan. Offices, temples, and shrines were destroyed. People and animals were killed by the tsunami in Kochi, Nankai, Tokai, and Seika. Rice fields of 12 km^2 were inundated in Kochi.
887	Ninwa 3	M8.6 (8-8.5)	3		Earthquake centered offshore of the Kii Peninsula. The tsunami attacked Kii, Shikoku, and Osaka. Settsu and Osaka were especially heavily damaged. It reached Hyuga in Kishu.
1099	Shotoku 3	M8.0	?		Earthquake centered offshore of the Kii Peninsula. No details of the tsunami exist, but it is certain that one was generated.
1361	Seihei 16	M8.4 (8.25-8.5)	3	Taikei-ki reported 1700 destroyed homes and about 60 dead, with 1700 at Shiki, Kochi, and at Shikoku and Osaka.	The earthquake was centered offshore of the Kii Peninsula. The tsunami attacked the area from Kii to Tosa. Heavy damage was reported in Kochi and Osaka.
1498	Meio 7	M8.6	?		A large earthquake of Tokai, with intensity of 6 in Shizuoka, Kofu. The strong probability of tsunami generation has been pointed out (Tsuji, 1999).
1605	Keicho 7	M7.9	3		This was a joint earthquake with epicenters off Boso and Muroto. Heavy damage was reported from Inubo to Kishu. Damage at Shikoku was the worst.
1707	Hoei 4	M8.4	4	4,900 dead, 29,000 destroyed homes; other reports describe more than 20,000.	The earthquake occurred throughout the Nankai Trough area. The ensuing tsunami attacked Pacific Ocean coastal areas from Izu to Kishu, and Osaka Bay, Harimanada, Iyonada, and Yanaguchi in the Seto Inland Sea. The worst damage was at Kochi.
1854	Kaei 7	M8.4	4	2,658 dead, 17,486 destroyed homes	The Tonankai earthquake happened only 32 h after the Tokai. Damage was reported from Boso to Kyushu. The story of “Fire of god” in Hiro, Wakayama is well known.
1944	Showa 19	M7.9	3	998 dead, 3,059 destroyed homes, reported numbers differ among documents.	The tsunami attacked from Izu to Osaka. Heavy damage was reported in Shizuoka, Aichi, and Mie.
1946	Showa 21	M8.1	3	1,330 dead, 11,506 destroyed homes, of which 1,451 washed away, 2,598 burned	The earthquake happened off the Kii Peninsula. Damage was reported from Chubu to Kyushu. Particularly heavy damage was reported at Kochi, Tokushima, and Wakayama. Tsunami of 15-50 cm were observed at Hawaii and California. Up-lifted crustal movement was observed at Shikoku and Kii.

the tsunami inundated rice and vegetable fields and ponds in inland areas. Reportedly, many dead people drifted in heaps at a pond connected with the Horikawa River [5].

2.1.2. The 1854 Ansei Tsunami

At Nishimachi, Shimmachi, Hamacho, Hara, and Kogura, most structures along the shore, such as an old storehouse, were flooded and destroyed. All bridges built

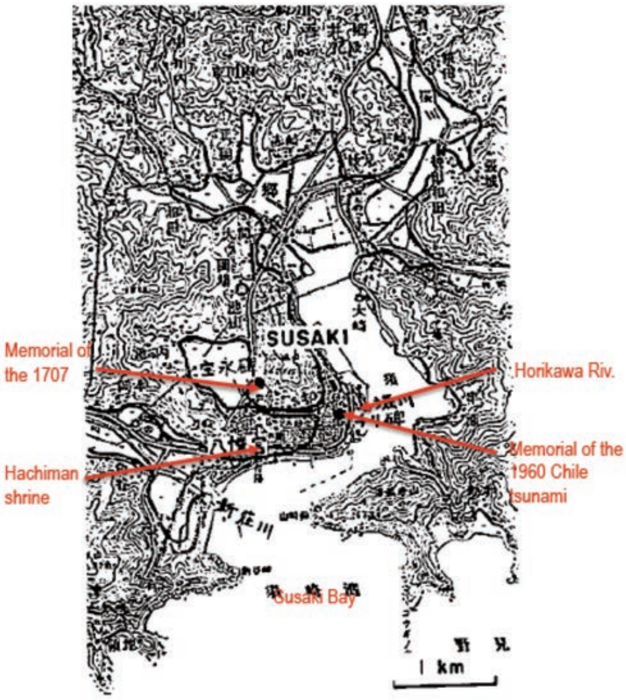

Fig. 3. Inundation by the 1946 tsunami at Susaki Bay with information of other tsunamis [5].

over Horikawa River collapsed because of the tsunami run-up into the river [5]. However, the Hachiman Shrine, located on a prominence of 5.1 m, was not flooded. Furthermore, during this tsunami, more than 30 people who attempted to take refuge by ship were lost and were later recorded as missing. In fact, 270 houses were swept away; the loss of only 35 dead people represents a marked decrease from the casualties reported for Susaki Ura and Susaki village when compared to data reported for the 1707 Hoei tsunami. The 1854 Ansei tsunami was smaller than the 1707 tsunami. We infer that the lessons learned from the 1707 Hoei tsunami were probably recalled by many residents, who were thereby able to prepare and act better against the latter tsunami.

2.1.3. The 1946 Showa Tsunami

The tsunami attacked the area about 10 min after its generation by an earthquake. It apparently attacked six or seven times afterward with a period of around 20 min during two and a half hours until dawn. Reportedly, the tsunami then intruded into the bay and the wave broke in a shallow region. Small boats were floated aloft on the front of the breaking wave. The tsunami proceeded to invade into Haramachi warehouses on the south side to the Haramachi northern end; the southern flow entered between Susaki Station – Shiroyama to Horikawa and joined the flow that flowed ashore from the eastern and southern parts. In the Hamacho neighborhood and the old pier northwest side, 30 houses were collapsed by floating debris at the time of the second wave in particular and were washed away. The tsunami rose to 1.24 m from the surface of the sea at the position of the tracks and railway. The tsunami passing over that area collapsed homes even

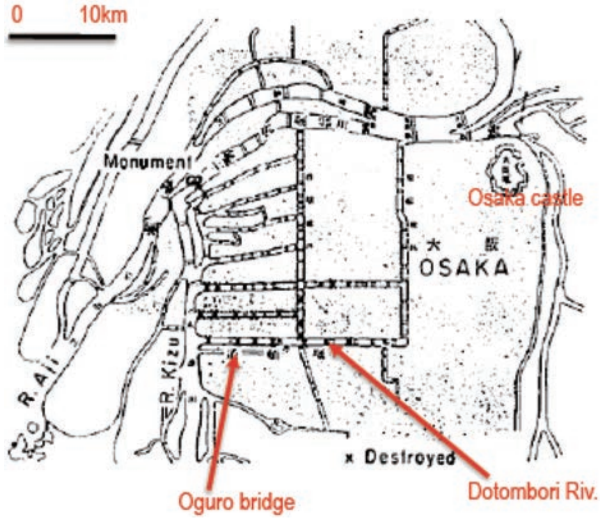

Fig. 4. Bridges destroyed by the 1854 Ansei tsunami in Osaka (referred from Hatori, 1974 [4]).

Fig. 5. Ukio-e print of the ships awash in the 1854 Ansei tsunami at Osaka [6].

on the north side. Apparently, it disturbed the delay of the tsunami invasion from the old storehouse area, which was unexpected. Moreover, a notable delay of the refuge existed because of blockage of refugee routes by the destruction of houses and the resulting debris.

2.2. Damage at Osaka

2.2.1. The 1707 Hoei Tsunami

Earthquake damage was reported as serious: 1,061 collapsed houses (of 17,279 total houses) and 663 deaths (population 349,704). Osaka, which is located on a sandbank at the mouth of Yodogawa River, has notably weak ground in support of structures. Damage to buildings occurred as a result of the strong quake. Reportedly, 26 bridges were collapsed and 4 were destroyed completely [3, 6]. Subsequently, the tsunami moved up the Aji and Kizu rivers one and a half hours after the earthquake, washing away large boats anchored in the river mouths and sides. As many as 320 large boats were pushed from their moorings and lifted up into the city, destroying 603

Table 2. Damage at Susaki, Kochi by tsunamis propagating from the Nankai Trough [5].

	Dead and missing	Houses washed away	Houses destroyed	Damaged rice fields and farms	Ships washed away	Maximum tsunami height
1707 Hoei	331	432	?	58,000 m^2	?	11.7 m
1854 Ansei	50	550	95	357,000 m^2	137	7.1 m
1946 Showa	56	45	136	912,000 m^2	483	4.5 m

Table 3. Damage at Osaka by tsunamis propagating from the Nankai Trough [3, 6, 10].

	Dead and missing	Damage to houses and boats	Tsunami height (Watanabe, 1998)
1707 Hoei	663 by the quake (Tsuji, 1999) 534 (Usami, 1996) More than 10,000 reported	1,061 houses, 1,000 boats	Osaka, 2.5-3.0 m
1854 Ansei	341 (Watanabe, 1998) More than 7,000 (Usami,1996)	26 damaged brides, 662 destroyed boats	Osaka, 2.5-3.0 m (6 m) Sakai, 2.5 m
1946 Showa	32 (Usami, 1996)		Osaka, 0.6-1.0 m, Sakai, 3.0 m

houses on the land, where many people died. Many in the sunken boats and ships died. More than 10,000 casualties were estimated [2, 3, 6].

2.2.2. The 1854 Ansei Tsunami

Eight hours after the 1854 Ansei Tokai earthquake occurred, the Ansei earthquake occurred with seismic intensity of around 5 at Osaka. **Fig. 4** presents related maps. **Fig. 5** shows an illustration of the tsunami, which attacked and inundated the downtown Osaka of those days. Many people who were frightened by the earthquake's strength and who sought to escape from fires after the earthquake sought refuge on a ship floating in the moat. They were among the first to be killed as the tsunami caused great damage during its passage through channels and rivers. The lessons of the 1707 Hoei tsunami seem to have remained unheeded at the time of the 1854 Ansei and in modern day Osaka as well. The tsunami height was around 6 m at its greatest. Notably, an anchorage for large boats of 1,500 piling-stones was cut: consequently, its ships were set adrift. The tsunami invaded from Aji River, on the river mouth of Kizu, to the city area.

Big ships, as at Sengoku, were as many as 200 on the Aji River and 60 on the Kizu River. At Oguro Bridge in Dotombori, a main area of Osaka, ships were piled one on top of the next and "decks were washed away" [6]. The masts of the ships crashed in on one another, destroying a wooden bridge and causing the collapse of another bridge. At the Kizu, Aji, and Dotombori rivers, 662 vessels were grounded, wrecked, or submerged. In Osaka River, recorded shipwrecks included 568 submerged vessels and 68 washed away.

2.2.3. The 1946 Showa Tsunami

Damage caused by the 1946 Showa tsunami is presented in **Table 3**, but victims of the tsunami were not clarified. Reportedly, the wave height was around 0.6-1.0 m at Osaka (Watanabe, 1998) [3]. Apparently, no great damage occurred. The 1946 Showa tsunami was around 1.0 m, whereas the tsunami height was around 2.5-3.0 m in the 1707 Hoei and the 1854 Ansei. The different scale of only around 1 m is apparently a threshold of severe damage.

The scale of the tsunami sweeping in from the Kii Channel strongly determines the eventual human damage occurring in the Gulf of Osaka. This is important information to estimate tsunami damage in Osaka after the earthquake. Although it seems that inundation expansion resulting from the flow has not been able to damage ships, the possibility of the damage would be high because of acceleration of tsunami flow in the complicated channel system. Furthermore, all water gates constructed after World War II would not have been closed before the tsunami attacked Osaka, because of a large number of gates those are not automatically closed by the remote operation.

3. Tsunami Physics and Damage

3.1. Physics of Tsunami Propagation and Run-Up

Most tsunamis resulting from undersea earthquakes occur in the deep sea and propagate rapidly through the ocean. When the wavelength is greater than the water depth and because the wave amplitude is negligible, we can assume that linear long wave theory is useful and applicable for analyses. It yields the following wave propagation speed, called celerity, as

$$c = \sqrt{gh} \quad \quad (1)$$

where g signifies the acceleration of gravity and h is the water depth.

Once the tsunami waves reach shallow water, they are transformed dramatically. The tsunami speed is a function of the water depth given by Eq. (1), the root of the gravity acceleration multiplied by the water depth. The wave slows as it nears the shore. However, because its energy remains almost constant, the wave height increases tremendously in shallow water. This is known as the shoaling effect. It is given by Green's law as

$$\frac{a_1}{a_2} = \sqrt[4]{\frac{h_2}{h_1}} \quad \ldots \ldots \ldots \ldots \ldots \quad (2)$$

where a_1 and a_2 respectively denote the wave height in h_1 and h_2 depths. For example, a wave height of 1 m in 4000 m depth can be amplified to 4.4 m in 10 m.

During the time in which it nears the shoreline, the tsunami height increases and becomes comparable with the water depth so that the nonlinearity in the convection term gains importance. Shallow-water equations including the effect of convection and bottom friction are usually used. The theory subsumes a value of hydrostatic pressure, but incorporates the finiteness of the wave amplitude. The frontal wave slope becomes steeper. The water projects into the air if the water particle velocity at the front exceeds the local phase velocity. Consequently, a breaking bore is formed. Finally, the tsunami performs its run-up and inundates land areas. The run-up heights of a tsunami depend upon the shore and land configurations, diffraction, standing wave resonance, and the edge wave generation. Narrow valleys on land are expected to focus the kinetic energy: a tsunami can ascend to the top of the valley and then run down. A strong back current that is thereby accelerated on the slope can cause erosion of land and shore areas. Furthermore, a tsunami can propagate many times through a river mouth, forming an edge bore or solitary waves. Over time, the bottom friction, and existence of resistant structures and vegetation on land are expected to dissipate the energy imparted by the waves.

3.2. Several Types of Damage

Tsunami damage is classifiable into two types: that on land and that in the sea. Damage on land includes that to houses, facilities (tide embankments and sluices), including also personal suffering, sand scoring, fire damage, economic damage (service stoppage), lifeline damage (water and sewage services, electric power, gas, and communications), traffic damage (roads and railways), agricultural damage (salt water infiltration to rice fields), ground damage (erosion and accretion), and sand movements (Shuto, 1998) [7].

Damage in the sea includes oil and wood outflows, causing coastal environmental pollution, facilities damage (coastal facilities such as breakwaters), and damage to ships and fisheries. The sequence of complex damage related to a tsunami should be classified on the land as well as in the sea for each area.

Once the probability of damage and its potential are identifiable, damage should be evaluated based on occurrence criteria. For example, the appearance of residential destruction depends on the extent of the flood of depth if past damage cases are apparent. The damage level of earlier frame houses in Japan has three classifications according to the flood depth, as depicted in **Fig. 6**. The greatest damage occurs initially; it becomes greatest from the ceiling up when flooding is above the floor level at 0.5-1.0 m level. Frame houses begin to move only when flooded, according to the building buoyancy. Frame homes will be destroyed because they are light. Therefore, joints with the structure foundation are important to limit damage to individual structures and others. Floating objects such as ships are carried by the tsunami. In addition, the destructive power might be increased, and damage might be great.

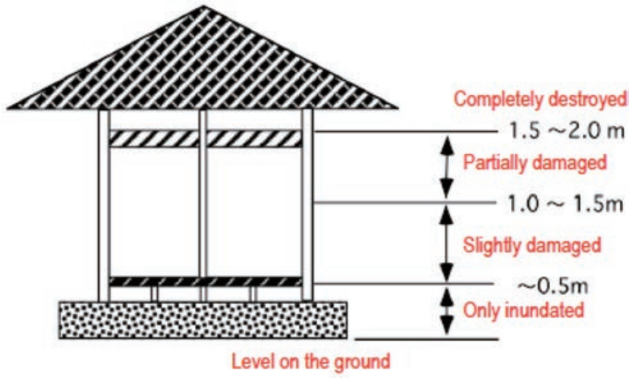

Fig. 6. Damage to a house by a tsunami.

Regarding damage to homes such as that at Banda Aceh in Indonesia (Koshimura et al., 2008) [8], the related table shows that excessive damage to the number of homes results from differing depths of flooding. Strong flood depth flow velocity both destructive power. The destruction generation standard of the house might be presumed as that at flow velocity.

The damage to ships inside the harbor and in coastal areas increases with drifting. Many examples of damage to fishing boats have been reported. As typical patterns of damage, boats are capsized or overthrown by the pushing waves and are run aground because of an undertow; they are launched onto land areas at times. Two examples are reported in the literature of ships thrown by the tsunami destroying structures in residential areas. Damage expansion caused by drifting was feared not only in the past; it also presents frightful prospects for the future.

Large-scale fires were observed when the 1993 earthquake generated a tsunami that swept onto Hokkaido's Okushiri Island. Because a tsunami is a wave of water, it would seem that fire disasters would be of little concern, and that fires would be extinguished. Nevertheless, fires have actually occurred. Inflammable materials such as oil and gas are regularly stored in coastal areas. They can flow seaward and landward in large quantities when storage tanks are destroyed by an earthquake or tsunami. The tsunami flow moves and diffuses such materials to large areas. Ignited by an electrical short, for example, a small fire can quickly grow to a huge conflagration. Reported cases such as those of Niigata earthquake tsunamis in the 1933 Sanriku earthquake and in 1964 included reports of tsunami-related fires.

4. Estimating Damage by the CDPC

A special investigative committee of the Central Disaster Prevention Council (CDPC) predicted damage caused by earthquakes, fires, and tsunamis, if two earthquakes were to occur simultaneously [1]. Tremors of six or less on the JMA seismic intensity scale were simulated around the Pacific Ocean side from Tokai on Shikoku. Results show that about 40,000 houses would be destroyed completely, with as many as 8,600 deaths [1]. The tsunami would affect a wide area from Kanto to Kyushu, reaching as high as 12 m on the coast of Shikoku, as at Kochi Prefecture at Tosashimizu City. This estimation of damage resulting from the two earthquakes is the first reported for Japan. According to the damage or impact to each area, "Disaster Prevention Measures Promotion Regions" were selected by the CDPC. Those municipalities around the country were chosen as target areas for special disaster countermeasures.

Among the reported assumptions for the prediction, the scale of concurrence of the Tonankai and Nankai earthquakes was presumed as about M 8.6. Large seismic intensity of 6 would be expected in Shizuoka Prefecture, west Ise Bay, the Kii Peninsula on the southern part Shikoku in Pacific Ocean side, with seismic intensity in Nagoya City including Osaka, and partial intensity in Ehime and Miyazaki prefectures. The tsunami was 10 m or more by the Kii Peninsula and the southern coast of Shikoku, but areas with waves of 5 m or more are many. Waves would be higher in the case of a flood tide. Some places of 3-5 m also exist in Osaka Bay, the Inland Sea of Seto, and Kyushu's eastern shore. That in Tokyo Bay is assumed as 1-2 m.

This is the first reported estimation of tsunami hazards and damage there. It should be improved by incorporating the following information to yield more reliability and a better perspective.

(1) Identification of tsunami generation patterns attributable to various seismic source processes of earthquakes propagating from the Nankai Trough

(2) Improvement of criteria to estimate tsunami-induced damage considering damage imparted by recent events, including the 2004 Indian Ocean tsunami

(3) Production of a new tsunami risk and mitigation map. Such a map is producible by compiling more information and designing the map to support discussion of countermeasures against "synchronization type" disasters.

5. Need for Tsunami Research Related to the Nankai Trough

Earthquake disaster prevention measures of modern Japan do not assume a case in which three earthquakes occur, but damage that might affect Japan is forecast when a super-giant earthquake of a synchronized type occurs. The reason for the distinction between a Tokai earthquake and a Tonankai and Nankai earthquake is that they are separated. Concrete prior measures to assume synchronization are not set even when the precaution declaration of the Tokai earthquake is announced officially. Synchronized Tonankai and Nankai earthquakes would present a very damaging event.

The possibility exists that anti-earthquake and tsunami measures in the country cannot make the best use of results as matters stand, although the Ministry of Education, Culture, Sports, Science, and Technology advances policy research on estimation of damage and restoration and revival based on a synchronized evaluation. It is important to convert anti-earthquake and tsunami measures that are connected directly with the reduction of damage to "Synchronization type" as soon as possible.

Techniques for highly accurate forecasting of the tsunami wave height at the coast, flooding of inland regions, and running up rivers are developed based on the earthquake and tidal wave scenario obtained from earthquake occurrence forecast simulations. Tsunami generation mechanisms are influenced by ground deformation at the bottom of the sea. Furthermore, sector collapses attributable to a local tsunami are also affected by the sea bottom structure, as shown by detailed measurement results of geographical features. Furthermore, evaluation of the sea level rise attributable to global warming can be done. Tsunami damage to human communications and material damage of different kinds are predicted based on obtained tidal wave hazard information. This information can serve as a basis for compiling hazard risk into a topographical map, a land-use map, satellite images, etc. Finally, information related to regional disaster prevention power and correspondence power is compiled. A restoration revival map showing facts quickly can then be examined.

The following studies have been undertaken for forecasting tidal wave damage by a giant earthquake and for reduction of personal suffering.

(1) Tsunami simulation hybrid model development targeting seismic and non-seismic tsunami.

A tsunami simulation model was developed for use to analyze synchronization-type huge earthquakes of the M8-9 classes. This simulation model can incorporate tsunami generation mechanisms from different sources – such as slow earthquakes or tsunami earthquakes, and undersea landslides – corresponding to probabilities of various seismic source processes of Nankai Trough earthquakes.

(2) Compilation and evaluation of tsunami risk estimation.

The tsunami risk in coastal areas considering the new type damage form is assessed based on realistic influences: true sea level changes using detailed geographical characteristics, land use, and global warming.

(3) Human damage reduction strategies.

The tsunami wave height at the coast, run-up in rivers, and flooding are forecast with high accuracy using a hybrid tsunami simulation based on an earthquake scenario obtained from earthquake occurrence forecast simulations. Then a tsunami disaster map is produced based on a new tsunami risk technique. Using this information, human damage reduction strategies can be proposed. Here, correspondence based on a time series script from the earthquake occurrence is offered hourly.

6. Conclusions

Historical information related to tsunamis generated in the Nankai Trough and its damage were reviewed and compiled to examine the frequency and type of damage imparted to wide areas of western Japan. Especially, we selected Kochi and Osaka to examine details of tsunami behavior and their damage at the area, where multiple damage caused by floated ships, damage to bridges, and road blockage by destroyed structures were reported. The tsunami damage of type and magnitude should be changed according to the location and sequence of the faults. Thereby, the ranges of tsunamis' influences differ, as well as their period and amplification processes at the coast. Furthermore, a recent study revealed large-scale dislocation to be affected by the asperity, not only by single slips on the fault; heterogeneity was also recognized among faults [8]. Since the tsunami wave component is long in comparison with the seismic wave, space resolution to find the heterogeneity is not as high as seismic wave. However, using records of tsunamis observed by tidal stations, the non-homogeneity are being examined energetically.

Large tsunamis influencing wide areas accompany earthquakes propagating from the Nankai Trough. They impart damage not only in areas with prior damage. They are also expected to cause damage in urban areas such as those circumjacent to the Gulf of Osaka. Moreover, neither human damage from a possible second disaster nor economic damage to important facilities such as ships and fisheries should be disregarded.

Acknowledgements

This study was supported by a Grant-in-Aid from the JSPS (F. Imamura No. 18201033). This study was also supported by Research Project of the "Improvements of strong ground motion and tsunami simulation accuracy for application of realistic disaster prevention of the Nankai-Trough mega-thrust earthquake" of the Ministry of Education, Culture and Sport, Science and Technology.

References:

[1] Central Disaster Prevention Council (CDPC), "Report of the Special Investigation Committee," 2009 on the following WEB site: http://www.bousai.go.jp/jishin/chubou/nankai/index_nankai.html

[2] T. Usami, "Earthquake damage in Japan," Univ. Tokyo Press, p. 493, 1996 (in Japanese).

[3] H. Watanabe, " Tsunami damage in Japan," Univ. Tokyo Press, p. 238, 1998.

[4] T. Hatari, "Sources of Large Tsunamis in Southwest Japan," J. Japan Seismological Society – JIshin, 27, pp. 10-24, 1974 (in Japanese).

[5] Kochi Susaki City, "Record of Nankai and Chile tsunamis – caution from the sea," p. 151, 1995 (in Japanese).

[6] Osaka Tsunami Ukio-e-zu, Osaka Castle Museum.

[7] N. Shuto, "Old records on the tsunami sand sedimentation," Technical Report on Tsunami Engineering, Tohoku University, 15, pp. 1-36, 1998 (in Japanese).

[8] S. Koshimura, T. Oie, H. Yanagisawa, and F. Imamura, "Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Ache, Indonesia," Coastal Engineering Journal, JSCE, 2009 (accepted).

[9] Y. Tanioka, "Evaluation of slip distribution estimated from tsunami wave forms for 1944 and 1946 Nankai earthquake," Journal of Japan Geography, 110-4, pp. 491-497, 2001 (in Japanese).

[10] Y. Tsuji, "Nankai earthquake and the ensuing tsunami," Gekkan Chikyu, 24, pp. 36-49, 1999 (in Japanese).

[11] K. Ishibashi, "Status of historical seismology in Japan," Annals of Geophysics, 47, pp. 339-368, 2004.

Name:
Fumihiko Imamura

Affiliation:
Professor, Disaster Control Research Center, Graduate School of Engineering, Tohoku University

Address:
6-6-11 Aoba, Sendai, Miyagi 980-8579, Japan

Brief Career:
1992- Assoc. Prof., DCRC, Tohoku Univ.
1993-1995 Assoc. Prof., Asian Institute of Technology
1997-1998 Affiliate Assoc. Prof., DPRI, Kyoto University
2000- Prof., DCRC, Tohoku University

Selected Publications:
- "Field investigation on the 2004 Indian ocean tsunami in the southwestern coast of Sri Lanka," Proc. of special Asian tsunamis session at APAC (Asian and Pacific Coasts) 2005, pp. 93-106, 2005.
- "Effects of coastal forest on tsunami hazard mitigation, Tsunami – Case studies and recent developments," Springer, pp. 279-292, 2005.
- "A huge sand dome formed by the 1854 earthquake tsunami in Suruga bay, central Japan," ISET Journal of earthquake technology, No.462, Vol.42, No.4, pp. 147-158, 2005.

Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineering (JSCE)
- American Geophysical Union (AGU)
- Japan Society of Natural Disaster Science (JSNDS)

Name:
Kentaro Imai

Affiliation:
Earthquake Research Institute, University of Tokyo
Center for Integrated Disaster Information Research, Interfaculty Initiative in Information Studies, Graduate School of Interdisciplinary Information Studies, University of Tokyo

Address:
1-1-1 Yayoi, Bunkyo-ku, 113-0032, Tokyo, Japan

Brief Career:
2008-present Project Researcher, CIDIR, Interfaculty Initiative in Information Studies, Graduate School of Interdisciplinary Information Studies, University of Tokyo

Selected Publications:
- K. Imai and H. Matsutomi, "A hydraulic resistance law on trees considering deformation of foliage and numerical simulation of inundated flow on a coastal forest with the law," Doboku Gakkai Ronbunshuu B, Vol.64, No.3, pp. 214-225, 2008 (in Japanese).
- K. Imai and H. Matsutomi, "Hydraulic characteristics on tsunami inundation in a coastal vegetated area," Doboku Gakkai Ronbunshuu B, Vol.62, No.3, pp. 258-269, 2006 (in Japanese).

Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineering (JSCE)
- Seismological Society of Japan (SSJ)
- American Geophysical Union (AGU)