TSUNAMIS, DISASTERS AMD COUNTERMEASURES

By

SHUTO Nobuo

ARISH, Nihon University, Japan

1. Introduction

Our goal in tsunami study is not only to understand tsunamis as a natural phenomenon from the viewpoint of natural science but also to prevent tsunami disasters with the aid of engineering and social sciences. Since the Nicaragua tsunami in 1992, international cooperation in post-tsunami survey has been well organized for the first purpose. After the 2004 Indian Ocean tsunami, viewpoints of social sciences such as public education attracted many people’s concern.

It may be a good time to review tsunami effects from an engineering point of view for the future development of disaster prevention. Then, briefly introduced is the tsunami defense works guideline in Japan that recommends both engineering and social sciences, standing upon the state-of-the-arts natural sciences. In addition, numerical simulation as an indispensable means in forecasting and hind-casting is examined whether or not the computed results are accurate enough to be used in defense planning.

2. Disasters

1) Kinds of disasters

Table 1 summarizes several kinds of disasters caused by tsunamis in the past. In the future and/or at different places, different kinds of disaster can occur. A natural disaster is an expression of the interaction of a natural force and the human society. Even if the natural force is the same, the magnitude and type of the disaster is quite variable, because of the change and difference of the coastal society. It is, therefore, strongly recommended to estimate the possible disaster in the future with flexible imagination, on referring Table 1 that is based upon the experience in the past.

2) Loss of lives of coastal residents

Miyano and Ro (1992) obtained the following relations for the number of the dead, P, and the number of the injured, Q, in terms of the number of houses washed away and/or destroyed, W, in case of the 1944 Tonankai earthquake tsunami.

$$P = 0.07W^{1.018}, \quad Q = 5.584\times10^{-4}W^{1.961}$$

This gives seven dead per one hundred destroyed houses. In case of the 1896 Meiji Great Sanriku tsunami, a typical tsunami earthquake when no effort was taken to evacuate, Shuto (1991) found seven dead per one destroyed house.

Kawata (1997) plotted the rate of death in terms of tsunami height and Oya et al. (2006) added the case of Banda Ache as shown in Fig.1.

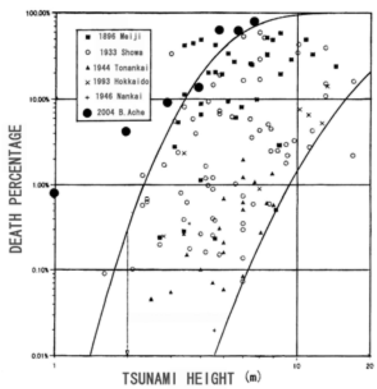

Fig.1 Dead vs. Tsunami Height

Table 1　Kinds, Types and Causes of Tsunami Disaster

Human Lives

Drowned. Injured hit by debris etc. Disease caused by swallowing alien substances during drifting.

Houses

Washed away. Destroyed. Flooded.

Coastal Structures

Toe erosion, displacement and overturning of sea walls, sea dikes, breakwaters and quay walls. Scattering and subsidence of concrete blocks.

Traffic

Railway	Erosion of embankments. Train wagons overturned. Displacement of rails and bridges. Rails buried by sands.
Highway	Displacement and falling down of bridges. Overturning of bridge abutment by erosion. Erosion of embankment　Closure of traffic by debris on roads.
Harbor	Change in water depth (erosion and accumulation).

Lifelines

Water supply	Destruction of hydrants by collision of debris.
Electricity	Overturning and washed-away of electric poles.
Telephone	Damage to telephone lines and poles.Overturning of relay tower for portable telephone. Cut-off of underground telephone line at the junction to the aerial lines.　Submergence of telephone receivers.

Fishery

Damage to fishing boats. Destruction and loss of rafts, fishes and shells in aquaculture.

Loss of fishing nets and other fishing gears.　Closure of port entrance by fishing gears washed-away.

Commerce and Industry

Depreciation of goods by submergence.

Agriculture

Physiological damage to crops due to submergence.　Damage to farms buried by sands.

Closure of irrigation channels filled by sands and debris.

Forest

Physical damage (breaking and overturning of trees. Soil erosion). Physiological damage by sea water and sands.

Oil Spill

Environmental pollution.　Spread of fires.

Fire (causes)

Kitchen fire.　Heating.　Engine room of fishing boats.　Collision to gasoline tanks.　Electricity leakage.　Submerged batteries of fishing boats.

In the original Kawata diagram, there is a big difference between the upper and lower limits of the death percentage that was simply explained by whether residents tried an early evacuation or not. Different from Japanese coast where high hills are nearby, the case of Banda Ache in the 2004 Indian Ocean tsunami tells us the vertical evacuation is more important than horizontal evacuation.

3) Loss of lives of harbor laborers

The 1983 Nihonkai-Chubu earthquake Tsunami hit a site where concrete caisson walls were being constructed offshore. The area between the sea walls and the shore would be filled with sand to reclaim the land for a power olant. When the tsunami hit, there was no way for laborers to evacuate to land.

Table 2 shows the results. All the laborers on caisson were swept away and half of them were lost. Only 10% of them were intact. Many small boats were overturned; more boats if closer to the caissons. Larger the boats and farther from the caisson, the safer the boats are.

Table 2 Loss of lives in case of harbor construction laborers

Place		**No. of people**	**Fall into sea**	**Dead (A)**	**Injured (B)**	**A + B**	**Overturned vessels/total vessels**
On structures		53	53 (100%)	24 (45)	24 (45)	48 (91)	
On boats moored	**Small boats**	35	31 (89)	3 (9)	15 (43)	18 (51)	13/15
	Large boats	64	2 (3)	3 (5)	16 (25)	19 (30)	1/9
On boats just left	**Small boats**	29	8 (28)	3 (10)	3 (10)	6 (21)	3/11
	Large boats	5	0	0	1 (20)	1 (20)	0/1
On boats far away	**Small boats**	29	5 (17)	1 (3)	5 (17)	6 (21)	2/12
	Large boats	62	0	0	0	0	0/12

4) Damage to houses

i) Percentage of damaged houses in a flooded area, R_{HD}

Hatori (1984) correlated tsunami height and R_{HD} defined as follows,

$$R_{HD} = (a + 0.5b)/(a + b + c),$$

where a, b and c are numbers of houses washed away & completely destroyed, partially damaged, and only flooded, respectively (Fig.2).

He (1964) also tried to express more hydro-dynamically and obtained

$$R_{HD} = 9 H^{1/2} \cdot V,$$

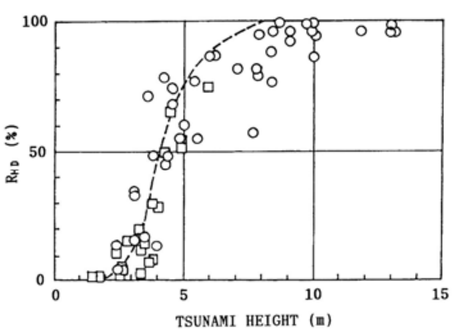

Fig.2 R_{HD} vs. Tsunami height

where H (m) is the measured tsunami height above ground, and V (m/s) is the estimated current velocity.

He (1984) also applied the same idea, using the results of numerical simulation to improve the accuracy of current velocity. His new findings were that R_{HD} was larger than his former result, especially for V>5~9 m/s. He considered that for this high velocity range, the impact of broken houses became more effective than the water current.

ii) Individual house

A rough estimate of damage to individual house is given in terms of tsunami height and type of house as in Fig. 3 (Shuto, 1993), by collecting data of post-tsunami surveys in the past.

Matsutomi has been trying to express the damage to houses in terms of drag force estimated from the difference between the fore- and rear-inundation heights. Iizuka and Matsutomi (2000) gave the destruction condition shown in Table 3.

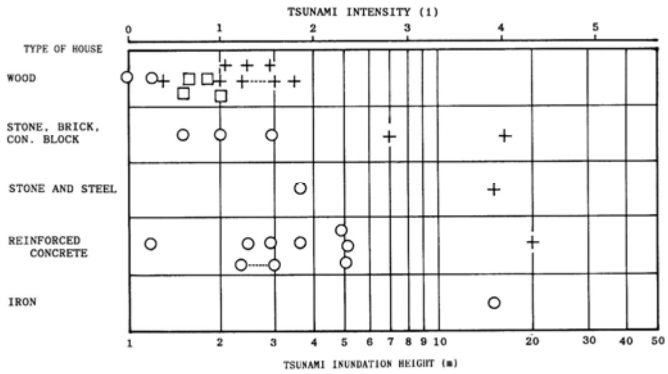

Fig.3 Damage to houses. Circles; withstand. Squares; partially damaged. Crosses; Washed away.

Matsutomi (1999) succeeded to give impact of a single lumber, too.

Under an actual condition, not a single lumber but a group of lumbers are more realistic impact. This is for the future study.

Table 3 Damage to houses in terms of inundation depth, current velocity and drag force

Type of building and house	Partially destroyed			Completely destroyed		
	H_f (m)	u (m/s)	F_D (kN/m)	H_f (m)	u (m/s)	F_D (kN/m)
Reinforced concrete B.	-	-	-	>7.0	>9.1	>332~603
Concrete-block B.	3.0	6.0	60.7~111	7.0	9.1	332~603
Wooden House	1.5	4.2	15.6~27.4	2.0	4.9	27.4~49.0

5) Fishing boats

Damage percentage of boats is defined as follows.

$R_{BD} = (a+b+0.5c+0.25)/(a+b+c+d+e)$

where a is number of boats washed away, b totally destroyed, c partially damaged, d slightly damaged and e intact.

Figure 4 is an example (Shuto, 1993). Damage may begin with tsunami height 2 m, and R_{BD} is 100 % if tsunami height is over 8 m. Once washed away, a boat becomes destructive force to damage houses.

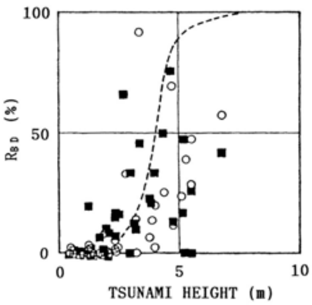

Fig.4 R_{BD} vs. Tsunami height

6) Destruction of Road- and Railway Embankments

Major causes of destruction of embankments made of soil are,

i) Erosion of slopes by overflowing water, and

ii) Scouring of embankments near abutment.

Erosion begins at the toe or at the shoulder of the embankment. Back slopes that are usually not covered by such materials as concrete or stone but by grass are eroded by the flood flow.

There are six factors that govern the condition of destruction and the degree of damage due to the erosion of slopes by overflowing tsunami: (a) the structure of the embankment, (b) the height of the embankment, (c) the overflow depth, (d) the number of times overflow occurs, (e) the duration of overflowing, and (f) the storing capacity of the landside ground.

In Fig.5 (Shuto, 2001a), white circles are for undamaged embankments, white squares for partially damaged, black triangles for mostly destroyed and black circles for totally destroyed or washed-away. Data with vertical bar are data of good accuracy. Two white circles mentioned as undamaged but ineffective are for embankments having very narrow spaces between the embankments and mountains behind. These areas were so quickly filled by the overflowed water that there were no enough time for the water to directly hit the toe and the back-slope of embankments.

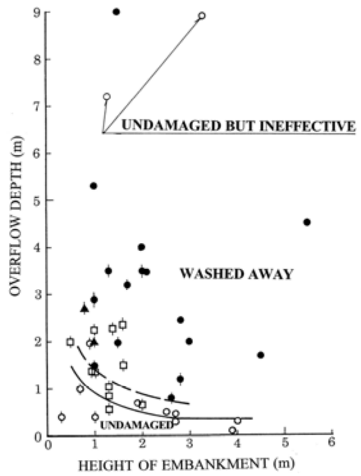

Fig.5 Damage to embankment

iv) Oil-related fires

Among many disasters, fire can devastate the coastal area, if triggered by a tsunami and assisted by inflammable materials stored in a large quantity. There are five examples in the history of tsunamis. All occurred in 1964; Three in Alaska, USA, one in California, USA and one in Niigata, Japan. A fire starts from such a source as kitchen fire when houses are destroyed by earthquakes and tsunamis.

In March 1964, three towns in Alaska and one city in California suffered this kind of fire when the 1964 Great Alaska tsunami hit. One of them, Whittier was a developed community closest to the epicenter of the earthquake. Three waves hit from local origins and from the major fault, during and after the earthquake. The second and third waves crested at 13 m and 10 m. The wave toppled Union Oil and U.S. Army storage tanks, causing an oil spill that caught fire and burned over 3 square miles.

In June of the same year, the city of Niigata, Japan, was hit by an earthquake and its low land was flooded by the tsunami. Oil leaked from a tank damaged by the earthquake and spread over the flooded area. Five hours after the earthquake, the oil caught fire from unknown source, other tanks ignited, the fire continued for 15 days, and 300 houses were burnt.

Goto (1985) developed a two-layer model to simulate the spread of oil transported by tsunami, by solving simultaneously water-and-oil layers. The computed area contaminated by oil approaches the Fay formula (1969) of the oil spreading with the lapse of time.

The possible burnt area might be estimated from the boundary between the gravity-viscous and surface tension-viscous regimes of the oil spreading, because volatile components that are an important driving force in the later regime may be burnt up before the oil slick becomes thin. Taking typical values of the density of oil, capillary force at the air-oil-water interface and empirical coefficients given by Fay, the burnt area A_B (m^2) is related to the volume of oil V (kl) by A_B = 324V (Shuto, 1991). This relationship approximates but is a little smaller than the Whittier case, in which V was 2.8×10^4 kl.

4. Geophysical Effects

Under a special condition, a tsunami may give a formidable damage which is never recovered. An example is found at Miyako-jima, Okinawa, Japan that was hit by a giant tsunami in 1771. Its highest run-up was over 80 meters. When the tsunami receded, it eroded and washed away the fertile soil from agricultural fields. The barren areas were left and are not yet recovered (Makino, 1968). In the followings, examples of topographical change are shown (Shuto, 2001).

1) Erosion of Barrier spits, Tombolos, and Sand Bars

There are several example of cutting of sand spits, tombolos, and sandbars since olden days. An old example is found in the legion of the generation of the Habu Harbor, Izu-Oshima Island, Tokyo. The 1703 tsunami cut the sand barrier 50 m wide that had separated a fresh water lake and the sea, and connected the lake and the sea by a channel 100 m wide. Since then, the lake became a good harbor.

Table 4 Change of barrier spits, tombolos, and sand bars

Location	Year	(1)	(2)	(3)	Remarks
Izu Oshima	1703	110 m		10 m	Barrier spit
Imagire, Hamana	1707	90 m	2.1~2.4 m	3 m	Barrier spit
Takahama, Miyako	1933	90 m		2 m	Sand bar
Kiritappu, Hokkaido	1960	100 m	2~6 m	4.2 m	Tombolo 1~2 m high
				(2.5~3 m/s)	

(1) Width of opening, (2) Water depth after tsunami, (3) Tsunami height and velocity

2) Depth Change of Natural and Artificial Channels

Table 5 shows eight examples for which quantitative information is available, two for the 1854 Ansei tsunami and six for the 1960 Chilean tsunami. All of them are for narrow channels. Two of them are the case of deposition and others are the case of erosion. For this kind of change, not the tsunami height

Table 5 Change of artificial and natural channels

Location	Year	(1)	(2)	(3)	Remarks
Imagire Inlet	1854	1.5~1.8 m	5~6 m		Inlet to Hamana Lake
Semizo Straight	1854	-1 m	>2 m		Musiake, Okayama Pref.
Kushiro River	1960	-3 m	2.5 m	2 m/s	Bottom was exposed.
Hachinohe Harbor	1960	>5 m	3.6~4 m	8~13 m	Along breakwaters
Kesen-numa Bay	1960	9.9 m	2.8 m		Along a groin
Watanoha Inlet	1960	1 m	3.1 m	20 km/h	Near Ishinomaki
			Total amp. 6 m	(5.5 m/s)	
Ishinomaki Harbor	1960	2 m	2.6~2.7 m		In the Kitakami River
Nakaminato Harbor	1960	1.7~2.1 m	Total amp.2.12	7 knot	At the river mouth

(1) Erosion Depth. (-) means deposition, (2) Tsunami height, and (3) Current velocity.

but the tsunami-induced current is important. No measured current velocity is obtained. Witnesses estimated the current velocity from the movement of ships trapped in the current or from their experiences based upon daily observation as fishermen

The case of Kesen-numa Bay is discussed below in detail with efforts to numerically simulate it.

3) Tsunami Deposit on Land

Tsunami archaeologists use sand deposits as a proof of paleo-tsunamis. These deposits can tell the existence of a tsunami, some indication of tsunami inundation but no information of the movement of the tsunami. It is a little difficult to estimate the tsunami energy from these data, because the thickness of deposit is affected not only by tsunami characteristics but also by the availability of sediment source.

Table 6 shows the thickness of deposits and related tsunami height in the past tsunamis.

Table 6 Tsunami deposit

Location	Year	Thickness of deposit	Tsunami height
Masuda, Simane Pref.	1026	20~30 cm	Unknown
Shishikui, Tokushima, Pref.	1605	30~45 cm	5~6 m
Misaki, Chiba Pref.	1703	60 cm	4~5 m
Ago, Mie Pref.	1707	15~30 cm	7~8 m
Ago, Mie Pref.	1854	30~90 cm	6~10 m
Misaki, Kochi Pref.	1707	>80 cm	6~7 m
Ishigaki, Okinawa Pref.	1771	1 m	9 m
Iruma, Shizuoka Pref.	1854	>4 m	13~16 m
Niigata, Niigatqa Pref.	1833	1.2~1.5 m	3~4 m
Taro, Iwate Pref.	1933	25~35 cm	7 m
Taro, Iwate Pref.	1933	1 m	10 m
Minato, Miyagi Pref.	1933	8~30 cm	3.4~4.8 m
Kido, Fukushima Pref.	1933	30 cm	2.7 m

Among these 13 data, three cases are eliminated. For the Masuda case, tsunami height is unknown. The Iruma case is exceptionally large, due to unknown cause. The Niigata case of 1833 is the deposition at the upstream side of local obstacles. Ten data are plotted in Fig.5. The dotted line shows the upper boundary of data. Roughly speaking, the deposit 1 m thick can be caused by the tsunami height of 7 m, if there is neither exceptional concentration of tsunamis due to local topography nor existence of local obstacles to accumulate sediments, and if the amount of sand near shore is plentiful enough with no limitation.

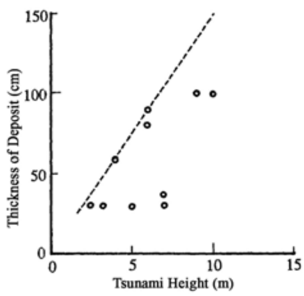

Fig.5 Tsunami deposit thickness

The case of Iruma shows an extremely thick deposition caused by tsunami. A tsunami nicknamed as the 1854 Ansei Tokai tsunami built a sand hill 4 to 8 m high at Iruma, Izu Peninsula at the bottom of a tiny bay, the entrance of which is about 200 m. Asai et al. (1998) evaluated the total volume of this hill to be more than 700,000 cubic meters. The tsunami run-up height of 13~16 m at Iruma is also very high compared to those of 5 m in the neighborhood. No one has yet succeeded to simulate this sedimentation.

4) Numerical Experiments to Simulate the Scouring in the Kesen-numa Case

The most important factor in erosion and deposition caused by tsunamis is the current velocity induced by the tsunamis. As long as tsunami height concerns, there are several ways to determine it from measured data such as tide records and tsunami trace heights. On the contrary, it is quite rare that the tsunami-induced current velocity is measured in the past. The Chilean tsunami of 1960 in the Kesen-numa Bay may be the only one case for which the current velocity can be evaluated from the aero-photos consecutively taken.

The Kesen-numa Bay in Miyagi Prefecture is composed of two parts, the inner bay 2 km long and 1 km wide and the outer bay 8 km long and 2 km wide. There is a narrow (Hachigasaki Narrow) 350 m wide between the two parts. A comparison of bathymetry maps before and after the tsunami showed a scouring of 7 m at the Hachigasaki Narrow. A high current velocity of 6 m/s was experienced by a fishing boat, but the time of its occurrence is not exactly known. The tsunami began around 4:00 a.m. in the bay and aero-photos were taken at 12:23 a.m. when the sixth ebb was in the bay. Next to the Hachigasaki Narrow, there was a tide station, Kogoshio where a complete time history of the tsunami was recorded.

A numerical computation was carried out by Takahashi et al. (1991) to simulate the tsunami height, tsunami-induced current and the resulted bottom change. The input tsunami at the bay entrance was carefully adjusted to simulate well the tide record at the Kogoshio station. The computed maximum velocity at the Hachigasaki Narrow was 5 m/s for the topography before the erosion and 3 m/s for that after the erosion. The spatial distribution of the computed velocity was compared with the measured at the sixth ebb at 12:23 a.m. The computed was 1/2 to 1/3 of the measured.

The location of erosion and deposition was qualitatively well simulated but not quantitatively. The main cause of this difference may depend upon the accuracy of the computed current velocity.

Two other efforts (Takahashi et al., 1993; Fuiji et al., 1998) to simulate this erosion by using different laws of erosion could only succeed to result in half the actual erosion depth.

5. Countermeasures in Japan

1) Since the 1960 Chile Tsunami to the 1993 Hokkaido Nansei-Oki Earthquake Tsunami

In 1960, a tsunami that propagated from Chile caused large-scale damage in wide areas from Hokkaido to Okinawa, although the height of inundation reached only 5~6 m. One year before, in 1959, the Ise Bay Typhoon significantly damaged dwellings and other structures and left 5,000 dead in the Ise Bay area.

These two large-scale seashore disasters, Ise Bay Typhoon and Chile Tsunami which occurred in two consecutive years, gave opportunity to make fundamental form of coastal defense structures afterwards. Because both disasters can be coped with by coastal dike 5~6 m high or so, hard defense countermeasures were given first priority, being supported by the fact that the plan to double the nation’s income built up national strength at that time.

In addition to construction of coastal dikes, another effort has been continued to refine tsunami forecasting that began in 1941.

In the Hokkaido Nansei-Oki Earthquake Tsunami in July 1993, an unexpected situation arose. First, tsunami forecasting was too late. Second, in Okushiri town, the 5th district of Aonae that was protected by seawalls 4.5 m high, which was supposedly tsunami-proof, and while the seawalls themselves remained almost intact, the entire community was washed away without a trace. Housing not damaged by the tsunami burned down due to unexpected fire outbreaks.

2）“Guidance on reinforcement of tsunami disaster prevention countermeasures in local disaster prevention planning”

After this disaster, 7 government offices concerned with tsunami disaster prevention policies agreed to “guidance on reinforcement of tsunami disaster prevention countermeasures in local disaster prevention planning”（National Land Agency etc, 1997）.

The planned tsunamis are selected as follows.

This involves the largest past tsunami from which credible materials can be obtained and possible tsunamis caused by the largest earthquake that can be supposed to occur based on present knowledge and science such as seismo-techtonics. After comparing both tsunamis, one with the higher water level on coast is selected as the standard tsunami to ensure safety insofar as possible.

Tsunami selection thus involves past records and scientific prediction. This is a quite different method to select standard tsunami from previous one. The Central Disaster Management Council announces earthquakes and tsunamis thus estimated as the standard force to be prepared for, especially after the Indian Ocean Tsunami in 2004. This adopted scientific prediction in tsunami preparedness for the first time.

As the countermeasures, defense structure, tsunami-resistant town development, and defense systems are to be combined.

Although the “defense structure” is the basic form of tsunami defense countermeasures, the level of defense structures is set considering the local situation and the effect of structures and examined comprehensively combined with tsunami-resistant town development and defense systems. Thus this level of preparedness by structure does not always correspond to standard tsunami.

From the viewpoint of “town development”, as a realistic problem, many cases exist in which not all housing and important facilities can be relocated, so it is important to convert potentially dangerous places to tsunami-resistant through land use, reinforcement of buildings etc., being consistent with medium- and long-range regional land use planning.

Seaside zones and hinterland require different use and various facilities to promote local industries and improve living environments. To promote safety against tsunamis in response to area planning, it is important to continue tsunami-resistant land use consistent with such use of seaside zones in each area.

In order to encourage such land use and to improve evacuation & relief countermeasures, it is important to incorporate the viewpoint of tsunami defense countermeasures in improving transport and public facilities that are the backbone of land use.

The “defense system” is generally stipulated in Disaster Countermeasures Basic Act etc. and this “guidance” explains the main points to be examined in tsunami disaster prevention. These points are improvement in tsunami forecasting and warning, evacuation based on this information, disaster prevention training in response to tsunamis and disaster prevention education to make people aware of tsunamis and what to do in the event of tsunamis.

6. Urgent Needs to Improve Numerical Simulation Technique

Numerical simulation is indispensable in defense planning, because even if the planned tsunami is one of the past tsunamis, we need tsunami data for areas where no old data exists. It is possible to verify the computed results with the old data in the neighborhood. When we prepare for a tsunami that is estimated with the modern theory such as seismo-techtonics, we do not have any means to verify the computed results. It is important to carry out simulation as accurately as possible, by eliminating incredible factors.

1) Equations

Evolution, decay and rebirth of undulating bores at the tsunami front are not yet well simulated with the present technique. Such a term as the artificial diffusion introduced to express well the growth of solitons at their final stage lacks physical basis.

There is no theory to explain edge bores.

2) Initial Profile

Heterogeneity of vertical displacement in the tsunami source area is not well understood. Only one measured initial profile in case of the 1964 Great Alaska Earthquake shows the importance.

3) Grid size in relation to topography

In the following 4 cases, necessary grid size can be determined, taking the topography into consideration.

i) Simple uniform slope (Sayama et al., 1988).

ii) A conical island (Fujima et al., 1998)

iii) Small V-shaped bay (Inagaki et al., 2001).

iv) Harbor (Inagaki et al., 2001).

For other cases, there is no criterion of how to discretize sea bottom topography.

4) Credibility of bathymetry data

Hydrographic charts that are often used as the source of bathymetry data for numerical simulation are originally made for the navigation purpose. If the water is sufficiently deep for navigation, no details are usually surveyed. We need more detailed data, especially in the area shallower than 100 m.

7. Concluding Remarks

The greatest difficulty in tsunami defense is resulted from the infrequent attack of major tsunamis. Even if coastal residents forget severe experiences of their own and their ancestors, researchers should not forget but continue their works to improve their knowledge and technique step by step, and prepare for the next tsunami.

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