Review

Tsunami hazard mitigation

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Abstract: The effect of giant tsunamis such as the Indian Ocean Tsunami in 2004 and the Great East Japan Earthquake Tsunami in 2011 has been devastating. In this study, a numerical simulation of the tsunami has been developed to estimate the physical characteristics of tsunamis and their effect on human society. Several laws and equations have been introduced for the simulation of tsunami propagation in the ocean, tsunami refraction, and tsunami run-up on land under a stable computational condition with acceptable accuracy. Our proposed method has been accepted as the world standard since 1997 and has been widely distributed to many countries through UNESCO.¹⁾ Computer graphic animations prepared by using the results of numerical simulation have been effectively used in public education and to increase the understanding of behaviors of the tsunami on the earth. When the numerical prediction of tsunami becomes possible with sufficient accuracy, then their results can be used to predict future damages and prevent the occurrence of a disaster. Data in the past were collected and expressed in terms of a newly introduced tsunami intensity which is related to the locally observed tsunami heights.

Keywords: tsunami, numerical simulation, tsunami intensity

1. Introduction

Even though Japan is known to be the most tsunami-frequent country in the world, the interval of occurrence of tsunamis is longer than the interval of generation change, which makes it difficult to use the knowledge obtained from previous tsunamis. Until very recently, it was formidable to analyze tsunamis with purely scientific means to solve real problems.

On 3 March 1933, immediately after the Showa Sanriku tsunami, was the first time that recovery and restoration measures were taken under the initiative of the Japanese government and Iwate and Miyagi prefectures. The primary action of the reconstruction measures was the relocation of the coastal communities to higher ground (CEDP, 1933).²⁾ The construction of seawalls was limited to four locations, such as Kamaishi and Taro, because of their high

cost. Matuo (1934)³⁾ conducted hydraulic experiments on the seawalls using a small model to quantitatively evaluate their effect on the beach and found that the effect was greater when the seawall was constructed inland than that of offshore. However, the similarity law of hydraulic experiment was not clear at that time, and quantitative conclusions could not be drawn. Takahasi (1934)⁴⁾ conducted experiments on the occurrence of tsunamis but were small-scale experiments.

Situations were changed when the Chile Tsunami hit Japan in 1960. The government was in a better economic condition and had a plan to increase its income by two-fold. In addition, while the damage caused by this tsunami was increasing around the various coasts of the Pacific Ocean, its height was recorded to be approximately 4–5 m. It was then decided that the structural measures taken were effective to control the tsunami, which was similar to the countermeasures taken against the Ise Bay Typhoon that occurred in the previous year. As a result, the Chile Tsunami Special Measures Law stipulated that “Tsunami countermeasures would be new constructions or new improvement of protective structures.” At this time, in addition to seawalls,

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tsunami floodgates were planned to prevent the penetration of tsunamis into rivers and tsunami breakwaters at the entrances of bay mouths.

The effect of the tsunami floodgates was confirmed by conducting large-scale hydraulic experiments. However, it was impractical to conduct hydraulic experiments on the bay entrance breakwaters because the target area was too large. Since then numerical simulations became an important strategy to deal with tsunamis, but the simulation technology had not developed adequately due to the limited capacity of the computer. Therefore, numerical simulations were being performed by assuming that tsunamis enter from the breakwater entrance and instantaneously spread across the bay.

In 1968, the tsunami caused by the Tokachi-oki earthquake hit immediately after the construction of the protective structural measures that were initiated soon after the Chile Tsunami in 1960. The structures were found to be effective, which supported the idea that structural countermeasures were enough to defend tsunami. In the United States, the situation was serious due to the fact that the tsunami-related budget was limited to the tsunami forecasting by the National Oceanic and Atmospheric Administration (NOAA), and the remainder of the budget was distributed to the marine development through National Science Foundation (NSF). Therefore, in the United States, tsunami-related research became inactive for approximately 15 years until the occurrence of the 1983 Nihonkai-Chubu earthquake and tsunami.

In Japan, the research on tsunami never stopped, even though the number of researchers was small. During the 1970s, research on tsunami was less active, but there were two significant developments.

First, Mansinha-Smylie (1971)⁵⁾ developed a method to estimate the vertical displacement of the ocean bottom, which is the initial tsunami waveform, as a result of earthquake information. Previous numerical simulations of tsunami only reproduced past tsunamis from measurements of coastal floods, but from this point onward, it became possible to estimate future effects of the tsunami.

The second development was the improvement in computer simulation due to the appearance of high-speed computers. As the speed of simulation rapidly increased, the profiling of tsunami became possible over a wide area. However, the simulations will not practical unless their accuracy can be guaranteed. Therefore, we developed a numerical

simulation technology for tsunami by solving problems individually. Finally, the technology was developed as a standard for UNESCO in 1997 and is described in Section 2 of this article.

When numerical predictions become possible, the results can be used to predict future damage and prevent disaster. It is, therefore, necessary to gather historical data on tsunamis and quantitatively analyze the damage caused during that occurrence. Although previous studies have been performed based on the past tsunamis, such as on the damage ratios of fishing boats and houses, it is still not possible to propose a countermeasure against tsunamis unless the individual conditions of housing and building damage can be determined. In addition, it is important to quantitatively clarify the mitigation effect of the coastal forest, which is thought to be an effective countermeasure, except for concrete seawall structures.

Section 3 describes the collection and analysis of damages caused by tsunamis. The results are identified by introducing the parameter called tsunami intensity, which corresponds to the local tsunami energy. Unlike the magnitude of the tsunami, which corresponds to the tsunami energy of the entire coastal area where the tsunami is hit, the tsunami intensity expresses the local tsunami energy against coastal objects.

2. Development of the tsunami numerical simulation method

2.1. Assurance of the stability and accuracy of the propagation simulation. To find answers in the numerical simulation of the tsunami, continuous equations, called differential equations, are replaced with discrete equations, called difference equations. To solve these equations, we must ensure that a numerical instability will not occur during the simulation and that the simulation will provide enough accuracy for further usage.

First, the simulation needs to be performed stably without any divergence. Because tsunami is a wave motion, in order to stably solve the wave equation, the condition of Courant–Friedrichs–Lewy (CFL) must satisfy the relationship between the spatial grid size (Δx) and temporal grid size (Δt) so that the “tsunami propagation speed in the numerical simulation ($\Delta x/\Delta t$)” is equal to or faster than “the propagation speed of the actual tsunami phenomenon (c).”

$$\Delta x/\Delta t \geq c. \quad [1]$$

However, the CFL condition alone does not guarantee the accuracy of the results. In case of the actual calculations, not the original differential equation but the difference equation will be solved in which various accompanying errors are also included. The discussion below proceeds on the assumption that a numerical difference method, called a leap-frog method, is adopted.

First, the effect of the spatial grid size has been discussed. The accuracy of the reproduction of a tsunami waveform decreases when the spatial grid size increases. However, the simulation time increases and the truncation errors are more accumulated when the spatial grid size is small. The following example shows the simulation of tsunami propagation in the ocean. At a sea depth of several kilometers, the tsunami wavelength can be approximately 100 km, and the wave height can be less than 10 m. Since the ratio of the water depth to the wavelength is the order of 10^{-2} and the ratio of wave height to the wavelength (wave steepness) is in the order 10^{-5} , such a problem can be treated as a linear long wave.

The Alaska tsunami in 1964 is used as an example of the tsunami waveform. Since the location of the occurrence of Alaska tsunami was shallow, the vertical displacement of the seafloor surface as the initial tsunami waveform was able to be confirmed by a bottom sounding after the earthquake (Plafker, 1965).⁶⁾ This is the only example of such a tsunami in the world. Taking a sectional profile of the tsunami generated by the Alaska earthquake measured along the A-A' line in Fig. 1 as the initial profile, the one-dimensional propagation on the water of a constant depth is computed with the linear longwave theory (Shuto, 1991).⁷⁾ This theory gives a unique wave celerity that is not influenced by phase and amplitude dispersion effects.

The true solution, therefore, should only give the translocation without any change in the wave profile. However, from Fig. 2, it is evident that the wave profile deforms, depending upon the spatial grid length Δx (DX in Fig. 2) and travel distance. The smaller the grid length and the shorter the travel distance, the truer the solution becomes.

The change is that the leading wave is reduced in height, and a small trailing wave appears behind it.

To eliminate this type of numerical decay in wave height, the grid length should be carefully determined. According to the numerical experiments performed by Shuto *et al.* (1986),⁸⁾ one local tsunami wavelength should be covered by more than 20 grid

Fig. 1. Initial waveform of the 1964 Alaska tsunami (Shuto, 1991).⁷⁾

points. Thus, the decay is less than 5% after the wave travels over a distance of four wavelengths, which is the longest travel distance for the first wave in the case of a typical near-field tsunami near the Japanese Archipelago. This condition should be satisfied not only in deep oceans but also in shallow seas.

2.2. Accuracy assurance of refraction. The traveling speed of a tsunami depends on the depth of water. As a linear long wave, the speed is proportional to the $1/2$ power of the water depth h and is given as $(gh)^{1/2}$. Here, g is the acceleration of gravity. Therefore, if the incoming waves are not perpendicular to the contour line, the wave's direction will turn to a shallow region. This phenomenon is the same for the refraction of light, the so-called Snell's law. To reproduce this phenomenon using a numerical simulation, the answers depend on the spatial grid size.

Since the shape of the wave direction at a uniformly inclined slope can be theoretically obtained, it is possible to determine the arrival position at the shoreline. This position is compared with the arrival position of the direction of the wave line obtained by the numerical calculation and is eval-

Fig. 2. Numerical results of the linear longwave theory for different grid lengths (Shuto, 1991).⁷⁾

Fig. 3. Refraction of the obliquely incident long waves on a uniformly sloping beach, demonstrating an error induced by the coarse discrete grid size.

uated according to the error of the position on the shoreline (Fig. 3). Figure 4 shows the results. The number attached to the line is the error (%) of the arrival position. Obviously, the larger the angle of incidence is, the smaller the spatial grid size that is required (Sayama *et al.*, 1988).⁹⁾

Fig. 4. Variation of the errors induced by refraction. A finer grid size is required for a larger incident wave angle θ (see Fig. 3 for definition of θ and N).

2.3. Simulation of the tsunami inundation.

Euler's equation, which is used to calculate water waves, is expressed using fixed spatial coordinates. Therefore, it is necessary to apply the movable boundary condition for the tsunami run-up simulation. Certainly, the Lagrangian description of the fluid motion is convenient to the tsunami crawl-up by following the position of water particles on the land before the start of movement (Shuto, 1967).¹⁰⁾ However, the Lagrangian description is only advantageous for a one-dimensional problem. If there is a planar spread like a real phenomenon, water particles gather at places where the tsunami concentrates and the precision at other places drops remarkably (Shuto and Goto, 1978).¹¹⁾ Therefore, in a practical

Fig. 5. Models for the moving boundary of the run-up tip. (a) Iwasaki-Mano model and (b) Aida model.

calculation, the expression of the fixed spatial coordinate system is used, and the movable boundary condition is applied to the tip portion.

Usually, Iwasaki-Mano's condition (1979)¹²⁾ or Aida's condition (1977)¹³⁾ is used to calculate the flow to the land-side grid with no water at the next time step.

Iwasaki and Mano (1979)¹²⁾ assumed that the line connecting the water level in the computation completed grid and the bottom of the land side grid gives the surface slope to the first-order approximation (Fig. 5(a)). Aida (1977)¹³⁾ evaluated the discharge into the dry cell with the broad-crested weir formulas in which the water depth above the bottom of the dry cell is substituted (Fig. 5(b)).

Those two approximations are convenient to handle but introduce numerical errors (Goto and Shuto, 1983).¹⁴⁾ The run-up height computed with the Iwasaki-Mano method agrees with the theoretical solution (Shuto, 1967)¹⁰⁾ with a 5% range of error if the following condition is satisfied:

$$\Delta x / \alpha g T^2 < 4 \times 10^{-4} \quad [2]$$

where Δx is the spatial grid size, α is the bottom slope gradient, g is the gravitational acceleration, and T is the period of the tsunami.

2.4. Instability control near the tip. Figure 6 shows the calculation instability that occurs at the tip portion after the second wave. This oscillation occurs at the front of the second wave, which runs up against the backwash of the first wave. The second wave is retarded, its front surface steepens, and oscillation occurs. With a smaller grid length, the length of the instability waves is shorter. Evidently, this is a numerical instability that is dependent on the grid length used. In Fig. 6, the vibration wavelength in Case A, which has $\Delta x = 12.5$ m, is shorter than that of Case B, which has $\Delta x = 25.0$ m.

Goto and Shuto (1983)¹⁴⁾ introduced a method to eliminate this instability. They used an artificial diffusion that acted to cancel the unstable waves only

Fig. 6. Oscillation induced by numerical computations at the wave front running up against the backflow. Case A, $\Delta x = 12.5$ m. Case B, $\Delta x = 25.0$ m. Case C, wave profiles without oscillations obtained with the artificial diffusion term.

in the vicinity of the wavefront. When the artificial diffusion acts well, the front surface becomes more gently sloping than it should be. Artificial viscosity is used to amend this over-smoothing at the expense of a negligible dissipation of energy. Case C is an example of this method (Fig. 6).

Fig. 7. Survey results of the 1933 Showa Sanriku tsunami in Kuwagasaki Town, Miyako City, showing significant difference in tsunami heights in a short distance apart; (a) Earthquake Research Institute (Tokyo Imperial University, 1934),¹⁵⁾ (b) Miyako port office (Matuo, 1933).¹⁶⁾

2.5. Application of the computer graphics animation.

2.5.1. Localities of tsunamis. Tsunami heights can differ by several meters in a short distance apart. As an example, Fig. 7 shows the survey results of the 1933 Showa Sanriku tsunami in Kuwagasaki Town, Miyako City. Figure 7(a) is obtained from the Earthquake Research Institute, and 7(b) is obtained from the Miyako port office. The tsunami height is approximately 3–4 m (Fig. 7(a)), but 7 m of the tsunami was measured only 50 m away from a point where the tsunami height was 4 m (Fig. 7(b)). What is the cause of this difference?

Because the size of the tsunami is large, physical experiments by using a water tank or a wave flume are not possible, but visualization of the tsunami using a numerical simulation is possible. In the simulation, the tsunami generation, propagation to the coast, and inundation are simulated. Therefore, the simulation visualizes the tsunami using numbers. Figure 8 shows an example of a snapshot of a tsunami hitting a building near the coast. This is the world's first tsunami animation, which was made in 1987. In the animation, we can see that the tsunami strikes the front of the building and can only move upward. However, the tsunami that was to the side of the building passed without changing its height, which is why a difference of 2–3 m height can easily occur at a distance of only 20 m. This example explains the localities of tsunamis.

2.5.2. Tsunami behavior in the Pacific Ocean.
(1) Effect of the Coriolis force: The initial waveform

Fig. 8. An animation demonstrating the reflection on the building wall that explains the reason why the tsunami height can differ near a building.

of the Chile Tsunami in 1960 was in the form of one elevated hump on the sea side and one depression on the land side. The wavelength was approximately 700 km, and the wave height was almost 10 m. In other words, the tsunami heading toward Japan was led by the elevation part. However, the Chile Tsunami first arrived in Japan with a depression or receding wave.

When reviewing the animation of tsunami propagation in the whole Pacific, it was found that the elevation wave preceded until the equator but preceded with the depression when the tsunami entered the northern hemisphere. It is likely that

the direction of the Coriolis force changed the pattern of tsunami waveforms when crossing the equator (Imamura *et al.*; 1990).¹⁷⁾

(2) Reflection from the Asian continent: The Chile Tsunami occurred on the 22 May 1960. However, the tsunami that arrived on 24 May 1960 was larger on the northern coast of Valparaíso in central Chile. According to Sievers *et al.* (1963),¹⁸⁾ it is unlikely that this difference was due to another earthquake that occurred somewhere in the south or a reflection from the Asian continent.

This question was solved by reproducing the Chile Tsunami throughout the Pacific Ocean and creating an animation. Chile is located 16,000 km away from Japan on the opposite side of the Earth. However, this distance is equal to 22–23 wave cycles of the Chile Tsunami, which had a wavelength of 700 km. The animation confirmed that the reflected tsunami from the Asian continent concentrated and returned to Chile. Such a tsunami animation over a wide area helps to understand the tsunami phenomenon.

3. The actual condition of tsunami damage

3.1. Tsunami profiles near the shoreline (Shuto, 1993, Fig. 9).¹⁹⁾ Before discussing the damage caused by a tsunami, we should begin with a summary of tsunami profiles near the coast based on

Fig. 9. Percentage of the different types of tsunami appearance in the nearshore zone based on approximately 160 eyewitness accounts after the 1933 Showa Sanriku tsunami. (Shuto, 1993)¹⁹⁾

the results of the interview of approximately 160 respondents. These interviews were conducted just after the 1933 Showa Sanriku tsunami. With this analysis, we will be able to obtain the characteristics of the local tsunami with a tsunami period of approximately 5 to 10 min.

Type I wave is somewhat like a tide. This type of wave is described as “the water level made a slow rise like a tide,” “the tsunami was like a rapid tide,” or “the tsunami quietly advanced shoreward and rose suddenly at the breakwaters.” Some of the waves had a wavy front “like ridges in the field.” These short waves sometimes break (Subtype I’). Type I are waves with a gentle steepness on a steep bottom slope. Forty-two examples were found for this type. Seven of them showed the breaking of short waves at the front.

Type II waves are characterized by “a rapid growth near the shoreline, although the tsunami is not recognized in the offing.” This expression means that the bottom slope is relatively steep. In total, 70 examples of this type were found. This type of wave is described as “the water level rapidly swells near the shore,” “the water swells from the bottom,” or “the water level is raised by a train of short waves, the succeeding waves overtaking and lying upon the preceding ones.” Four examples, mostly of great heights, showed spilling breaking near the crest and are classified as Subtype II’.

Type III (22 examples) waves are characterized by “a rapid growth, near the shoreline, of the tsunami that is well recognized in the offing.” This type of wave occurs for a tsunami that has a relatively gentle bottom slope. This type of tsunami is described as “a tsunami like a bank,” “a tsunami like a stretched curtain,” or “a wall with splash at its crest in the offing.” Half of these waves (Subtype III’) are accompanied by spilling breakers, even though they are not so high.

Type IV (26 examples) waves represent a plunging breaker. The second, third, or later waves of relatively low height (the smallest is approximately 2 m) may show this breaking when they meet the receding current of the preceding waves. The very high first wave (four examples, Subtype IV’) shows this plunging breaking wave. The smallest height of the plunging first wave is approximately 7 m.

Tsunamis often generate unusual sounds. These sounds are an important warning for people where information is difficult to reach (Shuto, 1997).²⁰⁾

The types of sounds generated by tsunamis can be classified and correlated with the types of wave

Table 1. Classification of tsunami sounds

Tsunami Intensity	0	1	2	3	4	5
Tsunami Height (m)	1	2	4	8	16	32
Wave Profile						
On a mild slope	Sudden rise near the shore	Wall of water in the offing. Second wave breaks	Wave front often breaks	First wave may show plunging breakers		
On a steep slope	Rapid tide					
Sound		Continuous sound caused by spilling breaking at the wave front. (Like a sea roar, a storm, a locomotive, or large truck.)				
			Sudden loud sound caused by plunging breaking on the beach. (Like a thunderbolt. Only audible at the beach where breaking occurs.)			
				Loud sound caused by impact of tsunami on cliffs. (Like a distant thunder or an explosion. Audible at distant places.)		

profiles and tsunami heights. Table 1 gives the relationships in terms of the tsunami intensity defined by Eq. [6] in subsection 3.6. The sounds caused by a strong ebb, an impact on cliffs, and continuous spilling breaking may be used as a natural warning of a coming tsunami. A strong ebb causes a violent motion of beach gravel on a relatively steep beach, which is the cause of the sound. The generation condition, however, is not determined in this analysis. A plunging breaker in tsunamis higher than 5 m yields a loud sound if it hits coastal cliffs. The sound is like that of distant thunder. This sound can be used as a precursor of a tsunami that provides sufficient time for evacuation. A tsunami higher than 2.5 m in the shallow sea often generates a continuous noise like a locomotive because of spilling breaking at the front, which can also be used as a sign of a coming tsunami. These sounds are useful for making an *in-situ* judgment of the danger of an arriving tsunami.

3.2. Damage percentage of villages composed of wooden houses. Hatori (1984)²¹⁾ defined the percentage of damaged houses R_{HD} in a given village as follows:

$$R_{HD} = (a + 0.5b)/(a + b + c) \quad [3]$$

where a is the number of houses washed away and completely destroyed, b is the number of houses partially damaged, and c is the number of houses flooded.

Figure 10 shows the percentage of damaged houses as a function of the tsunami height. Damage

Fig. 10. Percentage of damaged houses in the case of the 1933 Showa Sanriku tsunami (circles) and the 1960 Chile Tsunami (squares) by Hatori (1984).²¹⁾

to houses begins at a tsunami height of approximately 2 m.

The tsunami height may not be a good parameter to express damage to houses. Houses are broken, destroyed, and washed away due to buoyancy, drag force, and the impact of water and floating materials. Therefore, such mechanisms should be used in place of the tsunami height. Aida (1977)¹³⁾ considered that the drag force was a better parameter and defined it as the product of the water depth and square of the current velocity. Since no measured current velocity is available, the computed result is generally used. Figure 11 shows the percentage of damaged houses

Fig. 11. Percentage of damaged houses in terms of Aida's hydrodynamic drag force: open circles represent the 1944 Tonankai earthquake tsunami and 1960 Chile Tsunami based on the computed velocities (Hatori, 1984),²¹⁾ open circles with a vertical bar represent the 1960 Chile Tsunami based on the measured data (Hatori, 1984),²¹⁾ circles with a horizontal bar represent the 1983 Nihonkai-Chubu earthquake tsunami (Shuto *et al.*, 1986),²²⁾ and squares represent a flood (Sato *et al.*, 1989).²³⁾ The dotted line corresponds to the dotted line in Fig. 10.

in terms of Aida's drag force obtained by Hatori (1984)²¹⁾ and Shuto *et al.* (1986)²²⁾ for tsunamis, including the cases obtained by Sato *et al.* (1989)²³⁾ for floods. The dotted line in Fig. 11 corresponds to the dotted line in Fig. 10 when we assume that the

drag force F_D is given in the usual expression as follows:

$$F_D = (1/2)\rho C_D A V^2 \quad [4]$$

where ρ is the density of water and C_D is the drag coefficient. If it is assumed that the projection area $A \equiv H$ and the current velocity $V \equiv (gH)^{1/2}$, there is a one-to-one correspondence, as shown in Figs. 10 and 11, with $C_D = 0.06$, which means that the expression in terms of Aida's drag force is equivalent to that in terms of the tsunami height.

3.3. Damage to individual houses. The degree of damage depends on the structure of the houses and inundation height. Twenty-seven examples were collected from old documents all over the world. The data are from the Krakatau tsunami in Indonesia (1883), the tsunami generated by the Messina earthquake in Italy (1908), the Showa Sanriku tsunami in Japan (1933), the Aleutian tsunami in America (1946), and the Chile Tsunami in Japan and America (1960). Figure 12 shows the results (Shuto, 1993).¹⁹⁾

3.4. Impact on fishery.

3.4.1. Damage to fishing boats. Damage of fishing boats caused by tsunamis depends on the moored places, which changes with the times. The size of a fishing boat, whether the mooring place is a natural beach or whether it is shielded by a breakwater, are examples of differences.

In the case of the 1983 Nihonkai-Chubu earthquake tsunami, the damage percentage R_{BD} is defined by

Fig. 12. Type of houses, tsunami intensity (or tsunami height) and degree of damage. Circles: Withstand. Squares: Partially damaged. Crosses: Washed away.

Fig. 13. Damage percentage of small (circles) and large (squares) fishing boats in the case of the 1983 Nihonkai-Chubu earthquake tsunami.

$$R_{BD} = (a + b + 0.5c + 0.25d)/(a + b + c + d + e) \quad [5]$$

where a , b , c , d , and e are the number of boats washed away, seriously damaged, half damaged, slightly damaged, and not damaged, respectively. The tsunami height is the measured tsunami trace height near the shoreline. Figure 13 shows the results (Shuto, 1993).¹⁹⁾

As a result of the recent tsunami, the damage to large fishing boats (solid squares) is slightly larger than that to small fishing boats (open circles). This difference is caused by the recent development in fishing harbors. Large and expensive fishing boats grew in number. Many fishing harbors are now protected by breakwaters. Wharves are constructed for the efficient use of harbors, and therefore, natural beaches scarcely remain inside harbors. This change yields a complicated current system inside harbors and increases the chance of larger boats colliding with solid structures.

The dotted line in Fig. 13 gives a measure of the damage percentage in terms of the tsunami height at the shoreline, with no regard to the size of the fishing boats.

3.4.2. Damage to aquacultures. Detailed surveys of the damage done to pearl culture rafts were conducted by Sato (1960)²⁴⁾ in Matoya Bay, Kii Peninsula, Japan after the 1960 Chile Tsunami. The definition of the degree of damage is as follows:

Fig. 14. Damage to aquaculture rafts in the case of the 1960 Chile Tsunami.

“Damaged” means that a raft is washed away from its original position, destroyed, or sunk and that more than 70% of the mother shells are lost. “Partially damaged” means that a raft is washed away, collided with other rafts, and that 20–30% of the mother shells are lost from the raft. “Undamaged” means that even if a raft is moved, it is not washed away and the mother shells are safe.

Since the measured current velocity is not available, Nagano *et al.* (1991)²⁵⁾ used the computed results to explain the degree of damage in terms of the tsunami height and current velocity at the raft’s location. Figure 14 shows the results.

Circles represent without damage, triangles represent partially damaged or moved, and crosses represent completely destroyed or washed away. The maximum water level has no effect on the degree of damage because loosely moored rafts could follow the change in water level.

If the maximum velocity does not exceed 1 m/s, pearl culture rafts are safe even for a tsunami higher than 3 m. In shallow bays and channels, a tsunami of 1 m high may induce a current of 1 m/s, and damage to rafts begins.

3.5. The effectiveness of tsunami control forests. There are two contradictory opinions of the effectiveness of forest along a shoreline on the reduction of tsunami energy. Affirmative views assert that a forest is effective because 1) it stops driftwood and other drifts; 2) it reduces the water flow velocity and inundation height; 3) it provides a lifesaving

means by catching persons carried off by the tsunamis; and 4) collects windblown sand and raises dunes, which act as a natural barrier against tsunamis.

A negative opinion is that a forest may be ineffective against a giant tsunami, and at worst, trees themselves could become destructive forces to houses if cut down by the tsunami. Shuto (1987)²⁶⁾ tried to provide answers for this by analyzing 45 examples in Japan. The hydrodynamic effect of a forest is expressed in terms of the summed tree diameter dn and the existence of undergrowth, where d is the average diameter of breast-high trees in centimeters and n is the number of trees along the direction of the water flow per unit of shoreline length. Figure 15 shows the results in which the tsunami height is the inundation height.

In Region A, no tree is damaged and drifts are efficiently stopped but no tsunami is reduced.

In Region B, trees may be damaged. In Sub-Region B-1, trees are tilted or turned down, but

drifts are stopped. In Sub-Region B-2, trees are cut down and no effect is expected.

In Region C, if there is dense undergrowth, a reduction in the tsunami energy, as well as the stoppage of drifts, is expected. In Sub-Region C-1, both trees and undergrowth are not damaged. In Sub-Region C-2, some trees on weak soil or at the fringe of the forest may be damaged and the soil around the trees may be scoured. However, damage does not occur on such a large scale that the forest is completely destroyed.

In Region D, a forest is thick enough and a similar effect in Region C is expected even without undergrowth. In Sub-Region D-1, neither damage to the trees nor damage to the soil occurs. In Sub-Region D-2, although the soil in the forest may be scoured and damaged to some extent, the current velocity and inundation height are decreased and the degree of damage is reduced behind a forest compared to the area not protected by the forest.

3.6. Introduction of the tsunami intensity.

Imamura (1942)²⁷⁾ introduced the parameter " m " to quantitatively express the tsunami magnitude. The Meiji Sanriku tsunami was evaluated as $m = 4$, and the Showa Sanriku tsunami was evaluated as $m = 3$. Iida (1963)²⁸⁾ made it possible to judge the magnitude of the tsunami by using the maximum wave height H_{max} on the coast near the source of the tsunami.

However, this Imamura-Iida scale, which corresponds to the total energy of the generated tsunami, is not suitable for expressing phenomena and damage to local coastal areas. Therefore, the tsunami intensity " i " is defined by the following formula, and the events and damage described in the foregoing sections are classified with

$$i = \log_2 H \quad [6]$$

where H is the local tsunami height in meters (Shuto, 1993).¹⁹⁾

For the tsunami profile and damage to fishing boats, H is the tsunami crest height above ground level at the shoreline. For damage to an individual house and the effectiveness of a tsunami control forest, H is the inundation height. For damage to an aquaculture raft, H is the maximum tsunami crest height above the mean sea water level at the raft location. To evaluate the percentage of damaged wooden houses in a coastal village, H is taken to be equal to the maximum run-up height H_R , and the corresponding intensity is expressed as i_R .

Fig. 15. Effectiveness of tsunami control forests. Open circles: no damage to the trees with the effectiveness of stopping drifts. Triangles with a vertical bar: no damage to the trees with the effect of stopping drifts when a tsunami behaves as a standing wave. Solid circles: damage to some of the trees maintaining the effectiveness of stopping drifts. Solid squares: cut-down damage of the trees. Open triangles: reduction of the current velocity and inundation depth with no damage to the forest. Solid triangles: reduction of the tsunami energy behind the forest with damage to the forest. Underlines: dense undergrowth. Brackets: damage to trees in poor condition. Horizontal bars: the actual tsunami height is larger than the values indicated in this figure.

Table 2. Tsunami intensity and damages

Intensity	i	0	1	2	3	4	5
Wooden House		Partial Damage	Demolished				
Stone House		Withstand		(No Data)	Demolished		
R. C. Building		Withstand			(No Data)		Demolished
Fishing Boat			Damage Begins	Damage >50%	Damage =100%		
Tsunami Control Forest		Negligible Damage Stop Drifts Reduce Tsunami		Partial Damage Stop Drifts	Damaged Ineffective		
Aquaculture Raft		Damage Begins					
Low-Lying W. H. Village (Max. Runup Height: m)		1	2	4	8	16	32
	i_R	0	1	2	3	4	5

Based on Figs. 10 and 12–15, Table 2 shows the degrees of damage, which are classified in terms of the tsunami intensity and defined by Eq. [6].

The definitions of the tsunami intensity are described as shown in Table 3.

Incidentally, the damage percentage of a coastal village composed of wooden houses is expressed in terms of i_R .

For $i_R = 1$ ($H_R = 2$ m), damage to houses begins.

For $i_R = 2$ ($H_R = 4$ m), 50% of houses in the flooded area are demolished.

For $i_R = 3$ ($H_R = 8$ m), 100% of houses in the flooded area are demolished.

4. Closing

The 1970s was a low activity period for tsunami research, which was mainly due to the United States turning the budget to marine development studies. For the next approximately 15 years, there was not much going on in tsunami research until the tsunami after the 1983 Nihonkai–Chubu earthquake. During that period, the numerical simulation method was developed at Tohoku University, aiming at the numerical model to be applicable to real tsunami disaster-related problems. The simulation results are presented in the form of animations, which are an effective alternative to hydraulic models. The presentation of the first tsunami animation was intro-

duced at Novosibirsk in 1989, and it received a great response and was well recognized.

In the 1990s, Japan and Morocco jointly proposed the International Decade for Natural Disaster Reduction, which was adopted unanimously at the General Assembly of the United Nations. A project called the Tsunami Inundation Modeling Exchange (TIME) was adapted as a related project between tsunami researchers and practitioners. The aim of this project was to distribute and share the tsunami numerical simulation model developed by Tohoku University. This method is published as UNESCO's Manual and Guides No. 35 by the Intergovernmental Oceanography Committee (IOC). As of February 2011, it has been handed over to 48 organizations in 24 countries. Based on this numerical method, the Japan Meteorological Agency (JMA) is issuing tsunami forecasts since 1999 (Kusano and Yokota, 2011).²⁹⁾

With the numerical model, we can simulate a future tsunami. Combining the simulated results with the intensity of the tsunami, we are now capable of estimating the damage that a tsunami can cause. In the Urban Renaissance Agency (2013),³⁰⁾ based on the survey results after the Great East Japan Earthquake in 2011, the major difference in the damaged condition of wooden houses was due to the flow depth of 2 m. Beyond this criterion, the

Table 3. The definitions of the tsunami intensity

$i = 0$, $H = 1$ m	In the case of a steep bottom slope, the tsunami is like a tide without breaking.
	In the case of a gentle bottom slope, the tsunami swells rapidly near the shoreline, although it is not recognized in the offing.
	Damage to aquaculture rafts begins.
	Some of wooden houses are partially damaged.
$i = 1$, $H = 2$ m	In the case of a steep bottom slope, the tsunami is like a tide, which sometimes has breaking short waves on its front.
	In the case of a very gentle bottom slope, the tsunami can appear like a wall in the offing. Sometimes the crest of the wall-like tsunami shows the spilling breaker.
	The second, third and later waves can form the plunging breaker because they meet the receding current of the preceding waves.
	Most wooden houses are demolished. Stone, brick and concrete block houses can withstand.
	Damage to fishing boats begins.
$i = 2$, $H = 4$ m	Tsunami control forests can stop drifts. If the undergrowth is thick, the tsunami energy is reduced.
	The tsunami profiles are similar to the case of $i = 1$, with an increasing percentage of the appearance of the breaking front.
	Some stone houses are demolished.
	Reinforced concrete buildings can withstand.
$i = 3$, $H = 8$ m	50% of fishing boats are damaged.
	Tsunami control forests are partially damaged, but they are still effective at stopping drifts.
	No tsunami shows a tide-like rise of water level. The first wave becomes a plunging breaker.
	Stone houses are demolished.
	100% of fishing boats are damaged.
	Most tsunami control forests are ineffective.

percentage of total destruction substantially increases. Careful and diligent data collection and analysis from the past tsunamis uniquely experienced in Japan, together with the developments of numerical models, made future tsunami damage predictions possible.

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Profile

Nobuo Shuto was born in Oita Prefecture in 1934. He graduated from the Department of Civil Engineering, Faculty of Engineering, The University of Tokyo in 1957. He entered the Ministry of Construction and worked for river improvement, dam construction and coastal engineering research. He began his tsunami study in 1960 when the Chile Tsunami hit Japan. After this experience, the major subject of his research has been tsunami itself and tsunami-related damage. He moved to Chuo University in 1966 and was promoted to Professor in 1971. He also worked in Asian Institute of Technology in Thailand, Tohoku University, Iwate Prefectural University and Nihon University until 2010. He obtained a doctorate of Engineering in 1968, for “Run-up of long waves on a sloping beach”. A new field, Tsunami Engineering was originated with him. He received several awards concerning tsunami. Major awards are: (1) JSCE Paper Award for the study on the highly accurate forecasting for near-field tsunamis, Japan Society of Civil Engineers in 1989, (2) W.M. Adams Award for outstanding long-term contributions to research on earthquake, tsunami, and tsunami warning systems, Tsunami Society in 1991, (3) International Coastal Engineering Award in recognition of the pivotal roles and worldwide leadership he has displayed over the past 30 years in the research of tsunamis, American Society of Civil Engineers in 1996, and (4) The Japan Academy Prize in 2014.