Review

A short history of tsunami research and countermeasures in Japan

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Abstract: The tsunami science and engineering began in Japan, the country the most frequently hit by local and distant tsunamis. The gate to the tsunami science was opened in 1896 by a giant local tsunami of the highest run-up height of 38 m that claimed 22,000 lives. The crucial key was a tide record to conclude that this tsunami was generated by a ''tsunami earthquake''. In 1933, the same area was hit again by another giant tsunami. A total system of tsunami disaster mitigation including 10 ''hard'' and ''soft'' countermeasures was proposed. Relocation of dwelling houses to high ground was the major countermeasures. The tsunami forecasting began in 1941. In 1960, the Chilean Tsunami damaged the whole Japanese Pacific coast. The height of this tsunami was 5–6 m at most. The countermeasures were the construction of structures including the tsunami breakwater which was the first one in the world. Since the late 1970s, tsunami numerical simulation was developed in Japan and refined to become the UNESCO standard scheme that was transformed to 22 different countries. In 1983, photos and videos of a tsunami in the Japan Sea revealed many faces of tsunami such as soliton fission and edge bores. The 1993 tsunami devastated a town protected by seawalls 4.5 m high. This experience introduced again the idea of comprehensive countermeasures, consisted of defense structure, tsunami-resistant town development and evacuation based on warning.

Keywords: hazard mitigation, numerical simulation, coastal dikes, comprehensive countermeasures

1. Introduction

The 2004 Sumatra Earthquake and Indian Ocean Tsunami gave us a vivid description of menace of major tsunamis. It also suggested that tsunami science and engineering were inevitable to save human society, industries, and natural environment.

An answer can be found in Japan. Japan is the country the most frequently hit by tsunamis in the world. The experiences are well documented and are continued as the local legends. In 1896, the tsunami science started when the Meiji Great Sanriku Tsunami claimed 22,000 lives. An idea of comprehensive countermeasures was officially introduced after the 1933 Showa Great Sanriku Tsunami. The major works taken after this tsunami, however, were the relocation of dwelling houses to high ground and tsunami forecasting that started in 1941. The 1960 Chilean Tsunami opened the way to the tsunami engineering by elaborating coastal structures for tsunami defense. The 1983 Japan Sea Earthquake Tsunami that occurred during a fine daytime cleared the veil of actual tsunamis. The 1993 Hokkaido Nansei-Oki Earthquake Tsunami led to the practical comprehensive tsunami disaster prevention used at present, in which three components, defense structures, tsunami-resistant town development and evacuation based on warning are combined.

The present paper briefs the history of tsunami research in Japan that supports countermeasures.

2. Before the 1933 Showa Great Sanriku Tsunami

On December 23rd, 1854, the Ansei-Tokai Earthquake occurred at the east side of the Kii Peninsula.

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On the next day, the Ansei-Nankai Earthquake followed at the west side of the Peninsula. The two earthquakes generated tsunamis that gave heavy damages in the wide area. The height of tsunami was 5 m on an average with locally high value of 10 m. After this tsunami, a coastal dike was built at Hiro village in Wakayama Prefecture at the private expense of a local influential person who became world-widely well known as the hero of ''The Fire of Rice Sheaves'', a story used in the public education after the 2004 Indian Ocean Tsunami. The construction of coastal dike was quite rare before 1960.

At night on June 15th, 1896, the Meiji Great Sanriku Tsunami hit the pacific coast of the northeastern Japan, called as the Sanriku Region. The highest tsunami run-up height was 38 m at Ryori Shirahama in Iwate Prefecture. The earthquake was a typical ''tsunami earthquake'' that had negligibly weak ground shaking, and therefore, no residents tried to evacuate. This resulted in the death toll of 22,000. The economic damage amounted to about 10% of the national budget of those days. After this tsunami, several villages were relocated to high ground at private expenses of individual person or village leaders.

A research group of earthquake, the Council on Earthquake Disaster Prevention (CEDP) of the Ministry of Education had been established 5 years ago, after the 1891 Nobi Earthquake. In an article about the 1896 Meiji-Sanriku event published by the CEDP, earthquake was mentioned as one of forerunning phenomena of tsunami. After 1896, there was a hot academic debate about the generation mechanism of this tsunami. Because of the extremely weak ground shaking, many researchers doubted an earthquake but underwater eruption or landslide as the origin of the tsunami. The key to the solution was the tide records showing quite a long wave period. Only the large fault motion could explain the generation of such a long wave. In around 1910, researchers understood that a fault motion of earthquake was the cause of tsunami.

After the 1923 Kanto Earthquake that devastated the Tokyo Area, the central government fully led the restoration of the metropolis. At the same time, the central government and academic society participated in drafting countermeasures against earthquake and tsunami. The 1933 Showa Great Sanriku Tsunami was the first major tsunami under the modern knowledge and the modern system.

3. Age of the empirical total tsunami-mitigation from 1933 to 1960

In the early morning on March 3rd, 1933, 37 years after the Meiji event, another major tsunami struck the Sanriku Region. The maximum run-up height was 29 m at Ryori Shirahama. Most of coastal villages on the Sanriku Region suffered devastating damages again. Because the ground shaking was strong this time, many residents were awaken and evacuated to high ground; however, the death toll reached 3,000.

The CEDP proposed a total system of tsunami disaster mitigation three months later.[1)] They listed the following 10 countermeasures with comments:

- Relocation of dwelling houses to high ground: This is the best measure against tsunami.
- Coastal dikes: Dikes against tsunamis may become too large, and financially impractical.
- Tsunami control forests: Vegetations may damp the power of tsunamis.
- Seawalls: These could be effective for smaller tsunamis.
- Tsunami-resistant areas: If the tsunami height is not so high in a busy quarter, solid concrete buildings are to be built in the front line of the area.
- Buffer zone: Dammed by structures, a tsunami inevitably increases its height. In order to receive the flooding thus amplified, rivers and lowlands are to be designated as buffer zone to be sacrificed.
- Evacuation routes: Roads to safe high ground are required for every village.
- Tsunami watch: Because it takes 20 minutes for a tsunami to arrive at the Sanriku coast, we may detect an approaching tsunami and prepare for it.
- Tsunami evacuation: The aged, children and weak should be evacuated to safe higher ground where they could wait for about one hour. Ships more than a few hundred meters offshore, should move farther offshore.
- Memorial events: Holding memorial services, erecting monuments, etc. may help keep events alive in people's mind.

This idea proposed by researchers who worked in the field survey after the 1933 tsunami covers major necessary items in the tsunami prevention. It revived in 1997. See Section 7.

The central government made the restoration plan based on the above proposal. The basic policy was that cities could be restored at the original location surrounded by sea walls but the tsunami-resistant areas and buffer zones should be prepared, and fishing villages should be basically relocated to high ground.

In 1941, a tsunami warning organization was founded for the Sanriku coast. A tsunami forecasting chart was drafted empirically. By the Meteorological Business Act enacted in 1952, the forecasting system was made to cover the whole coast of Japan.

4. Impact of the 1960 Chilean Tsunami

4.1 Chilean Tsunami and research of far-field tsunamis. On May 23rd, 1960 (in Japanese local time), an earthquake occurred off Chilean coast. The tsunami generated by the earthquake attacked the Japanese coast on the next morning. Coastal residents in Japan did not feel any ground shaking. The Japan Metrological Agency did not issue a tsunami warning. Thus, the residents were suddenly attacked by the tsunami. Among the Japanese Pacific coast from Hokkaido to Okinawa, the Sanriku Region was the most seriously damaged. The economic damage was 2.2% of the national budget of those days.

The wave period of the 1960 Chilean Tsunami was from 40 minutes to 1 hour, longer than that of near-field tsunamis that was usually 5 to 20 minutes. Its initial profile in the direction to Japan had the wave length longer than 700 km. Even if short components were included in the initial profile, they were more easily scattered by or trapped around islands and sea mounts during the travel over the Pacific Ocean. In addition, short components retarded due to dispersion effect and then long components arrived first.

The tsunami height, 3 to 6 m, was not so high in comparison of such near-field tsunami as the Meiji and Showa Tsunamis.

In order to judge whether the dispersion effect is non-negligible for a far-field tsunami or not, Kajiura theoretically introduced a criterion.[2] On assuming that an initial waveform is simply parabolic or rectangular, the non-dispersive theory, that is, a linear long wave theory is valid if $(6h/R)^{1/3}(a/h) \geq 4$ is satisfied, where h is the water depth, a the horizontal scale of a tsunami source in the direction of propagation and R the distance to the tsunami source. Judged with this criterion, the linear long wave theory including the Coriolis force and dispersion effect expressed with longitude-latitude coordinates is used for the Chilean Tsunami. Imamura *et al.* numerically simulated the Chilean tsunami with this conclusion.[3]

Kajiura[2] also discussed the energy transfer from the sea bottom to the water in relation to the duration of the bottom movement. If the duration is less than several minutes, the deformation may be considered to be abrupt as far as the tsunami is concerned. However, if the movement is completed in a few second, the energy transferred to the compressional water waves might be larger than the tsunami energy.

His theoretical results are broadly known as the basis of the current tsunami research.

4.2 Chilean Tsunami countermeasures. Shore protection works started in 1950 and were legally authorized under the Seashore Act enacted in 1956. The Act stipulated to embody ''the Standards on Construction of Shore Protection Facilities'' that worked out in 1958.

In 1959, the Ise Bay typhoon generated a storm surge with the amplitude of 3.5 m at Nagoya port. This storm surge yielded the most serious damages to Nagoya area. This resulted in the death toll of 5,000 and the economic damage of about 9% of the national budget. Coastal embankments made of soil with solid covers only on the seaside surface were completely washed away by overflowing sea water. After this experience, the design standard was revised. Three surfaces (seaward slope, landward slope and crown) of soil embankment should be armored by concrete.

By the Chilean Tsunami, serious damage occurred in the areas that had been believed safe for the past near-field tsunamis. A good example is the area at the bottom of the Ofunato Bay, Iwate Prefecture. This area was hazardless for the past near-field tsunami and was being developed as the industrial and urbanized areas. The long Ofunato Bay became resonant to long wave period of the Chilean Tsunami, producing the largest inundation at the bottom of the bay. The response of bays in the Sanriku Region to the near- and far-field tsunamis was first cited by Watanabe.[4] Figure 1 shows the distinct difference in amplification characteristics between the near-field tsunami (the 1933 event, white circles) and the far-field tsunami (the 1960 Chilean Tsunami, black circles).

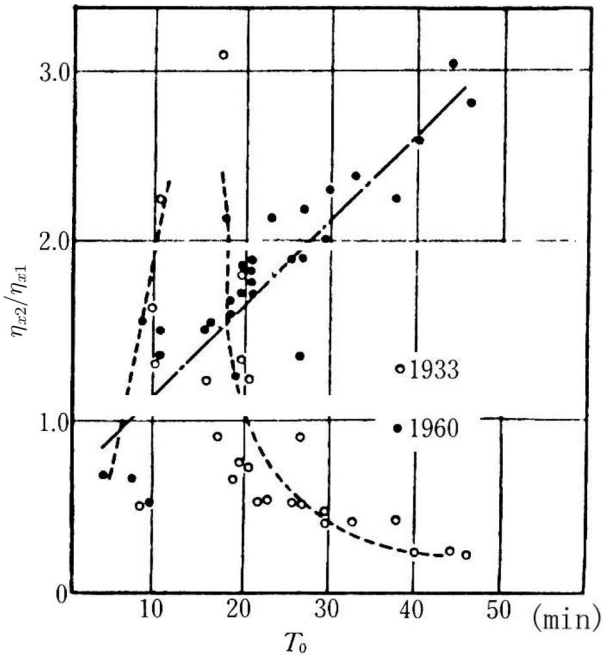


Fig. 1. Relative run-up height at the bottom of a bay in Sanriku region; T_0 = period of natural oscillation of a bay, η_{x1} = maximum run-up height at the bottom of a bay, η_{x2} = maximum run-up height at the mouth of a bay (From Watanabe[4]).

Major defense countermeasures after this tsunami consisted mainly of the construction of seawalls and coastal dikes, because the tsunami height was 5–6 m at most. Seawalls were made of concrete and coastal dikes had front, top and back covered with concrete, applying the experience of the Ise Bay typhoon.

It should be mentioned that the first tsunami breakwater was constructed at the mouth of the Ofunato Bay, where the maximum water depth was 38 m. The effect of this breakwater was investigated through numerical simulation. This was the first stage of computer in the tsunami science and engineering.

In addition, it should also be mentioned that an international cooperation of tsunami warning was started after the Chilean Tsunami.

In 1968 when all urgent Chilean Tsunami defense countermeasures were completed, the Tokachi-Oki Earthquake Tsunami struck Hokkaido and Sanriku Region. Fortunately, its tsunami height was not higher than the crown height of just completed structures, and there were no damages. But unfortunately, many person including coastal residents became to believe that there would be no threat of tsunami in the future, forgetting such huge tsunamis as the Meiji and Showa events.

5. Development of numerical simulation and the TIME project

Mansinha and Smylie developed a way to calculate the initial profile of a tsunami from fault parameters in 1971.[5] With this initial condition, a numerical tsunami simulation can be started, but the simulation should cover a wide area and be continued for a long time. Progress in the ability of computer since late 1970s assisted the development of tsunami numerical simulation.

In order to obtain reliable solutions, a simulation should be carried out without any instability and within allowable numerical errors. The stability is ensured by the CFL (Courant-Friedrichs-Lewy) condition that the artificially introduced propagation velocity $\Delta x/\Delta t$ should not be smaller than the physical wave celerity of long waves.

In 1982, Goto and Ogawa proposed a numerical method to solve a near-field tsunami from its source to the final run-up on land with the hydrodynamic wave equations in the Eulerian description.[6),7)] They used the linear long wave theory in the deep sea and the shallow-water wave theory in the shallow sea and on land. Their difference equations assume the staggered grid in space with the upwind scheme for the convection term and the leap-frog explicit scheme in time. A moving boundary condition necessarily introduced because of the Eulerian description is another source of instability and numerical errors.

The conditions to limit numerical errors in the Goto-Ogawa scheme are given by Shuto *et al.*[8)] and more thoroughly by Imamura and Goto[9)] in relation to local wave length, by Goto and Shuto[10)] in relation to the moving boundary condition as well as by Fujima and Shigemura[11)] in relation to the local bottom topography.

This scheme is used as the basis of the JMA tsunami numerical forecasting that began in 1999.[12)]

Aida introduced two measures, K and κ, in order to judge whether or not a simulation gives satisfactory run-up heights.[13)] The measure K is a geometric mean of the ratio of the measured run-up height to the computed, and κ is the corresponding standard deviation. If K falls between 1.2 and 0.8 and κ is less than 1.4, the simulation is judged satisfactorily carried out.

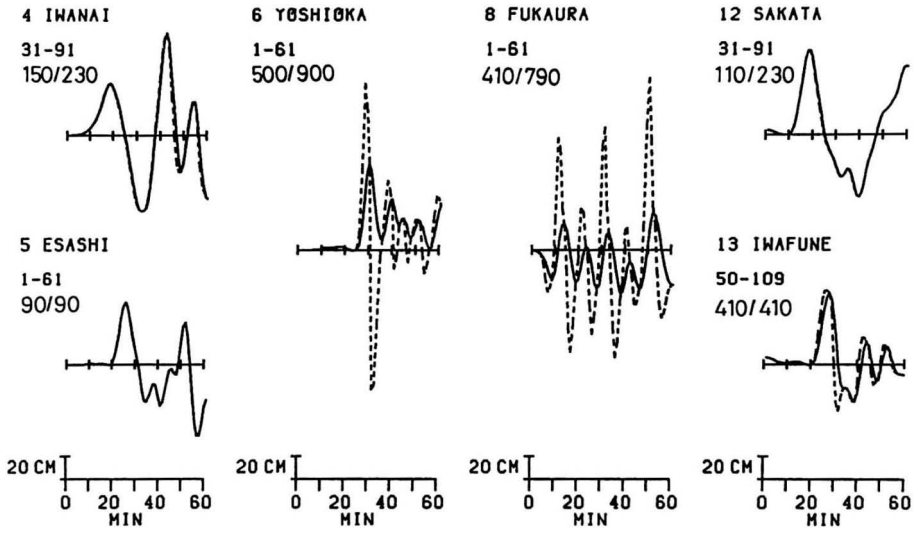


Fig. 2. The tide gage records of the 1983 Japan Sea Earthquake Tsunami (solid line) and the corrected waveforms for the tide gage response (dotted line) (From Satake *et al.*[15]).

During the IDNDR (International Decade for Natural Disaster Reduction) in 1990s, the tsunami committee of IUGG (International Union of Geodesy and Geophysics) and IOC/UNESCO carried out the TIME (Tsunami Inundation Modeling Exchange) project, by which the Goto-Ogawa's TUNAMI (Tohoku University's Numerical Analysis Model for Inundation) code had been transferred to organizations and countries that needed the numerical technique. The TIME project is still working under the supervision of Prof. Imamura, Tohoku University. The code was transferred to 43 organizations in 22 countries. It is used to predict tsunami damages and to produce hazard maps.

6. The 1983 Japan Sea Earthquake Tsunami

Just at noon, on May 26th, 1983, an earthquake occurred in the Japan Sea. It was a quite fine day, without wind and wind waves. In the Japan Sea, the tidal range is small. Under these conditions, if there were some abnormal sea phenomena, all of them were caused by the tsunami. Many persons witnessed the tsunami, recorded it by photos and videos. These data were energetically collected and analyzed to reveal the true face of the tsunami.[14]

The two facts gave impact to the tsunami research. One is the reliability of tide records and the other is necessity of the dispersion terms that are neglected in the analysis of near-field tsunamis regarded as a matter of course.

Tide gauges are designed to cut such short period oscillation as wind waves, the wave height of which is much bigger than that of tide. To avoid this disturbance, installed is a hydraulic filter consisted of a narrow and long conduit pipe. This hydraulic filter also acted to reduce much the tsunami records of near-shore origin. Satake *et al.* conducted a thorough survey of all the tide gauge stations in Japan and proposed the way to obtain the true tsunami from the filtered tide record.[15] Figure 2 shows the comparisons of the original tide gage records (solid lines) and the corrected waveforms (dotted lines). Fortunately, in the case of the 1960 Chilean Tsunami, this hydraulic filter was not effective due to the long wave period of the far-field tsunami.

Another impact was the generation and development of a train of short waves at the tsunami front. The wave period of each wave is nearly 10 seconds, similar to wind waves. This phenomenon, so-called "soliton fission" was observed and recorded on a video. In the linear long wave theory and the shallow-water equations used in the tsunami numerical simulation, the vertical acceleration of water particle is assumed to be negligible. To include the effect of curvature of water particle path, a higher-order approximation is necessary, such as the Peregrine equation, the Goto equation[16] and the Madsen-Sørensen equation. Iwase *et al.*[17] and Iwase *et al.*[18] concluded that the integrated Peregrine equation or Madsen-Sørensen equation was appropriate for tsu-

nami numerical simulation. Shigihara and Fujima showed the characteristics of several schemes theoretically and recommended an implicit scheme to solve the dispersive long wave equations without any instability.[19)]

7. The 1993 Hokkaido Nansei-Oki Earthquake Tsunami and the modern comprehensive disaster prevention

7.1 Revival of the comprehensive countermeasure planning. At night on July 12th, 1993, an earthquake off west coast of Hokkaido generated a tsunami. The southernmost area of Okushiri Island was completely devastated by the tsunami, even though the area was protected by seawalls constructed after the 1983 Japan Sea Earthquake Tsunami. The crown height of seawalls was 4.5 m above sea water level, and the tsunami height was estimated to be over 11 m. This fact called for serious reflection to the conventional method after 1960 that relied mainly on structures.

In 1997, ''A Guidance on Reinforcement of Tsunami Disaster Prevention Countermeasures in Local Disaster Prevention Planning'' was agreed by National Land Agency and other six government offices concerned tsunami disaster prevention planning.[20)] There are two points to be mentioned.

The first is the selection of the design tsunami. One candidate is the largest past tsunami from which credible materials can be obtained, and another is the possible tsunamis caused by the largest earthquake that can be supposed to occur based on present knowledge and science. After comparing both tsunamis, one with the higher water level on coast is selected as the standard tsunami to ensure safety insofar as possible.

The second is the combination of three components; defense structure, tsunami-resistant town development and evacuation based on warning, in an improved and revised form of those proposed by CEDP[1)] in 1933.

7.2 2D/3D hybrid simulation. The highest run-up was found at the bottom of a narrow valley on the west coast of Okushiri Island. At the entrance of the valley 50 m wide, the tsunami trace height was about 22 m, and the maximum run-up 31 m high was marked at a horizontal distance 50 m from the entrance. In this case, it is obvious that the assumption of long waves is no longer valid.

This accelerates the introduction of 2D/3D hybrid simulation; two-dimensional (2D) long wave equations for wide areas and three dimensional (3D) original wave equations for the area where vertical acceleration should be fully taken into consideration. If applied to the case of Okushiri Island, the two-dimensional simulation outside the valley is continued to the three-dimensional simulation in the valley in the neighborhood of the valley entrance.

The method of Fujima *et al.*[21)] and the STOC (Storm surge and Tsunami in Oceans and Coastal areas) code developed by Tomita *et al.*[22)] are typical 2D/3D hybrid simulation. Not only in run-up simulation but also in computation to simulate the deformation and destruction of structure, the idea of 2D/3D hybrid is now used enthusiastically to develop new numerical methods such as SPH (Smoothed Particle Hydrodynamics), DEM (Discrete Element Method), and so on.

8. Other research topics

8.1 Tsunami hazard map and CG animation in public education. In order to make coastal residents recognize the tsunami risk, a useful means is tsunami hazard maps for the past tsunamis and the possible tsunamis in future. After the 1990s, many local governments have been publishing tsunami hazard maps, prepared with the numerical methods described above.

Cabinet Office *et al.* published ''A Manual of Tsunami and Storm Surge Hazard Map'' in 2004.[23)] This manual recommends hazard map not only for residents but also for companies and fishermen.

Katada *et al.* introduced ''moving hazard maps'' in which every resident's action is expressed as the movement of dot, being connected with the motion of the expected tsunami.[24)] This gives a clear image of quick evacuation that can save many lives.

One of quite powerful means in public education is three-dimensional CG animations. Many coastal residents who know a huge tsunami in the past only as a tale become to recognize the natural threat and prepare for it at their own initiative.

8.2 Damage assessment and large scale hydraulic experiment. A rough estimate of damage caused by the past tsunamis was given in terms of tsunami intensity.[25)] In order to obtain more detailed estimates, knowledge based upon theoretical and experimental consideration is required.

For example, damage to houses is caused not only by tsunami force but also by impact of drifted

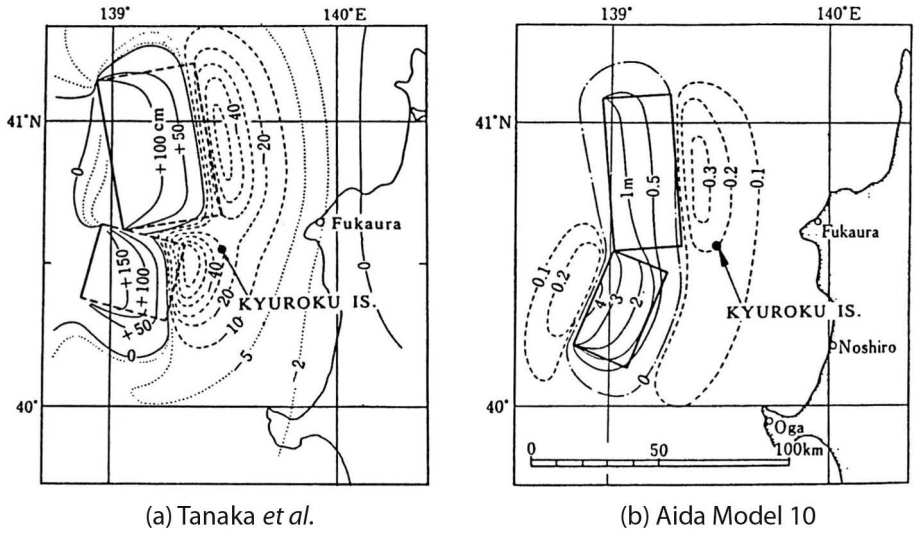


Fig. 3. Initial tsunami profiles obtained by Tanaka *et al.*[36] and by Aida.[37]

lumbers and boats. Matsutomi obtained a formula to evaluate the impact of lumbers as a result of large scale experiments.[26]

After the 2004 Indian Ocean Tsunami, many examples were collected for coastal forests that might damp the tsunami power. In case of Japan, limit and effectiveness of pine forests is given.[27] Harada and Imamura introduced an equation to assess more quantitatively and be applicable to other kind of forests.[28]

Large scale hydraulic experiments are being carried out in many institutes and laboratories. Arikawa *et al.* conducted the experiments on deformation and destruction of a concrete slab and a framework of steel materials using their prototype wave channel.[29] Prior to Arikawa's experiments, Asakura *et al.* carried out experiments on wave force by overflowing tsunamis.[30] Another example is Ikeno *et al.*'s work that concerns the wave force of soliton on land.[31] Interesting is a human-related hydraulic experiment. Nishihata *et al.* measured the walking ability in an open channel flow, and discussed the possibility of evacuation if a man is caught by water flow.[32]

8.3 Tsunami archeology. After the 1980s, investigation on tsunami deposit was started.[33] Historical literatures tell us the events only in recent 1,000 years. With geological data, we can know events in prehistoric age. Sawai *et al.* succeeded to excavate geologically recorded tsunamis during the past 5,500 years in eastern Hokkaido.[34] This technique is being applied in countries where tsunami occurrence is rare and no documents are available.

8.4 Initial profile. The biggest problem we have to solve in the near future is the detailed profile of a tsunami when it is born.

When seismological data were not available, the inversion propagation method was used to determine the source area and rough estimate of the distribution of vertical displacement. For example, see Hatori.[35]

In case of the 1983 Japan Sea Earthquake Tsunami, Tanaka *et al.* obtained a profile with the Mansinha-Smylie method from fault parameters. The highest vertical rise was 1.5 m (Fig. 3a).[36] Aida carried out tsunami simulation and found that this rise was not enough to explain the tsunami measured and observed along the shore.[37] After several trials, he concluded that the highest rise of 4 m (Fig. 3b) was necessary to simulate well the measured data.

When the Mansinha-Smylie is used, it is assumed that the fault motion is homogeneous in a fault plane. Satake introduced an inversion method to estimate heterogeneous fault motion, by using tide records.[38] This idea, if combined with the asperity model in seismology, may become a good tool in estimating the initial tsunami profile of large fault movement.

For the further development, inevitable is the

accumulation of tsunami records near the tsunami source. The 2003 Tokachi-Oki Earthquake Tsunami was recorded by a tsunami gauge of pressure type just in the source area, as the first case of the tsunami birth. On November 5th, 2004, an earthquake occurred off Kii Peninsula. A tsunami was generated and recorded on a GPS tsunami gauge installed at the water depth of 100 m, 23 km offshore. The computed tsunami with the initial profile estimated by the Mansinha-Smylie method agreed very well with the recorded.[39)]

9. Concluding remarks

So many vivid videos and data were taken in 2004 Indian Ocean Tsunami. Those gave tsunami researchers various suggestions. However, the researchers who are going to use data of Indian Ocean Tsunami often face difficulties. Because some videos recorded the local event occurred nearby video-men, and those do not give a total information of the tsunami. In addition, there are some areas where accurate chart and map are not available.

Among recent tsunamis, the 1983 Japan Sea Earthquake Tsunami is the treasure house of actual faces of tsunami. In the 1983 event, several tsunami features were looked down from hills and airplanes, and they were recorded in videos and photos. Most of them are vividly shown in a video edited and published by NHK (Japan Broadcasting Corporation, Japan).

Both the 1983 Japan Sea Earthquake Tsunami and the 1993 Hokkaido Nansei-Oki Earthquake Tsunami were surveyed very accurately and in details. The latter was used as the data for an international bench mark test, in which many modelers competed to show the superiority of their numerical model. In order to support such competition, there is other necessary condition, that is, good charts and good maps are extremely important. Both are often lacked in many developing countries. However, in Japan, the Hydrographic Department of the Japan Coast Guard completed detailed bathymetric maps after the 1983 event. Accurate land maps are available from the Geographic Survey Institute.

Tsunami research has been developing in Japan, because the country suffers tsunami disaster frequently in comparison with other countries. That is why the tsunami research is of great importance in Japan. Basic materials such as bathymetric charts for the research easily obtained, and the seed and hint of the research can be found in well-filed documents and records.

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