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TSUNAMI DISASTERS AND THEIR PREVENTION IN JAPAN －TOWARD THE PERFORMANCE DESIGN OF COASTAL DEFENSES－

S. Takahashi
Director, Tsunami Research Center, Port and Airport Research Institute
3-1-1, Nagase, Yokosuka, Japan, 239-0826
takahashi_s@pari.go.jp

ABSTRACT: Disaster prevention technologies developed from experience with many tsunamis in Japan are reviewed in this paper. Also introduced is recent research on real-time tsunami prediction and the prediction of disasters following the devastating Sumatra Earthquake Tsunami. To enable safe evacuation, people should be given adequate information on actual tsunami inundation disasters, which includes the actual potential of damage to coastal defenses and buildings, in addition to information on tsunami height. This paper proposes a new performance design concept for coastal defenses to enable comprehensive and systematic tsunami disaster prevention measures, including prediction of the extent of actual disasters.

1. INTRODUCTION

Civil engineering research on the coastal zone is very active in Japan as this zone is very heavily populated and economically very important. Recent research has been directed toward disaster prevention and environmental preservation.

Intensive research is being done on disaster prevention in the coastal zones of Japan. Research on typhoon disasters started after the Isewan Typhoon in 1959, which killed about 5,000 people. After the Chilean Tsunami disaster in 1960, research began on tsunami disasters, with significant progress after the Nihonkai-chubu Tsunami in 1983 and the Hokkaido-Nanseioki Tsunami in 1993.

On December 26, 2004, the devastating Indian Ocean Tsunami disaster occurred, killing about 300 thousand people [1-5]. Studies have been focused on clarifying the factors of the tsunami disaster and also to establish integrated disaster mitigation measures around the world.

The contents of this paper are as follows:

1. Introduction
2. Tsunami Disasters in Japan
3. Research on New Integrated Tsunami Countermeasures
4. Performance Design of Coastal Defenses
5. Concluding Remarks

Section 2 briefly reviews recent tsunami disasters and countermeasures against expected tsunamis in Japan using reference documents reported by the Ports and Harbor Bureau of the Ministry of Land, Infrastructure and Transport, Japan. Section 3 introduces integrated research being conducted at the Port and Airport Research Institute. New disaster mitigation measures are needed to reduce the casualties due to huge tsunamis. Section 4 describes our performance design concept. We believe that comprehensive mitigation measures should be prepared systematically under viable performance design concepts for coastal defenses.

2. TSUNAMI DISASTERS IN JAPAN

2.1 Recent Tsunami Disasters in Japan and development of countermeasures

“ Tsunami” is a Japanese word written using two Chinese characters. ‘Tsu” means harbor and ”nami“ means wave, and therefore “tsunami” means “harbor wave” in Japanese. It became internationally popular after the Meiji-Sanriku Tsunami in 1896 and the Showa-Sanriku Tsunami in 1933. News reports of devastating damages appeared around the world.

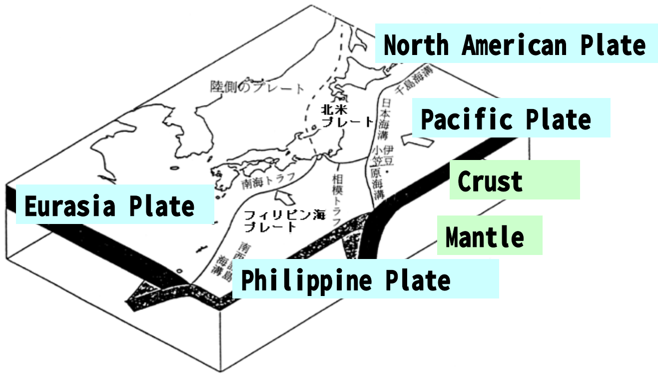

Fig. 1 Subduction zones and plates around Japan

In Japan, tsunami disasters occur very frequently. Historical tsunami disasters can be found in many old documents including the first documented tsunami in 684. Tsunami disasters occur approximately once every 10 years, and huge disasters once in a 100 years. This is due to the active movement of tectonic plates around the Japanese Islands. The vertical displacement of plates due to subduction zone earthquakes results in tsunami generation[6,7].

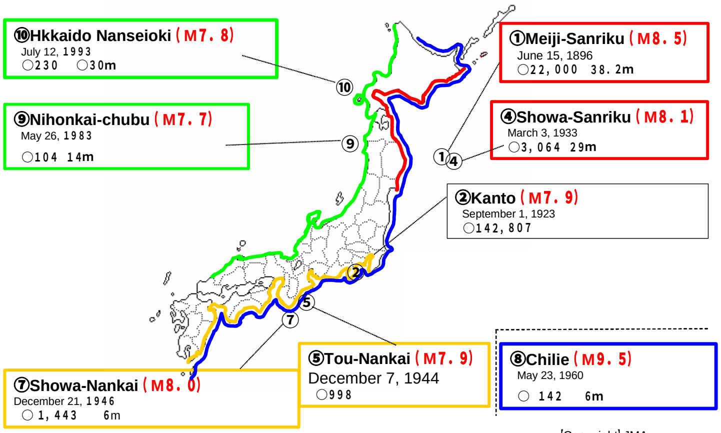

Fig. 2 Recent major earthquakes in Japan (The figure is from reference paper of Ports and Harbor Bureau of MLIT modified from the original figure of Japan Meteorological Agency.)

Figure 2 shows the recent major tsunamis in Japan. Tsunamis attack not only the Pacific Ocean coastline but also the Japan Sea coastline. All of these tsunamis were generated from seas near the Japanese Islands, except that from the Chilean Tsunami in 1960.

Figure 3 shows a picture about the Meiji-Sanriku Tsunami in 1896 which killed 22,000 people, the largest casualty in modern-age Japan. The shaking due to the earthquake was not significant along the coast, and therefore the people did not realize that there was a risk of a tsunami attack and did not evacuate. The tsunami hit at night (8 o’clock at night, 35 minutes after the quake) at heights exceeding 10 m (maximum recorded runup height 38.2 m).

Figure 3 A picture of the Sanriku Tsunami Disaster

This disaster can be considered to be similar to that of the Indian Ocean Tsunami since no warning (no evacuation) and almost no coastal defenses existed against such a large tsunami. In 1933, the Showa-Sanriku Tsunami attacked the same region again but the number of casualties was greatly reduced to 100 due to evacuation before the tsunami attack.

From the 1950’s, many administrative measures for disaster prevention have been taken, including those against tsunami disasters. In 1952, a tsunami warning system was established in Japan. In 1956, the Seacoast Law was implemented from the viewpoint of management of seacoasts including countermeasures against tsunamis and storm surges. In 1961, the Disaster Countermeasures Basic Act was established and in 1962, an act went into effect concerning special financial support to deal with designated disasters of extreme severity. A Central Disaster Management Council has been established and in 1963, a Basic Disaster Management Plan was prepared.

Figure 4 shows an inundation disaster caused by the Chilean Earthquake Tsunami arising from an earthquake off the Chilean coast. The tsunami reached Japan after about 22.5 hours, travelling approximately 18,000 km with a speed of about 800 km/h. The tsunami attacked various locations in Japan from Hokkaido in the north to Okinawa in the south. People could not comprehend the tsunami danger from such a distance and the tsunami warning system did not work. After this disaster, international cooperation for a distant tsunami warning system was established.

Just before the Chilean Earthquake Tsunami disaster, a devastating storm surge attacked the Isewan Bay in 1959 killing about 5,000 people. After these two coastal disasters, the research on coastal disasters was promoted and the construction of coastal defenses was accelerated throughout Japan.

Fig.4 Inundation in Suzaki due to Chilean Tsunami

Fig. 5 Inundation due to Nihonkai-chubu Tsunami in Iwasaki Village

Fig. 6 Wave runup at Matsuzaki Port

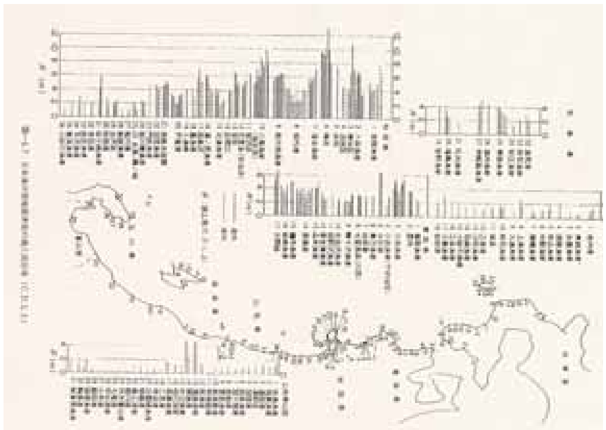

Fig. 7 Tsunami height along Japan Sea coasts

Fig. 8 Aonae in Okushiri Island just after Tsunami attack

Figure 9 Damaged houses and ships

Figure 5 shows a photo of the Nihonkai-Chubu Tsunami disaster, which occurred 20 years ago. Figure 6 shows a photo of the tsunami running up to 5 m near Matsuzaki Port; it was taken by a construction worker. Due to the warning system, the number of casualties was reduced to about 100. Also, coastal defenses against the storm waves were effective. The casualties included children who were on a picnic on the coast and people working in the sea, such as fishermen and marine construction workers. The transmission of the warning to these people was difficult. Figure 7 shows the distribution of tsunami heights along the Japan Sea coast. It should be noted that significant damage appeared where the tsunami height exceeded 4 m and devastating damages occurred where the tsunami height was near 10 m[8].

Figure 8 is a photo of the Aonae district of Okushiri Island just after the Hokkaido Nanseioki Earthquake Tsunami[9], which is known as the Okushiri Tsunami, because the most serious damage was to Okushiri Island. The maximum tsunami run-up height was more than 30 m and more than 200 people were killed.

2.2 Current Measures for Tsunami Disaster Prevention

(1)Okushiri Island

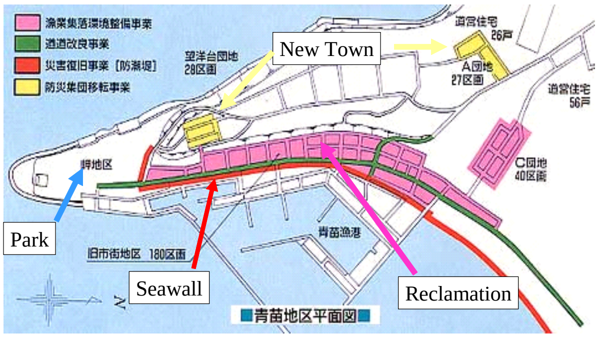

Figure 10 Land use planning in Aonea district

Fig. 11 Completed tsunami mitigation works

After the disaster, construction work was implemented to establish a total disaster prevention system for Okushiri Island. Figure 10 shows a map of land use planning, where houses in the most severely damaged areas were to be moved to high land areas and some land reclamation would be done to create higher land areas. Figure 11 shows the seawalls in front of the reclaimed lands and an artificial high ground in the fishery port where fishermen can work daily on the first floor and use the second floor for evacuation.

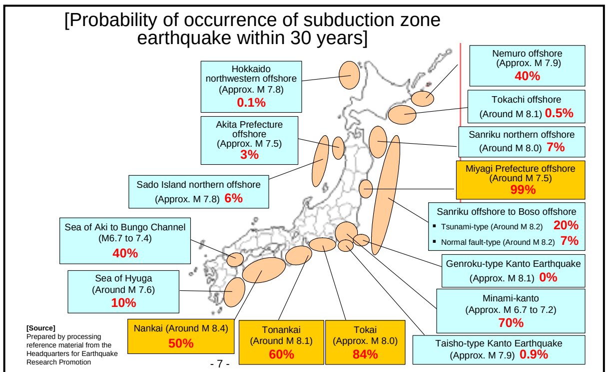

Fig.12 Expected earthquakes(from reference material of the execution office of the Earthquake Research Committee)

(2) Expected Tsunamis

Figure 12 shows the occurrence probabilities within 30 years of subduction zone earthquakes around the Japanese Islands. In the very near future, earthquakes have been predicted for the Tokai, Tonankai and Nankai regions in addition to the area off the Miyagi coast. The central and local governments in these regions are preparing for expected tsunamis in various ways.

Fig.13 Tsunami breakwater in Suzaki

The Central Disaster Management Council of the Cabinet Office is responsible for disaster mitigation. The Ministry of Land Infrastructure and Transport is implementing countermeasures against natural disasters including tsunamis. To prepare for the expected earthquakes and tsunamis, the Large-Scale Earthquake Countermeasures Special Act was passed in 1978, which encourages having basic plans for earthquake disaster prevention including the definition of jurisdictions and responsibilities for disaster management, a disaster management system and plan, disaster preparedness, emergency actions and recovery, financial measures, state of emergency plans, etc. A new law, the Tonankai and Nankai Earthquake Countermeasure Special Act, was passed in 2002.

(3)Hardware countermeasures
Many hardware countermeasures are being prepared against calculated tsunami heights, including tsunami seawalls, river water-gates, and on-land water gates.

Figure 13 shows a tsunami breakwater which is under construction at a baymouth in Suzaki Port, Japan. Tsunami breakwaters were and are being constructed in expected tsunami areas (especially areas affected by major tsunamis in the past) to reduce the intrusion of a tsunami into the harbor. Ordinary breakwaters can also prevent a tsunami to some extent, especially reducing a direct attack of the tsunami wave front, as has been observed in recent tsunamis in Japan[10].

Fig. 14 Hazard map for Suzaki City

(4) Software Countermeasures
The disaster caused by the Nihonkai-chubu Earthquake Tsunami showed that not only hardware measures but also software measures are needed to mitigate expected tsunami disasters. Software measures include:

a. Tsunami warning system
b. Dissemination of tsunami knowledge
c. Land usage planning
d. Effective evacuation measures for low-lying areas.
(hazard maps, evacuation towers etc.)

The Japan Meteorological Agency developed a new warning system for local earthquake tsunamis from 1999 to issue a warning within 3 minutes using a tsunami database of 100,000 calculated tsunamis. The agency also has a warning system for distant earthquake tsunamis that was established with international cooperation.

Figure 14 shows a hazard map prepared for Suzaki City. The ‘Manual for Tsunami and Strom Surge Hazard Maps[11]’ has been used by some local governments to prepare hazard maps in collaboration with engineers and local citizens. Such a map can be useful for effective evacuation of the residents and also aid in the planning of disaster mitigation.

3. RESEARCH ON NEW INTEGRATED TSUNAMI COUNTERMEASURES

Figure 15 Galle city

Intensive studies have begun to establish integrated disaster mitigation measures in various research institutions around the world after the Indian Ocean Earthquake Tsunami. The Port and Airport Research Institute (PARI) established a tsunami research center to develop new integrated countermeasures for expected huge tsunamis in Japan. This section explains four current research projects at PARI:

1. Disaster prediction with ‘dynamic hazard maps’
2. Hardware countermeasures
3. Scattered evacuation in tsunami-resistant buildings
4. Real-time tsunami prediction with monitoring

3.1 Disaster Prediction with Dynamic Hazard Maps

Fig. 16 Tsunami attack in Galle

People around the world were shocked by videos taken during the Indian Ocean Tsunami attack. Having people be aware of the danger of a tsunami disaster is very valuable.

Figure 15 shows a map of Galle City in southern Sri Lanka. Figure 16 shows a picture from the video which was given to a Japanese government survey team that visited there. The video was taken at the bus terminal and shows the tsunami attacking the area. The tsunami came from the southeast, washed the old market place and came into the bus terminal area. Watching the video led me to reconsider the current tsunami mitigation technologies.

1. The tsunami current on land is very strong and includes various kinds of debris. This phenomenon was unexpected and is difficult to be reproduced numerically in a simulation.
2. If I had been there I probably would not have been able to find a way to escape from the tsunami.
3. Engineers do not really understand what will actually occur during a tsunami attack.
4. Videos and photos can be easily understood by the public. We need the technology to disseminate images of disasters like these videos to make people fully aware of what can occur.

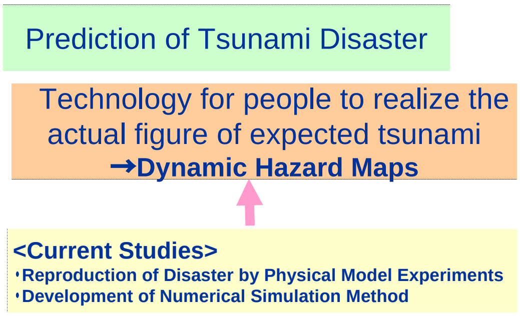

Fig. 17 Studies for tsunami disaster prediction

Figure 17 explains a research project to develop tsunami disaster prediction technologies. We are conducting model experiments and developing a new numerical simulation method to prepare dynamic hazard maps. The dynamic hazard map is for the local people to visually understand what will actually occur during a disaster.

Fig. 18 Large scale tsunami experiment

Figure 18 shows a model experiment to investigate the damage to an ordinary house during a tsunami attack. It was conducted at the Large Hydo-Geo Channel of PARI measuring 184 m in length, 3.5 m in width and 12 m in depth. It was constructed in 2000 to conduct prototype wave experiments using 3.5 m waves. The wave maker was modified to produce 2.5 m tsunamis in the channel. Various experiments are underway to investigate the actual tsunami damage to buildings and coastal facilities.

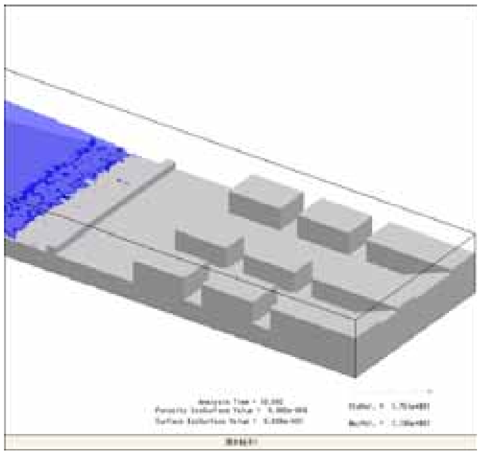

Fig. 19 STOC calculation

Figure 19 shows a picture produced by STOC[12], a numerical simulation for tsunami. STOC can calculate tsunami behavior from its generation to on-land run-up using 3-D direct fluid simulation. A dynamic hazard map can be made with visualization of the calculated results by STOC.

Figure 20 shows an experiment to examine what happens when people are caught in currents. This was done to observe the danger of overtopping waves from seawalls and breakwaters[13]. Figure 21 shows a result of the experiments which allow us to identify the unstable condition due to the current and the water level. For example, if the water level is 55 cm and the current speed exceeds 150 cm/s, then people cannot remain standing. The fundamental behavior of tsunami-induced current is the same as that of

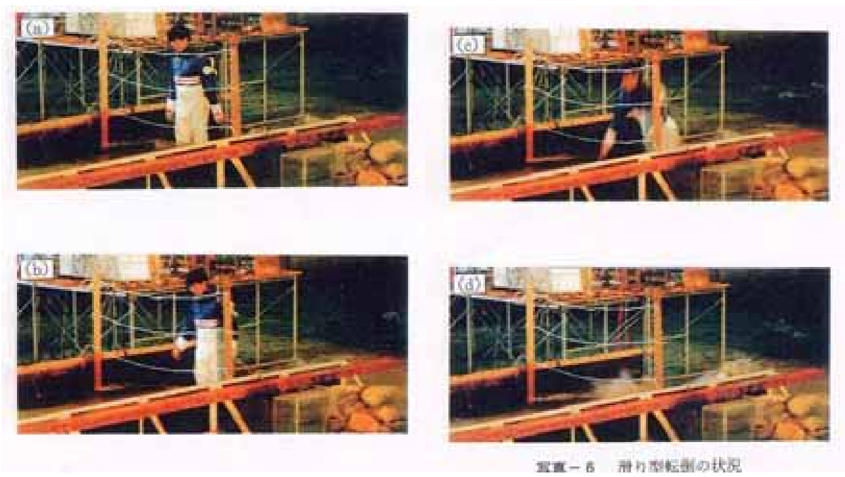

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Fig. 20 Stability tests of human bodies against currents waves.

Cooperative studies should be done considering accumulated research results on tsunami and ordinary waves[14-19].

3.2 Hardware Countermeasures

In Japan, the population is very dense and economical activities are very intensive in coastal zones. It is not enough to simply have people evacuate from the area. Facilities in the coastal zones must also be protected. Hardware countermeasures such as seawalls and breakwaters are necessary to prevent failure of vital facilities in coastline areas.

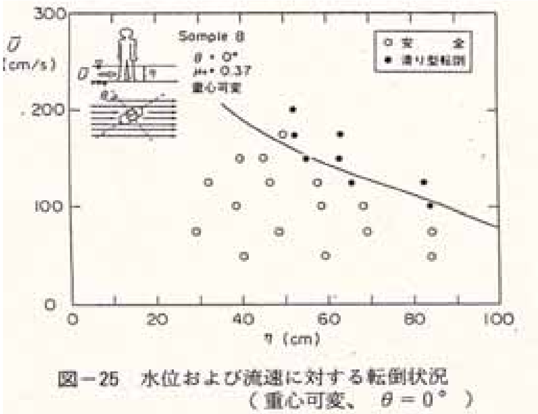

Fig. 21 Stability of human bodies against currents

Figure 22 shows new water gates to be installed at a breakwater mouth for protection against tsunami intrusion. They are being developed as cooperative projects with private companies. The breakwater can prevent tsunami intrusion, and closing the breakwater mouth is very effective to reduce intrusion. A tsunami has tremendous energy and is very difficult to stop. Therefore, it is important to develop economically feasible and technically effective protective hardware measures.

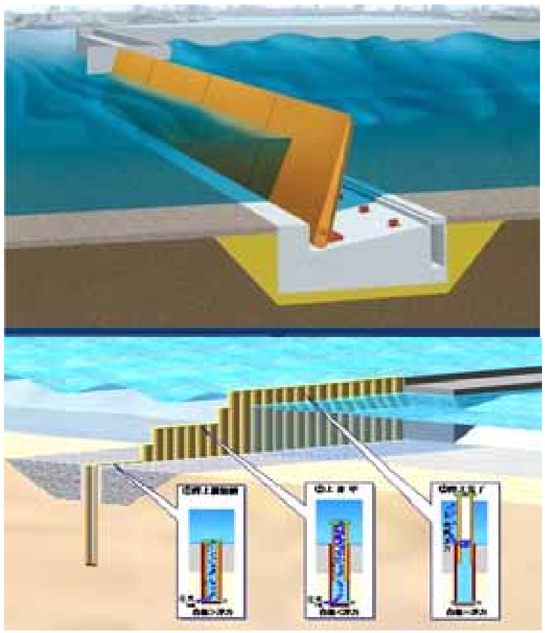
Fig. 22 New water gates

3.3 Scattered Evacuation in Tsunami Resistant Buildings

The predicted Tokai Tsunami is expected to attack the coastline within several minutes. What must be considered are the dangers to encounter the tsunami current during evacuation. Rather than trying to escape, it could be safer to seek refuge in a tall strong building nearby. Figure 23 shows a traditional evacuation building in Japan called a 'mizuya' or 'water building.' Such buildings have been constructed in low-lying areas near rivers within farming residences to prepare for river flooding.


Fig. 23 Evacuation building 'Mizuya'

Figure 24 shows a temporary evacuation place for the neighborhood in Tanabe Town, Wakayama Prefecture. People in this small community will first escape to this high land from tsunami and then to move to a large city-designated evacuation place located more than 1 km away. At first, it would be better to evacuate to a high place like this or a high building nearby. The temporary evacuation building should be reinforced to resist a


Fig.24 Temporary evacuation place


Fig. 25 Evacuation tower

tsunami attack. Figure 25 shows an evacuation tower in Japan. If high buildings are not available nearby, such an evacuation building should be prepared or public buildings should be modified and reinforced with anti-tsunami design to provide those in the neighborhood with shelters in case of an emergency.

3.4 Real-Time Prediction of Tsunami with Monitoring

Even if there are tsunami warnings, the actual tsunamis are sometimes not as large as predicted. If such ”false warnings” are repeated, the number of people who evacuate will decrease. Therefore, it is very important to increase the reliability of the warning by monitoring tsunamis and basing their real-time prediction on such data. Research is in progress to directly measure the tsunami in offshore area using new systems including pressure gauges, GPS devices and HF radars.

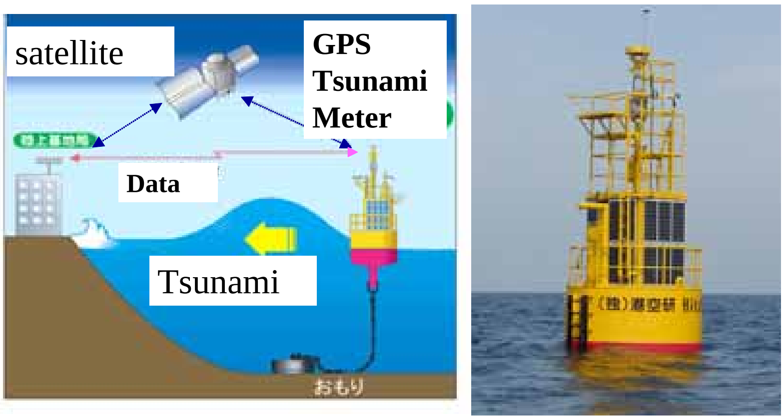

Fig. 26 GPS tsunami meter

The Port and Harbor Bureau of the Ministry of Land Infrastructure and Transport has a nationwide surveillance network named ‘NOWPHAS’ to observe waves[20-22]. NOWPHAS has more than 50 stations along the Japanese coasts with mainly ultrasonic wave gauges. NOWPHAS has succeeded in measuring some tsunamis, but its measurements are limited to areas relatively near the shore. Figure 26 shows a new device called a ‘GPS tsunami meter’ which was installed 13 km off Kochi Port and successfully measured the Tokaido-Oki Tsunami that occurred last year. The tsunami was small but was clearly measured 9 minutes before arrival at Kochi Port. The Ministry is planning to install GPS tsunami meters near the subduction zones to have real-time prediction of tsunami.

4. PERFORMANCE DESIGN FOR COASTAL DEFENCES

4.1 Performance Design and Accountability

Performance design is a design process that systematically and clearly defines performance requirements and the respective performance evaluation methods. This approach began in the 1960’s and has been applied for the stability design of buildings against earthquakes, especially after the Northridge Earthquake (California) in 1994. We believe that performance design should be applied to the design of coastal defenses.

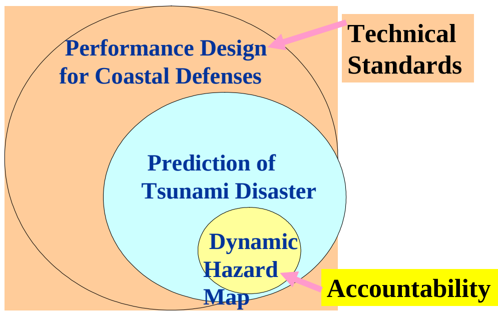

Figure 27 Performance design

The prediction and mitigation of tsunami disaster should be systematically conducted. The performance of coastal defenses is essential to predicting tsunami disaster. Therefore, dynamic hazard maps should be prepared as a part of the performance design of coastal defenses from the administrative viewpoint. Figure 27 shows the concept for the performance design system.

Accountability is a high priority for civil engineers in Japan. Especially for the construction of coastal defenses, accountability is essential. This is not to be evaluated by the frequency of explanation but its quality. Responsible engineers must be able to explain to the local residents what can actually occur during a tsunami attack, including the damage to the coastal defenses and the consequent degradation of their function based on performance evaluation of the facilities.

The performance design for coastal structures has been discussed by many researchers. It was also discussed during the International Workshop on Advanced Design of Maritime Structures in the 21st Century in 2001[23]. We are presently developing performance design criteria for coastal defenses[24,25].

4.2 Performance Matrix

The performance matrix is a key tool for performance design. Figure 28 shows a conceptual figure of the performance matrix. The vertical axis is the design level and the horizontal axis is the performance level. The symbols A1, A2 and A3 indicate the importance of the facility, where A1 is ordinary, A2 is important and A3 is very important.

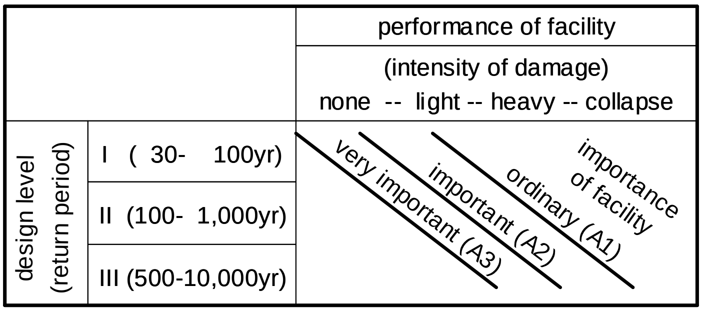

Figure 28 Performance matrix

Multiple design levels are needed. At present, there is only one design level, which is insufficient. We must consider multiple scenarios depending on different design levels including a design level much larger than the current one.

5. CONCLUDING REMARKS

I recently visited the United States to observe the aftermath of the disaster caused by Hurricane Katrina. The height of the storm surges and the severity of the damages were shocking. Japan has also recently experienced many typhoons causing severe damages. One of the reasons for such an extent of damage is the deterioration of coastal structures to dangerous levels. The prediction of disaster including the evaluation of current performance level is an urgent task for Japan.

Performance design should be employed as a basic concept of government technical standards for coastal defenses. The performance design should include performance evaluation of entire coastal defenses along with existing and planned coastlines in each local area and disaster prediction of the target area against tsunamis and storm surges. Performance design is actually a scenario-making process of the predicted disasters and the dynamic hazard map is one of the tools to help local residents grasp the extent of the potential disaster. Multiple scenarios should be prepared to correspond to different design levels, not only the current design level. Efficient use of such tools should help Japan be better prepared for potential tsunami disasters.

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