Paper:

History and Challenge of Tsunami Warning Systems in Japan

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History of development of Tsunami Warning System in Japan started in 1952 after the tsunami warning/forecast system formulated at Sanriku is introduced. The system estimated the earthquake epicenter and magnitude, and issued the forecast by referring to the tsunami forecast maps. In 1999, the Japan Meteorological Agency (JMA) has introduced the computer-aided simulation system for quantitative tsunami forecasting, in which tsunami arrival times and heights are simulated and stored in the database for forecasting tsunamis. The JMA has been further updating the system and now can issue the forecast 2 to 3 minutes after occurrence of an earthquake. By reviewing the response of the people for past tsunamis forecasting and information in an example case of the 2006 Kurile Earthquake tsunami, we discuss the issues such as accuracy, detail and canceling in order to improve the system.

Keywords: tsunami forecasting, warning, evacuation,

1. Introduction

A tsunami caused by an earthquake under the sea strikes coastal areas some time (several minutes at the shortest, and normally 10 to 30 min in the case of a near field tsunami around Japan) after it is unleashed by an earthquake. It is therefore possible to protect and save the people by disseminating the information or warning that tells whether or not a tsunami has been caused by the earthquake and allowing them to take prompt and adequate action.

This concept became reality in the form of the tsunami warning system for the Sanriku Coastal Area in 1941. It officially started service in 1952 and developed into the quantitative forecast systems in 1999. These systems have been continuously updated to a world-leading level of development in terms of forecast time, warning/information content, and content transmission. However, the problems involved in these systems have been pointed out as of late. Future improvements have been discussed, including forecast updating with using real-time data and information.

2. History of Tsunami Warning Systems

A systematic forecast/warning system was established in Japan in September, 1941 for the Sanriku Coastal Area, an area which was devastated by the Sanriku Tsunami of 1933 (Morita, 1942). It was a pioneer system in which estimation of the earthquake epicenter and magnitude, the criteria for judging whether a tsunami has been generated, the wording of the warning, and the transmission routes of the information are established to issue, in 10 to 20 min, the warning to the sites in danger of being affected by the tsunami. However, the system could not be expanded to other areas because of limited resources for communication during the world war II. A number of deaths were caused thereafter by the tsunamis that followed the Tonankai Earthquake in 1944 and Nankai Earthquake in 1946.

The United States was hit by a tsunami following the Aleutian Earthquake in April 1, 1946, which caused 173 deaths in the Hawaiian Islands. This led to the USGS's establishment of the tsunami warning system, which started services in 1948. The area which it covers has been expanded from the Hawaiian Islands to the entire Pacific (Murty, 1977). The US situations affected Japan. In October 3, 1949, the Occupation Forces requested that the Government of Japan establish systems for adequately and urgently issuing, to wide areas, information related to earthquakes and the tsunamis they might possibly cause by them (Earthquake Section, Japan Meteorological Agency, 1950). The Government of Japan formulated "the tsunami forecast transmission comprehensive plans" in the cabinet meeting of December 2, 1949, and the Central Meteorological Observatory started tsunami forecasts on a nationwide scale. The plans were formulated in two short months because of the extralegal order by the Occupation Forces to formulate the plans "within 60 days," and the tsunami warning/forecast system, which had already been formulated for the Sanriku Coastal Area, served as a example model. The forecast systems started services on April 1, 1952, after the service and legal systems were developed (Imamura and Shuto, 2000).

3. Development of the Tsunami Warning System

3.1. Start of Warning Services

The warning system was first established based on the assumption that a tsunami follows an earthquake by about 30 min. The major services are described below. Within five minutes of having observed an earthquake having an intensity of at least IV or having a maximum total amplitude of at least 10 mm, as observed by a displacement-type seismograph of one magnification, a local observatory sends an emergency telegram (tsunami telegram) covering the time the earthquake occurred, its seismic intensity, its total amplitude and first break, its total amplitude, and first break to the tsunami forecast center. Within 15 min, the center then estimates the earthquake's epicenter based on these data and S-P time at the center to determine, based on the epicentral distance and total amplitude by referring to tsunami forecast maps, the magnitude of the tsunami, and a forecast was issued. The wording of the forecasts were "no tsunami," "minor tsunami," "major tsunami," and "forecast cancelled." The area of Japan covered by the forecasts was divided into 15 districts (Hirono, 1970).

An earthquake having a magnitude of approximately 6.5 and above may cause a tsunami when it occurs at a depth of less than 100 km below the ocean floor. It is essential for the tsunami warning to promptly determine these parameters. Therefore, the seismic data observed throughout Japan by the Meteorological Office, as well as that observed by the related institutes and academic organizations, are collected in the Office, which promptly determines the epicenter and intensity of earthquake.

On February 28, 1950, a tsunami forecast was issued for the first time in Japan after the Sea of Okhotsk Earthquake (Earthquake Section, Japan Meteorological Agency 1950). The tsunami following the Tokachi-Oki Earthquake (March 4, 1952) was the first major one after the establishment of the warning system. The warning system worked well to help reduce the damage (Watanabe, 1985). A total of 46 warnings were subsequently issued following major earthquakes, including those occurring off the Kamchatka Peninsula (1952), the Boso Peninsula (1953), and Ostrov Iturup (1958), until the Chile Earthquake occurred in 1960.

3.2. Tsunami Warnings After the Chile Earthquake

Following the Chile Earthquake (1960), the coastal areas of Japan were struck by a tsunami which caused major damage and 139 deaths and missing persons (excluding the damage in Okinawa). The JMA (Japan Meteorological Agency) issued tsunami warnings after it received abnormal tidal levels from the local observatories. The JMA failed to issue a prompt tsunami forecast despite the knowledge that Japan may be hit by tsunamis following distant earthquakes. This was because the system at that time principally covered earthquakes occurring in adjacent waters (Japan Meteorological Agency, 1975).

The JMA failed to effectively warn the people of the tsunamis reaching Japan after the Chile Earthquake of May 23, 1960 (Japan time). Consequently, not much property damage was saved. The tsunamis following the earthquake started to reach the Pacific coastal areas of Hokkaido and the Tohoku District at about 2:30 AM on May 24, and after 4 AM they grew to abnormal tidal levels which could cause disasters. However, it was at approximately 5 AM when the warnings were issued after the tsunamis were recognized as being caused by the Chile Earthquake (Sekita, 2000).

The Earthquake Section of the Observation division of the JMA grasped the fact that a major earthquake had occurred off Chile before noon on May 23, and that the tsunamis caused by the earthquake might hit Japan after 2:00 PM on May 24. Despite that, the agency failed to issue the effective warnings for the following two reasons:

(1) the agency estimated that the tsunami could reach about 50 cm in height at the highest, and

(2) the agency believed that no major tsunami had occurred because they were not informed of any tsunami by the Geomagnetic Observatory in Honolulu.

3.3. Improvement in Forecast Time

Experience in tsunami forecasting, expanded observation networks, and the development of communication systems have continuously sped up the forecasting/warning times as well as improved their accuracy and content (Earthquake Section, Japan Meteorological Agency, 1977). For example, numerous electromagnetic seismographs have been introduced since 1970. These have improved the reading of earthquakes, especially in terms of when they might occur. In the area of communications, Morse code was gradually replaced by tele-typed communications in the late 1950s, and computer systems have been in service since 1969 to speed things up. The introduction of earthquake magnitude has been discussed since the late 1950s, and the warning system has been used stepwise on the spots. Tsunami advisories were introduced in 1976, and tsunami forecast maps have been updated in response to increased public concern over minor tsunamis (Earthquake Section, Japan Meteorological Agency, 1977).

In the case of the earthquake which occurred in the middle of the Japan sea in 1983, the Meteorological Office issued a tsunami warning about 14 min after the occurrence of the earthquake. However, the tsunami actually reached coast of Japan 7 min after the earthquake and caused 100 deaths, mostly in the coastal areas of Akita Prefecture. The agency has been updating the tsunami forecast system since that time and can now issue a forecast within 7 min after the occurrence of an earthquake.

The agency issued a warning 5 min after an earthquake occurred in 1993 off the southwest coast of Hokkaido. However, Okujiri Island was hit by the tsunami within 5 min after the earthquake, causing 230 deaths, because

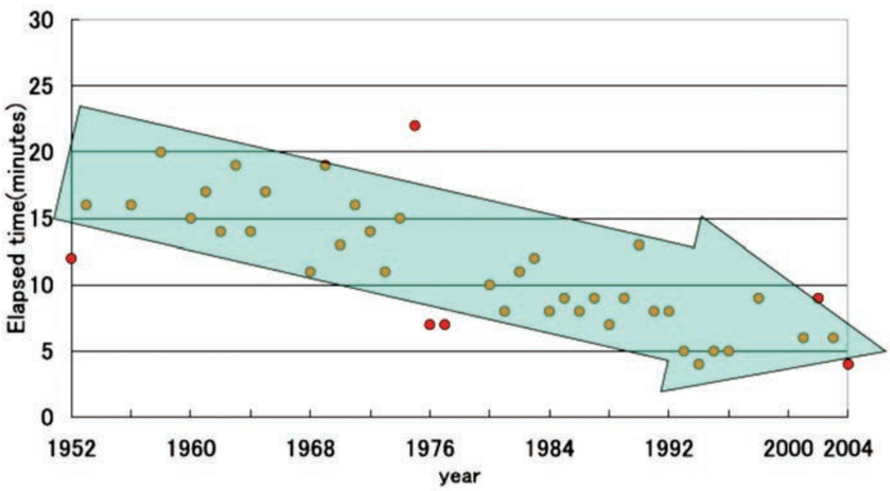

Fig. 1. Elapsed time for tsunami warning (Japan Meteorological Agency, 2005).

its epicenter was immediately beneath the island. The agency has continued updating the system and can now issue the forecast 2 to 3 min after occurrence of an earthquake.

Figure 1 shows improvements in time elapsed before the warnings are issued after earthquakes. As the graph illustrates, the lag time has decreased year by year, and forecast time range, which was about 10 min in 1952, has also been reduced.

The agency has been promptly analyzing the data observed by seismographs located near earthquake epicenters since August 1, 2006 to start pioneer services of "emergency quick reporting" for disaster prevention by estimating wave arrival time and intensity before major temblors strike each area. The agency has been attempting to shorten lag time before the forecast is issued after an earthquake. Since October, 2006, the tsunami forecast time has been shortened to 2 min in some areas by automatically processing the data to be reported. The agency issued the forecast 100 sec after the Noto Peninsula Earthquake of March 25, 2007.

4. Latest Quantitative Tsunami Warning System

4.1. Utilization of Database

The Japan Meteorological Agency introduced a computer-aided simulation system in 1999 for quantitative tsunami forecasting, in which tsunami arrival times and heights are simulated and stored in a database for the forecasting of tsunamis after an earthquake actually occurs by referring to the stored data. The system allows for the issuance of tsunami forecasts, including tsunami arrival times and heights for each area (now divided into 66 districts) in Japan. **Fig. 2** shows the quantitative forecasts displayed on a TV screen, and **Table 1** shows the information typically broadcast.

The agency stores the tsunami propagation data simulated using an analogy based on the relation between the magnitudes of an earthquake and its fault. It uses these data to issue forecasts by including the earthquake epicenter data collected immediately after an earthquake occurs. The analogy is a statistically developed empirical correlation defined by the following formulae (1) to (3), wherein M is the earthquake magnitude, L is the fault length, W is the fault width, and D is the average slippage (National Research Institute for Earth Science and Disaster Prevention, 2000):

$$\log L = 0.5 * M - 1.9 \quad (1)$$

$$W/L = 0.5 \quad (2)$$

$$\log D = 0.5 * M - 3.2 \quad (3)$$

The analogy gives fault width and length using the earthquake center data collected immediately after an earthquake occurs. It uses a fault width/length ratio of 1/2, which may be 1/4 in a major earthquake that can cause a tsunami. The fault parameters used by the analogy, which is statistically developed based on the past experiences, may be different from the actual ones.

4.2. Future Challenges

Problems are found in the quantitative tsunami forecast system, based on the database storing about 100,000 simulation results. When an earthquake (magnitude: 7.9) occurred east of the Kurile Islands after 8 PM on November 15, 2006, the tsunami warnings/advisories were issued to the coastal areas and totally cancelled by 1:30 AM on November 16. However, the maximum tsunami height was observed at about 4 AM at Miyake Island after the forecasts were cancelled. It is estimated that the maximum height evolved by the waves being reflected or scattered by mountains on the seabed east of the earthquake epicenter. These effects are not reflected in the numerical simulation system.

An earthquake occurred on January 13, 2007 at almost the same place as that of the Kurile Earthquake and at almost the same depth. It had a larger magnitude, 8.2, than the Kurile Earthquake, and the Japan Meteorological

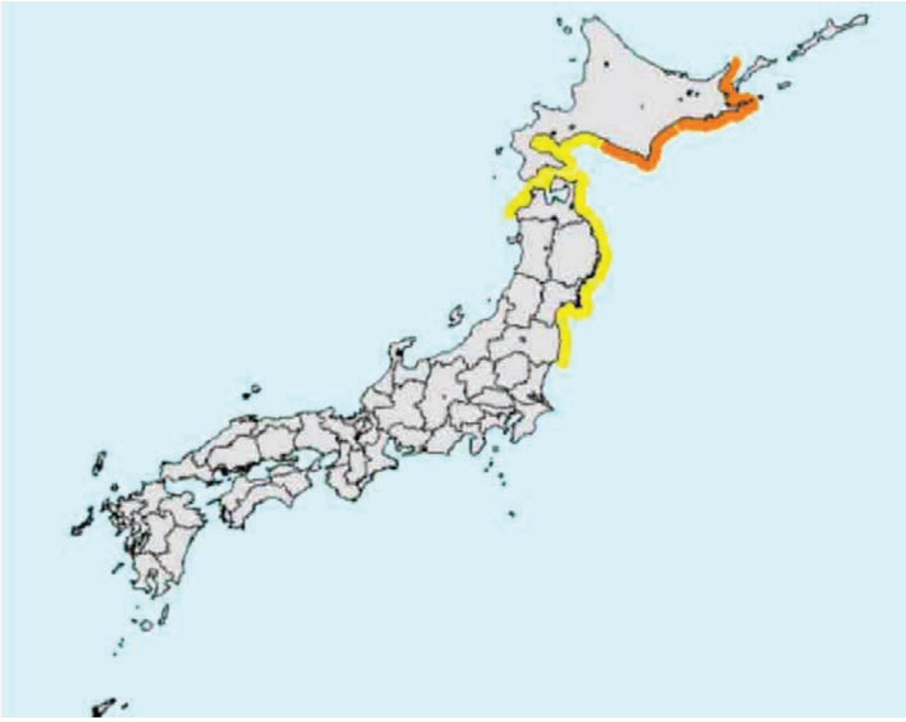

Fig. 2. Examples of tsunami warnings and advisories, issued at the time of the Tokachi-Oki Earthquake, warnings colored in orange and advisories in yellow.

Table 1. Content of Tsunami forecasts.

Category of Tsunami Forecast		Tsunami Heights to be including in the message
Tsunami warning	Major tsunami above 3 m	3m, 4m, 6m, 8m, over 10m
	Tsunami 1 to 2 m	1m, 2m
Tsunami advisory	Tsunami attention above half meter	0.5 m

Agency announced a higher tsunami height in the forecasts/advisories. However, the actually observed height was lower than that caused by the Kurile Earthquake, because the fault taken in the simulation system gave a higher tsunami than the actual fault (Abe and Imamura, 2007).

In general, the "tsunami database" is based on the worst case estimated from the earthquake epicenter and magnitude.

It is therefore necessary to adequately inform people that there can be some errors in the tsunami height predicted. The agency is now considering improving tsunami prediction accuracy by further refining the database.

5. Conclusion-Future of Tsunami Warning System

Challenges remaining for the Japan Meteorological Agency to tackle include improving the accuracy and level of detail of the information issued. As previously mentioned, the Office now divides Japan into 66 districts; however, these are not sufficient in considering the locality of tsunami and local measures against tsunami. There are phenomena called tsunami earthquake in which a major tsunami may be caused by a minor earthquake, or called distant earthquake which cannot be sufficiently predicted by the standard procedures alone. It is essential to observe actual tsunamis on remote shores and to incorporate the results observed into the warning system. Great expectations are placed on expanded monitoring networks for coastal areas and the introduction of GPS tsunami gauges.

Various types of information related to earthquake and tsunami observation results are available, including quick emergency messages which cover the arrival of tsunamis on coastal areas, the emergence of maximum waves, and the time of the eventual "blowing over" of tsunamis. Reliability (accuracy) tends to be sacrificed in prompt messages based on limited amounts of information. Therefore, the forecast system should update the messages as time advances. Moreover, it is possible to provide each coastal area with detailed information by refining the databases.

There are two major problems related to the public who receive the messages. One is how to judge the necessity of evacuation with the current information (tsunami height and arrival time), and how to estimate damage to specific coastal areas. Major tsunamis may not always cause major damage, and minor tsunamis can cause major damage. The magnitude of the damage varies depending on the difference between the external force and response (damage-mitigation) capability. It is therefore difficult to estimate the magnitude based only on information related to the external force, and necessary to reduce the difference or evaluate the damage-mitigation capability. The necessary data should be prepared beforehand. The inundation maps and disaster-mitigation maps provide information for reducing the difference. The other problem comes from the tendency of the public to base their judgments of damage on individual standards. They may optimistically construe various types of information and fail to take adequate measures. They should correctly understand tsunami messages and be aware of damage reduction measures. In other words, they should correctly grasp actual situations and select adequate countermeasures.

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References:

[1] Japan Meteorological Agency, "100 years of JMA History," 740pp, 1975 (in Japanese).

[2] Earthquake section, Japan Meteorological Agency, "Change and present of tsunami prediction," Quarterly Journal of Observation, 44, pp. 123-170, 1977 (in Japanese).

[3] Earthquake section, Japan Meteorological Agency, "Revision of Tsunami forecasting chart – Lower limit of Tsunami advisory," Quarterly Journal of Seismology, 41, pp. 83-93, 1977 (in Japanese).

[4] Japan Meteorological Agency, "Material for meeting for the 2004 Indian ocean tsunami," 2005 (in Japanese).

[5] M. Morita, "Tsunami waning system for Sanriku coast," Quarterly Journal of Seismology, Vol.13, No.2, pp. 37-43, 1942 (in Japanese).

[6] T. S. Murty, "Seismic sea waves TSUNAMI," Depart. Fisheries & Environment, Ottawa, Canada, Bulletin 198, 337pp, 1977.

[7] T. Hirono, "Tsunami warning system and its dissemination," book of Tsunami, storm surge, and ocean hazards, edited by K.Wadachi, Kyoritu Publish company, pp. 197-208, 1970 (in Japanese).

[8] Y. Sekita, "Impact of the 1960 Chilean tsunami on the tsunami warning system," Special issue of 40 years anniversary of the 1960 Chilean tsunami, Journal of Natural Disaster Science, 19, pp. 291-294, 2000 (in Japanese).

[9] I. Abe and F. Imamura, "Possibility of tsunami prediction in real time for the 2006 Kuril earthquake and tsunami," Technical report of Tsunami Engineering, Tohoku University, 24, pp. 23-28, 2007 (in Japanese).

[10] F. Imamura and N. Shuto, "Research and technology of Tsunami called a world word C, Journal of Japan Society of Civil Engineers," December, pp. 59-64, 2000 (in Japanese).

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- "Effects of coastal forest on tsunami hazard mitigation, Tsunami – Case studies and recent developments," Springer, pp. 279-292, 2005.
- "A huge sand dome formed by the 1854 earthquake tsunami in Suruga bay, central Japan," ISET Journal of earthquake technology, No.462, Vol.42, No.4, pp. 147-158, 2005.

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