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Paper:

Real-Time Tsunami Prediction System Using DONET

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We constructed a real-time tsunami prediction system using the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET). This system predicts the arrival time of a tsunami, the maximum tsunami height, and the inundation area around coastal target points by extracting the proper fault models from 1,506 models based on the principle of tsunami amplification. Since DONET2, installed in the Nankai earthquake rupture zone, was constructed in 2016, it has been used in addition to DONET1 installed in the Tonankai earthquake rupture zone; we revised the system using both DONET1 and DONET2 to improve the accuracy of tsunami prediction. We introduced a few methods to improve the prediction accuracy. One is the selection of proper fault models from the entire set of models considering the estimated direction of the hypocenter using seismic and tsunami data. Another is the dynamic selection of the proper DONET observatories: only DONET observatories located between the prediction point and tsunami source are used for prediction. Last is preparation for the linked occurrence of double tsunamis with a time-lag. We describe the real-time tsunami prediction system using DONET and its implementation for the Shikoku area.

Keywords: tsunami, real-time prediction, DONET

1. Introduction

The March 11, 2011 Tohoku-oki earthquake brought tremendous damage to the broad coastal areas, most of which was caused by the tsunami. The Nankai trough region has also been hit by repeated M8-class megathrust earthquakes in the past, where the damage caused by tsunamis was extensive. It is important to examine what actions can be taken during the time available before a tsunami arrives in terms of evacuation, since the arrival of a tsunami lags behind the ground motion. Thus, preparing evacuation plans based on several tsunami occurrence scenarios and being prepared by conducting evacuation drills can lead to the reduction of tsunami damage. To this end, it is important to detect earthquakes and tsunamis earlier and to have a grasp of and monitor the behavior of tsunamis, from their generation, arrival to land areas, and inundation, until normality returns.

M8-class megathrust earthquakes and tsunamis have repeatedly occurred along coastal areas facing the Nankai trough, including the 1944 Tonankai earthquake, 1946 Nankai earthquake, 1854 Tonankai and Nankai earthquakes, and 1707 Hoei earthquake [1, 2]. These earthquakes are known as subduction-zone earthquakes. The focal region of these earthquakes is located from the subduction front next to the trough axis to the region around where the top of the subduction plate comes into contact with the Moho (Mohorovičić discontinuity) of southwest Japan. In particular, large crustal movements and tsunamis occur when the focal region lies in the vicinity of the subduction front, as was the case in the 2011 Tohoku-oki earthquake [3, 4]. It is known that fast rupture occurred along the plate boundary at the subduction front in the Nankai trough region as well [5], and recent observations of crustal movements indicate that the locked zone is extensive [6]. Regions protruding into the ocean topographically, such as the southern tip of the Kii Peninsula or Muroto Cape, are located within the focal region, where there is only a short time lapse between the occurrence of a tsunami and its arrival.

The above megathrust earthquakes that occurred in the Nankai trough region have the characteristics of occurring in conjunction. The 1946 Nankai earthquake occurred two years after the 1944 Tonankai earthquake, while the time difference between the 1854 Tonankai and Tokai earthquakes is said to have been 30 hours [7]. Such a pattern of occurring in conjunction has been reproduced in simulation studies in recent years, and they depend on the top shape of the plate and spatial distribution of friction parameters [8]. This means that megathrust earthquakes expected to occur in the future in the Nankai trough region will repeat this pattern of occurring with a certain time lag in between; so, there is a need to be prepared for

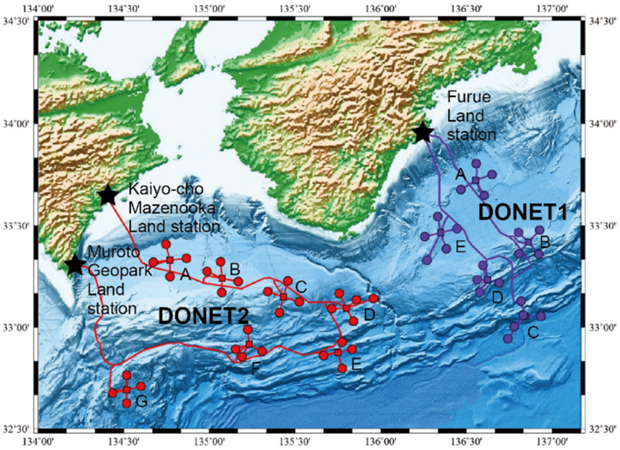

Fig. 1. Map of DONET installation. Observatories of DONET1 and DONET2 are indicated by purple and red circles, respectively. Stars are land stations. Squares with alphabet letters indicate nodes (branching apparatuses).

variations in the time interval. It is necessary to be prepared for cases such as the 2011 Tohoku-oki earthquake, which caused an immense tsunami, as well as cases in which two or more earthquakes occur in conjunction, such as the 1944 and 1946 earthquakes and the 1854 Tonankai and Nankai earthquakes.

The Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) has been installed in Kumanonada, which is the focal region in the Nankai trough region for the Tonankai earthquakes, and the off Kiisuido Channel, which is the focal region for the Nankai earthquakes [9, 10]. DONET1 and DONET2 cover the Tonankai and Nankai earthquake rupture zones, respectively, and consist of 51 stations in total, each of which is equipped with a strong-motion seismometer, broadband seismometer, pressure gauge, and others, composing a system that allows continuous monitoring over an extensive area (**Fig. 1**). The Japan Meteorological Agency is already using DONET data for their Earthquake Early Warnings and Tsunami Warnings.

A real-time tsunami prediction system was developed using DONET [11]. In this system, the data obtained by the strong-motion seismometers, broadband seismometers, and pressure gauges of the DONET observatories are transmitted to an institution that carries out real-time prediction of tsunami arrival time, tsunami height, and inundation area of coastal target points. In this paper, we provide an overview of the real-time tsunami prediction system and describe recent improvements and implementations.

2. Real-Time Tsunami Prediction System

2.1. Overview

A tsunami occurs when seawater is lifted by the vertical components of crustal movements on the ocean floor, and the tsunami propagates to coastal areas. The propagation speed of tsunamis is a function of the water depth and has the characteristic of becoming slow in shallow waters. This means that, in cases in which the tsunami propagates from deep to shallow waters, the propagation speed decreases while the tsunami height increases. Defining the ratio by which the tsunami increases in height as the tsunami amplification factor, the correlations of these factors between the DONET observatories and coastal target points are computed and stored in a database. The tsunami amplification factors are evaluated from the observed DONET pressure data as the input and then used in turn to evaluate the tsunami height at the various target points [12]. Based on this principle, Baba et al. (2013) [12] estimated the tsunami amplification factors along coastal areas of the Tohoku region, and they evaluated the extent of inundation areas using pressure data obtained by Tohoku University during the tsunami caused by the 2011 Tohoku-oki earthquake. Since their prediction results were in good agreement with the measurements, we employed the same principle to construct the tsunami prediction system.

To construct the system for the Nankai trough region, it is necessary to establish the fault configuration over the entire Nankai trough region, use it to compute tsunami waveforms at coastal target points and all DONET observatories, and store them in a database in advance. The fault models were constructed by adopting a subset of those given by Baba et al. (2013) [12]; thus 1,506 fault models along the Nankai trough were obtained, representing a range of fault depths and inclinations as well as seismic magnitudes. Four magnitudes, 7.6, 7.9, 8.2, and 8.5, were used, the faults were given depths between 5 km and 20 km, and the inclinations were set at 5, 10, and 25 degrees (but 15, 25, and 35 degrees off the Boso peninsula, which displays different fault inclinations). Based on these fault models, the tsunami waveforms at the various DONET observatories, locations of the Meteorological Agency tide gauges, and coastal target points are computed. At the same time, inundation maps are computed for the coastal target points and the results are stored in a database. In this manner, the tsunami travel times to and peak amplitudes at each DONET observatory and each coastal target point are stored for each fault model. The tsunami amplification is obtained from the correlation between the peak amplitude of DONET pressure gauges data and the maximum tsunami height at the coastal target point (**Fig. 2**). The coastal target points were established off the coast where the water depth was 5 m or more, since the tsunami amplitude cannot be properly evaluated in cases when the sea floor becomes exposed when the tsunami arrives.

The prediction system operates in the following manner. 1) After the earthquake and tsunami are detected, the epicenter direction is narrowed down. 2) The average amplitudes recorded by the DONET pressure gauges are successively computed and used as the inputs, and the fault models corresponding to the input values are extracted from among the 1,506 models using the correlation diagrams between the DONET observatories and coastal target points. 3) The models with the five highest tsunami

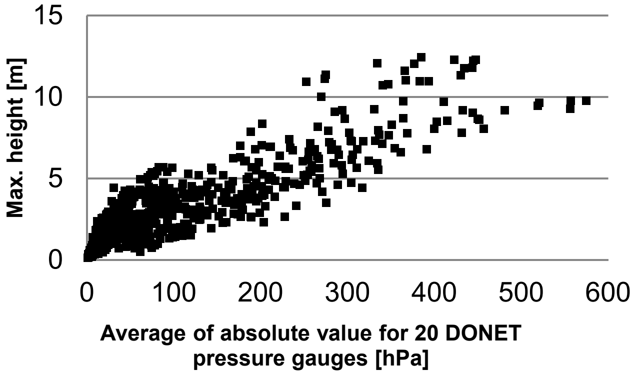

Fig. 2. Example of correlation diagram between DONET input data and maximum tsunami height at coastal target point.

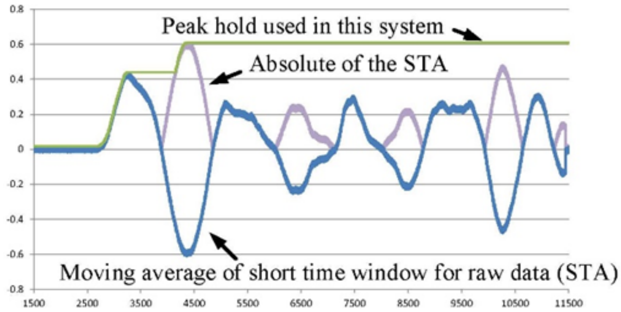

Fig. 3. Data processing for data input. Blue and purple lines represent the original waveform and absolute values, respectively. The peak-hold waveform of the purple graph is used as the input (green line) of the system.

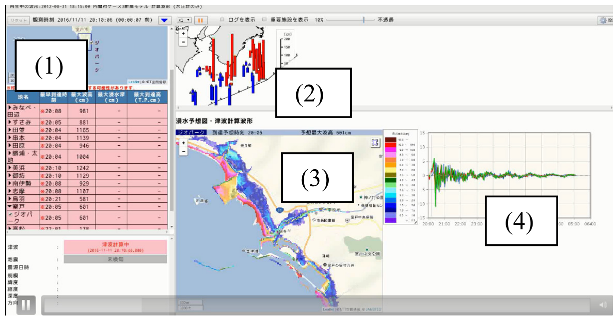

Fig. 4. Example of the tsunami prediction system display. The table of predicted tsunami arrival time and maximum tsunami height (1), real-time DONET data (2), inundation map (3), and calculated tsunami waveform at the predicted point using extracted fault models (4) are displayed in a single window.

heights and a shortest tsunami arrival time are further extracted from the models obtained in the previous step, and inundation maps computed from the tsunami heights are drawn. At the same time, the tsunami waveforms at the target points are computed based on the fault model used for map construction, and they are displayed along with the map. 4) The extracted fault models are updated whenever an increase of the inputted DONET pressure gauge data is registered, and the tsunami arrival time, maximum tsunami height, and inundation map are updated accordingly.

The predicted tsunami amplitude can be overestimated when the recorded DONET pressure measurements, which may contain ground-motion signals, are directly used as inputs. To avoid this, we examined the method of event triggering to make start the real-time tsunami prediction system using records of the ocean-bottom pressure gauges installed off the coast of Miyagi Prefecture by Tohoku University, obtained for the 2011 Tohoku-oki earthquake [13]. Event triggering is thus based on the ratio of short-term to long-term averages, with a time difference introduced between computations in order to minimize the delay of tsunami triggering. In the final form, tidal correction is carried out on the pressure-gauge data, and the long- and short-term averages are computed twice each, with the respective time windows of 300 and 50 seconds, with a 300-second time difference between the two ratio computations [14]. Thus, the absolute values of two types of window averages of the pressure gauge data, subjected to tidal correction, are calculated and the peak-hold data used as the input values (**Fig. 3**).

While prediction of tsunamis is carried out in this manner, the visualization process is important. It is necessary to grasp an overall image of the operational system for visualization. Thus, the system is designed to be set up in the prefectural governments, which manage the prediction information of all coastal target points within their jurisdictions, while the disaster prevention department personnel of the individual municipalities confirm the target points within their municipality from the prefecture-released information. Determining how to deal with missing data is the most important item prior to visualization. A strong earthquake may cause a submarine landslide, which may cut off submarine cables. Even when the data from DONET observatories is collected by land stations, slope failures may break continuous data transmission. It is therefore necessary to deal with missing data. In the present system, we release the registration of the observatories with missing data and continuous zero-valued data from the system. At the same time, it is necessary to enable personnel to confirm the DONET pressure gauge data in real time so that they can be aware of lack of data. Following this, personnel must be able to monitor an earthquake or tsunami detected by DONET observatories at a glance. After having grasped the overall detection status, the operators in charge are expected to distribute information as they confirm the detection with correct data and the validity of the prediction. The earliest tsunami arrival time, maximum tsunami height, estimated inundation map, and the tsunami waveforms computed from the extracted fault models are displayed in a format that enables all items to be observed at a glance without scrolling (**Fig. 4**). The map can be enlarged or contracted freely so that monitoring personnel can check points of special interest.

2.2. Improving Prediction Performance

In this chapter, we describe measures introduced to improve the accuracy of the prediction system in response to the completion of DONET2 in 2016. Previously, the average of the absolute values of all pressure gauges data installed at DONET1 observatories was used. With the completion of DONET2, it has become possible to respond to tsunamis by the Nankai earthquakes including the Hyuganada or the Tosa Bay, as compared to the system based on only DONET1. The prediction system is intended to be used to grasp the detailed information of individual points rather than obtaining a macroscopic picture of extensive inundation areas covering two or more prefectures. It has been confirmed in our investigation so far that the database corresponding to earthquakes up to M8.5 sufficiently covers M9-class tsunamis predicted by the Cabinet Office model [11]. For the coastal residents of the island of Shikoku, a tsunami arising in off Tokai caused by an M9-class earthquake has relatively minor effects, in terms of the maximum tsunami height. In other words, it is more important to consider the amplitudes observed at the nearest DONET observatories for specific target points. Since it is not possible to identify different tsunami propagation behaviors for each area by using the average of absolute values of all observatories, we adopt the approach of fine-tuning the correlation charts corresponding to individual target points. Specifically, this entails two items: 1) narrowing down the fault models from among the 1,506 models and 2) the dynamic selection of DONET stations based on the tsunami propagation directions at coastal target points. In particular, the prediction accuracy was improved by making it possible to reflect locally observed large tsunamis by selecting DONET observatories located along the propagation route of the tsunami travelling from the wave source toward the target point and by releasing the registration of the observatories recording tsunami that has already passed through.

Previously, there have been cases in which the accuracy of tsunami prediction was poor because there were no DONET observatories between the fault that excited the tsunami and the coastal target point. When the tsunami propagation path from the wave source to the DONET observatory was different from that to the coastal target point, the use of the pressure data of the DONET observatory sometimes resulted in overestimation of the tsunami's magnitude because of the damping effect caused by the longer propagation. Therefore, we decided to narrow down the fault models from the 1,506 models by computing the hypocenter direction from the seismic and pressure records.

First, the data of the strong-motion seismometer is used as the event trigger; the different trigger times of multiple DONET observatories are used to determine the hypocenter direction, from which the fault models are narrowed down (**Fig. 5**). From the time difference of the DONET observatories and travel, the source region is assigned to one of four areas: the eastern and western sides of the DONET array, within the array, and far field areas. Triggering of a tsunami event follows that of an earthquake event. The fault is narrowed down by the sequence in which the DONET observatories are tsunami-triggered (**Fig. 6**). The fault models are narrowed down based on the join of faults narrowed down from the earthquake and tsunami trigger statuses (**Fig. 7**). This makes it possible to respond to cases such as tsunami earthquakes with small ground motions.

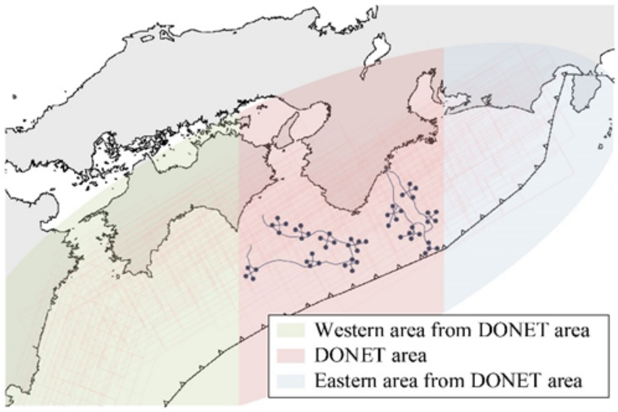

Fig. 5. Identification of the source region. The system identifies the source region by comparing the travel times of P-waves between DONET stations and narrows down the fault models.

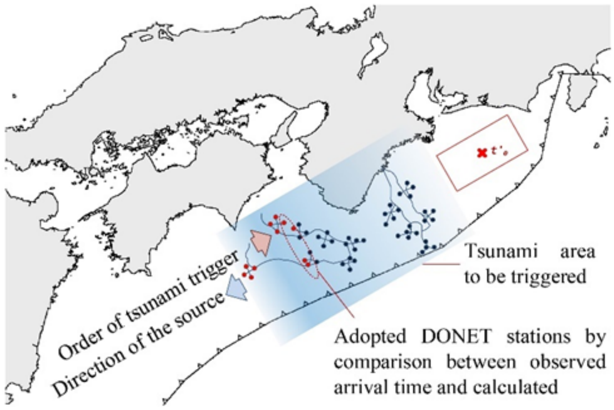

Fig. 6. Selection of fault models based on the tsunami trigger pattern at DONET stations.

While the process of narrowing down the fault models described above has the effect of releasing models with large dispersions of the type shown earlier in **Fig. 2**, we also took measures to narrow the dispersion itself. When the tsunami arrival time determined from a tsunami-triggered observatory and target point, based on pressure data updated every second, indicates that a tsunami is approaching, that observatory is incorporated into the computation (**Fig. 8**). Thus, observatories that indicate a propagation path that does not lead to a target point or a departing tsunami front are removed from analysis. Only those DONET observatories that indicate that a tsunami is approaching a coastal target point are used for tsunami prediction for that point.

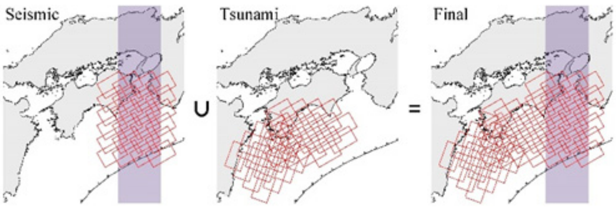

Fig. 7. Narrowing down fault models using seismic and tsunami data.

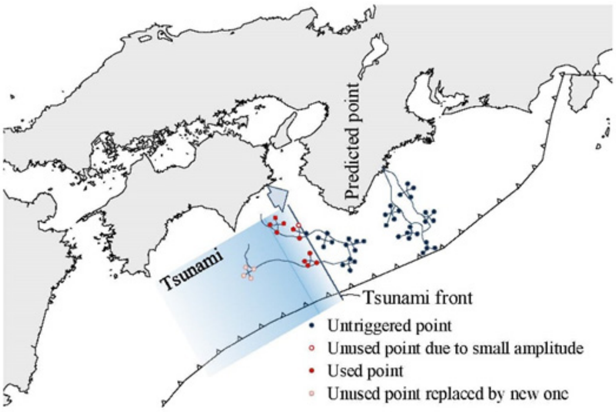

Fig. 8. Dynamic selection of DONET stations. Closed and open red circles respectively indicate triggered DONET stations and stations removed from among those triggered.

Previously, the observatories affecting a specific target point were grouped according to the tsunami arrival times back-computed from that point, with each group given a 1-minute window, and the dispersion of the correlation chart for each group was evaluated [11]. As a result, the correlation tended to be high in cases when observatories close to the target point were used. Yet, early detection performance suffers when only those observatories close to a target point are used. Therefore, it was decided to update the selection of observatories according to the tsunami propagation status and to compute the average absolute pressure among the DONET observatories each time the selection was updated. This amounts to shifting the fault-model data shown by dots in **Fig. 2**, along the horizontal direction as the selection of used observatories changes.

However, if the used observatories are changed each time a different observatory is triggered by a tsunami event, the predicted value may fluctuate back and forth, i.e., the tsunami height may increase and decrease alternately or the inundation area may expand and contract. This would reduce the reliability of the prediction outcome. If the average absolute pressure with the newly triggered observatory is found to be lower than the previous value, therefore, the data is updated after that observatory used previously has been released. Moreover, measures were taken to prevent making the prediction from a small number of observatories because of the high likelihood of noise contamination within a network of seafloor observatories.

Table 1. Comparison of the calculated maximum tsunami height and that predicted by this system. The two columns on the right present examples based on Model Case 10 [15] and the 1946 Nankai earthquake [16].

		Case 10, Cabinet Office model		1946 Nankai earthquake	
	Prediction point	Calc (m)	Pred (m)	Calc (m)	Pred (m)
West Kishu	Yamauchi	5.17	8.67	1.67	4.24
	Shiba	5.70	8.89	1.70	4.24
	Haya	5.07	8.89	1.52	3.73
	Mera	4.98	8.93	1.54	3.73
	Tenjinzaki	4.51	6.62	1.35	2.40
	Suehirocho	5.21	7.36	1.48	2.44
	Mori	5.39	8.51	1.55	2.67
	Shinjo 1	5.51	8.17	1.76	2.48
	Shinjo 2	5.85	9.05	1.89	3.36
	Higashi shirahama	5.80	8.29	1.60	2.56
	Seto	4.42	6.94	1.72	3.07
	Shirarahama	4.39	6.16	1.54	2.83
Kushi moto	Arida	7.08	10.19	0.68	1.72
	Takatomi	9.17	11.70	1.66	3.01
	Kushimoto 1	9.95	12.45	1.74	3.14
	Kushimoto 2	7.91	10.17	1.52	1.65
	Kushimoto 3	6.67	11.07	1.57	1.56
	Hime	12.41	11.71	0.76	1.30
	Ohshima	5.15	9.53	0.32	1.47
East Kishu	Uragami	5.49	9.48	1.01	1.29
	Shimosato	7.47	8.74	0.54	1.23
	Taiji 1	4.33	8.68	0.54	0.83
	Taiji 2	7.44	8.86	0.41	0.76
	Tsunewatari	4.10	9.54	0.77	1.26
	Moriura	6.60	11.09	0.93	1.56
	Niko	4.89	10.49	1.04	1.52
	Tsukiji	4.13	9.70	0.82	1.55
	Katsu'ura	8.49	9.36	0.59	1.21
	Tenma	10.79	10.60	0.96	1.80
	Hamanomiya	10.59	11.54	1.01	2.02

This system, incorporating a new logic focusing on tsunami propagation from the tsunami source to coastal target points, was tested against the Cabinet Office-released fault model (Case 10), which predicts relatively high overall tsunami heights, and the 1946 Nankai earthquake model [16], with a relatively low tsunami height. **Table 1** presents the results at various locations computed from these models as well as those predicted from the tsunami waveforms at DONET observatories and coastal target points. While the predicted results are somewhat overestimated on the whole, there are few underestimations. The predictions for two locations (Hime and Tenma) are slightly underestimated but can be considered to be roughly equal in view of the computational precision.

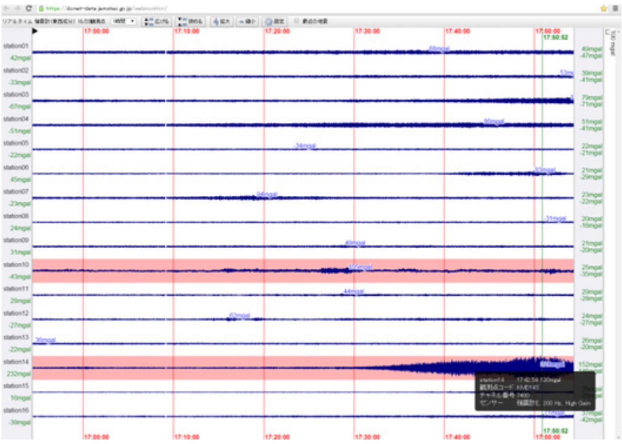

Fig. 9. Example of real-time waveform monitoring. One can display waveforms of either seismic or tsunami signals.

2.3. Operation

From the operational standpoint, in addition to minimizing the risk of false information, it is important to confirm the record immediately in the case of false information and cancel its distribution. Therefore, it is necessary to operate the system while monitoring the waveform information in real time. **Fig. 9** shows an example of the monitoring screen. The screen display can be readily modified, including magnifying or contracting the wave amplitude or changing the wave intervals or time scale, and incorporates a function to display propagating seismic or tsunami waveforms in real time [17]. Since the system displays the maximum amplitudes within the window as well as peak amplitudes, it allows one to grasp the extent of the signals observed by the DONET observatories in real time. There are also functions to send emails to predetermined disaster-prevention personnel whenever a DONET observatory is tsunami-triggered as well as to cancel the prediction process when it is found that there is no risk of a tsunami. The prediction process can be stopped by pressing a reset button, which returns the system to the initial status before triggered.

While the system is normally used to monitor seismic and tsunami activities by inputting the observed data, it also has functions that allow it to be actively used for educational activities. Thus, the tsunami waveforms at the DONET observatories and target points based on a given fault model can be computed in advance and stored in a database. Based on this function, it is possible, for instance, to incorporate a tsunami equivalent to the Cabinet Office M9-class earthquake model as DONET data in real time and to then observe how the tsunami prediction system operates. This can provide an index of tsunami evacuation activities in the vicinity of coastal target points.

Mega-thrust earthquakes that occur along the Nankai trough are expected to be accompanied by crustal movements. When this occurs, offsets will occur between DONET observatories affected by crustal movements before and after the earthquake. When an observatory has offset on the pressure gauge data, it will be registered by the system as being the same as the continuous occurrence of a tsunami. Since the system displays the maximum predicted tsunami, the system may incorrectly estimate the observed tsunami if a second mega-thrust earthquake occurs while the offset still remains. Therefore, we introduced the ultra-long-term average and made it possible to reset the offset of DONET pressure gauge data when the difference in the amplitudes of the ultra-long-term and short-term averages is sufficiently low.

3. Tsunami Countermeasures for Southern Tokushima Prefecture

When an M9-class earthquake, such as the one predicted by the Cabinet Office model, occurs, the southern part of Tokushima Prefecture will be subjected to crustal movements. The south will tend to be uplifted, while the north will tend to subside. The Tokushima Prefectural government has estimated the tsunami inundation based on the Cabinet Office hypocenter model [18]. According to this, the effects of a tsunami at the Shishikui fishing port in the town of Kaiyo, Tomoura fishing port, and the central part of Asakawa port will begin 6, 4, and 11 minutes respectively after the earthquake's occurrence, which would seem to make it difficult to evacuate before the tsunami arrives. However, as indicated in the waveforms computed for Asakawa port (within the breakwater) shown in **Fig. 10**, there is actually some time before it becomes difficult to evacuate. Noting that DONET observatories connected to the same node are indicated by the same color, it can be seen that the observatories connected to nodes G, C, and D, which lie seaward, display large negative values. This indicates that a large uplift occurs at these stations. Meanwhile, positive values are displayed at points within Asakawa port shortly after the earthquake, which indicates that a small uplift has occurred, following which the tsunami height slightly falls. In other words, the tsunami begins with a drawback, after which it suddenly grows large. While there is little time before the effects of the tsunami appear, some time remains for evacuation action to be taken. This shows that, in addition to emphasizing that the tsunami will arrive in a few minutes, it is important for the residents to inform the necessity to evacuate immediately in advance.

From the standpoint of tsunami prediction, it is characteristic that the seaward observatories display large negative values. Large tsunamis are created by large crustal movements. Although tsunami earthquakes do not always produce intense ground motions, it is possible to confirm the presence of crustal movements by monitoring the records of DONET observatories. Since the tsunami height increases when the tsunami front enters shallow seas, as mentioned earlier, it is important to educate system users so that they do not obtain a "false sense of security" from the low pressure waveforms recorded at the DONET observatories. The principle for this, however, is relatively simple and should not be difficult to communicate.

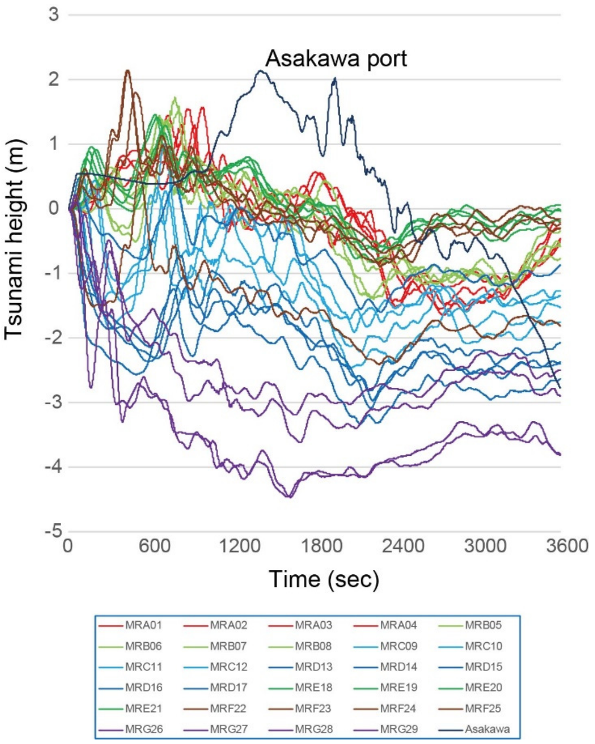

Fig. 10. Calculated waveforms of pressure gauges of DONET2 stations and tsunami height at Asakawa port, the town of Kaiyo, Tokushima, using Model Case 5 proposed by the Japan Cabinet Office. Stations indicated by the same color are connected to a single node.

The system has so far been installed by Wakayama and Mie prefectures, the city of Owase, and infrastructure company. In particular, the system places weight on the prediction of areas important to the local governments, which can be, for example, bases for restoration. In cases with inadequate highways and others for evacuation and with insufficient disaster preparedness in local government, it is important to have decision which area should additional disaster prevention resources be invested. Our real-time tsunami prediction system is useful for local government to give such decision, because it brought us relative differences on damages. Meanwhile, the most critical item for local residents is to evacuate. The residents living in Nankai coastal areas generally receive education about disaster prevention and take evacuate drills well. However, tsunami earthquakes do not necessarily produce strong ground motions. Although tsunami-prediction information cannot be made available to the larger public due to a Japanese regulation, we consider it might be helpful to show real-time DONET waveforms to them carrying out educational activities.

4. Conclusions

We had constructed a system to predict tsunamis in real-time based on DONET1 data and implemented it in Wakayama Prefecture, other local governments, and an infrastructure company. Recently, construction of DONET2 off the Kii-suido Channel was completed, and we incorporated improvements in the tsunami prediction system. While it was possible in the previous system to make predictions for only the Tonankai earthquakes in the Kumanonada with DONET1, the concurrent use of DONET2 data and improved prediction methods have made it possible to predict tsunamis caused by Nankai earthquakes in real-time as well. In real-time prediction, we introduced advance processing of the waveform inputs to the system, narrowing down of the fault models, and dynamic selection of the DONET observatories used for prediction according to the coastal target point, and we verified the prediction accuracy using fault models by the Cabinet Office (Case 10) and the 1946 Nankai earthquake [16]. Although a few results were slightly overestimated, the predicted values were generally satisfactory. Since unexpected events may occur, such as missing data, during its operation, it is important to confirm the waveforms in real time and operate the system while ensuring the reliability of the data. Operating the system for the Shikoku region, it was found that there was extra time for evacuation beyond the predicted tsunami arrival time at specific locations. Although the system itself cannot be made available to the general public, it may be helpful to show DONET waveform data to the general public; however, it will be necessary to inform users of certain precautionary items. In the end, it is important for individual residents to be aware of scenarios for escaping tsunamis by checking the process of tsunami arrival through evacuation drills and other methods.

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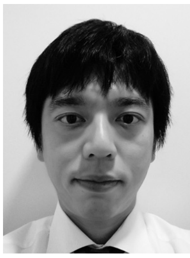

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