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REAL-TIME TSUNAMI INUNDATION FORECAST SYSTEM USING S-net DATA

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Abstract

One of the causes of enormous damages of the 2011 megathrust Tohoku earthquake (M 9.0) was the underestimation of the first tsunami warning, which was issued three minutes after an earthquake by JMA as well as the insufficient dissemination of the tsunami information to the public due to power failures. To reduce the fatalities due to tsunamis, it is essentially important to deliver prompt and accurate forecast to the on-shore residences. At the time of the 2011 Tohoku earthquake, offshore observations were insufficient. In response to this situation, Japanese government has started to construct the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net). One of the most important contributions of S-net is that we obtain additional lead time for earthquake and tsunami early warning. To maximize the advantage of S-net, we are developing a new methodology of real-time tsunami inundation forecast system. In our algorithm, we quickly select several appropriate tsunami scenarios that can explain offshore tsunami observations by using multiple indices from the proposed Tsunami Scenario Bank (TSB), which contains offshore tsunami waveforms etc. An advantage of our method is that tsunami inundations are estimated explicitly without any source information, which may have large estimation error. We carry out many calculations to investigate the sensitivities of the source models to coastal tsunami heights along the Pacific coast of Chiba prefecture. Furthermore, we will evaluate and improve our system through the demonstration experiments with local governments.

Keywords: real-time tsunami forecast, tsunami inundation forecast, S-net

1. Introduction

One of the causes of enormous damages during the 2011 megathrust Tohoku earthquake (M 9.0) was the underestimation of the first tsunami warning of the Japan Meteorological Agency (JMA) forecast as well as the insufficient dissemination of the tsunami information to people due to power failures [1]. To reduce the fatalities due to tsunamis, it is essentially important to deliver prompt and accurate forecast to the on-shore residences when a megathrust tsunami is generated by a huge subduction-zone earthquake. To achieve the accurate and effective disaster prevention information, it is also important suitable evaluation of appropriate protection facilities, such as breakwater, seawall, etc. Furthermore, it is also needed to prevent secondary disasters after the earthquake because it is expected the possibility of the occurrence of a large aftershock. We need to achieve and improve real-time tsunami inundation forecast to derive the information required for evacuation before the arrival of a tsunami on the coast.

We have launched the new project titled "Innovative Research toward Tsunami Disaster Mitigation" in the "Enhancement of Societal Resiliency against Natural Disasters", which is one of the Cross-ministerial Strategic Innovation Promotion Program (SIP) [2] themes that addresses the most important social problems facing Japan and is a national project for science, technology and innovation, spearheaded by the Council for Science, Technology and Innovation (CSTI) as it exercises its headquarters function to accomplish its role in leading science, technology and innovation beyond the framework of government ministries and traditional disciplines. Fig. 1 shows an overview of our project, which consists of three sub-topics: 1) developing real-time tsunami inundation forecast technology using offshore observation network for earthquakes and tsunamis, 2) improving high precision three dimensional tsunami inundation simulator, and 3) improving on-demand sea-floor crustal deformation measurement system. In this paper, we introduce a development of real-time tsunami inundation forecast system.

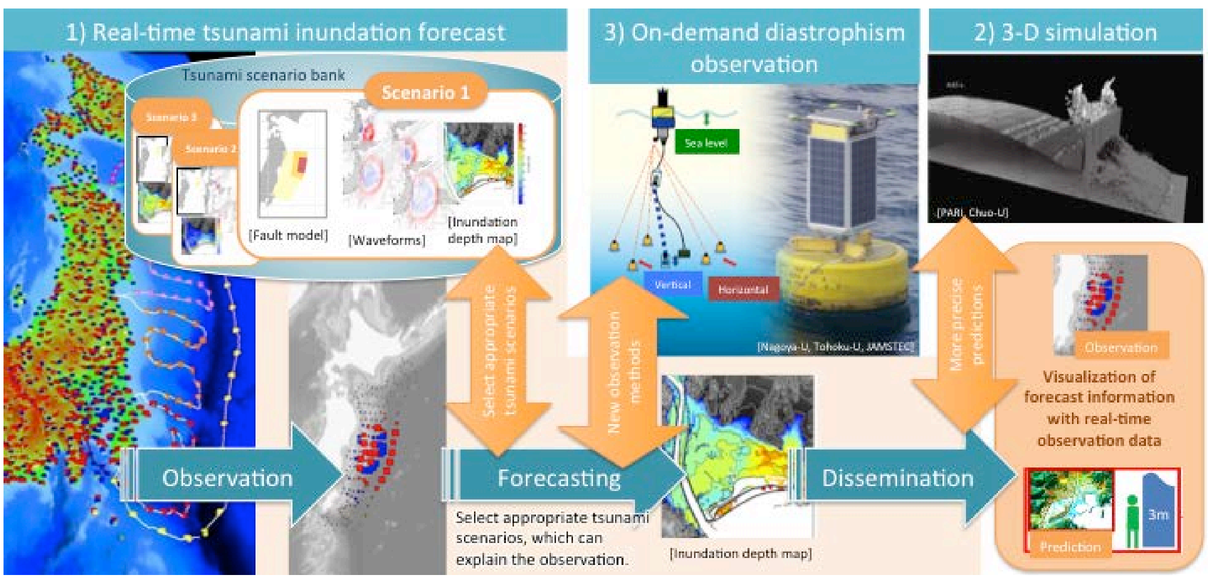

Fig. 1 – Overview of "Innovative Research toward Tsunami Disaster Mitigation"

The expected tsunami height and arrival time on the coastlines are forecast by the current Japanese tsunami early warning system officially operated by the Japan Meteorological Agency (JMA), which generally uses the epicenter and magnitude estimated by short-period seismic wave data from an onshore earthquake observation network [3]. Because propagation speed of seismic waves is much faster than that of tsunamis, this approach enables the rapid acquisition of tsunami forecasts for the first tsunami warning announcements. At the 2011 Tohoku earthquake, they could disseminate the first tsunami warning announcement three minutes after the earthquake occurrence. However, it was difficult to estimate immediately in real-time a magnitude of the earthquake for a megathrust subduction-zone earthquake, which is larger than M8 by using short-period seismic wave data. As a result of this difficulty, the initial tsunami warning was 1 to 6 m on the Pacific coastline in Japan using the underestimated magnitude of 7.9. Furthermore, they could not update more accurately their tsunami warning using a moment magnitude derived by broadband seismograph network which is expected to issue about 15 minutes after the earthquake occurrence, because almost of all broadband seismographs operated by JMA which are used for their real-time analysis to derive a moment magnitude were saturated.

At the time of the 2011 Tohoku earthquake, in the Pacific coasts of Kanto, Tohoku and Hokkaido districts, offshore observations were insufficient and the observed data essential for efficient tsunami forecast was very poor. In response to this situation, Japanese government decided to construct the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net) [4,5] and the National Research Institute for Earth Science and Disaster Resilience (NIED) is now constructing this observation network under the sponsorship of Ministry of Education, Culture, Sports, Science and Technology (MEXT). S-net consists of 150 ocean-bottom observatories linked by ocean-bottom fiber optic cables with the total length of approximately 5,700 km. This dense network covers the wide area of the Japan Trench and the southernmost Kuril Trench offshore the Kanto, Tohoku, and Hokkaido, and every source area of an earthquake of magnitude larger than 7.5 includes at least one observatory. One of the most important contributions of S-net is that we could obtain additional lead time for earthquake and tsunami early warning. For the best case, the additional lead time by using data from S-net is about 20 minutes for a direct direction for a tsunami generated by an earthquake that occurs in the Japan Trench, and 30 seconds for earthquake early warning.

Many tsunami forecast methods have been studied (e.g., [6]). For near-field tsunami forecast, “tsunami Forecasting based on Inversion for initial sea-Surface Height” (tFISH), which estimates the best tsunami source model by inversion analysis of tsunami waveform data from ocean-bottom pressure gauges, was proposed [7]. In their method, arrival times and tsunami amplitudes at the coasts are forecast by linearly combining pre-calculated Green’s functions. However, obtaining direct measurements of tsunamis requires more time to detect tsunami signals than obtaining seismic wave. Attempting a breakthrough, a method using relationship of tsunami height between offshore and near coast is successfully proposed [8]. In addition the rapid method to estimate tsunami source location using a dense offshore observation network was proposed [9]. Although direct measurements of tsunamis are used in their methods, the required estimation time is comparable to that achieved using real-time Global Navigation Satellite System (GNSS) data [6]. For real-time tsunami inundation forecast, some researchers have proposed new methods that use on-demand forward simulations with inverted tsunami source models [10,11]. However, these methods require enormous computer power, hence the coastal region to be forecast is limited. To achieve a real-time tsunami inundation forecast on high-resolution topography, a new method is proposed [12]. In their method, the best-matched tsunami scenario selected by comparing pre-calculated tsunami waveforms and synthetic tsunami waveforms calculated using forecasted tsunami source information is forecast.

2. Developing real-time tsunami inundation forecast toward tsunami disaster mitigation

We have started to develop a real-time forecast of tsunami inundation as well as the coastal tsunami heights using ocean-bottom pressure data to be obtained by S-net and construct a prototype system that achieves the real-time forecast for the Pacific coast of Chiba prefecture. To maximize the advantage of S-net, we are developing a new methodology of real-time tsunami inundation forecast system. We adopt an approach to prepare the database called tsunami scenario bank (TSB) in advance for at least thousands of source scenarios because the inundation is a highly non-linear phenomenon and its calculation costs are rather heavy. In our method, a forecast is carried out by comparing observed ocean-bottom pressure data and pre-calculated data and selecting several possible appropriate tsunami scenarios to represent forecast uncertainties which can almost evenly explain observations according to a particular criteria. An advantage of our method is that tsunami inundations are estimated explicitly without any source information, which may have large estimation error, especially for real-time analysis.

2.1 Tsunami inundation simulation model

To make appropriate TSB for the real-time tsunami inundation forecast, we construct tsunami inundation simulation model, which consists of high-resolution topography along the target coastline and develop an automatic system for generating the optimal mesh model based on the adaptive mesh refinement (AMR) method.

We first construct two different digital elevation model (DEM) around the target coastal region: DEM for offshore modeling (DEM1) and on-shore DEM (DEM2). A configuration of four nesting layers with a minimum mesh size of 90 m was used for the land side, and larger mesh sizes of 270, 810, and 2,430 m were used for the sea side for DEM1, which is used for offshore waveform calculation and coastal tsunami heights. For DEM2, which is required for the tsunami inundation calculation, a configuration of six nesting layers with a minimum mesh size of 10 m was used. In addition, we prepared line data of seawall to consider the destruction of seawall by tsunami overflow.

To construct TSB, an efficient tsunami modeling is indispensable for heavy calculations of tsunami inundation simulation using various source models. For the efficient tsunami modeling, reduction of number of grid is important. To reduce the grid number, it is important to construct the most suitable grid spacing according to the topography of the seafloor and to connect the grids appropriately because the grid spacing depends on a propagation speed of tsunamis. A nesting mesh system is generally used. However, the nesting grid has difficulty in constructing the most suitable grid spacing because regions for finer grid spacing are determined manually. In our project, we employ the adaptive mesh refinement (AMR) by discretizing a domain spatially using tree-structure grid automatically based on the Courant-Friedrichs-Lewy (CFL) condition [13].

2.2 Tsunami Scenario Bank

In this study, we first calculate the tsunami waveforms at offshore stations, the maximum coastal tsunami heights, and inundation depths from any possible tsunami source models and register them in the TSB. When a tsunami occurs, we use multiple indices to quickly select dozens of appropriate tsunami scenarios that can explain the offshore observations. At the same time, coastal tsunami information coupled with the selected tsunami scenarios are forecast.

To construct TSB, if we could consider all possible tsunami scenarios, the tsunami forecast would be highly precise. However, the number of tsunami scenarios that can be prepared is limited, due to heavy calculation loads for tsunami inundation simulations, i.e., it is important to appropriately assume the source models. To investigate the sensitivities of the tsunami source models to coastal tsunami heights, we first carry out many calculations based on low-resolution simulation, which only requires much less calculation time comparing with high-resolution simulation. Based on a large number of sensitivities analyses, we could construct the TSB that efficiently covers possible tsunami scenarios affecting the target region.

We investigate the sensitivities analysis for the location, magnitude, and shape of fault models for coastal tsunami heights along the Pacific coastline of Chiba prefecture (Sotobo). Fig 2a and 2b show maximum coastal tsunami height and average of coastal tsunami height along the coastline of Sotobo for the locations of fault models, which are boundary plate models, Mw 8.0 along the Japan Trench, Kuril Trench, and Izu-Ogasawara Trench. These figures indicate that the fault models distributed offshore of Ibaraki prefecture and Sotobo region make large tsunami, which are possible run-up on-shore. Fig. 2c represents the results of sensitivities spatial intervals between fault models. When we require HVR is larger than 0.7. If we choose half pitch interval (0.5), the continuities of variety of fault models is enough for Ibaraki, Tohoku, and Hokkaido. However, fault models offshore Sotobo, are need to be more densely intervals. We then register tsunami scenarios to the prototype of Tsunami Scenario Bank.

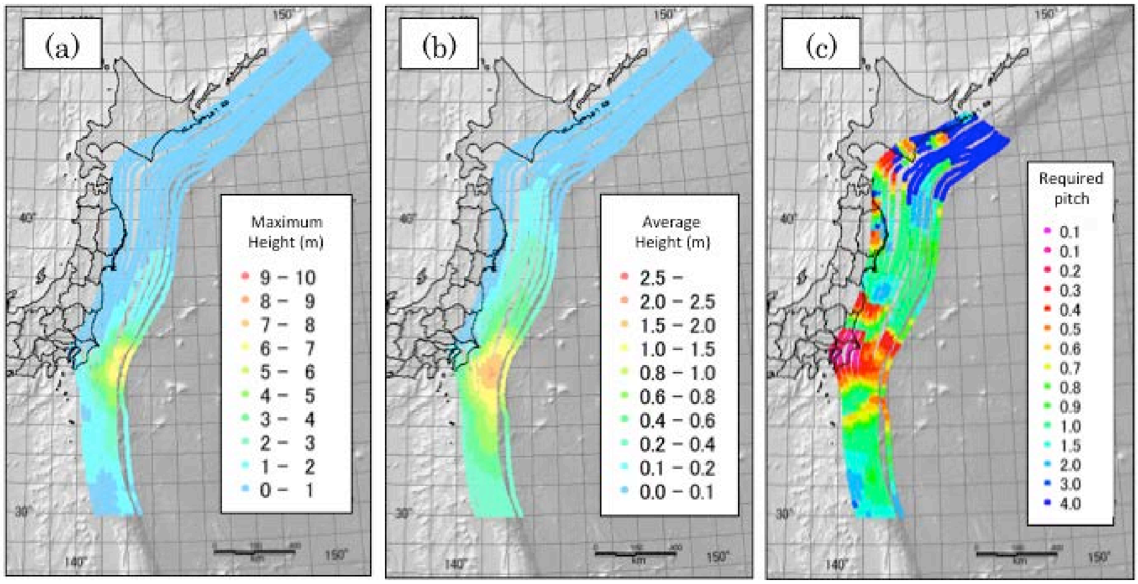

Fig. 2 – Sensitivity analysis for Mw 8.0 tsunami source models along the Japan Trench

2.3 Multi-index method

Here we describe a multi-index method [14,15,16] for comparing the observed waveform O($\boldsymbol{r}_i$,t) and the pre-calculated waveform C($\boldsymbol{r}_i$,t) registered in the TSB, for the i-th observation unit at a position $\boldsymbol{r}_i$ after a time t has elapsed following an earthquake. In the current study, we use three indices, the correlation coefficient and two kinds of variance reductions, to compare O($\boldsymbol{r}_i$,t) to C($\boldsymbol{r}_i$,t). The correlation coefficient R(t) is expected to be sensitive to the tsunami location, because R(t) strongly depends on the difference between spatial distribution of O($\boldsymbol{r}_i$,t) and C($\boldsymbol{r}_i$,t). However, R(t) could be close to 1 when their spatial distribution are similar, even though the amplitudes of O($\boldsymbol{r}_i$,t) and C($\boldsymbol{r}_i$,t) are very different. Next, we also define variance reductions to discriminate between good and bad matching accuracy. In this study, we use two variance reductions, VRO(t) and VRC(t), as functions of time t normalized by the L2-norm of either the observed waveform O($\boldsymbol{r}_i$,t) or the calculated waveform C($\boldsymbol{r}_i$,t). The both variance reductions become 1 when O($\boldsymbol{r}_i$,t) equals C($\boldsymbol{r}_i$,t), i.e., variance reductions of 1 indicate the best matches. These values become smaller as O($\boldsymbol{r}_i$,t) becomes more different from C($\boldsymbol{r}_i$,t). VRO(t) and VRC(t) are sensitive to overestimation and underestimation of C($\boldsymbol{r}_i$,t) with respect to O($\boldsymbol{r}_i$,t). Therefore, we conclude that the combination of three indices rather than a single index allows us to achieve a more accurate tsunami forecast. In our method, we avoid the mismatch caused by wave phase differences by using the maximum value of the absolute values of the observed waveforms O($\boldsymbol{r}_i$,t) and calculated waveforms C($\boldsymbol{r}_i$,t).

2.4 Numerical test of our method

We investigate whether it is possible to select appropriate tsunami scenarios from TSB by using the three indices. In this examination, we assume that the synthetic observed waveforms is “pseudo-observation” waveforms because the S-net has not yet been used to record actual tsunami observation data. We then calculate tsunami waveforms by using the slip distribution of the 2011 Tohoku earthquake tsunami [17]. Although this source model was estimated by considering the effect of the rupture process on the fault plane, we assume that the co-seismic crustal deformation is immediately completed at time t=0. To construct the TSB, we set up about 2,000 tsunami source models in the region of the Japan Trench [18], the location of which is such that it can affect the Pacific coast of Kanto, Tohoku, and Hokkaido.

We examine the selected tsunami scenarios by comparing the maximum coastal tsunami height distributions of the pseudo-observation scenario and the selected tsunami scenarios. Our multi-index method selects 56 tsunami scenarios under the criteria of VRO(t=5 min) >= 0.0, VRC(t=5 min) >= 0.0, and R(t=5 min) >= 0.7. Fig. 3a plots the selected tsunami scenarios on the VRO-VRC diagram. Fig. 3b represents diagram of the correlation between the offshore indices at time t=5 min and the coastal indices. In these figures, colored squares indicate the selected tsunami scenarios. As shown in this figure, all coastal VR values for the selected tsunami scenarios are closer to 1 than the offshore VR values for the corresponding tsunami scenarios are (coastal VR is larger than offshore VR(t=5 min)). Therefore, we confirm that it is possible to select appropriate tsunami scenarios that have maximum tsunami height distributions constrained within the criteria used for the offshore waveform comparison. A variety of the maximum coastal tsunami height distributions along the Pacific coast of Kanto, Tohoku, and Hokkaido shown as grey lines in Fig. 4a, which indicate overestimation and underestimation by the pseudo-observation scenario (red line), could express the uncertainties of a tsunami forecast. Fig. 4b and 4c show inundation depth map around the Pacific coast of Chiba prefecture for the pseudo-observation and the best-matched tsunami scenario.

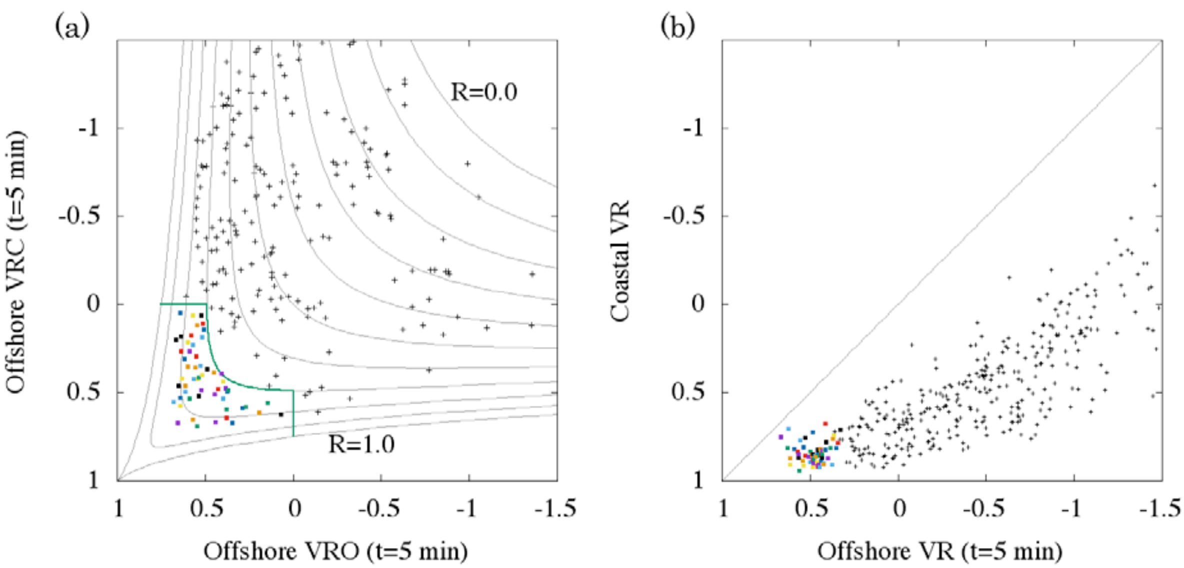

Fig. 3 – Offshore and coastal indices for the 2011 Tohoku earthquake tsunami

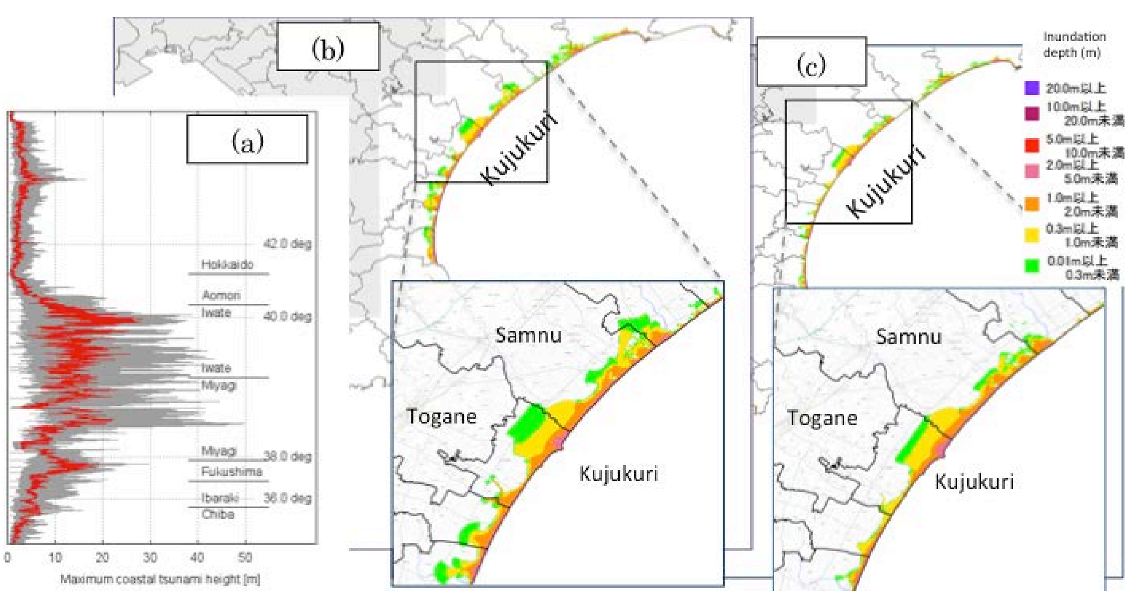

Fig. 4 – Evaluation for coastal tsunami heights and inundation depth for the 2011 Tohoku earthquake tsunami

3. Improving dissemination toward tsunami disaster mitigation

In order to reduce human damage caused by tsunamis, it is important to encourage the necessary of evacuation by providing the appropriate and accurate disaster prevention information. Under such awareness of the problem, we develop a prototype of the Web-based Application Programing Interface (Web API), which enables that the computer program could retrieve observation data for earthquakes and tsunamis and/or predicted information. Then we implement a prototype of web-browser based real-time ground motion and tsunami monitor using this API. The monitor has a function for real-time display of the current observation records by integrating the information of K-NET and KiK-net in addition to the S-net and a function of the past events for disaster prevention training and demonstrations. Moreover, it is possible to show simulated past tsunamis and/or expected tsunamis. Furthermore, cooperation with external systems developed by the other SIP program, such as a “real-time earthquake information system for damage estimation and situation assessment” developed under the program of “Reinforcement of Resilient Function for Preventing and Mitigating Disasters” could be archived through this API [19].

We are also currently developing applications for smartphones on the Android OS (Fig. 5) and iOS that display real-time ground motion and will be kicked by a trigger of earthquake using Push notifications. These applications are suitable to disseminate predicted information for the citizens to avoid misjudgment of evacuation.

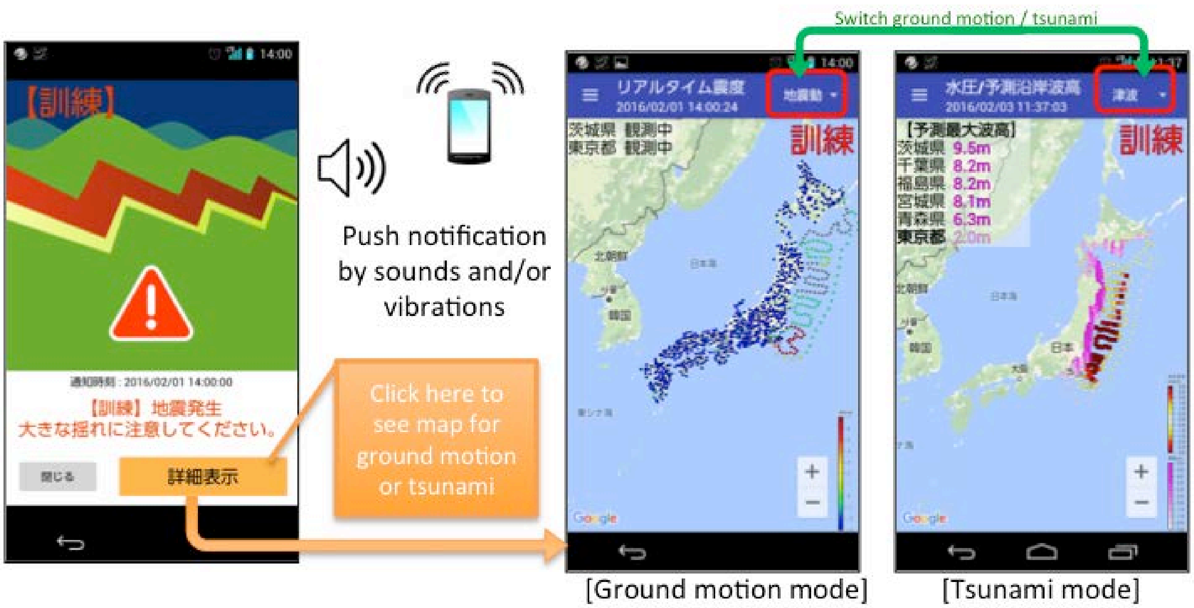

Fig. 5 – Snapshots of mobile application for Android OS

We are planning a demonstration experiment to evaluate and improve our real-time tsunami inundation forecast and dissemination system. For advance preparation, we have regular meetings with Chiba prefecture and JMA and conduct a questionnaire survey for persons in charge for disaster prevention in 16 local governments along the Pacific coast of Chiba prefecture about current status of the provision for earthquakes and tsunamis and the usage for real-time tsunami inundation forecast information. As a result of a questionnaire survey, we confirm that it is expected to be able to use for the first tsunami warning to evacuate from tsunamis and finishing warning for leaving emergency evacuation area for their home.

4. Concluding remarks

In this paper, we introduced real-time tsunami inundation forecast system using S-net data in "Innovative Research toward Tsunami Disaster Mitigation" in the "Enhancement of Societal Resiliency against Natural Disasters" in SIP, which is a national project for science, technology and innovation. One of the causes of enormous damages during the 2011 megathrust Tohoku earthquake (M 9.0) was the underestimation of the first estimation for tsunami height of JMA forecast as well as the insufficient dissemination of the tsunami information to public due to power failures. To reduce such fatalities, it is essentially important to deliver prompt and accurate forecast to the on-shore residences when a megathrust tsunami is generated by a huge earthquake. Therefore, we are developing real-time tsunami inundation forecast system using data to be taken from S-net, which is a dense and large scale offshore observation network under construction along the Japan Trench by NIED. For further works, we will share observed data and predicted results with local governments through our API and/or information sharing system proposed by the other SIP project (e.g., "real-time earthquake information system for damage estimation and situation assessment" provided by the project of "Reinforcement of Resilient Function for Preventing and Mitigating Disasters"). Furthermore, we evaluate and improve our system via demonstration experiments with local governments.

5. Acknowledgements

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