A tsunami of a size exceeding any foreseen was generated with the 2011 Earthquake off the Pacific Coast of Tohoku. While JR East suffered damage to railway facilities and rolling stock in the tsunami, there were no major injuries to passengers on trains or at stations.

Conventional countermeasures against tsunamis are done based on tsunami hazard maps prepared by local governments, but research has progressed recently on a method of predicting the scope of flooding by tsunamis of individual earthquakes using information that can be gained in the time between an earthquake occurring and the tsunami reaching the coastline. We thus assessed the possibility of using that method for railways as a countermeasure against tsunamis.

Keywords: Tsunami, Scope of flooding, Tsunami hazard map, Real-time tsunami prediction

1 Introduction

The frequency at which tsunamis occur is low, but they can bring about great damage when they do occur. A tsunami of a size greatly exceeding assumptions was generated with the March 11, 2011 Earthquake off the Pacific Coast of Tohoku, resulting in tremendous damage. While JR East suffered damage to railway facilities and rolling stock in the tsunami, there were no major injuries to passengers on trains or at stations.

JR East has created manuals for responding to tsunamis that stipulated areas of caution according to tsunami hazard maps prepared by local governments. However, those hazard maps only predict the scope of flooding in tsunamis of pre-assumed earthquakes. In an earthquake differing from those pre-assumed earthquakes, there will be areas with remarkable difference between the scope of actual flooding and that shown on hazard maps.

Research is thus underway to predict in real time the scope of flooding by tsunamis using information that can be gained in the time between an earthquake occurring and the tsunami reaching the coastline. If real-time predictions of tsunamis can predict the scope of flooding promptly and accurately after an earthquake, there is a high probability that such a method can be used as a countermeasure against tsunamis for railways. This article introduces a method of predicting the scope of flooding by tsunamis in real time, assessment of its accuracy along, and the outlook for the future in utilizing it for railways.

2 Railway Damage in 2011 Earthquake off the Pacific Coast of Tohoku

Railway facilities on seven JR East lines on the Pacific coast (Hachinohe, Yamada, Ofunato, Kesennuma, Ishinomaki, Seneksi, and Joban lines) suffered major damage due to the tsunami caused by the earthquake. Fig. 1 shows the lines damaged by the tsunami, and Table 1 shows the length and main damage of the sections of the seven lines affected.

Fig. 2 (a) shows an example of damage to bridges. Nozawa et al. investigated the state of damage of 153 bridge piers where bridge girders were washed out to study the effects of the tsunami on the bottom parts of bridges. The results of that investigation show that 37 were fractured or tilted and four collapsed.

Fig. 2 (b) shows an example of damage to embankments. Fujisawa et al. made on-site investigations at locations where the tsunami is assumed to have topped embankments on the Hachinohe, Yamada, Ofunato, Kesennuma, Ishinomaki, and Seneksi lines, which suffered major tsunami damage. The
Methods of predicting the scope of flooding in a tsunami are by preparing tsunami hazard maps that predict the scope of flooding by tsunamis based on pre-assumed earthquakes and real-time tsunami prediction using information that can be gained in the time between an earthquake occurring and the tsunami reaching the coastline to predict the scope of flooding.

### 3.1 Tsunami Hazard Maps

Tsunami hazard maps prepared by local governments were traditionally prepared based on the Tsunami and Storm Surge Hazard Map Manual (March 2004). This manual defines anticipated earthquakes as imminent earthquakes that have occurred repeatedly in the past and that the possibility of occurring in the near future is high based on those experienced in the past few hundred years for a certain area. And tsunami hazard maps are prepared by predicting the scope of flooding in a tsunami based on information on those earthquakes. However, if an earthquake other than those anticipated occurs, differences in the actual scope of flooding and that anticipated in hazard maps may result. Fig. 3 shows an example of comparison of actual and anticipated scope of flooding in the 2011 Earthquake off the Pacific coast of Tohoku. In the tsunami accompanying that earthquake, the scope of flooding matched that of hazard maps for the most part in some locations such as Miyako City, but it greatly exceeded the scope anticipated on hazard maps in many areas such as Ishinomaki and Ofunato cities. The reason the extent of flooding was so large was that the earthquake was a magnitude (MW) of 9.0, greater than earthquakes in the past few hundred years used for prediction in the Tsunami and Storm Surge Hazard Map Manual.

The Cabinet Office Central Disaster Prevention Council thus decided in September of 2011 that, in future assumption of earthquakes and tsunamis, massive earthquakes and tsunamis of the largest class possible should be considered. In light of that, local governments are updating tsunami hazard maps to assume the largest class of massive earthquake.

In the JR East tsunami response manual, sections requiring caution in tsunamis are stipulated based on tsunami hazard maps prepared by local governments. For that reason, individual branches are revising sections requiring caution in terms of tsunamis and other details based on hazard maps currently being updated by local governments.

### 3.2 Real-time Tsunami Prediction

Real-time tsunami prediction involves predicting in real time the scope of flooding by tsunamis before their arrival using information that can be gained in the time between an earthquake occurring and the first or largest waves reaching the coastline. Time between an earthquake occurring offshore near Japan and a tsunami reaching the coastline is just a few minutes or a few tens of minutes. For that reason, starting to calculate prediction of the scope of flooding in a tsunami after an earthquake occurs is often too late. Even if it is in time, notification of the predicted
scope is delayed during the time calculations are being made. Real-time scope of flooding due to tsunamis of a variety of possible earthquakes is calculated in advance and the results of that calculation are stored in a database. When an earthquake strikes, the database is searched to predict the scope of tsunami flooding.

The Japan Meteorological Agency’s (JMA) tsunami warning system has tsunami heights that may result for a variety of possible earthquakes registered as a database. The most advanced warning system of its kind in the world, it predicts occurrence of a tsunami in 66 warning sections across Japan as well as specific tsunami height and tsunami arrival time for locations with tidal observatories, all within just a few minutes of the earthquake. Real-time tsunami prediction by Abe and Imamura takes this concept a step further to predict scope of flooding before the arrival of a tsunami.

Data that can be obtained between the occurrence of an earthquake and arrival of a tsunami is hypocenter of the earthquake (location, depth, magnitude) data and tsunami data observed offshore. Real-time tsunami prediction predicts the scope of flooding using that hypocenter location and magnitude along with tsunami data observed offshore.

With real-time tsunami prediction, hypocenter location and magnitude of variety of possible earthquakes along with results of calculating offshore tsunami height and scope of flooding from a tsunami resulting from such earthquakes are stored in a tsunami flooding prediction database. When an earthquake strikes, data such as the location of the hypocenter and the magnitude available immediately after the earthquake and tsunami height observed by wave meters offshore is matched with earthquakes in the database to predict the scope of tsunami flooding. Fig. 4 and the following show the flow of real-time tsunami prediction. (1) Hypocenter location and magnitude are read from the JMA earthquake early warning after an earthquake occurs. (2) As the first stage, earthquakes resembling that of the earthquake early warning are searched and extracted from the tsunami flooding prediction database to predict scope of tsunami flooding. (3) Tsunami height observed by wave meters offshore is read. (4) As the second stage, earthquakes with a hypocenter location close to that acquired in step 1 and offshore tsunami height observation close to that in step 3 are searched and extracted from the tsunami flooding prediction database, and the scope of tsunami flooding predicted is corrected if it differs from the scope in step 2.

3.3 Tsunami Flooding Prediction Simulation
Here we will cover the method of simulating scope of flooding used in this research as the method of numerically analyzing tsunami propagation to find the scope of tsunami flooding by tsunami hazard maps and real-time tsunami prediction. Fig. 5 shows an image of tsunami flooding prediction simulation. In tsunami flooding prediction simulation, scope of flooding can be found by expressing propagation by the long wave theory with initial sea level from sea floor uplift and subsidence due to the earthquake as the initial condition. Initial sea level used the amount of fault slip, size, and other parameters found by the similarity theory of hypocenter magnitude, applying the results of seabed ground vertical displacement distribution found by the Mansinha/Smylie method. Tsunami propagation at deep ocean of 50 m or greater depth was described by the linear long wave theory that ignores seabed friction and nonlinearity. Propagation at coastal shallow seas of less than 50 m or when running on land was described by the nonlinear long wave theory incorporating seabed friction and nonlinearity. Grids used in the simulation gradually became finer computational grids because tsunami wavelength becomes shorter as sea depth becomes shallower.
JR East is, as previously mentioned, conducting countermeasures against tsunamis based on tsunami hazard maps prepared by local governments. However, those hazard maps predict scope of flooding based on anticipated earthquakes, so differences may result between the actual scope of flooding and that anticipated in hazard maps if an earthquake other than those anticipated occurs. For that reason, real-time tsunami prediction could be useful as a countermeasure against tsunamis for railways if it can predict the scope of flooding quickly and accurately. We thus verified accuracy of prediction of scope of flooding and time required to issue predictions using the 2011 Earthquake off the Pacific Coast of Tohoku as an example so as to assess usefulness for railways of real-time tsunami prediction.

That massive earthquake with a hypocenter off the Sanriku coast at 38.10°N, 142.86°E (approx. 130 km east-southeast of the Oshika Peninsula), at a depth of 24 km, struck at 2:46 pm on March 11, 2011 with a magnitude (MW) of 9.0. That massive earthquake with a hypocenter off the Sanriku coast at 38.10°N, 142.86°E (approx. 130 km east-southeast of the Oshika Peninsula), at a depth of 24 km, struck at 2:46 pm on March 11, 2011 with a magnitude (MW) of 9.0. The largest waves of the ensuing tsunami reached Iwate Prefecture’s Ofunato approx. 32 minutes later at 3:18 pm, Kamaishi approx. 35 minutes later at 3:21 pm, Miyako and Miyagi Prefecture’s Ishinomaki approx. 40 minutes later at 3:26 pm, and near Nobiru in Miyagi Prefecture approx. 45 minutes later at about 3:30 pm.

4.1 Accuracy of First Stage Prediction
We examined prediction accuracy in the first stage, which uses only the location and magnitude of the earthquake hypocenter for real-time tsunami prediction. Four types of information regarding earthquakes are issued by the JMA after an earthquake: earthquake early warning, earthquake information (preliminary value), earthquake information (interim value), and earthquake information (definitive value). Earthquake early warnings and earthquake information (preliminary value) can be obtained immediately after an earthquake, but earthquake information (interim value) and earthquake information (definitive value) can be obtained immediately after an earthquake, but earthquake information (interim value) and earthquake information (definitive value) can be obtained immediately after an earthquake, but earthquake information (interim value) and earthquake information (definitive value) can be obtained immediately after an earthquake, but earthquake information (interim value) and earthquake information (definitive value) a few months later. Therefore, only earthquake early warnings and earthquake information (preliminary value) can be used for real-time tsunami prediction.

Table 2 Issuance of Earthquake Early Warnings

<table>
<thead>
<tr>
<th>Issuance time</th>
<th>Hypocenter details</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:46:45.6</td>
<td>36.2 142.7 10 km 4.3</td>
</tr>
<tr>
<td>14:46:46.7</td>
<td>36.2 142.7 10 km 5.9</td>
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<tr>
<td>14:46:47.7</td>
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</tr>
<tr>
<td>14:46:48.9</td>
<td>36.2 142.7 10 km 7.2</td>
</tr>
<tr>
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<td>36.2 142.7 10 km 6.3</td>
</tr>
<tr>
<td>14:46:50.9</td>
<td>36.2 142.7 10 km 6.6</td>
</tr>
<tr>
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<td>36.2 142.7 10 km 6.6</td>
</tr>
<tr>
<td>14:46:56.1</td>
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<td>14:48:25.2</td>
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</tr>
<tr>
<td>14:48:37.0</td>
<td>36.1 142.9 10 km 8.1</td>
</tr>
</tbody>
</table>

Fig. 4 Flow of Real-time Tsunami Prediction

Fig. 5 Image of Tsunami Flooding Prediction Simulation
estimated to be JMA magnitude of $M_J 7.9$. Fig. 6 (a) shows the predicted scope of flooding near Nobiru Station on the Senseki Line using the location and magnitude of the hypocenter from the 13th earthquake early warning. From that, we can see that predicted flooding was less than the actual scope of flooding near Nobiru Station.

In this way, the example from the tsunami in the 2011 earthquake shows that real-time tsunami prediction using location and magnitude of the hypocenter from earthquake early warnings can predict the scope of flooding by using hypocenter data issued approx. two minutes after an earthquake occurs. However, the resulting predicted flooding was less than the actual scope of flooding. Therefore, while real-time tsunami prediction using only hypocenter data from earthquake early warnings can be made at very close to actual real time, there are problems in terms of accuracy of predicted scope of flooding.

4.2 Accuracy of Second Stage Prediction

We examined prediction accuracy in the second stage, which uses the location of the earthquake hypocenter and tsunami height observations offshore for real-time tsunami prediction. Data of GPS wave recorders set up by the Ports and Harbours Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) at locations 10 to 20 km offshore are used for offshore tsunami observations. The largest wave height of the tsunami in the 2011 earthquake was observed earliest off Kamaishi, at 3:11 pm, approx. 25 minutes after the earthquake occurred. Fig. 6 (b) shows the predicted scope of flooding near Nobiru Station on the Senseki Line using the location of the hypocenter from the earthquake early warning and data of tsunami observation off Kamaishi. From that, we can see that predicted flooding closely matched the actual scope of flooding near Nobiru Station.

According to results of tsunami flooding prediction by Abe and Imamura for Sendai and Ishinomaki cities in Miyagi Prefecture using hypocenter data and GPS wave recorder data in the 2011 earthquake, accuracy of prediction can be increased by applying data on tsunami height observations by GPS wave recorders. That scope of flooding was found by a method similar to that of the JR East research.

In this way, the example from the tsunami in the 2011 earthquake shows that with real-time tsunami prediction using location of the hypocenter from earthquake early warnings and tsunami height observations by wave recorders offshore, predicted flooding closely matched the actual scope of flooding. However, the largest wave height of the tsunami was observed earliest approx. 25 minutes after the earthquake occurred, approx. seven minutes before the tsunami reached Ofunato. Therefore, we found that, while real-time tsunami prediction using hypocenter data from earthquake early warnings and tsunami height observations by wave recorders offshore predicts the scope of flooding with good accuracy, it cannot be done at close to actual real time.

5.1 Improving Accuracy of Hypocenter Data

In the 2011 earthquake, the estimated JMA magnitude of early earthquake warnings was a maximum of $M_J 8.1$ and the earthquake information (preliminary value) was $M_J 7.9$, smaller than the earthquake information (definitive value) moment magnitude $Mw 9.0$. For that reason, the predicted flooding of real-time tsunami prediction was less than the actual scope of flooding. JMA magnitude is calculated from maximum amplitude of displacement data recorded by seismometers, making it good...
for quick calculation a few minutes after an earthquake occurs. However, it is found to generally underestimate the magnitude of earthquakes much larger than magnitude Mw 8 (magnitude saturation) -10.

Verification of real-time tsunami prediction in this article only uses the example near Nobiho Station on the Senkoku Line in the 2011 Earthquake off the Pacific Coast of Tohoku. For that reason, we intend to make statistical assessment of prediction error in flooding in other areas by conducting similar verification. Moreover, we also intend to assess to what degree error in accuracy of hypocenter data in JMA earthquake early warnings impacts the predicted scope of flooding. And if accuracy of hypocenter data in earthquake early warnings can be increased, we believe that the scope of flooding predicted from hypocenter data in real-time tsunami predictions will become more accurate.

5.2 Expansion of Offshore Tsunami Observation
Real-time tsunami prediction can more accurately predict the scope of tsunami flooding by using tsunami observation data observed offshore. In the JR East area, 10 GPS wave recorders have set up at locations 10 to 20 km offshore by the Ports and Harbours Bureau of MLIT. The largest wave height of the tsunami in the 2011 earthquake was observed by GPS wave recorders earliest off Kamaishi at 3:11 pm, approx. 25 minutes after the earthquake occurred.

Meanwhile, the National Research Institute for Earth Science and Disaster Prevention is going forward with a project to densely locate cabled seafloor seismometers/tsunami wave recorders along the Japan Trench and southern Kuril-Kamchatka Trench from the Kanto to Tohoku areas. Plans also call for the project to set up those devices from the coast to the outer edge of the trench axis of the Japan Trench, a few hundred kilometers offshore. That will enable real-time observation of tsunamis at locations closer to the hypocenter than GPS wave records offshore. Hence, observation by seafloor seismometers will be possible closer to the hypocenter in earthquakes at sea, it can contribute to improving the accuracy of earthquake early warnings.

6. Conclusion
Real-time tsunami prediction has low accuracy in predicting the scope of flooding in tsunamis when relying only on hypocenter data at very close to actual real time. Conversely, accuracy becomes higher when introducing tsunami data observed offshore, but predictions using that data cannot be made at close to actual real time. For that reason, it is currently difficult to use real-time tsunami prediction for railways. JR East will continue to keep an eye on trends at related agencies while introducing the latest observation system data to real-time tsunami prediction so as to be able to utilize this method for railway safety in the future.

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Reference: