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Damage to the Railway System along the Coast Due to the 2011 Tohoku Earthquake Tsunami

Soichiro SHIMAMURA*
Fumihiko IMAMURA**
Ikuo ABE***

*Department of Civil and Environmental Engineering, Tohoku University
6-6-11-1106, Aoba, Sendai, 980-8579, JAPAN
**International Research Institute of Disaster Science, Tohoku University
***Department of Social Environment, Fuji Tokoha University

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ABSTRACT

The enormous Mw 9.0 earthquake with a hypocenter off Sanriku-oki that occurred at approximately 14:46 (JST) on March 11, 2011, and the subsequent tsunami, caused serious damage along the Pacific coast of Iwate, Miyagi, and Fukushima. The damage to infrastructure was remarkable, and the damage to the railway caused by the tsunami was the greatest damage ever to occur to the railway. JR-East reported that they checked the damage caused by only the tsunami along seven lines, which had a total distance of 325 km, and the form of damage varied by line.

This paper summarizes the damage to the railway (including damage to vehicles) and the evacuation guidance situation for each line and investigates how the trains were damaged based on the numerical analysis of the 2011 Tohoku Earthquake Tsunami.

Keyword: The 2011 Tohoku Earthquake Tsunami, Train, Numerical Analysis

1. Introduction

On 2011 March 11th 14:46 (JST), an enormous Mw 9.0 earthquake occurred with a seismic center on the coast of Sanriku. Due to a strong shake ranging from 6 to 7 on the Japanese scale and a subsequent tsunami, approximately 19,000 persons died or were missing (as of March, 2012) along the Pacific coast (including Iwate, Miyagi and Fukushima). Damage to the infrastructure, such as roads, bridges, plants, water and sewage, was also remarkable, and the damage to the railway caused by the earthquake and tsunami was the greatest damage ever to occur to the railway. According to JR East, the damage caused only by the tsunami was checked along 7 provincial routes over a total of approximately 325 km.

This paper presents an outline of the 2011 Tohoku Earthquake Tsunami, and, because the degree and form of damage differed by route, examples of train damage are summarized for each route. In addition, a numerical analysis of the tsunami, using the seismic deformation model of the 2011 Tohoku Earthquake Tsunami (Tohoku University model version. 1.0), was performed to determine the flow conditions in the area where the damage to the railway occurred. A new fall model of the damage to trains caused by the tsunami is proposed, and the mechanism of damage is discussed by comparison with the results of analysis.

2. Outline of the 2011 Tohoku Earthquake Tsunami

As described above, the 2011 Tohoku Earthquake Tsunami of Mw 9.0 caused enormous damage to most areas of the Pacific Ocean coast. Within a broad flood area (about 560 km2), the tsunami caused the collapse of reinforced concrete structures and the outbreak of fires. The waveform of the offing (Fig. 1) is an important feature of tsunami action. On March 11th, immediately after the main Mw 9.0 shock, three consecutive Mw 7 aftershocks occurred, causing an increase in wave height in two stages, as shown in the graph on the right (Fig. 1). These shocks caused a very high tsunami in the area along the shore, and evidence of the great height of the tsunami can be seen in various places (Fig. 2). In particular, along the Iwate rias coast, the run-up height was nearly 40 m.

This tsunami, with the greatest wave force ever and causing the greatest area of flooding also seriously affected the railway. Figure 3 shows damage in the JR East province. The form of damage, including damage to electrification pillars, displacement of the railway track, washout and burial of bridge beams, failure of signal and communication equipment, and

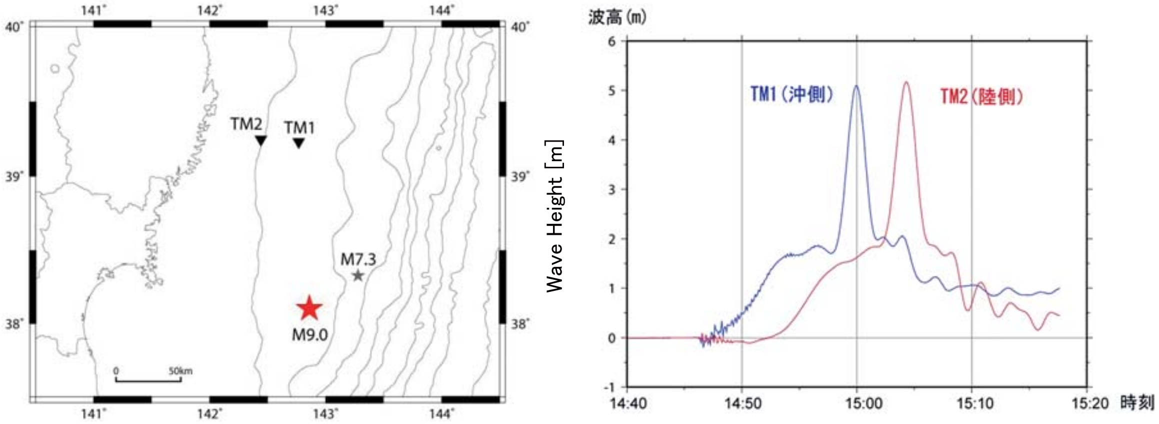


Fig. 1. Sea-level change recorded by the ocean floor cable seismometer off of Kamaishi (Earthquake Research Institute, The University of Tokyo)

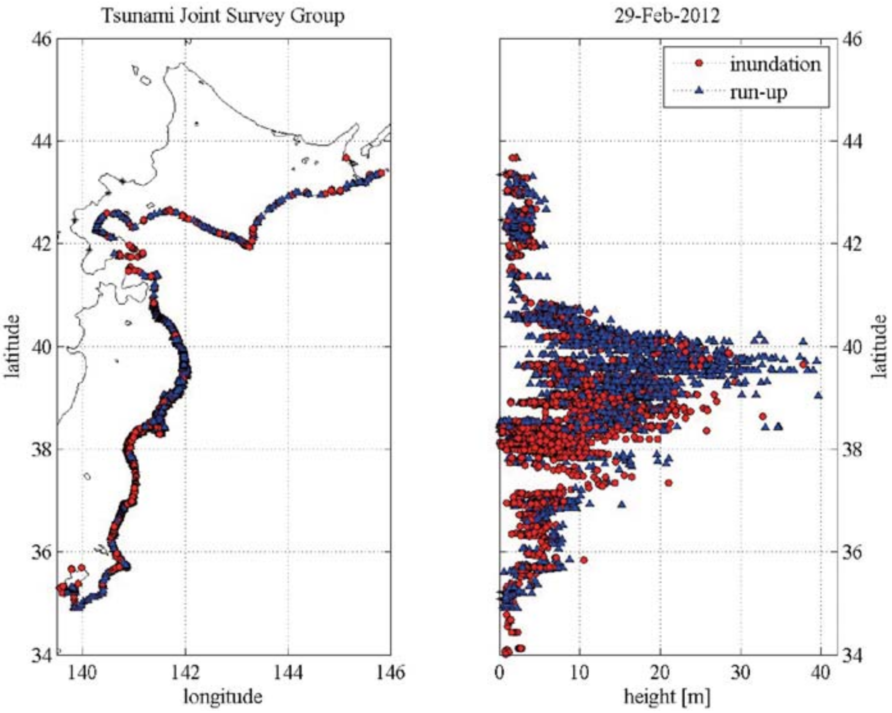
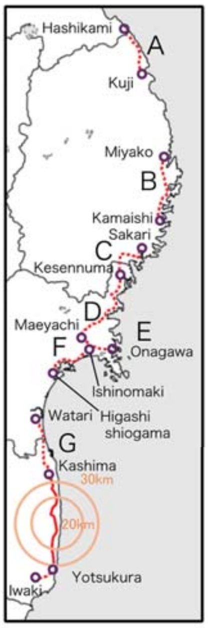


Fig. 2. The field survey result projected in the direction of latitude (The 2011 Tohoku Earthquake Tsunami Joint Survey Group)



Line	Section	Distance	Stations: Check Points	Stations: Washout Points	Stations: Other Damage	Damaged Places	Sum (Damaged Places)
A:Hachinohe	Hashikami - Kuji	37km	12	0	2	20	20
B:Yamada	Miyako - Kamaishi	55km	13	4	4	80	90
C:Ofunato	Kesennuma - Sakari	44km	12	6	1	70	80
D:Kesennuma	Maeyachi - Kesennuma	73km	21	9	3	250	260
E:Ishinomaki	Maeyachi - Onagawa	32km	11	1	3	70	70
F:Senseki	Higashishiogama - Ishinomaki	34km	16	0	8	390	400
G:Joban	Iwaki - Watari	50km	14	3	4	850	860
Sum		**325km**	**99**	**23**	**25**	**1730**	**1780**

Fig. 3. Damage to railway caused by the tsunami (JR East)

ballast outflow, varied significantly. In this paper, to give top priority to human life, the damage to trains is considered and summarized.

3. Damage to the railway

This chapter introduces examples of train damage caused by the tsunami.

3.1. Yamada-Line・St. Tsugaruishi (Iwate, Miyako : Photo. 1)

The interrupted section of the Yamada Line is the longest in the nine main disaster-affected routes, and the route passes through areas that were enormously damaged by the earthquake disaster, such as Yamada town and Otsuchi-Cho along the railway line. At Tsugaruishi Station, while the train for Miyako Station from Kamaishi Station stopped, it was affected by intense shaking. As the tsunami alarm from the operation management center was sounded promptly, the passengers evacuated to nearby Tsugaruishi Elementary School, but, because the tsunami reached the elementary school, they then evacuated to safety on the hill behind the school. According to JR staff, at approximately 15:20, the train was washed along in the Toyomane Station direction from Tsugaruishi Station, and it drifted approximately 80 m along the railway line from where it had stopped. The tsunami numerical analysis also shows that the tsunami arrived at Tsugaruishi Station, which is approximately 1 km from the coast.

Photo 1. Yamada-Line・St. Tsugaruishi (Provided by JR East)

3.2. Ofunato-Line・Ofunato-Shimofunato (Iwate, Ofunato : Photo. 2)

Along Ofunato Line, a train with a two-car formation was heading to Shimofunato Station from Ofunato Station at the time the earthquake occurred. Although the train came to an emergency stop at a location that was several meters higher than the surrounding land, the crew who received the evacuation directive helped the passengers down and proceeded with evacuation. They did not evacuate to Ofunato Elementary School, which is the designated evacuation building, due to the advice of a local passenger but rather went to Ofunato Junior High School, which is the same distance from the train as the elementary school but at a higher altitude. As a result, although the tsunami reached the schoolyard of the elementary school, they evacuated safely to the junior high school. The train, which had come to an emergency stop, was approximately 240 m from the coast and was spared derailment and drift, but the train chassis was covered with water and the train was immobile.

Photo 2. Ofunato-Line・Ofunato-Shimofunato (Provided by JR East)

3.3. Kesennuma-Line・Matsuiwa-Saichi (Miyagi, Kesennuma : Photo. 3)

A train with a two-car formation to Kogota was running between Matsuiwa and Saichi when the earthquake occurred. After the train made an emergency stop, the train driver received the tsunami alarm, had the passengers disembark and started the evacuation. It was necessary to walk approximately 200 m along the railway track, and the train driver saw the sea level decrease suddenly and evacuated at a hurried pace to the Junior High School, which is situated approximately 1 km inland. Although the passengers and the crew were safe, the train was derailed and drifted approximately 60 m in the direction of the tsunami.

Photo 3. Kesennuma-Line・Matsuiwa-Saichi (Provided by JR East)

3.4. Ishinomaki-Line・St. Onagawa (Miyagi, Onagawa : Photo. 4 and Photo. 5)

Along Ishinomaki Line (the whole line section (44.9 km)), the damaged section was only 700 m from Onagawa Station to Onagawa Tunnel but suffered crushing damage from the shape of the bay.

A train with a two-car formation was at rest and ready for departure in Onagawa Station yard when the earthquake occurred, but this train and the train used by some hot spring institutions were carried away by the tsunami. Among the trains in the two-car formation that drifted, one train drifted approximately 200 m and was completely destroyed, and the other train drifted 100 m more inland and stopped at a graveyard on a hill. In addition, damage to the station building and the railway track were serious, and both were severely damaged.

Photo 4, Photo 5. Ishinomaki-Line • around St. Onagawa

3.5. Senseki-Line・Tona-Nobiru (Miyagi, Hagashimatsushima : Photo. 6)

Senseki Line connecting Sendai and Ishinomaki runs approximately 200 trains a day as a route for

Photo 6. Senseki-Line・Tona-Nobiru (Provided by JR East)

commuters and school goers. Two trains were running when the earthquake occurred in this area, and one of them was the train to Aoba-Dori Station. The passengers evacuated according to the instructions of the crew to Nobiru Elementary School, which was the nearby evacuation building, but the tsunami reached this elementary school. Immediately afterwards, the train was derailed by the tsunami, turned at a right angle and stopped when it hit a house behind it. Another train (Photo. 7) for Ishinomaki that was stopped at this place went ahead approximately 1.5 km in the Ishinomaki direction from the train that was derailed. This train was stopped on a hill that was a little more than 10 m high. The crew decided to stay in the train with the passengers on the advice of local people, and they escaped the tsunami and were safe. The difference of a slight distance and a slight altitude are clearly distinguished by the light and shaded areas.

Photo 7. Senseki-Line・Tona-RikuzenOno (Provided by JR East)

3.6. Train damage in other areas

The Joban Line had the longest section interrupted by the East Japan great earthquake disaster. The main factors included the explosion at Fukushima First Nuclear Power Plant, but the damage caused by the tsunami was too serious. In particular, a train that was stopped and the station building at Shinchi Station of Fukushima were destroyed. In addition, there was damage to a freight train on the Joban Line. Between Hamayoshida to Yamashita, all of the containers that had been piled up were washed away and collided with private houses, and they were a factor in the extent of the damage. The damage to Sendai Airport access lines and North Rias Line, South Rias Line and Hachinohe Line were confirmed in other reports.

Photo 8. Joban-Line・St. Shinchi

Photo 9. Joban-Line・Hamayoshida-Shimoyama (Provided by JR East)

4. Tsunami Numerical Analysis

Tsunami numerical analysis was performed for each disaster area to examine the mechanism of the train damage caused by the tsunami, which is given in detail in the previous section. As described above, the seismic deformation model uses the Tohoku University model version 1.0 (Fig. 4). For the calculation conditions, a shallow water theory that integrates the

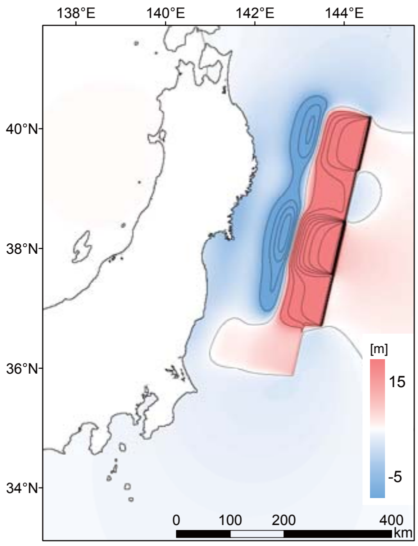


Fig. 4. Tohoku University model (Version 1.0)

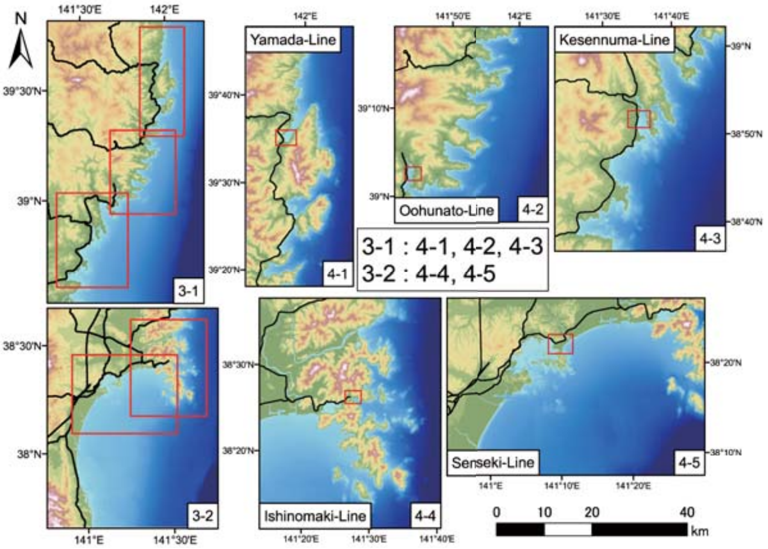


Fig. 5. Computational region

equation of continuity and the Navier-Stokes equation in the depth direction is the dominant equation and was calculated by the Leap-Frog difference method. In addition, public data from the Geographical Survey Institute (before the earthquake disaster) was used for the topography data, rough degree data, and dike data and the mesh size of the region was calculated at 1,350 m> 450 m> 150 m> 50 m. In five regions (Fig. 5, from the north, Yamada-Line, Ofunato-Line, Kesennuma-Line, Ishinomaki-Line, and Senseki-Line), analysis was performed using two patterns to represent shore structures functioning and failing entirely to show the lower limit and the upper limit of the actual damage, respectively. A reproducible examination was also performed by comparing the numerical analysis result in each region with the information in the train damage archive.

In addition, the damage was measured using a model (Fig. 6) that expresses the falling limit of the train caused by the tsunami with the balance of the moment. I used the tsunami force (F_t) calculation method described in H. Yeh (2007) in this model, which has been examined previously and expresses the fall limit of the train caused by tsunami using only the inundation depth.

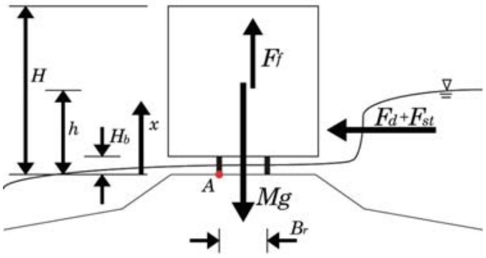


Fig. 6. Fall moment model

$$F_t = F_{st} + F_b + F_d$$

$$F_{st} = \rho gBLh\ , F_b = \rho gLh^2\ , F_d = \frac{1}{2}\rho C_d L(hu^2)_{max}$$

$$\frac{(hu^2)_{max}}{gR^2} = 0.125 - 0.235\frac{z}{R} + 0.110\left(\frac{z}{R}\right)^2\ , h + z = R$$

F_{st} : Hydrostatic Forces, F_b : Buoyant Forces, F_d : Hydrostatic Forces, ρ : fluid density [kg/m^3], g : acceleration of gravity [m/s^2], B : width of train [m], L : length of train [m], h : inundation depth [m], u : velocity [m/s], C_d : Drag Coefficient(=2.0), R : runup height [m]

This value is referred to as the "Falling Limits" and it was calculated to be 1.1 m. The precision of the "Falling Limits" was checked by comparison with the train damage archive.

The analysis results are shown in Fig. 7 and Fig. 8. Figure 7 shows the maximum inundation map in the train damage area (red frames of Fig. 5) in each region in two ways, including the shore structure and not including the shore structure. In addition, the mesh where the maximum inundation depth exceeded the Falling Limits (1.1 m) is shown in red, and less

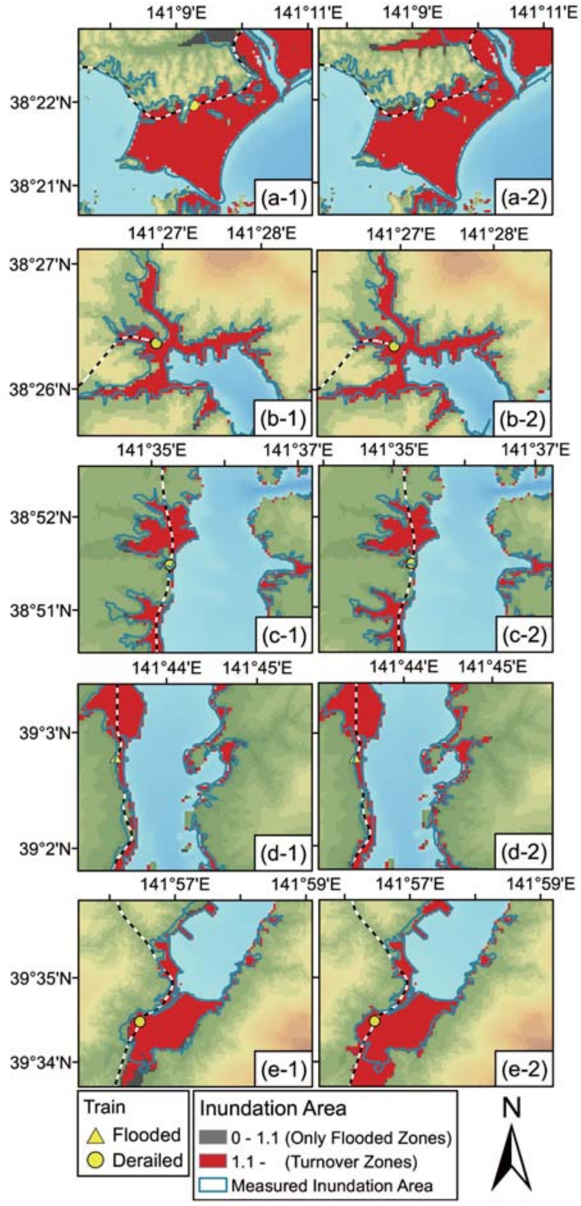


Fig. 7. Maximum inundation map (a:Senseki-Line, b:Ishinomaki-Line, c:Kesennuma-Line, d:Ofunato-Line, e:Yamada-Line, −1: with a shore structure, −2: without a shore structure)

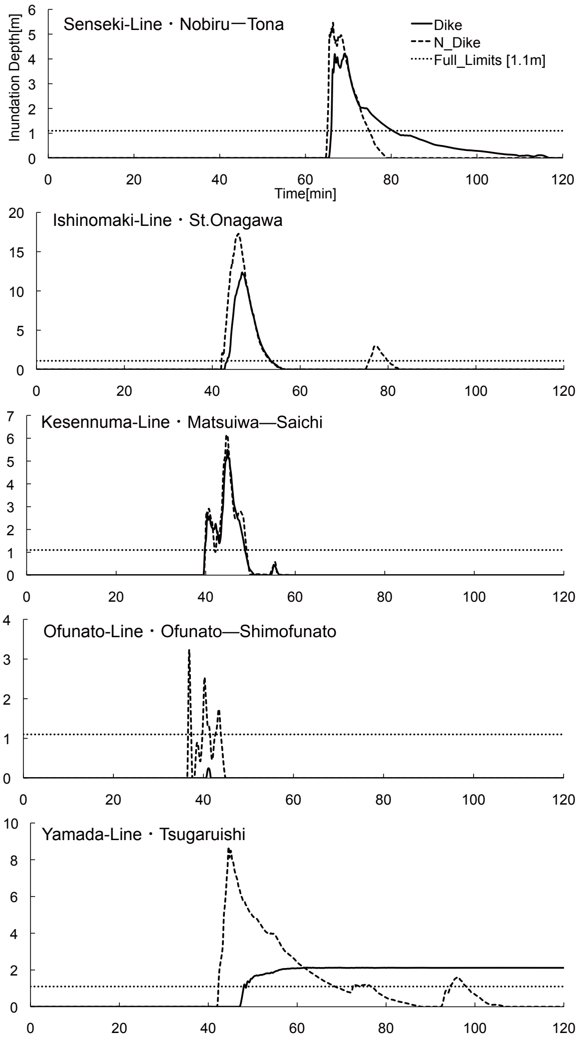


Fig. 8. The time-series wave height

than this limit is shown in gray. Most of the inundation area in the region analyzed here exceeds 1.1 m. The graph in Fig. 8 shows the time-series wave height at each train damage point. As described above, the true phenomenon depends on whether there were shore structures, but the inundation was over the Falling Limits (1.1 m) regardless of the presence of shore structures at the points where the derailment and fall of the train were due to the tsunami, except along Ofunato – Shimofunato Line. In Ofunato – Shimofunato, the only damage was due to the flooding of the train chassis by the tsunami, and the flooding depth reached 3.2 m in the case without the shore structure and did not reach 1.1 m in the case with the shore structure. In other words, the agreement with the real damage was because possibility that the inundation was only 1.1 m in two cases could not be denied, indicating the lower limit and the upper limit of the true phenomenon. However, for the inundation depth along the railway track, this analysis result is overestimated because the height of the railway track, which is the height of the railroad embankment, cannot be considered. Furthermore, Table 1 shows the tsunami arrival time and the influence start time (the falling limit time) determined from the time-series wave height at the train damage points. At Nobiru – Tona, Onagawa and Matsuiwa – Saichi Stations, the tsunami arrival time and the influence time were not signifi-

Table 1. The tsunami arrival time, the influence start time (the falling limit time), and the maximum inundation depth at the train damage points

	Nobiru-Tona	St. Onagawa	Matsiwa - Saichi	Ofunato - Shimofunato	St. Tsugaruishi
Arrivaltime of Tsunami [min]	65	42	39	40	47
	65	42	39	37	42
Time of falllimits [min]	66	43	39	—	48
	65	42	39	39	42
Max inundati on depth [m]	4.21	12.7	5.50	0.25	2.13
	5.46	17.3	6.12	3.23	8.70

cantly influenced by the presence of a shore structure, but an apparent difference caused by the presence of the shore structure along Ofunato - Shimofunato Line and at Tsugaruishi Station.

5. Examination of the drifting behavior in Tsugaruishi

In this report, the fall of trains caused by the tsunami was examined and the archived data and the results of tsunami numerical analysis were compared. However, Nagase (2011) notes that the diesel train that was stopped at Tsugaruishi Station might have floated and drifted for a long time. For most of the trains that were damaged by this tsunami, their behavior, such as rolling, sliding, and floating, is not known, but it is certain that they drifted several tens of meters. In Nagase (2011), the train might have floated because the waterline trace (1.76 m) left on this train was smaller than the trace (2.58 m) that remained at the station where this train was stopped, so he set "Floating Limits" from the balance of the mass of the train and the buoyancy due to the seawater. The result was 1.7 m. However, this analysis is only applicable to the sealed train model. A graph superimposed on the Floating Limits of the time-series wave height of the analysis result is shown in Fig. 9. Figure 9 shows that a wave height greater than 2 m occurred for a long time according to the pattern where the shore structures are considered, and it approached the Falling Limits earlier than the Floating Limits. However, this train approached the Floating Limit earlier than the Falling Limits and drifted because it could not fall down before floating by tsunami because there is no trace of contact with the train in the station yard where it stopped when the earthquake occurred, according to the field survey. Thus, an evaluation method for the train damage mechanism that uses only the inundation depth is limited, and it is necessary to establish a detailed evaluation method that takes into account the velocity, flow direction, among others. However, the evaluation method that uses only the inundation depth is very useful because it has the advantages of versatility and being easy to fit with existing predictive inundation maps.

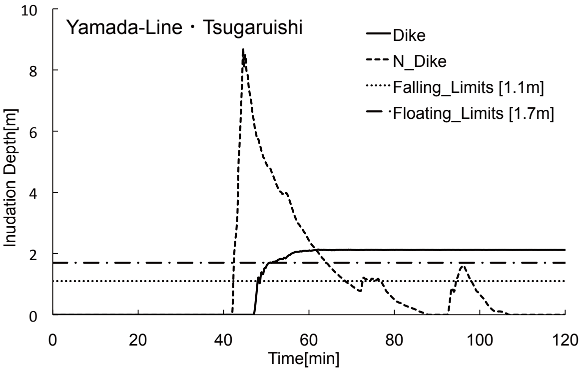


Fig. 9. The time-series wave height (Falling Limits & Floating Limits) In the figure above, change Inudation to Inundation

6. Conclusion

The train damage data was collected from the archive on train damage caused by the 2011 Tohoku Earthquake Tsunami and numerical analysis was performed using the Tohoku University model version 1.0 as the seismic deformation model and the maximum inundation map and the time-series wave height were output for each train damage point. In addition, a new fall moment model for train damage caused by the tsunami was suggested and the "Falling Limits" (1.1 m) were calculated using the tsunami wave force calculation of H. Yeh (2007). The correctness of the analysis results (Falling Limits) was confirmed by the actual damage according to the archive.

Nagase (2011), who considered the train behavior at Tsugaruishi Station as the train damage point, suggested that the Floating Limit at which the train floats due to the tsunami is 1.7 m and assumed that floating occurred before falling. This study limitedly examined train damage by considering the inundation depth alone, and thus further examination of the damage mechanism taking into account the velocity and flow direction is necessary.

Acknowledgment

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