Investigative Research on Bridges Subjected to Tsunami Disaster in 2011 off the Pacific Coast of Tohoku Earthquake

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ABSTRACT

The 2011 off the pacific coast Tohoku earthquake occurred on the 11th of March in 2011. The earthquake was magnitude 9.0(Mw) undersea megathrust earthquake off the coast of Japan, which is the largest earthquake ever recorded near Japan. The strong ground motion registered at the maximum 7 on the Japan Meteorological Agency seismic intensity scale. The hypocentral area of this earthquake extended from off-shore Iwate prefecture to off-shore Ibaraki prefecture where the length is about 450km. It was confirmed that there were 15,844 deaths and 3,393 people missing until the 17th of January in 2012. Powerful tsunami waves were caused by this earthquake and destroyed the cities in coastal area of Tohoku region. Although the structures were partly damaged by the seismic ground motion itself, the majority of distraction was caused by the tsunami waves. As far as bridges are concerned, numbers of superstructures were destroyed by the tsunami waves even though the substructures were remained. In this research, the authors investigated the bridges subjected tsunami waves in Tohoku area, and tried to find out the appropriate structural feature that is preserving the bridge against the attack of tsunami waves. Then the relationship between the flow mechanism of tsunami waves and structural feature of bridges was examined.

KEYWORDS

Tohoku earthquake; Tsunami wave; Bridge superstructure.

INTRODUCTION

A historical earthquake of magnitude 9.0 occurred off the Pacific coast of Tohoku, Japan, on the 11^{th} of March in 2011. The rupture area of fault was approximately 450km length by 200km width. And it generated powerful tsunami waves which brought the disastrous destruction of coastal cities in Tohoku area. In Fact, most of the infrastructures were not critically damaged by the ground motion of earthquake itself, however completely destroyed by the massive tsunami waves.

In regard to the bridges subjected to the tsunami waves, some superstructures were entirely washed away, but others remained with a slight damage. Authors travelled along the coastal cities of Tohoku area to investigate the bridges destroyed and not destroyed. Fig.1 shows the locations that authors visited and the height of the tsunami wave recorded there. After the investigation trip, some common characteristics of bridges which were not washed away were found. In this paper, the authors introduce the examples of the both cases that bridges survived and did not survive, and examine the reasons for these two cases.

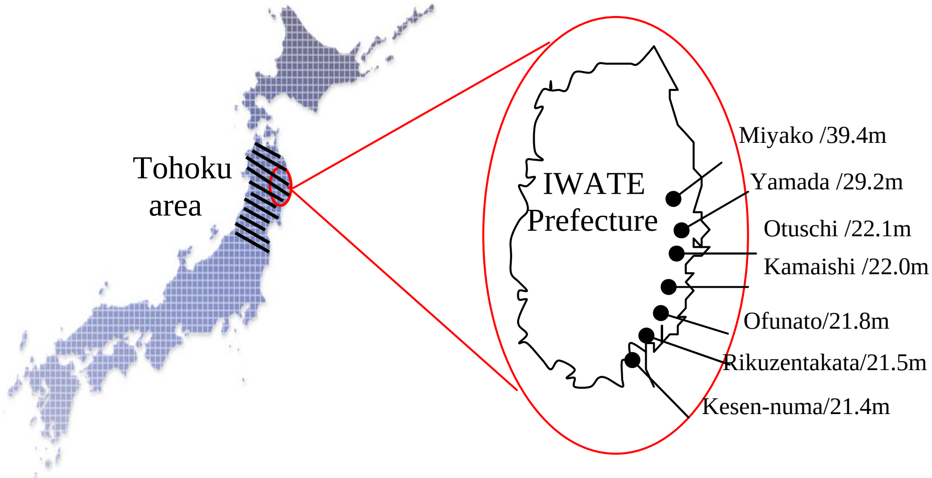


Figure 1 Coastal cities of Tohoku area / Recorded height of the tsunami wave
(The 2011 Tohoku Earthquake Tsunami Joint Survey Group)

INFORMATION ACQUIRED FROM OBSERVATION

Authors obtained some important information from observing the bridges subjected to tsunami waves.

Fall-off prevention devices tore off by tsunami waves

Figure 2 shows the fall-off prevention devices destroyed by tsunami waves. The wave force of tsunami can easily tear off the connectors of fall-off prevention device which are strong enough to carry the dead load of the bridge itself. Therefore, the fall-off prevention devices are almost useless to prevent the bridge from being washed away by the large tsunami waves.

(a) (b)

Figure 2 Fall-off prevention devices tore off by tsunami waves;
(a) Kitagami bridge (Long.; 141.423077 E., latitude; 38.547058 N.)
(b) Kesen biridge (Long.; 141.618096 E., latitude; 39.010101 N.)

Bridge superstructure weight related to the resistance to the tsunami wave load

Steel bridges are more likely to be washed away than concrete bridges, which means a bridge with large weight can resist the tsunami wave load. Good examples are given in Fig.3; the case of Miyako bridge and Yamada railway bridge. Miyako bridge is a multiple span reinforced concrete girder bridge and Yamada railway bridge is a multiple span simply supported steel girder bridge seen behind the Miyako bridge. These two bridges were located close to each other. However, 5 spans of the light steel railway bridge was washed away even though the heavy concrete bridge was not. And one more example is shown in Fig.4; the case of Horai bridge and it's pedestrian bridge. Horai bridge is a 2-span simply supported prestressed concrete bridge shown in Fig.4 (a). Horai bridge remained almost intact, and it was in service even after the tsunami wave struck the bridge. However, the pedestrian steel girder and deck bridge which was just along side of the Horai bridge was washed away and rolled over about 20m away from the original location (Fig.4 (b)). According to the investigation report of Y. Tanaka, *et al.*, nearly 75% of steel bridges were washed away, whereas more than 50% of concrete bridges remained. The investigation covered 150 bridges which were subjected to the tsunami waves.

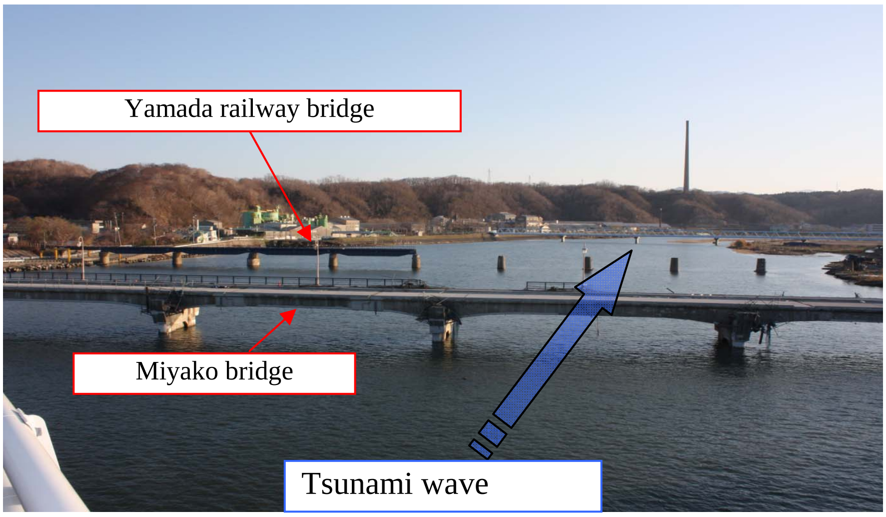
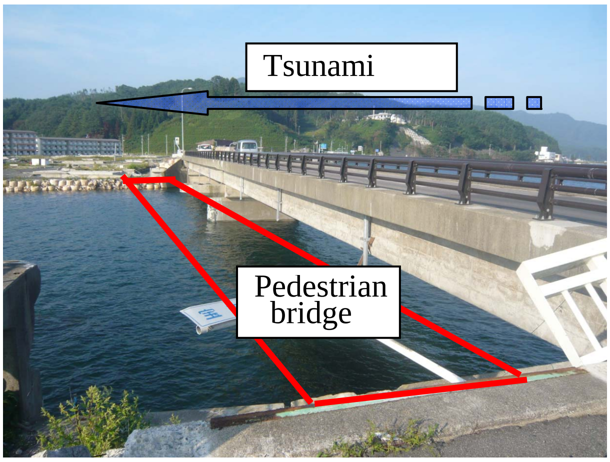
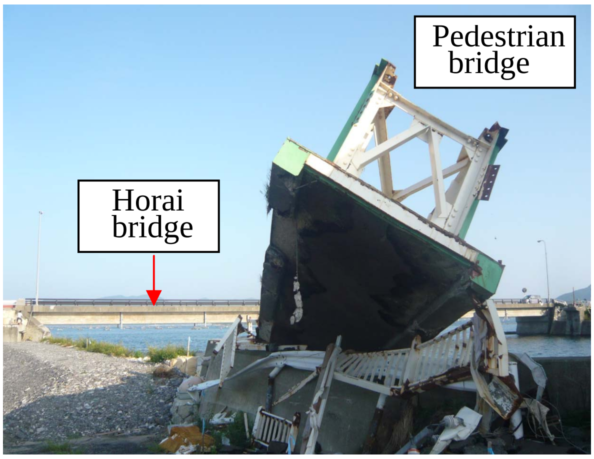


Figure 3 Miyako bridge and Yamada railway bridge
(Long.; 955633 E., latitude; 39.638926 N.)



(a)



(b)

Figure 4 Horai bridge (Long.; 141.951904 E., latitude; 39.474392 N.):
(a) Horai bridge; and (b) pedestrian bridge

Height of bridge superstructure related to the resistance to the tsunami wave load

In regard to the height of bridge superstructure, the superstructures that were located in lower height from the ground level tend to withstand the tsunami waves. On the contrary, the superstructures on the high piers are likely to be washed away when subjected to the tsunami waves. Fig.5 shows Furukawa bridge which superstructure is set only about 1m high from the water level. And this bridge survived through the attack of tsunami waves even though it is located just near the seaside. On the other hand, heavy concrete superstructures on the high piers were removed by the tsunami waves as shown in Fig.6(a); the case of Numata-kosen bridge. Numata-kosen bridge is a multiple span simply supported prestressed concrete bridge. And as can be seen in Fig.6 (b), concrete deck fell down to the ground. There was a mark on the pole of gas station near this bridge, that indicates that the height of the tsunami waves was as high as the deck of this bridge. This fact is examined in the next section.

Figure 5 Furukawa bridge
(Long.; 141.630678 E., latitude; 39.008261 N.)

(a) (b)

Figure 6 Numata-kosen bridge (Long.; 141.649598 E., latitude; 39.008795 N.):
(a) piers remained; and (b) concrete deck fell down.

TSUNAMI WAVE FORCE ACTING ON A BRIDGE DECK

The phenomenon that the bridge superstructures with high clearance tends to be swept away by tsunami waves is opposite to the result brought by the equation currently used to estimate the wave force. Therefore, in order to confirm this phenomenon, the tsunami wave force acting on a bridge deck is examined.

Some fundamental studies on the tsunami wave force working on a bridge have started since 2004 Indian ocean earthquake and tsunami (Iemura H. *et al*., 2007, Murakami S. *et al*., 2009, Kataoka S. *et al*., 2006, Shoji G. *et al*., 2009). Generally the removal of bridge deck is caused by the lateral wave force in conjunction with vertical force (Araki S. *et al*., 2010). However the detailed flow mechanism of tsunami wave has not been explained yet. Hence, we focus on only the lateral wave force working on a bridge deck in the different height.

In the existing research in Japan (Shoji G *et al*., 2009), the wave force p acting on the seawall at the height of h_c is estimated by Eq. (1)

$$p = C\rho g H \frac{3H - h_c}{3H} \quad (1)$$

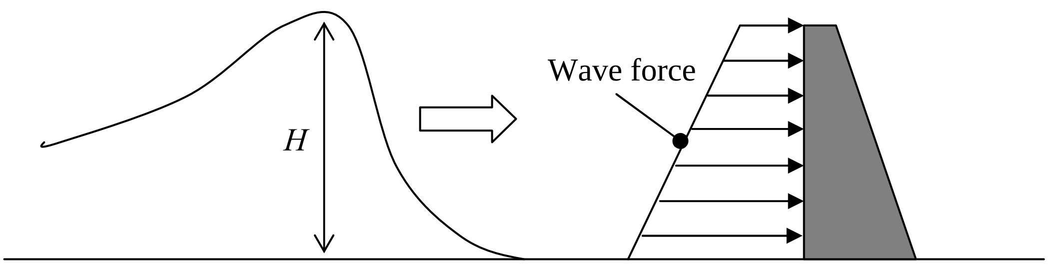


Figure 7 Lateral wave force distribution acting on a seawall

Here, C is coefficient; C=2.2 for Goda's formula and C=3.0 for Asakura's formula, ρ is density of water, g is gravity acceleration, H is the height or the wave from the still water level.

From Eq. (1), it is obvious that the higher the position on the seawall is, the smaller wave force works on that position (Fig.7). However, geometrical conditions of bridges and seawalls are quite different; a space exists under the bridge deck. Then, an interesting experiment on the wave force acting on a bridge deck was conducted by Shoji G. *et al*. in 2009. In this experiment, bridge deck model was set in the 3 different heights against the man-made tsunami wave with the height a_h shown in Fig.8. The result of this experiment indicated that as the height of the wave a_h became large, the rate of increasing wave force became larger for the bridge deck model of higher position. Especially, when the bridge deck model was located at the point where the wave breaks, the rate of increasing wave force became extremely large. For these reasons, Eq. (1) is not always applicable in the case that a bridge deck is subjected to tsunami waves.

Furthermore, tsunami waves also carried debris on their surface. Then, it is expected that the debris collided with the superstructure of the bridge and pushed it away. Therefore, if the bridge deck is located as high as the height of tsunami waves, the deck is subjected to not only the wave force but also the impact force of crashing debris (Iemura H. *et al*., 2005).

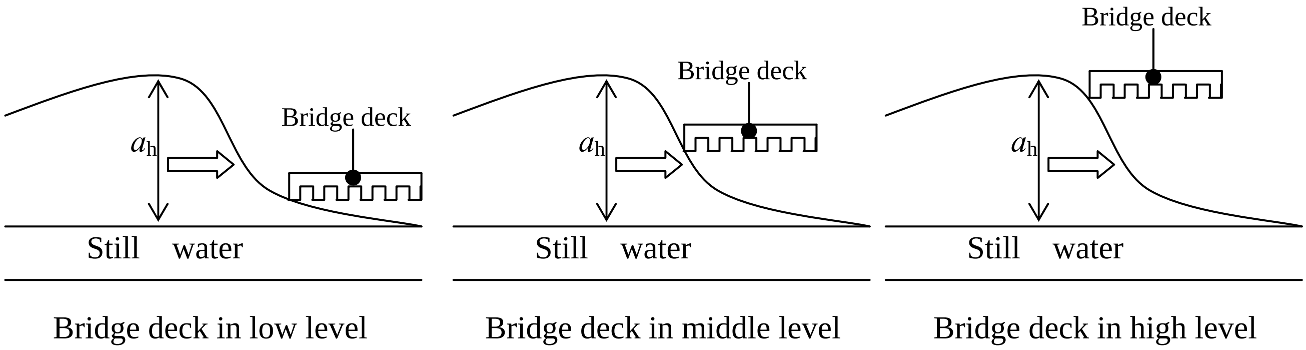


Figure 8 Experiment on wave force acting on a bridge deck in 3 different levels

CONCLUSIONS

The important remarks we have obtained from the investigation of bridges subjected to the tsunami waves in Tohoku area are as follows;

1) There is less possibility that fall-off prevention devices can prevent a bridge from being washed away by such massive tsunami waves as were observed this time in Tohoku area.

2) Heavy concrete bridges are unlikely to be swept away by tsunami waves comparing to light steel bridges. The reason is simply considered to be due to the difference of inertia between the two types of bridges, which means that bridges with large mass have resistance to both lateral and vertical tsunami wave forces.

3) From the investigation, it was confirmed that the superstructure on the high piers was possibly subjected to the larger wave force than the one close to the ground level. Furthermore, the floating debris could give additional impact load on the superstructure located near the surface of the tsunami waves under the actual condition.

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