EXPERIMENTAL RESEARCHES ON BEHAVIOR OF BEARING SUPPORTS IN HIGHWAY BRIDGES UNDER TSUNAMI-INDUCED FORCE

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Abstract

Tsunami has become an essential issue for disaster prevention of highway in Japan. A research project for studying tsunami effect acted on bridge structure and capacity of bridge system for resisting tsunami has been initiated in Center for Advanced Engineering Structural Assessment and Research (CAESAR), Public Works Research Institute (PWRI). This research project includes flume tests on bridge model for investigating tsunami effect acted on bridge structure, loading tests on model of entire bridge system and analytical studies on actual bridges for investigating capacity of bridge system for resisting tsunami. This paper introduces a brief report on the research results up to now.

Introduction

Many bridges were severely damaged by tsunami in the 2011 Great East Japan Earthquake (e.g. NILIM & PWRI, 2011, Hoshikuma, 2011, Marsh, 2011). Figure 1 shows a typical damage pattern of superstructure washed-away due to the tsunami-induced loading. Recovery of a function for bridges with severe damage including washed-away of the superstructures generally requires long time, which affects the post-earthquake emergency activities due to the missing link of highway network. For example, nearly four months were cost for building a temporary bridge for Kesen Bridge that the superstructures were washed away in the 2011 Great East Japan Earthquake. Potential disasters may also occur in other region of Japan because large subduction-type earthquakes including the Tokai earthquake, the Tonankai earthquake, the Nankai earthquake and earthquakes around the Japan Trench and Chishima Trench were predicted with high possibility of occurrence in the next few decades. Tsunami has become an essential issue for disaster prevention of highway in Japan. It is urgent to study the behavior of bridge structure under the attack of tsunami and then to develop countermeasures for mitigating tsunami effect on bridge.

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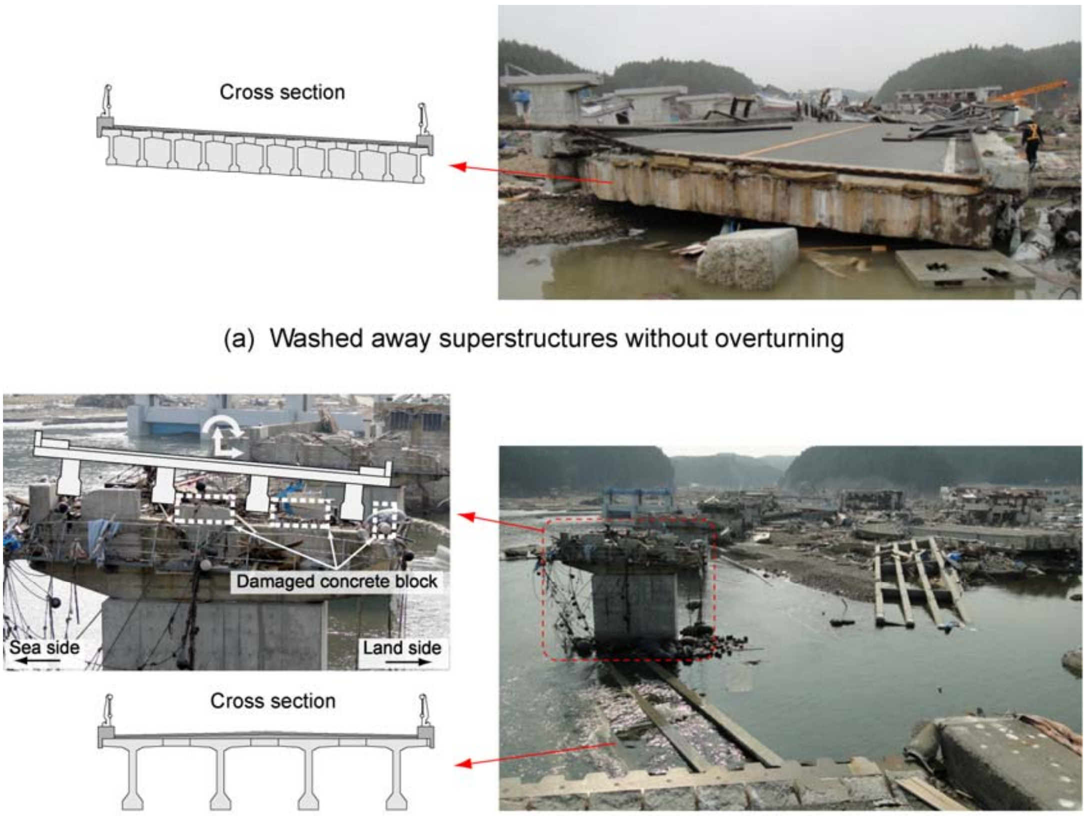
Institute (PWRI). This research project includes flume tests on bridge model for investigating tsunami effect acted on bridge structure, loading test on model of entire bridge system and analytical studies on actual bridges for investigating capacity of bridge system for resisting tsunami. This paper describes a brief report on the research results up to now.



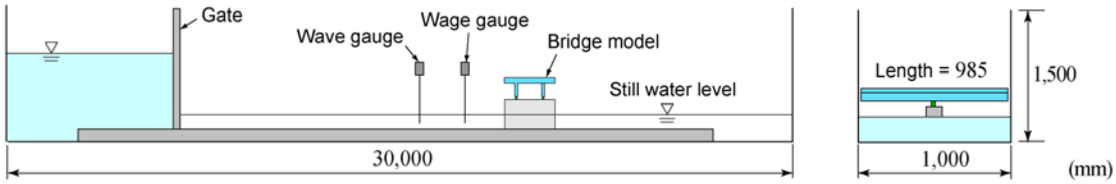
(a) Washed away superstructures without overturning

(b) Washed away superstructures with overturning

Fig. 1 Damage of a bridge that the superstructures were washed away due to tsunami induce by the 2011 Great East Japan Earthquake

Flume Tests for Bridge Model

A series of flume tests on bridge model were conducted for investigating the effect of the configuration of the superstructure on tsunami effect on behavior of bridges, particularly bearing supports. The tests were designed for modeling a bridge with 2 m clearance attacked by tsunami with a wave height reaching to the top surface of the bridge deck. Figure 2 shows the setup of flume tests. In this research, tsunami waves were generated by opening the gate of the water tank. Tsunami wave height was controlled by water level in the water tank.



(a) Setup of flume test (Left: Elevation, right: Cross-section)

(b) Photo of flume test

Fig. 2 Setup of flume tests

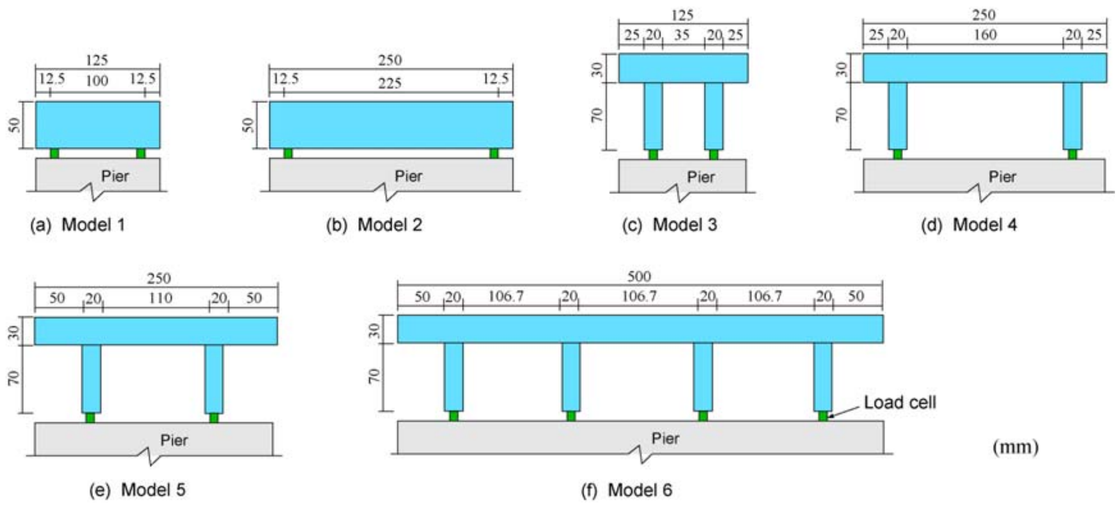


Fig. 3 Details of cross section of bridge models

Flume tests on six bridge models as shown in Fig. 3 are introduced in this paper. Models 1 and 2 were slab bridges and models 3 to 6 were girder bridges. Models 1 and 3 were scaled models of sidewalk bridges. Models 4 and 5 were designed with different length of overhang of slab. Each of the models was designed with two or four bearing supports and reaction forces both in horizontal direction and vertical direction at each of the bearing supports were measured in the test, which is to discuss the rotation behavior of the superstructure under the tsunami-induced loading by comparing the reaction forces developing at the bearing supports. It is considered that the reaction forces in the vertical direction consists of buoyant force, hydrodynamic forces in vertical direction and rotation forces of the superstructure induced by the hydrodynamic forces in horizontal direction. All the models were designed with a geometry ratio of 1/20.

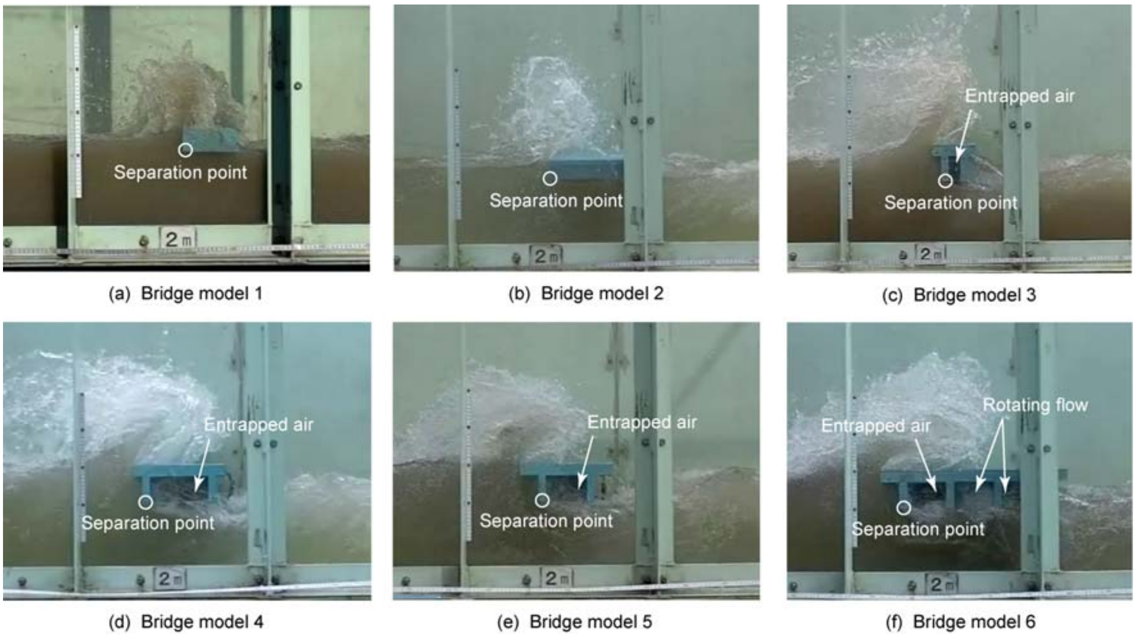


Fig. 4 Snapshots of the moment of tsunami wave impinging against the bridge model

Figure 4 shows snapshots of the moment of tsunami wave impinging against the bridge model. Figure 5 shows time histories of the reaction force in bearing supports and the wave pressure at the slab and the girder. Time histories of wave height shown in Figure 5 were measured at 1.0m front of the bridge model. The targeted tsunami was supposed to be as high as 3.0m for models 1 and 2, and 4.0m for models 3 to 6, respectively. It is noted that all engineering values shown in Figure 5 are converted into that for the prototype bridge using the geometry ratio of 1/20.

Trapped air between adjacent girders was observed in the tests of bridge models 3 to 6, which will increase the buoyancy force (Robertson, et al, 2007). As for bridge models 3 to 5, the vertical reaction force in two bearing supports were opposite to each other. The reaction force in the bearing support of the downstream side was uplift force, while the other bearing support was subjected to the compressive force. This implied that rotation moment occurred in the superstructure. Furthermore, it can be observed that the length of the overhang slab affects the uplift force developed in the bearing support of the downstream side. Uplift reaction force in model 5 was larger than that of model 4 because

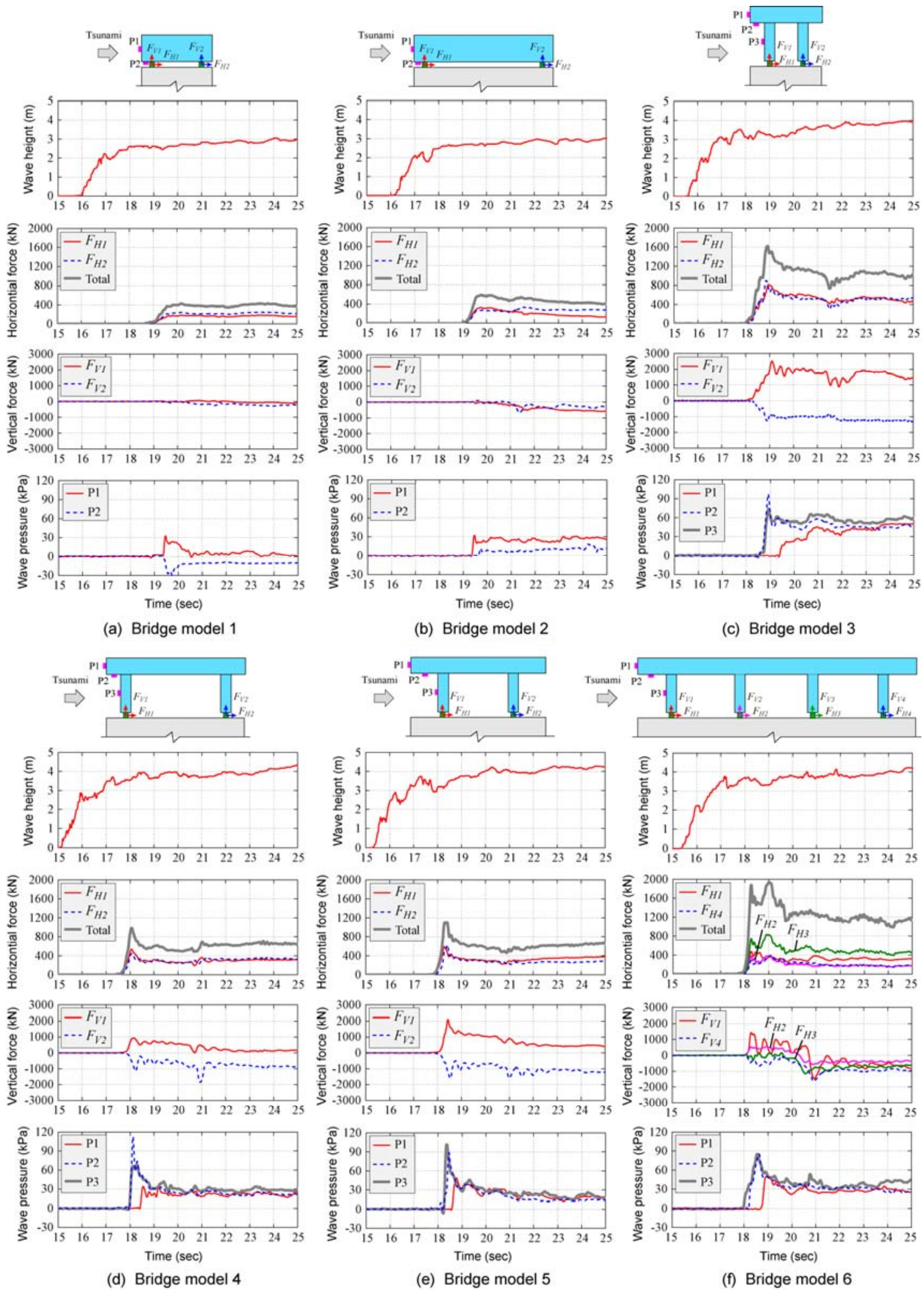


Fig. 5 Time histories of reaction force in bearings and wave pressure at slab and girder

overhang length of model 5 was longer. Uplift reaction force in model 3 was larger than that of model 4 because girder space of model 3 was shorter.

Loading Test on Capacity of Entire Bridge System for Resisting Tsunami

Modes of the washed-away superstructures and traces of damage in top of pier shown in Figure 1 indicated that the bridge structure was subjected to the tsunami-induced forces in both horizontal and vertical directions. In order to evaluate the capacity of bridge for the tsunami-induced force, it is necessary to investigate the resistant mechanism of the entire bridge system for the tsunami-induced force.

In Japan, a pot bearing was generally applied for girder bridges before 1980. This bearing support was generally designed with a seismic coefficient of 0.1 in vertical direction and a seismic coefficient with 0.2-0.3 in horizontal direction. Therefore, it can be generally supposed that the bearing support will be the weakest section in the entire bridge system when the tsunami-induced forces are applied to bridges in horizontal and vertical direction simultaneously.

A 1/2 scale existing bridge model with pot bearing supports, designed prior to 1980, was loaded with the purpose to investigate the capacity of bridge for resisting the tsunami-induced force. Figure 6 shows the setup of the loading test. The test unit is a 1/2 scaled model of pier P3 in Koizumi Bridge that the superstructures were washed away due to the tsunami in the 2011 Great East Japan Earthquake. The superstructure was supported by four pot bearings based on a figure of Koizumi Bridge. Figure 7 shows the details of the pot bearings. Resistance of this type of bearings in horizontal direction and vertical direction are provided by the stopper and the side block, respectively. Design capacity can be evaluated based on the allowable stress design method. In this test, the load was applied in a direction as shown in Fig.6, where this loading method was one of the loading case for simulating the case that the resultant of the horizontal force and vertical force acted on the side of the superstructure was about 60 degree to the horizontal direction.

It was confirmed that ultimate damage of the entire bridge system was the fracture of the No.1, No.2 and No.3 bearings with a fracture sequence of No.1 to No.3. The ultimate damage of the bearings was the fracture of the bolt that was used for fixing the side block to stopper. Figure 8 shows the damage mode of the side block before fracture of the bolt. Figures 9 and 10 show relationships between the load and the reaction force in vertical direction, where the applied force represents the capacity of the bearing-column structural system. It is noted from Figure 9 that the applied force reached to maximum when vertical reaction force of the No.1 bearings reached to ultimate capacity and it decreased sharply after the fracture of the No.1 bearings. Maximum applied force was 340kN which corresponds to1.3 times of the capacity of the bearing No.1 (254kN). Figure 10 shows that bearings No.1 to No.3 fractured due to uplift force, while bearings No.4 was in

Fig. 6 Setup of loading test on large-scale bridge model

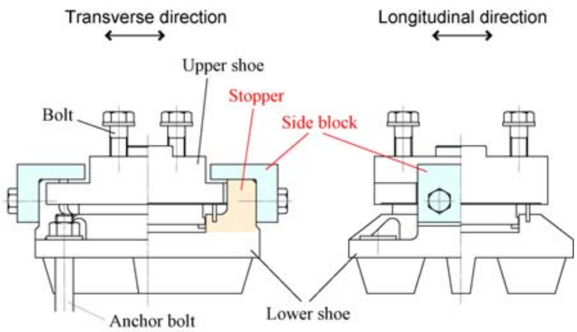


Fig. 7 Details of pot bearings

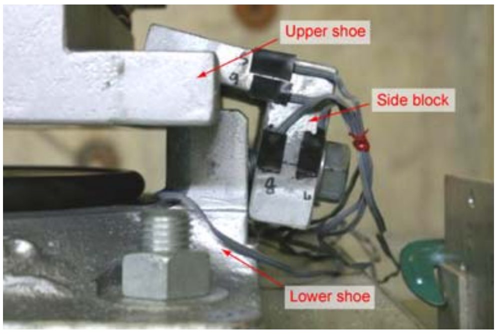


Fig. 8 Condition of the side block

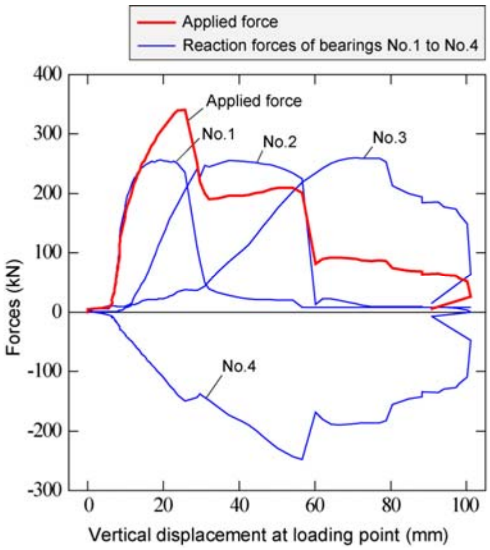


Fig. 9 Relationship between vertical force and vertical displacement at loading point

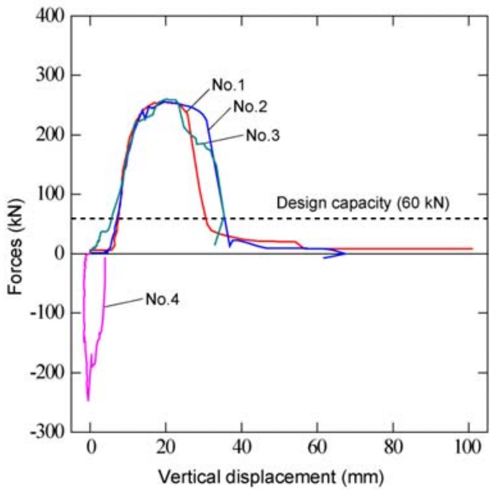


Fig. 10 Relationship between vertical force and vertical displacement

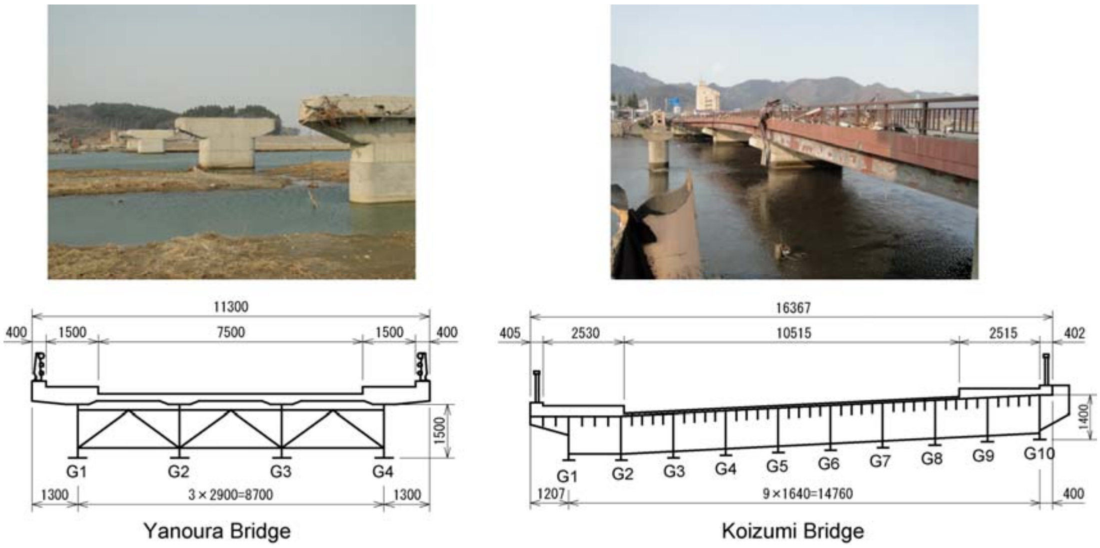


Fig. 11 Details of cross section

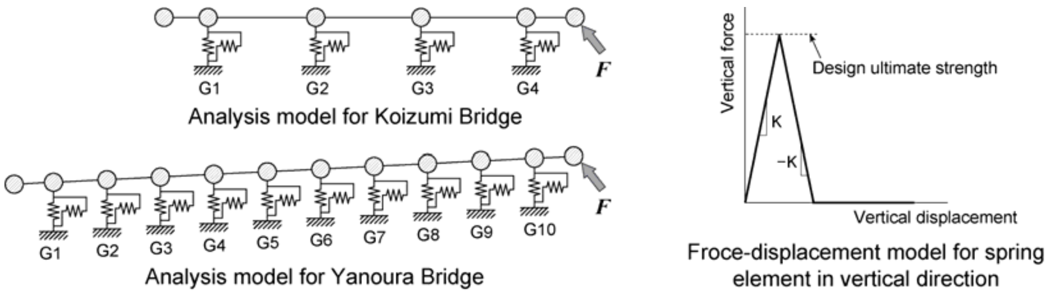
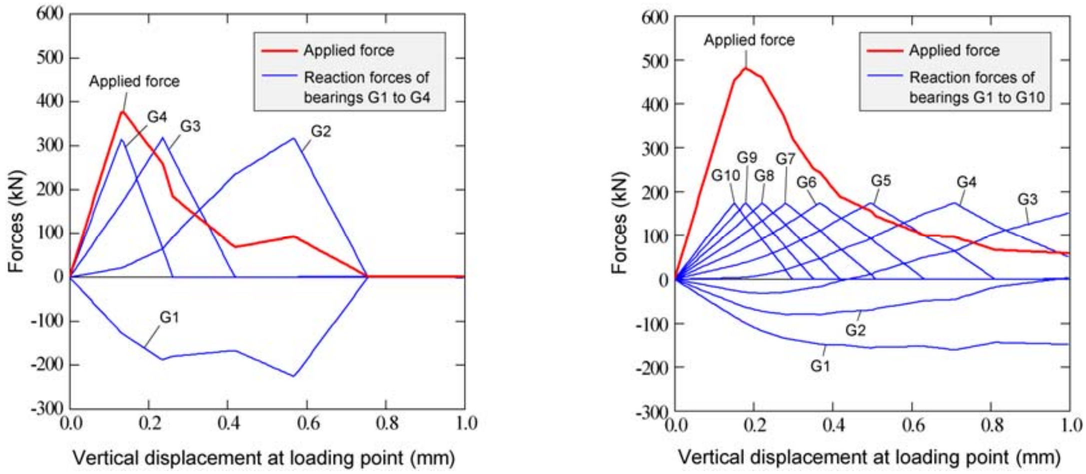


Fig. 12 Analytical model



(a) Koizumi Bridge (b) Yanoura Bridge

Fig. 13 Analytical results on capacity of entire bridge system and reaction forces in bearings compression during the loading test. Relationships between the vertical force and the vertical displacement for bearings No.1 to No.3 show a similar curve with each other. It should be also remarked in Figure 10 that capacity of bearings No.1 to No.3 obtained from test was about 4 times of the design capacity that is estimated based on an allowable stress method.

A Case Study on Capacity of Existing Bridges for Tsunami-induced Force

Capacity of bridge for the tsunami-induced force depends on not only characteristics of tsunami wave but also characteristics of superstructure. In this research, two actual existing bridge were employed to conduct a case study on the influence of characteristics of superstructure on capacity for tsunami-induced force, in which one bridge was washed away of superstructure while the other one survived from the tsunami. Figure 11 shows details of the cross section of superstructure in two bridges. Both of two bridges are steel girder bridge. Koizumi Bridge is a two three-span continuous steel girder bridge with a girder length of 90.3 m (total length 182 m). The superstructure comprised 4 steel girders supported by pot bearings. Design vertical capacity of each of the four bearings was 317 kN. Yanoura Bridge is a three-span continuous steel girder bridge with a girder length of 108.6 m. The superstructure comprised 10 steel girders supported by pot bearings. Design vertical capacity was 232 kN for bearings G1 and 179 kN for bearings G2 to G10.

Both of two bridges were modeled with beam-spring model as shown in Fig. 12, where superstructures were modeled with beam element and bearing supports were modeled with spring element. Loading direction was supposed to be an angle of 45 degree to the horizontal direction. Applied force and vertical reaction force in bearing supports obtained from the analysis were shown in Fig. 13. The maximum applied load for Koizumi Bridge was 380 kN. It is about 1.2 times of the capacity of each bearing support. On the other hand, the maximum applied load for Yanoura Bridge was 480 kN, which corresponded to about 2.7 times of the capacity of each bearing support. This means that the capacity of Yanaoura Bridge is higher than that of the Koizumi Bridge under the loading condition as applied in this test. The spacing of adjacent girders and thus the number of bearing supports in the transverse direction would be one of the control factors of the capacity for the tsunami-induced force.

Conclusions

Many bridges built along the coast line of the Pacific Ocean in Tohoku and Kanto areas were affected by the huge tsunami, while superstructures in some bridges inundated with the tsunami were survived. In order to study the hydrodynamic behavior of bridge under the tsunami-induced loading, flume tests were conducted with the 1/20 scaled bridge models and the effect of the cross-sectional configuration of the superstructure on the reaction force applied to bearing supports. Test results indicated that the long overhang slab increased the hydrodynamic uplift force applied to the overhang slab, which would cause the superstructure in the girder bridge to overturn. It was also observed that the air was trapped in the space between adjacent girders while the superstructure was inundated with the tsunami, and the trapped air caused the buoyancy force.

Static loading test for a bearing-column system was also preformed to study the resistance capacity of the system to the tsunami-induced force. In this test, failure of the steel bearing supports in existing bridges designed prior to 1980 occurred at the bolt connecting the side block to the lower shoe. It was also found that larger number of bearing supports in the transverse direction would exhibit larger resistance capacity for the overturning moment applied to the superstructure.

Based on the experimental researches described in this paper, the tsunami-induced force could be mitigated by choosing a rational structural plan for the superstructure and bearing supports, while more researches are required to clarify the hydrodynamic mechanism for bridges subjected to the tsunami effect.

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