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Numerical Analysis of Truss Bridge Subjected to Earthquake and Flood

S. Fujisawa, Y. Yamaguchi, S. Yotsui, Y. Satofuka and K. Izuno

Civil and Environmental Engineering, Ritsumeikan University, Shiga, Japan

Abstract

Although damage of bridges due to the shaking of earthquakes has been reduced these days, the safety of bridges against multi-hazards must be improved to protect human life. This paper discussed the safety measures of the Nishize Bridge as an example of the bridge suffered both a large earthquake and a flood. First, the earthquake response during the 2016 Kumamoto Earthquake was evaluated. During the Kumamoto Earthquake, the maximum force acted on the fixed bearing, which is larger than the estimated strength from the design specification at the time of construction. However, the root mean square value of the reaction force was small, which resulted in no damage during the earthquake. Second, the hydrodynamic force due to the 2020 flood was calculated using the one-dimensional analysis of riverbed variation. The drag was larger than the estimated bearing strength for more than 3 hours, and consequently the Nishize Bridge was washed away by the excessive drag. The maximum value of drag is smaller than the value of bearing strength required by the current design specification, which suggests that strengthening of the bearings to satisfy the current seismic design specification is an effective measure against not only earthquakes but flooding.

Keywords: earthquake damage, bridge hydraulics, flash flood, numerical simulation, truss bridge, bridge bearing

1 Introduction

Numerous natural disasters such as earthquakes and floods occur every year all over the world. In Japan, many bridges suffered damage during the 1995 Kobe Earthquake, which led to significant revisions of seismic design standards. Since then, seismic retrofitting of bridges has been promoted. Although huge earthquakes such as the 2011 Great East Japan Earthquake and the 2016 Kumamoto Earthquake occurred many times, a few retrofitted bridges suffered severe damage due to the shaking of earthquakes [1, 2].

While damage to bridges caused by earthquakes has decreased, bridges are still washed away by floods almost every year [3]. In the heavy rain event of July 2020, 17 bridges were washed away due to a flash flood in the Kuma River basin in Kumamoto Prefecture, Japan, including the Nishize Bridge [4]. The Nishize Bridge survived the 2016 Kumamoto Earthquake without any damage; however, it was washed away during the 2020 heavy rain.

The bridge was washed away because the water level rose to the height of the bridge girders and the water pressure exceeded the resistance of the bridge. The current Japanese specifications for highway bridges [5] do not assume flooding up to the girders, and only water pressure to the piers and hydrodynamic pressure during earthquakes are considered to act on the bridge piers for the planned high-water level.

Although damage to bridges due to the shaking of earthquakes has been reduced, the safety of bridges against multi-hazards must be improved to protect human life. This paper discussed the safety measures of the Nishize Bridge as an example of the bridge suffered both a large earthquake and a flood. First, the earthquake response during the 2016 Kumamoto Earthquake was evaluated. The Kumamoto Earthquake occurred in April 2016. The magnitude 7.3 main shock showed the maximum JMA intensity 7, and a total of 211 people died due to a series of the earthquakes. Second, the hydrodynamic force due to the 2020 flood was calculated using the one-dimensional analysis of riverbed variation. Then the forces due to the earthquake and the flood were compared to the estimated bearing capacity to examine the appropriate measure.

2 Methods

The Nishize Bridge is a 4-span simply supported Warren steel truss bridge and was constructed in 1967. The horizontal bearing strength was assumed to be determined by earthquake or wind loads. The bridge complies with the 1956 specifications for steel highway bridges [6], and the horizontal bearing strength was estimated to be 1.52 MN from the wind load in total and 380 kN per one fixed bearing. Further, earthquake load was calculated according to the 2017 specification [7] in order to compare with current standards, which resulted in the required strength of 9.35 MN in total.

First, the earthquake response analysis was conducted using the 2-D model as shown in Figure 1. As this bridge is a simply supported bridge, only one span of the bridge was modelled. As boundary conditions, one of the bridge bearings was fixed and the other was movable modelled as a bilinear spring with 5% friction. The truss members were linear elements made of steel with 5% damping.

The earthquake records of the 2016 Kumamoto Earthquake (April 16, 2016, 01:25, JST) at the KiK-net Hitoyoshi station of the National Research Institute for Earth Science and Disaster Resilience [8] was used as an input acceleration. The observed east-west and north-south earthquake records were modified their direction to the longitudinal direction of the Nishize Bridge as shown in Figure 2.

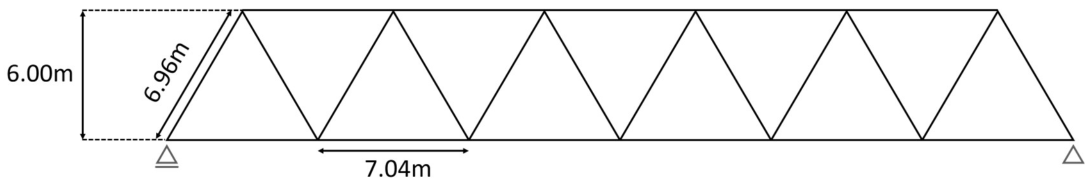

Figure 1: One-span 2-D model of the Nishize Bridge.

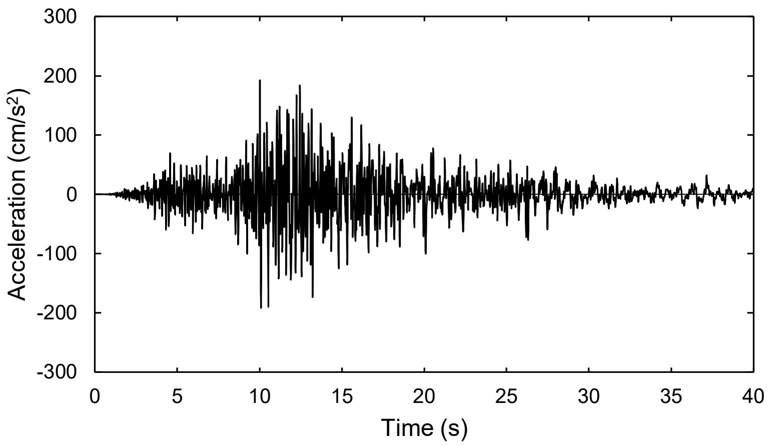

Figure 2: Input earthquake acceleration.

For the flood response, a program for one-dimensional analysis of riverbed variation developed by one of the authors [9, 10] was used to calculate the water level and flow velocity. A simplified model of the Nishize Bridge as shown in Figure 3 was used. The flow rate was calculated from the water levels observed by the Water Information System [11] of the Ministry of Land, Infrastructure, Transport and Tourism.

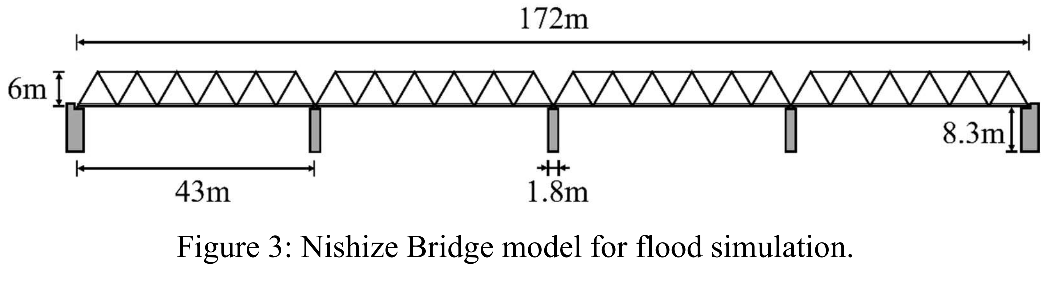

Figure 3: Nishize Bridge model for flood simulation.

The drag, horizontal hydrodynamic force acting on bridge, was calculated from the water level and flow velocity obtained from the analysis. If the bridge girder is partially submerged, the water level rises because of the interaction between the structure and water. Since this simulation program cannot directly reproduce the rise of the water due to the bridge, the afflux was reproduced by adding the submerged height of the girder to the original riverbed level.

3 Results

Figure 4 shows the horizontal reaction force acting on the fixed bearing during the 2016 Kumamoto Earthquake. The maximum force of 616 kN acted on the fixed bearing. The estimated bearing strength based on the design specification at the time of construction was 380 kN, which is less than the maximum horizontal reaction force. However, the root mean square value of the reaction force was 106 kN, which is less than 1/3 of the estimated bearing strength. This may explain why this bridge was not damaged by the 2016 Kumamoto Earthquake.

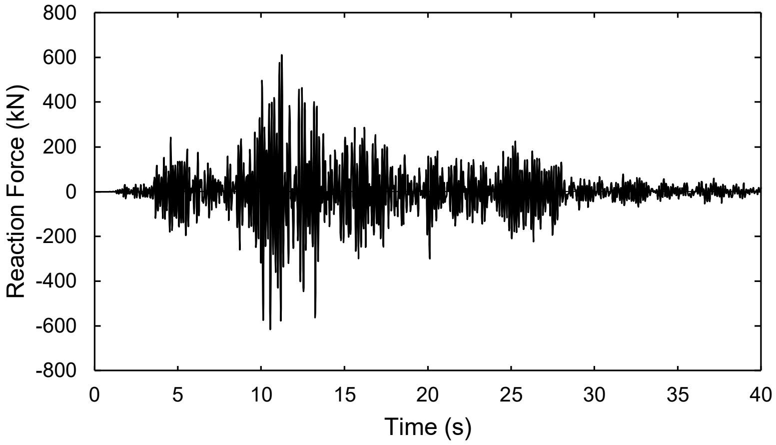

Figure 4: Horizontal reaction force at the fixed bearing due to the 2016 Kumamoto Earthquake.

The drag during the flood caused by the heavy rain event of July 2020 is shown in Figure 5. Figure 5 shows that the drag at 14.8 h on the horizontal axis of the graph exceeded the estimated bearing strength based on the design specification at the time of construction, which is indicated by the dotted line in the figure. The drag exceeded the estimated bearing strength for more than 3 hours, reaching a maximum of 2.8 times the bearing capacity. Consequently, the Nishize Bridge was washed away by the excessive drag. In addition, the maximum drag was 1.8 times larger than the horizontal reaction force subjected to the 2016 Kumamoto Earthquake.

On the other hand, the maximum value of drag is smaller than the value of bearing strength required by the current design specification, which suggests that strengthening of the bearings to satisfy the current seismic design specification is an effective measure against flooding.

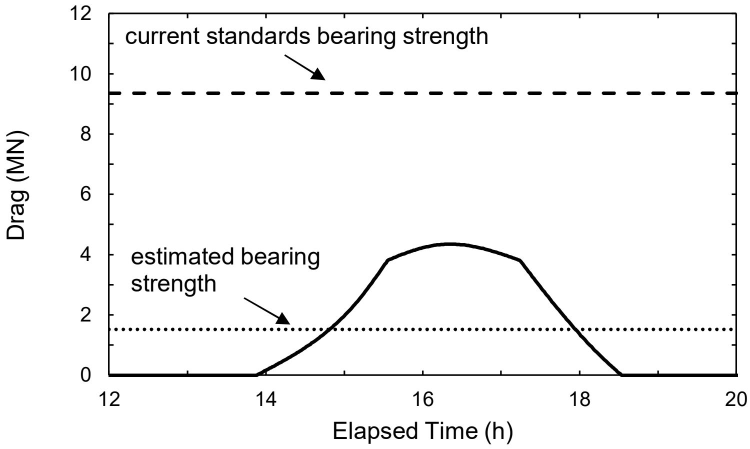

Figure 5: Drag due to flash flood caused by the heavy rain event in July 2020.

4 Conclusions and Contributions

This paper discussed the safety measures of a bridge for both a large earthquake and a flood. The bridge behaviour during an earthquake and a flood was evaluated through the earthquake response analysis and the one-dimensional analysis of riverbed variation. The main conclusions of this study are as follows:

(1) The Nishize Bridge in Kumamoto, Japan, was modelled numerically to evaluate the response to both an earthquake and a flood. This bridge suffered no damage during the 2016 Kumamoto Earthquake; however, it was washed away due to a flash flood caused by the heavy rain event in July 2020.

(2) Though the maximum horizontal reaction force (616 kN) was larger than the bearing strength (380 kN per one fixed bearing) estimated from the design specification at the time of construction, the Nishize Bridge suffered no damage during the 2016 Kumamoto Earthquake. This was due to the small root mean square value of the reaction force (106 kN) compared to the bearing strength.

(3) During the flash flood caused by the heavy rain event of July 2020, the drag was larger than the estimated bearing strength for more than 3 hours. Compared to the estimated bearing strength, the drag may have been at most 2.8 times larger, and consequently the Nishize Bridge was washed away by the excessive drag.

(4) The maximum value of the drag is smaller than that of the bearing strength required by the current design specification, which suggests that strengthening of the bearings to satisfy the current seismic design specification is an effective measure against not only earthquakes but flooding.

This study reveals that seismic reinforcement is an effective flood measure that is not specified in the current design specifications. Further, if the strength of the bearings is insufficient to withstand floods, further measures such as devices similar to an anti-earthquake unseating prevention system can be applied.

Acknowledgements

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