Seismic evaluation of stone arch bridge damaged in 2011 Great East Japan Earthquake before and after retrofit

Yasuo Sawamura[1], B.M. Lewis[2], and M. Kimura[1]

[1] Department of Civil and Earth Resources Engineering, Kyoto University, Kyotodaigaku Katsura, Nishikyo-ku, Kyoto 615-8540, Japan.
[2] Obayashi Corporation, Shinagawa Intercity Tower B, 2-15-2, Konan, Minato-ku, Tokyo 108-8502, Japan.

ABSTRACT

Tokiwa Bridge, a national heritage site in Tokyo, Japan, is a double-span stone arch bridge that was constructed in 1877. The bridge suffered damage in the 2011 Great East Japan Earthquake that included the displacements and expansions of several parts of the masonry. With the support of the Japanese Agency for Cultural Affairs and the Tokyo Metropolitan Government, the bridge has been undergoing seismic retrofitting as a disaster restoration project. Since the bridge is a national heritage site, the original components are to be reused to restore the structure as much as possible. In this study, the seismic resistance of Tokiwa Bridge before and after the retrofit is investigated through static pushover analyses of the central bridge pier and dynamic analyses of the entire structure. Additionally, as the excavation of the riverbed surrounding the bridge is being planned, in accordance with the city's river management plan, the effects of the excavation on the performance of the bridge are also taken into consideration. From the results, it is confirmed that the planned method of retrofit will improve the earthquake resistance of the bridge compared with the original structure. Furthermore, it is shown that the effects of the riverbed excavation will be limited.

Keywords: stone bridge; seismic retrofit; 2011 Great East Japan Earthquake; finite element analysis

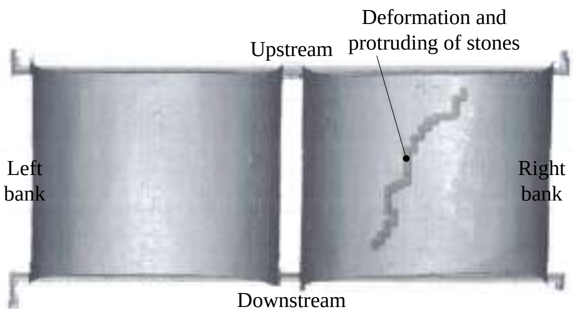
1 INTRODUCTION

Tokiwa Bridge (Fig. 1) spans the Nihon-bashi River in Tokyo, Japan. Originally, Tokiwa Bridge was one of the timber bridges crossing the outer moat to Edo Castle; it was reconstructed in 1877 (after the Edo period) as a double-span stone arch bridge by reusing the stone walls of Edo Castle. A modern Western-style design was adopted for the upper structure of the bridge based on the traditional stone bridge technology of masonry engineers on the island of Kyushu. The main feature of stone bridge technology is that the construction is performed without placing any bonding agents into the voids between the stones. In addition, the road width of the bridge is wide compared to other stone bridges constructed in the Edo period.

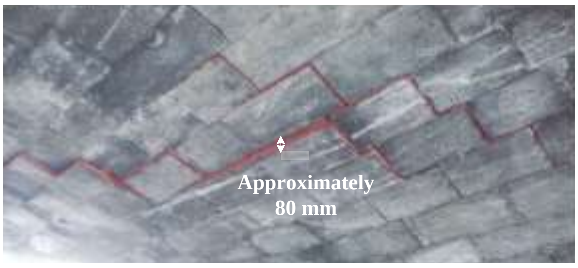
On March 11, 2011, however, the Great East Japan Earthquake (Mw: 9.0–9.1) caused serious damage to Tokiwa Bridge (Fig.2). Besides the large distortion throughout the arch bridge, as remarkable damage, a large crack appeared from the foundation to the top of the right arch and some voussoirs (stone blocks that form the arch) shifted during the earthquake such that they protruded inward along the crack. As a result of a damage survey of the bridge, it was judged that there was no other alternative but to perform a fundamental retrofit in order to avoid the falling of stone blocks and to correct the deformation arising in the arches. Since Tokiwa Bridge is a national heritage site, the original components should be reused for the retrofit. Moreover, due to the city's river management plan, the riverbed surrounding the bridge will be excavated and the level of the riverbed will be set to about 800 mm below the flooring surface of the foundation. Therefore, the retrofitting plan for the foundation involves the addition of new timber piles and the encircling of the bridge supports with sheet piles which was also done for the demolition work.

In this study, the seismic resistance of Tokiwa Bridge, before and after the retrofit, is investigated though 3-dimensional elastoplastic FEM analyses. The effects of the excavation of the riverbed on the seismic performance of the bridge are also considered.

Fig. 1. Tokiwa Bridge (Before 2011 earthquake).



(a) Back face of arch blocks



(b) Protruding of stones at right arch of bridge

Fig. 2. Damage to Tokiwa Bridge due to 2011 Great East Japan Earthquake.

2 STRUCTURAL FEATURES

Fig. 3 shows the geological strata below Tokiwa Bridge. In the periphery of the bridge, a clayey layer (Tc layer with an N value of 2 or so) of the Tokyo Formation, which is the Quaternary Pleistocene, is widely deposited. Fig. 4 shows a schematic view of the foundation structure of Tokiwa Bridge. The foundation is comprised of, from top to bottom, *neishi* (a granite stone plinth), *sutedodai* (wooden panels), *dogi* (smaller wooden panels placed on top of the piles) and a timber pile foundation, with timber stakes placed intermittently around the foundation to hold it in place laterally. Beneath the *neishi* are the *sutedodai* and *dogi*, which are long timber slabs arranged in a crossed pattern to form a footing-like base for the *neishi*. Supporting all of this is a timber pile foundation consisting of hundreds of tapered pinewood piles. These masses of timber piles are not expected to directly support the superstructure due to bearing or frictional resistance, but to improve the entire softer ground through the group pile effect by driving many piles densely.

3 NUMERICAL METHODS AND MODELING

In this study, soil-water coupling analyses were carried out using the 3-dimensional elastoplastic finite element analysis code "DBLEAVES" developed by Ye et al. (2007).

Tables 1 and 2 show the material properties used in the analyses. The subloading t_{ij} model (Nakai and Hinokio, 2004) was used for the soil. The parameters of the Tc layer were determined from the results of CU tests and isotropic consolidation tests on samples collected from the site. In addition, using the same

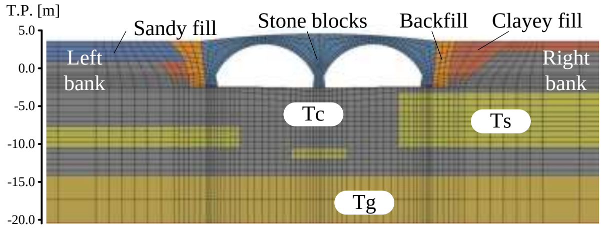
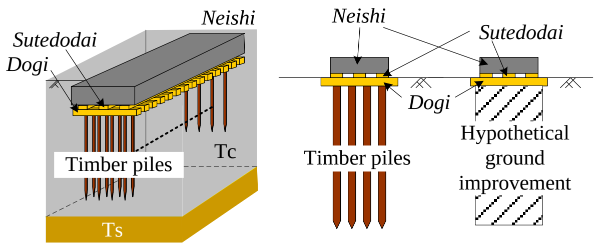


Fig. 3. Geological strata below Tokiwa Bridge.



(a) Foundation structure (b) Mechanical role of piles

Fig. 4. Foundation of Tokiwa Bridge.

parameters, reproducibility analyses of vertical and horizontal loading tests on a single pile conducted at the site were carried out in order to confirm the validity of the parameters. The parameters of Toyoura sand were applied for the sandy and gravel layers (Ts, Tg, sandy fill and backfill), and the relative density was changed according to the N values. The parameters of Fujimori clay were applied for the clayey fill. On the other hand, the masonry part, sheet piles and timber piles were modeled as elastic models using the general physical properties of granite, iron material and pinewood, respectively.

Two types of analyses, static and dynamic, were conducted. In chapter 4, pushover analyses of the central bridge pier were performed, and a new method for modeling a part of the clayey layer (Tc) with group piles was proposed. In chapter 5, dynamic analyses of the entire stone arch bridge were carried out using the same model developed in chapter 4, and the seismic resistance before and after the retrofit was examined.

4 PUSHOVER ANALYSES

Since the foundation of Tokiwa Bridge consists of a large number of timber piles, it is difficult to model all the piles when a dynamic analysis targeting the whole bridge system is conducted. Therefore, a new model which treats the timber pile foundation as a hypothetical area of ground improvement was developed.

Fig. 5 shows an outline of the pushover analyses performed on the central bridge pier. As shown in Fig. 5 (a), the irregularly arranged timber piles were classified into three groups, Groups 1 to 3, and a horizontal pushover analysis was performed for each group. As a result, it was confirmed that the load-displacement relationship of the pile head agreed in all the groups. Therefore, based on the concept

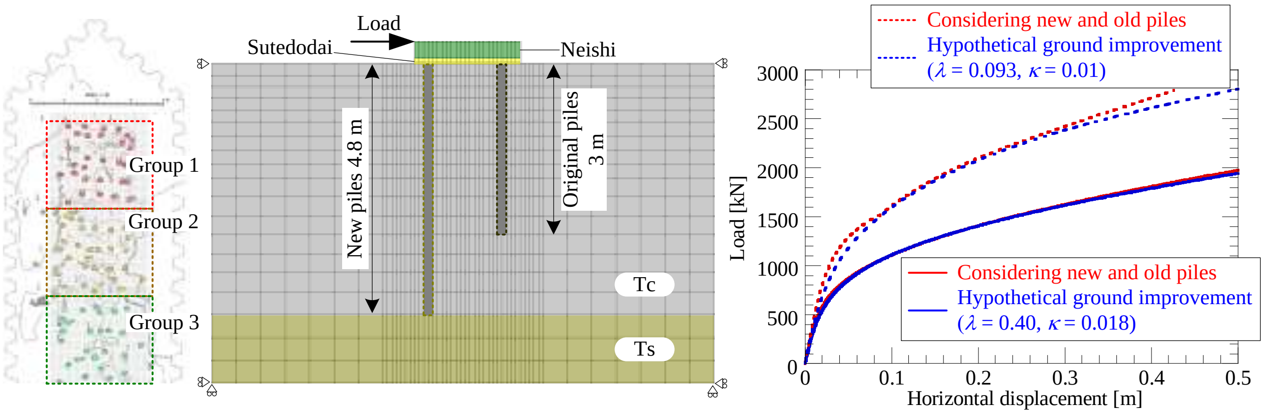
Table 1. Subloading t_{ij} parameters.

Subloading t_{ij} parameter	Tc	Ts	Tg	Sandy fill	Backfill	Clayey fill
Principal stress ratio at critical state R_{cs}	6.5	3.2				3.5
Poisson's ratio ν	0.20	0.20				0.20
Compression index λ	0.60 / 0.40* / 0.093**	0.07				0.09
Swelling index κ	0.02 / 0.018* / 0.01**	0.0045				0.02
N = e_{NC} at p = 98 kPa & q = 0 kPa	2.96	1.10				0.83
Density parameter a (ANN)	850	60				500
Parameter for stress-dilatancy relation β	1.5	1.5				1.5
Over Consolidation Ratio (OCR)	2.0	—				4.0
Relative density D_r [%]	—	80	90	90	75	—

* with timber piles, ** including new piles

Table 2. Elastic model parameters.

Elastic model parameter	Stone blocks	Concrete	Sheet pile	Timber pile	Sutedodai
Elastic modulus E [kPa]	1.00×10^7	2.00×10^7	2.00×10^8	5.42×10^7	
Poisson's ratio ν	0.33	0.15	0.30	0.33	



(a) Pile location (b) FEM mesh and length of piles (c) Load vs displacement (considering and neglecting piles)

Fig. 5. Pushover analyses for center pier.

shown in Fig. 4 (b), a model which treats the timber pile foundation as a hypothetical area of ground improvement was investigated. Assuming that new longer piles will be added in the retrofit (Fig. 5 (b)), the following two cases were examined: (1) only the original piles and (2) the original and the new piles. As a result, the influence of the group piles can be appropriately considered by changing the parameters (λ and κ) of the Tc layer, as shown in Fig. 5 (c).

Using the same parameters for the clayey layer determined by the above method, horizontal pushover analyses were performed on (1) the original foundation, (2) the foundation immediately after the retrofit and (3) the foundation after the retrofit and the excavation of the riverbed (Fig. 6). From Fig. 6, it is confirmed that the rigidity in the horizontal direction will be increased by the retrofit and that the effects of the excavation of the riverbed will be limited.

5 DYNAMIC ANALYSES

Based on the results in chapter 4, dynamic analyses on the whole system, including the double-span stone

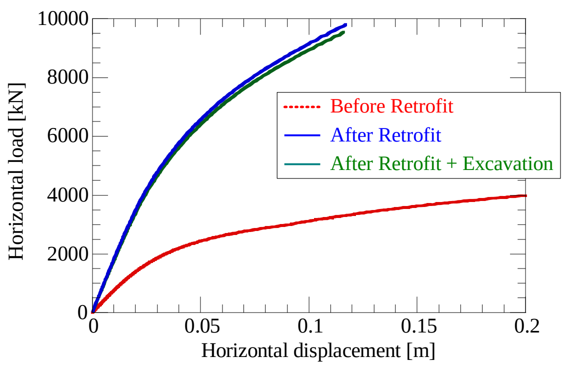


Fig. 6. Load-displacement curves for pushover analyses before and after retrofit and after retrofit and excavation.

arch bridge and its surrounding ground, were carried out using models in which timber piles and clayey soil were integrated. Fig. 7 shows the analytical mesh for the dynamic analyses. The analytical domain is set to 1/2 in the y-axis direction in consideration of symmetry. In terms of the boundary conditions, equal displacement boundary conditions were placed at nodes 100 and 200 meters from the bridge centerline. The damping of materials was considered by the Rayleigh damping model using stiffness damping only. Since the voids in the stone masonry were not filled with any filling material, it is considered that the stone blocks are likely to attenuate the vibrations during an earthquake. Therefore, based on a past study by Elmenshawi et al. (2010), the damping coefficient was set to 5%. Japanese level 1 earthquake motion (Japan Road Association, 2012) was input from the bottom of the analytical domain.

Fig. 8 shows the time histories of the relative displacements in the arch feet for the left and right arches. The relative displacements of the arch feet accumulate in the narrowing direction in both the left and the right arches with the earthquake. Comparing each case, the largest relative displacement occurs in the original foundation structure, and its residual displacement is also large. On the other hand, in the case of the structure after the retrofit, the relative displacements have drastically decreased and the residual displacement has also decreased. As shown in Fig. 6, it was found in the pushover analyses on the central bridge pier that the effects of the riverbed excavation would be slight. This was also confirmed in the dynamic analyses of the entire structure.

Fig. 9 shows the distributions of the axial stress generated in both arches at 4.7 seconds, when large relative displacement occurred in the right arch. Here, focusing on the effects of the earthquake, the changes in axial stress from the initial value are shown. In each arch, the axial stress increases from the top of the arch to the left foot, but the axial stress decreases in the right foot. Comparing the cases before and after the retrofit, in the case before the retrofit, where a large relative displacement has occurred, the amount of reduction in axial stress becomes maximum. Therefore, it was clarified that not only the relative displacement between the arch feet, but also the amount of decrease in the axial stress of the arch, can be improved by the retrofit.

6 CONCLUSIONS

In this study, the seismic resistance of a double-span stone arch bridge, Tokiwa Bridge, damaged in the 2011 Great East Japan Earthquake, was investigated through static pushover analyses of the central bridge pier and dynamic analyses of the entire structure before and after the retrofit. As a result, it has been confirmed that the planned retrofitting method would improve the earthquake resistance of the bridge. Furthermore, it was found that the effects of the riverbed excavation would be limited.

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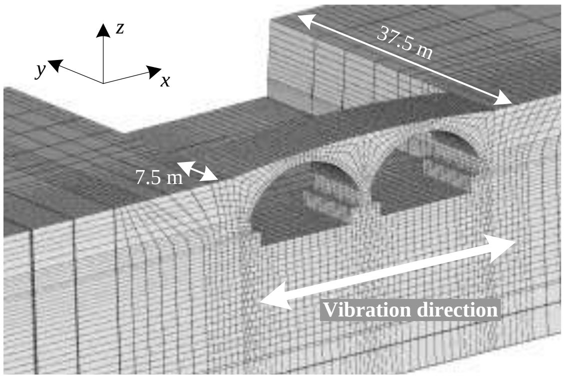

Fig. 7. Analytical mesh for dynamic analyses.

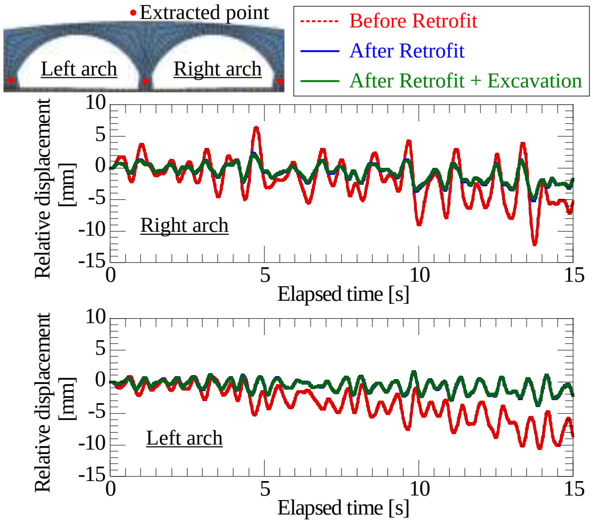

Fig. 8. Relative displacements of arch feet.

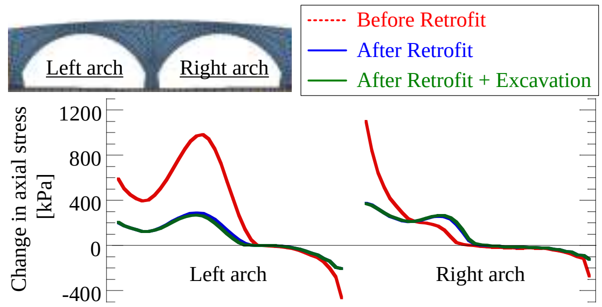

Fig. 9. Changes in axial stress in both arches at maximum relative displacement around 4.7 seconds.

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