Experimental study on seismic resistance of a two-hinge precast arch culvert using strong earthquake response simulator

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ABSTRACT

The design of traditional culvert structures in Japan has not considered seismic stability, because such structures have not suffered terrible damage in past earthquakes. In recent years, however, the construction of precast arch culverts, which include hinges in the main body and are outside the range of conventional culverts, has been increasing. In this study, large-scale shaking table test using a strong earthquake response simulator was conducted to clarify the seismic behavior of a two-hinge precast arch culvert. Furthermore, the inner space displacement and the earth pressure of the culvert were measured in each construction stage. From the results, it was found that the seismic response of the culvert is governed by the shear deformation of surrounding soil; and thus, a seismic deformation method will be probably applicable to the aseismic design. However, the modification mode of the component did not change according to the banking height and the culvert did not behave as expected in the construction stage.

Keywords: precast arch culvert, seismic resistance, level 2 earthquake, coefficient of earth pressure

1. INTRODUCTION

In the design of culverts in Japan, conventional culverts have been built over the past several years by applying methods which do not consider a seismic design. In recent years, however, opportunities for the construction of new types of culverts, which are outside the range of conventional culverts and are based on different design concepts, have been increasing. Representative of these culverts are precast arch culverts which include hinges in the main body. Precast arch culverts harness subgrade reactions positively by permitting deflection, and become mechanically stable structures. Therefore, compared with other forms which support external forces by the rigidity of the member, the thickness of the member is small and construction with a large section and a high overburden is possible. Furthermore, since the culvert is made from a precast product, there are advantages such as the saving of labor at the construction site, shorter work periods and high quality control. However, precast arch culverts have hinge functions on the main body, and thus, the conventional design method cannot be applied. Therefore, an evaluation of the seismic capacity of culverts and the dynamic interaction between the soil and the culverts has become an important issue.

Regarding the seismic stability of precast arch culverts, some experiments in the 1G gravitational field or under centrifugal conditions (Toyota and Itoh, 2000; Sawamura et al., 2014a, 2014b) and numerical analyses (Byrne et al., 1996; Hwang et al., 2006) have been conducted. However, their modeling has been limited, and the earthquake performance of the whole structure, including the hinge parts, has not been clarified. In this study, large-scale shaking table test using a strong earthquake response simulator was conducted to clarify the seismic behavior of a two-hinge precast arch culvert. Furthermore, since the precast arch culvert is designed by changing the coefficient of earth pressure and the ground spring according to the banking height, the inner space displacement and the earth pressure acting on the culvert were measured in construction stage.

2 EXPERIMENTAL OUTLINE

This experiment was conducted using the Strong Earthquake Response Simulator which belongs to the Disaster Prevention Research Institute at Kyoto University. Figure 1 shows the set-up of the culvert model and the arrangement of the sensors. A soil chamber, about 3.5 m long, 2.0 m deep and 1.0 m wide was used for the test. Since the lower part of the side wall and the bottom of the soil chamber are connected by a hinge, the side wall serves as a movable wall. Therefore, the soil chamber is a structure which permits simple shear deformation.

Kagawa (1978) reported the similarity rule for model tests in the 1G gravitational field. If the

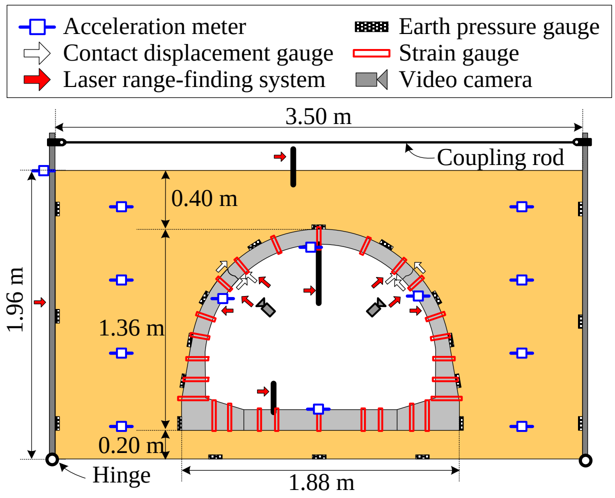

Fig. 1. Diagrammatic illustration.

Table 1. Properties of Edosaki sand.

Specific gravity of soil particle G_s	2.73
Particle size distribution D_{50} [mm]	0.18
Internal friction angle ϕ [Deg]	38.3
Cohesion c [kPa]	14.0
Optimum moisture content w_{opt} [%]	20.8
Maximum dry density ρ_{dmax} [g/cm^3]	1.64

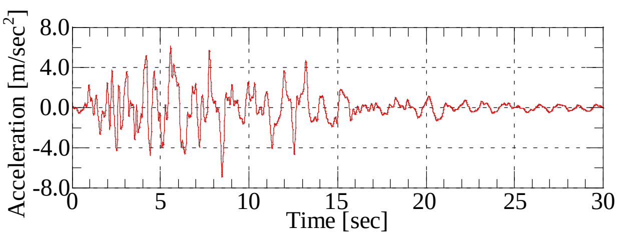

Fig. 2. Input wave (Level 2 earthquake).

similarity rule is applied, it is necessary to reduce the elastic coefficient of the culvert according to the model scale. However, considering that the purpose of this experiment is to investigate the behavior of an actual precast arch culvert, it is not appropriate to make the culvert model from materials other than reinforced concrete. Therefore, the culvert model was made from reinforced concrete, and the thickness of the member and bar arrangement were determined based on the design method according to the inner space and the overburden under this experimental condition. Thus, the culvert model used in this experiment is the same as the section used when the same scale culvert is actually constructed in the field.

Both the foundation ground and the filling were made from Edosaki sand. Table 1 shows the properties of Edosaki sand. The degree of compaction of Edosaki sand was set to 92 %, which is the construction standard for backfill soil in a precast arch culvert. The sand was compacted with the prescribed water content (w = 20.0 %) in 39 layers for every 50 mm.

In order to investigate the earthquake resistance during an epicentral earthquake and an aftershock, Level 1 and Level 2 earthquake motions were each input alternately two times. The Level 2 earthquake motion used in this experiment was measured according to the Southern Hyogo Prefecture earthquake of 1995. Figure 2 shows the input earthquake motion. In this paper, the results are explained for when the Level 2 earthquake motion was input.

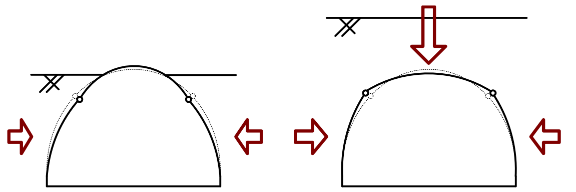

Fig. 3. Modification mode presumed in design.

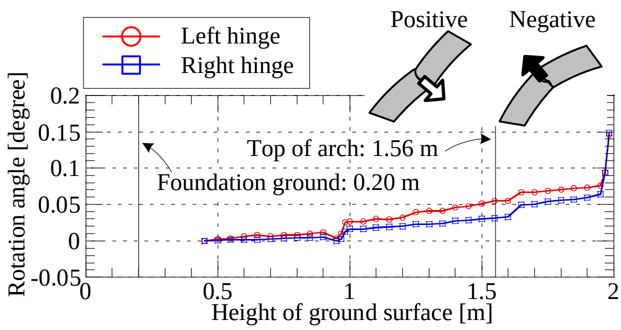

Fig. 4. Transition of the rotation angle of both hinge parts.

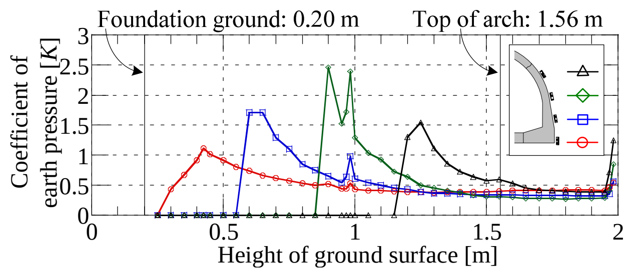

Fig. 5. Transition of the coefficient of earth pressure.

3 EXPERIMENTAL RESULTS

3.1 Deformation behavior in the construction stage

Figure 3 shows the modification mode presumed in the design of a two-hinge precast arch culvert. In the present design, it is thought that when the banking height is lower than the crown of the culvert, the crown displaces upwards because the horizontal earth pressure dominates. When the banking height is higher than the crown, however, the perpendicular earth pressure of the arch culvert dominates, and it is thought that the crown is gradually depressed downwards and the whole arch is deformed flatly. Based on this presumption of the design, the experimental results are arranged.

Figure 4 shows the transition of the rotation angle for both hinge parts at each banking construction stage. From the figure, it can be seen that the rotation angle changes discontinuously when the banking height is

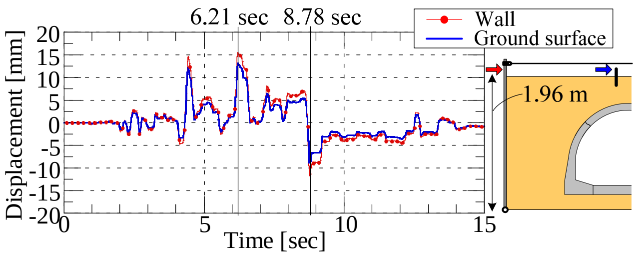

Fig. 6. Time history of horizontal displacement.

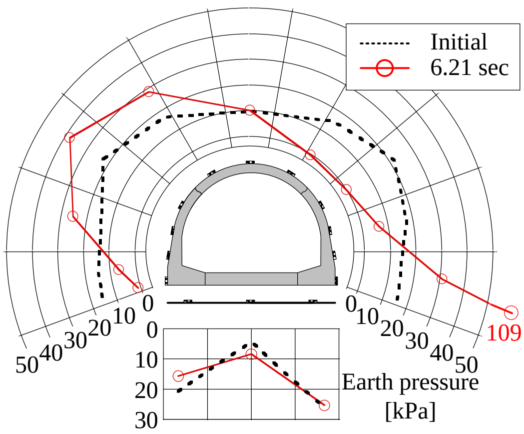

Fig. 7. Distribution of earth pressure at t = 6.21 sec.

0.95 m and 1.65 m. This is because the construction process extended to the following day at these points, and the culvert followed the ground consolidation. Moreover, since the PC steel rod was attached at the upper part of the walls before inputting the earthquake motion, the hinge parts were greatly displaced to the inner space when the banking height was 1.95 m. When the banking height was lower than the crown of the culvert, the hinge parts were slightly displaced to the inner space. This behavior indicates a similar tendency to that of the design presumption in Figure 3. However, in the design, the perpendicular earth pressure excels and the hinge parts are displaced to the outside, when the banking height is higher than the crown; such a mode was not observed in this experiment. One of the reasons was the culvert used in this experiment. Although the culvert was designed as a real structure, it is possible that the rigidity of the culvert was relatively large and the influence of the overburden decreased due to the scale effect.

Figure 5 shows the transition of the coefficient of earth pressure computed from the earth pressure acting on the right-hand side culvert at each banking construction stage. Although coefficient of earth pressure K becomes one or more under the influence of compaction, it gradually converges to a steady value as the banking height increases. The average value for the coefficient of earth pressure upon completion of banking construction is set to K = 0.35. It is the influence of the PC steel bar that causes the coefficient of earth pressure to increase to the banking height of 1.95 m at all positions. In the design of precast arch

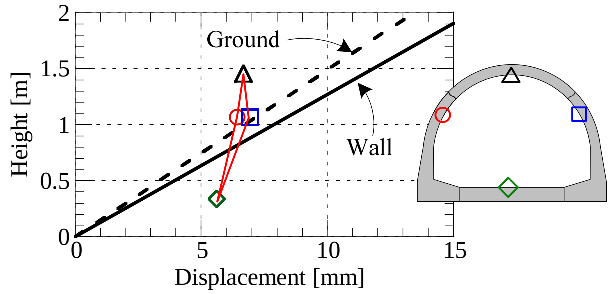

Fig. 8. Horizontal displacement at t = 6.21 sec.

culverts, the coefficient of earth pressure K is assumed to be 0.3 when the banking height is lower than the crown of the culvert. When the banking height is higher than the crown, however, the coefficient of earth pressure K is changed to K = 1 - sinϕ (usually, ϕ = 30 deg and K = 0.5), because the perpendicular earth pressure of arch culvert dominates and the whole arch is deformed flatly. On the other hand, in this experiment, even if the banking height became higher than the crown (1.56 m), no changes in the coefficient of earth pressure were observed.

3.2 Seismic behavior during Level 2 earthquake

(a) Horizontal displacement of wall and ground surface

Figure 6 shows the time history of the horizontal displacement of the wall (at the height of ground level) and the ground surface. Since the measurement position of the ground surface is near the center of the soil chamber and lies directly over the culvert, the displacement of the wall is slightly larger than that of the ground surface. The peak of the wall displacement corresponds to the peak of the acceleration, and the maximum displacement was 15.44 mm at t = 6.21 sec. The shear strain at this time was about 0.8%. It is reported that the amount of shear strain not accompanied by liquefaction was 1% in the Southern Hyogo Prefecture earthquake. Therefore, in this experiment, it can be said that shearing strain, comparable to this earthquake, occurred.

(b) Dynamic earth pressure acting on culvert

Figure 7 shows the distribution of earth pressure acting on the culvert at t = 6.21 sec. The earth pressure at the left shoulder and right foot are seen to increase from the initial state, while the earth pressure at the right shoulder and left foot are seen to decrease. In other words, the earth pressure is reversed to the direction of the culvert's height. The horizontal displacements measured in the embankment and at each position of the culvert at the time are shown in Figure 8. Comparing the displacement of the ground with that of the culvert, it is thought that the culvert has received rightward force from the left-hand side banking, since the displacement of the upper part of the culvert is smaller than that of the ground. On the other hand, the displacement of the lower part of the culvert is larger than that of the ground; this indicates the deformation

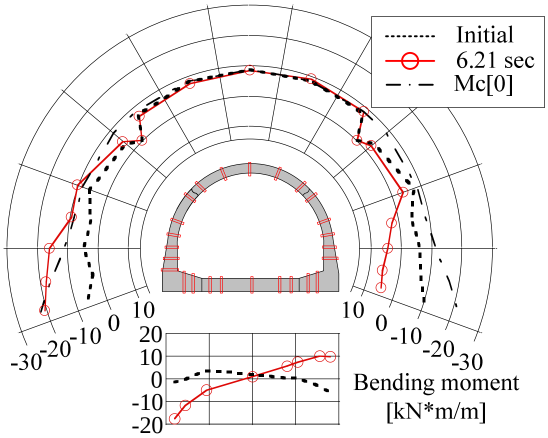

Fig. 9. Distribution of bending moment at t = 6.21 sec.

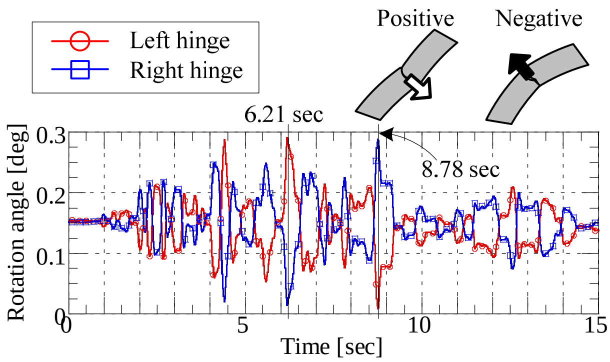

Fig. 10. Time history of rotation angle of hinge.

mode with culvert compression banking. Thus, it became clear that the seismic response of culvert is governed by the shear deformation of surrounding soil. Therefore, it is probable that a seismic deformation method will be applicable to the aseismic design of a two-hinge precast arch culvert.

(c) Bending moment

Figure 9 shows the distribution of bending moment at t = 6.21 sec. A positive bending moment is defined for the case in which tension is generated inside the culverts. The dotted line in the figure means a simple bending moment of crack generation. The bending moment changes significantly from the initial value at both feet because of the changes in earth pressure. Meanwhile, the bending moment at the vault hardly changes at all, so the vault behaves as a rigid deformation due to the effect of the hinge at the shoulder part. Although the maximum bending moment occurred in the left foot, the value is less than for the simple bending moment of crack generation. Therefore, it is confirmed that the two-hinge precast arch culvert used in this experiment has sufficient member capacity to withstand Level 2 earthquake motion.

(d) Rotation angle at hinge

Figure 10 shows the time history of the rotation angles of the hinges. The right and left hinges rotate symmetrically all the time. The maximum rotation angle occurred at around t = 6.21 sec when the horizontal displacements of the wall and the ground reached their maximum, and the rotation angle was about 0.3 deg at this time. However, the permissible rotation angle from the geometrical form of a hinge is + 8 ~ −5 deg; and thus, the rotation angle measured in this experiment is at a fully tolerant level. Therefore, it is confirmed that the possibility for the whole culvert to result in a collapse by the omission of a hinge part is low and that the two-hinge precast arch culvert has sufficient resistance to Level 2 earthquake motion within the range of this experimental work.

4 CONCLUSIONS

1) The two-hinge precast arch culvert has sufficient aseismic capacity against large earthquakes within the scope of this experimental condition.
2) The seismic response of the culvert is governed by the shear deformation of surrounding soil; and thus, a seismic deformation method will be probably applicable to the aseismic design.
3) The modification mode of the component did not change according to the banking height and the culvert did not behave as expected in the construction stage.
4) As a future subject, it will be necessary to conduct the same experiments using a thinner RC member to clarify the deformation behavior in the construction stage and in the ultimate limit state against large earthquakes.

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