Dynamic centrifuge tests on three-hinge type of precast arch culverts installed in embankment with asymmetrical overburden in culvert longitudinal direction

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ABSTRACT

Three-hinge precast arch culverts have been constructed as laborsaving equipment mainly along the highways in Japan since the 1990s. However, many of them suffered damage in the Great East Japan earthquake (11 March 2011), including severe damage like the deformation of the wall at the culvert mouth and the displacement of hinges. This damage occurred near the mouth of culverts installed in embankments at an oblique angle with an asymmetrical overburden. In this study, dynamic centrifuge tests are conducted on a three-hinge type of arch culvert with asymmetrical overburden pressure, and the behavior is monitored in the longitudinal direction in order to observe the reported deformation at the mouth wall and at the hinge sections. According to the results, uneven overburden along the cross section of the arch causes uneven distributions of the axial forces and the bending moments in the culvert mouth. This unevenness indicates that the combination of the orientation of the culvert and the seismic wave direction is likely to cause torsion, aperture, and other damage to the culvert arch members.

Keywords: Three-hinge precast arch culvert, dynamic centrifuge test, asymmetrical overburden, culvert longitudinal direction

1 INTRODUCTION

Three-hinge precast arch culverts are statically determinate structures whose hinges are positioned at both feet of the arch member and at the crown of the arch, respectively (Fig. 1(a)). The seismic performance of three-hinge precast arch culverts has been studied, in terms of their laborsaving function, since they were introduced by France in 1993 to Japan, a country which frequently suffers from earthquakes (e.g., Toyota and Takagai, 1995; Sawamura et al., 2016).

The old type of three-hinge arch culverts, installed in the 1990s, had relatively weaker structural connectivity than the current ones (Fig. 1(a)). They suffered severe damage in the Great East Japan earthquake (11 March 2011) and lost their serviceability. Abe and Nakamura (2014) reported continuous damage to the arch members and deformation of the mouth wall that appeared to be closely related to the magnitude of the seismic wave motion in the culvert longitudinal direction and the condition of the culverts' overburden at the mouth.

To elucidate these disaster mechanisms, dynamic centrifuge tests on a three-hinge arch culvert with an embankment in the culvert longitudinal direction and various patterns for the embankment shape have been conducted (e.g., Miyazaki et al., 2016). It was found that the seismic behavior of culverts is heavily dependent on the confining stress from the embankment. On the other hand, severe damage, such as the deformation of the wall at the culvert mouth and the displacement of hinges, occurred near the mouth of culverts installed in embankments at an oblique angle with an asymmetrical overburden.

Therefore, in order to observe the reported deformation at the mouth wall and at the hinge sections, dynamic

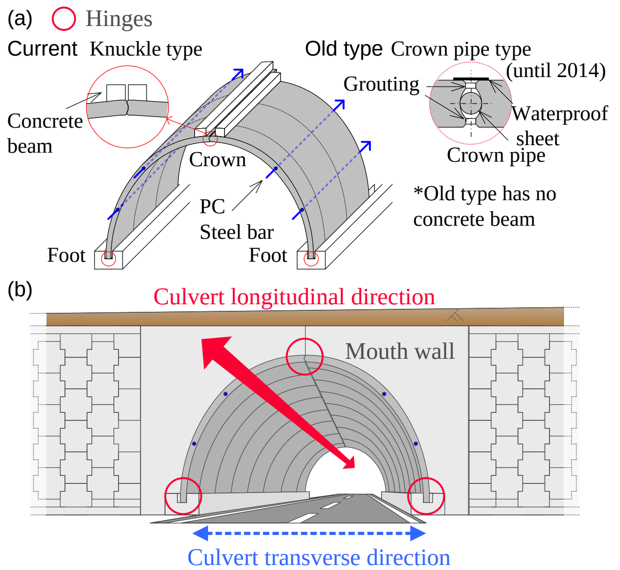

Fig. 1. Three-hinge type of precast arch culvert: schematic drawings of (a) structures and (b) road embankment.

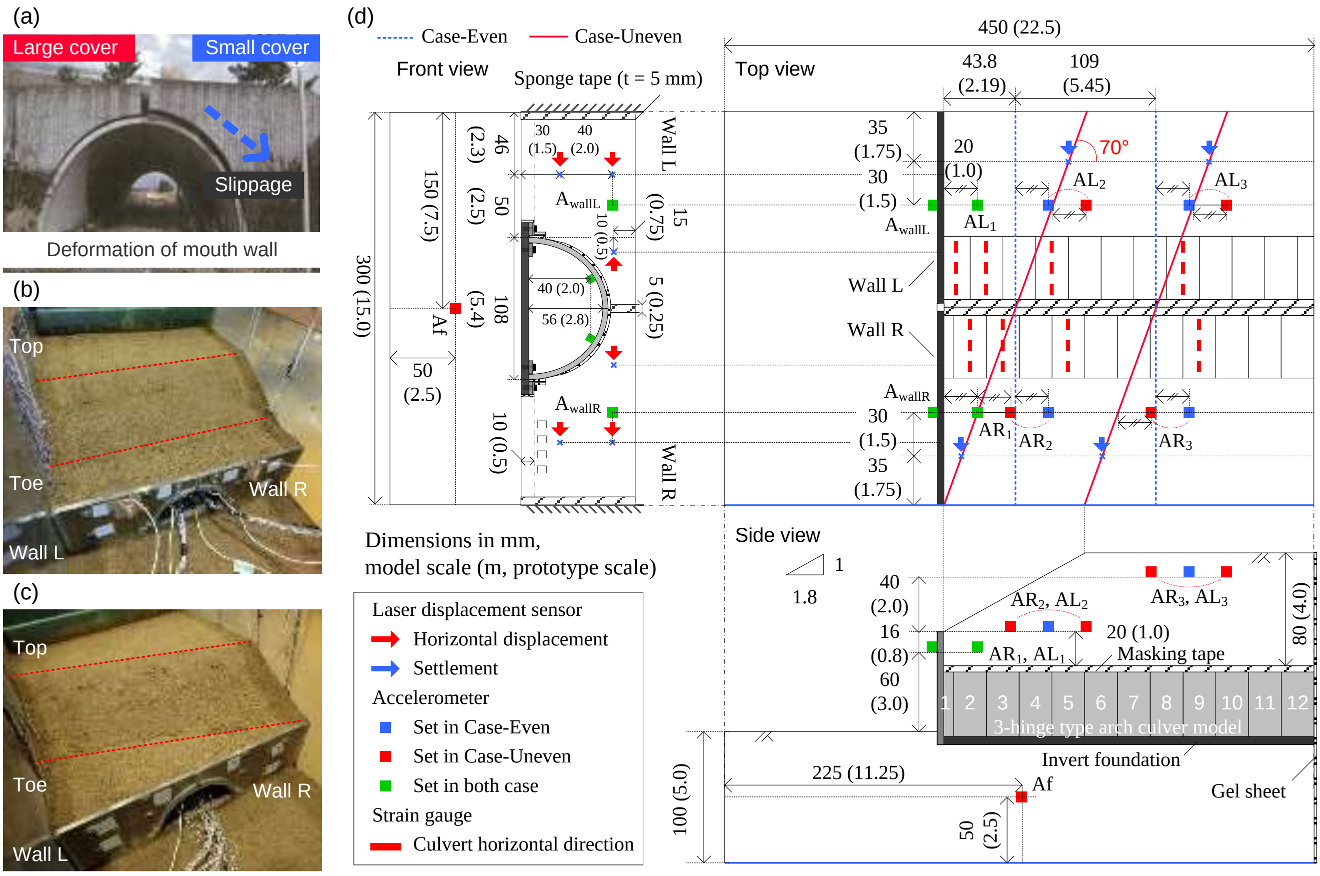

Fig. 2. Schematic drawings of experimental set-up: (a) referenced disaster example of Great East Japan earthquake (11 March 2011) cited from Abe and Nakamura (2014), (b) Case-Even, (c) Case-Uneven, and (d) experimental set-up of Case-Even and Case-Uneven.

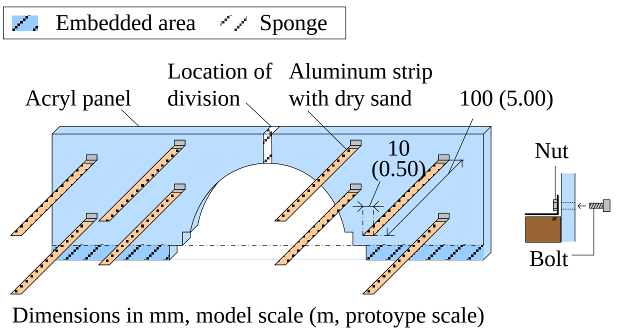

Fig. 3. Mouth wall model based on reinforced earth wall.

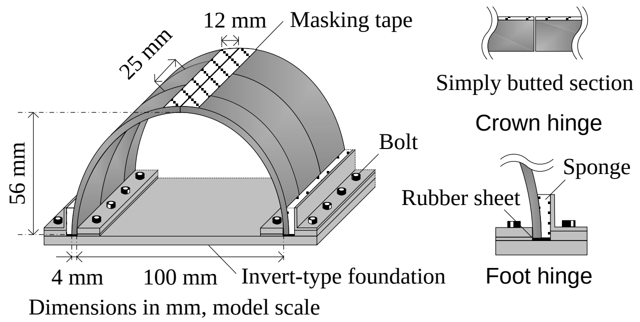

Fig. 4. Three-hinge type of arch culvert model

centrifuge tests, focusing on the asymmetrical overburden pressure have been conducted. And we monitored the seismic behavior in the longitudinal direction.

2 EXPERIMENTAL SET UP

This experiment was based on the previous experimental method. Details of the experimental model were described in an earlier publication (e.g., Miyazaki et al., 2016).

2.1 Physical model of culvert with embankment

Fig. 2 presents schematic drawings of the experimental set-up and the model of the three-hinge type of arch culvert constructed on a wet sand foundation under centrifugal acceleration of 50 G using a soil chamber with the dimensions of 340 mm (H) × 450 mm (W) × 300 mm (D).

Figures 2(a), (b), and (c) show the damaged culvert that was the basis for the models and the completed model culverts for Case-Even of a symmetrical overburden and for Case-Uneven of an asymmetrical overburden, respectively. The angle between the model embankment and the culvert in Case-Uneven is 70°, based on the observation of damaged culverts with 60° to 90° angles.

2.2 Mouth wall model and three-hinge arch model

The mouth wall of three-hinge arch culverts uses a separated wall structure, as shown in Fig. 3. To consider the structural characteristics of both the mouth wall and the oblique angle condition, the model wall for this experiment was made of two acrylic plates and the reinforcement was modeled with aluminum strips. Fig. 4 shows the three-hinge type of arch culvert

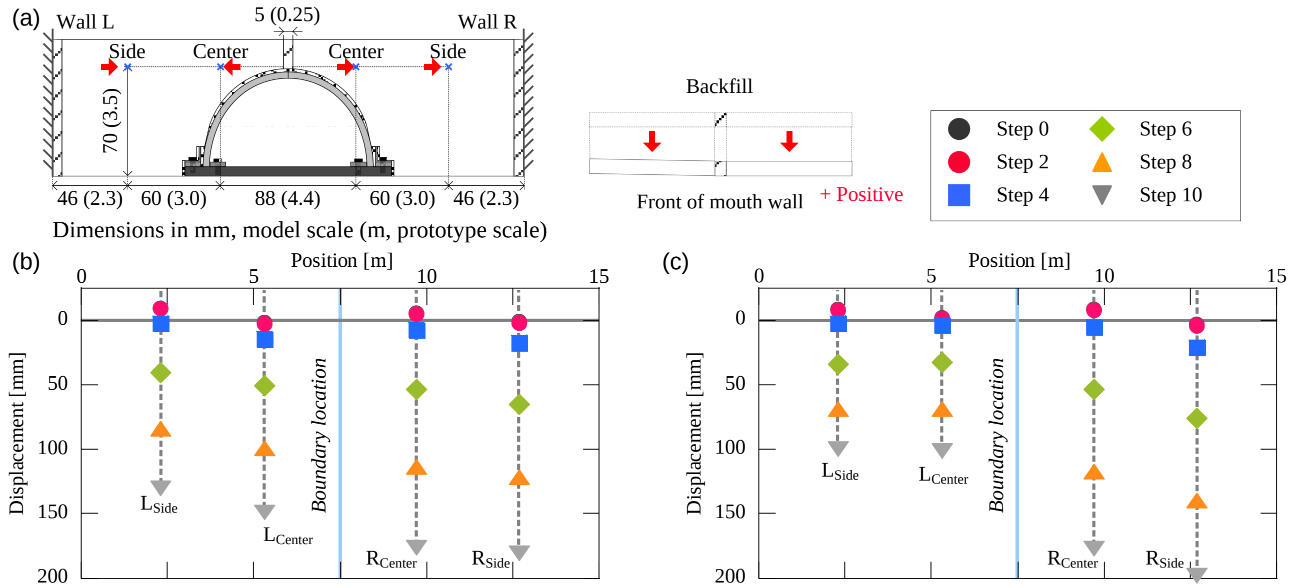

Fig. 5. Transition of horizontal wall displacement: (a) measurement position and results of (b) Case-Even and (c) Case-Uneven

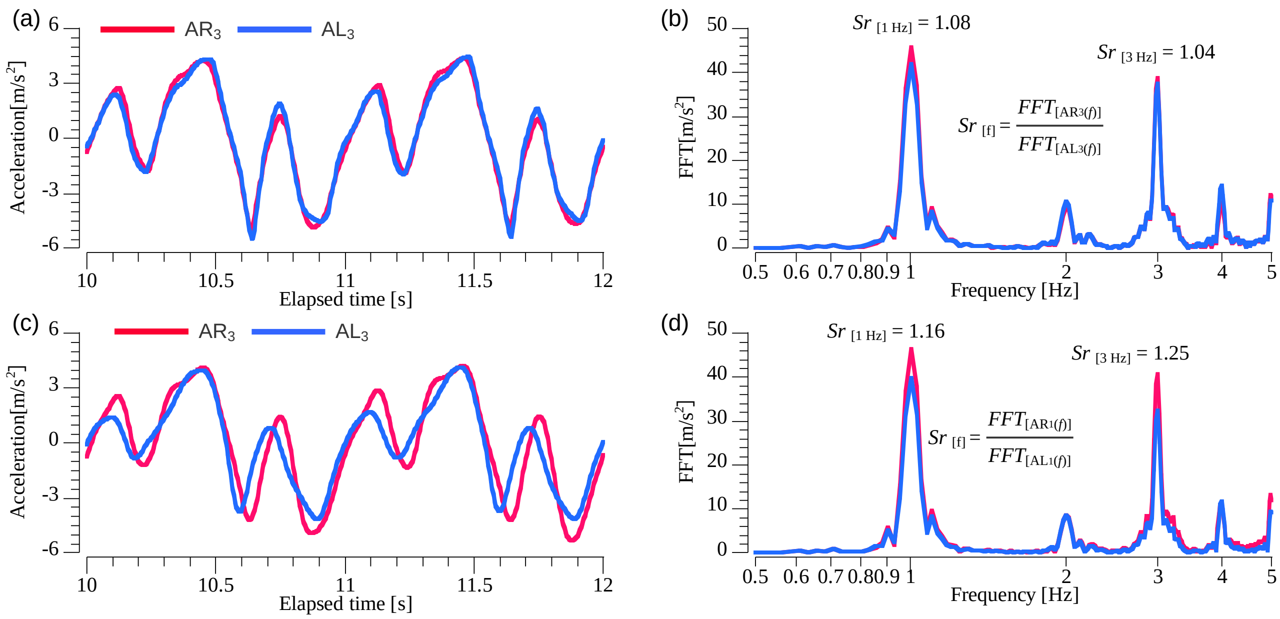

Fig. 6. Response acceleration of embankment at STEP 6 (Maximum acceleration is 3.0 m/s^2). Case-Even's (a) time history and (b) frequency component and Case-Uneven's (a) time history and (b) frequency component.

model. The structural connection of the model follows the current design condition which has a clear influence on the soil-structure interaction due to the simple connections of the culvert (Fig. 1).

2.3 Model ground and input wave

The model soil was prepared by compacting wet Edosaki sand to Dc = 92% and w = 17.8% (= w_{opt} of Edosaki sand). Due to concerns over the boundary conditions at the back end of the embankment, caused by chamber rigidity, a 2-mm-wide gel sheet (the compressive stress at 10 % strain is 0.07 N/mm^2) was applied. The wave motions were input in steps to observe the changes in displacement of the mouth wall and the response acceleration for different intensities of ground motions. A continuous tapered 1 Hz wave with 20 cycles of sine waves was applied 10 times, from STEP 1 to STEP 10, with a gradual increase of 0.5 m/s^2 per step.

3 RESULTS AND DISCUSSION

Fig. 5 presents the horizontal displacement of the mouth wall after excitation. Both Case-Even and Case-Uneven show larger deformation of Wall R after repeated excitations; it is especially significant in Case-Uneven. Fig. 6 shows the response acceleration at the top of the model embankment (AR_3, AL_3) for STEP 6, whose maximum acceleration is 3.0 m/s^2. Only the results from t = 10.0 s to 12.0 s are shown to clarify the differences in the two cases. In the figure, *Sr* is defined as the ratio of the Fourier Amplification Spectrum

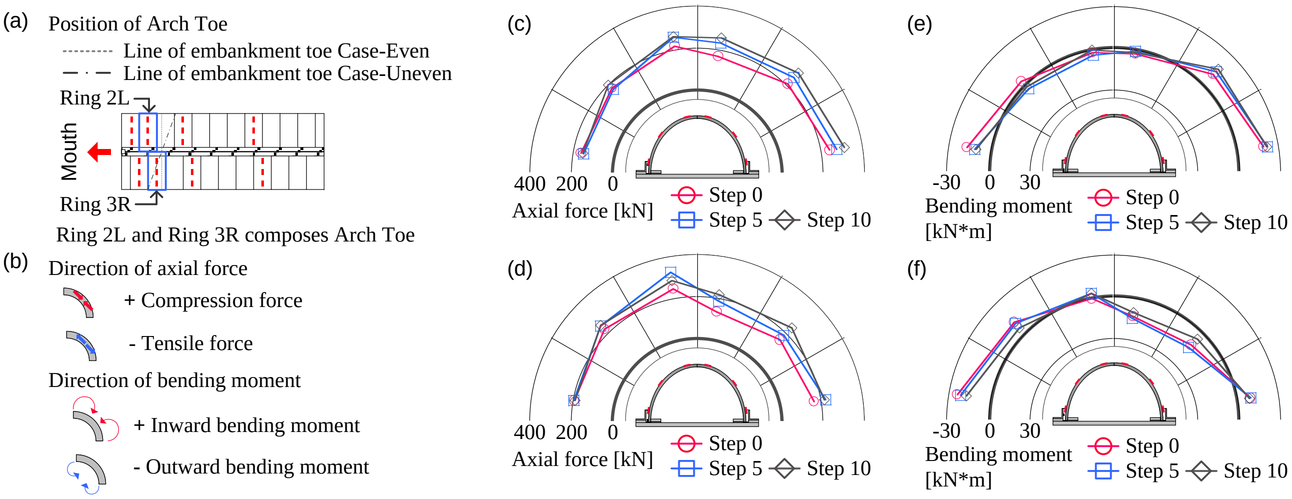

Fig. 7. Load condition of Arch Toe: (a) position of Arch Toe, (b) Definition of axial force and bending moment, axial force of (c) Case-Even and (d) Case-Uneven and bending moment of (e) Case-Even and (f) Case-Uneven.

(FAS) given by FAS to AR3 divided by FAS to AL3. In Case-Even, seen in Figs. 6(a) and (b), the response accelerations of AR_3 and AL_3 are almost coincident, while $Sr_{1\ Hz}$ of AR_3 shows amplification of about 10% over AL_3, which is likely to be the cause of the larger deformation of Wall R. In Case-Uneven, AR_3 shows a slightly different waveform from AL_3, and $Sr_{1\ Hz}$ and $Sr_{3\ Hz}$ of AR_3 are amplified by about 16% and 25%, respectively. Case-Uneven seems to experience uneven deformation at the mouth wall due to the uneven amplification and response acceleration at AR_3 and AL_3.

Fig. 7 presents the axial forces and bending moments of the Arch Toe in Case-Even and Case-Uneven. The Arch Toe is comprised of Ring 2L and Ring 3R under the embankment toe (Fig. 7(a)). In Figs. 7(c) and (d), the axial forces at the Arch Toe tend to increase with a shape similar to that of the initial condition. In Case-Uneven, the Arch Toe seems to be influenced by the settlement of the embankment toe and the resulting deformation of Wall R. However, the axial force of Ring 3R is smaller than that of Ring 2L. Moreover, in Figs. 7(e) and (f), the Arch Toe in Case-Uneven shows a relatively larger inward bending moment than that in Case-Even, which seems to be caused by the asymmetrical overburden. This asymmetrical loading condition, due to the relation of crossing between the road and the culvert, appears to give torsion to the arch members during earthquakes in the culvert longitudinal direction.

4 CONCLUSIONS

In this study, we investigated the seismic behavior of three-hinge precast arch culverts installed in an embankment oriented 70 degrees to the road with an earthquake wave of 1 Hz applied across 10 steps of continuous excitation. The following conclusions can be drawn from the results of this study:

1) Culverts installed in a road embankment at an oblique angle suffer uneven deformation of both the embankment and the wall due to changes in the response acceleration in the embankment at the location of the division between Wall L and Wall R of the mouth wall.
2) Uneven overburden along the cross section of the arch causes an uneven distribution of both the axial forces and the bending moments in the culvert mouth. This characteristic combination of a culvert's stress condition and seismic wave direction is likely to cause torsion, aperture, and other damage to the culvert arch members.

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