EXPERIMENTAL STUDY ON LIQUEFACTION-INDUCED EARTH PRESSURE ON BRIDGE ABUTMENT

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ABSTRACT

A bridge abutment, which is a type of retaining structures, needs designing against earth pressure from the backfilling. In addition to earth pressure from the backfilling during an earthquake, an abutment that is constructed on the liquefiable ground may be subjected to lateral movement of backfilling due to liquefaction. However, there remain many uncertaties regarding how earth pressure and earthquake behavior affect abutments through ground liquefaction-induced movement. Therefore, the authors conducted dynamic centrifuge tests for the purpose of studying how earth pressure affects bridge abutments. In this paper, we report the results of an experimental study, in which we focus on earth pressure on bridge abutments that occurs during an earthquake as well as earth pressure that occurs with ground movement.

INTRODUCTION

Liquefaction and the associated ground flow inflicted serious damage to various infrastructures including foundations of highway bridges in the 1995 Hyogo-ken Nanbu earthquake. At a bridge abutment on liquefied ground, the liquefaction of the ground causes the backfill to settle, causing earth pressure (liquefaction-induced earth pressure) to act on the bridge abutment. A bridge abutment is a type of retaining structures. While being subjected

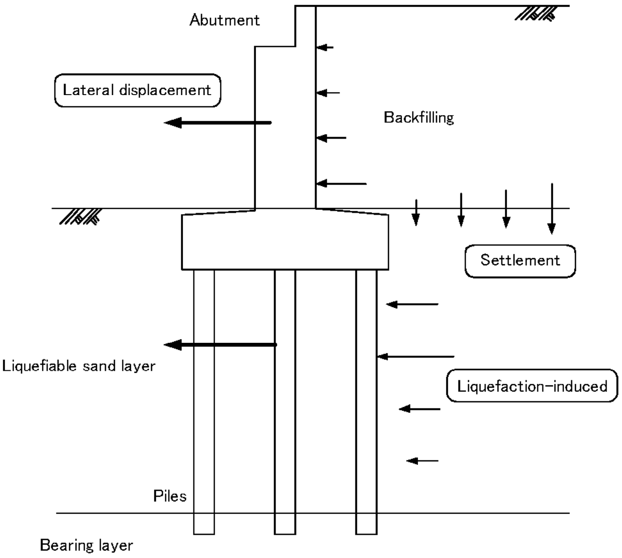

Figure 1. Schematic figure of piled bridge abutments on liquefiable sand layer

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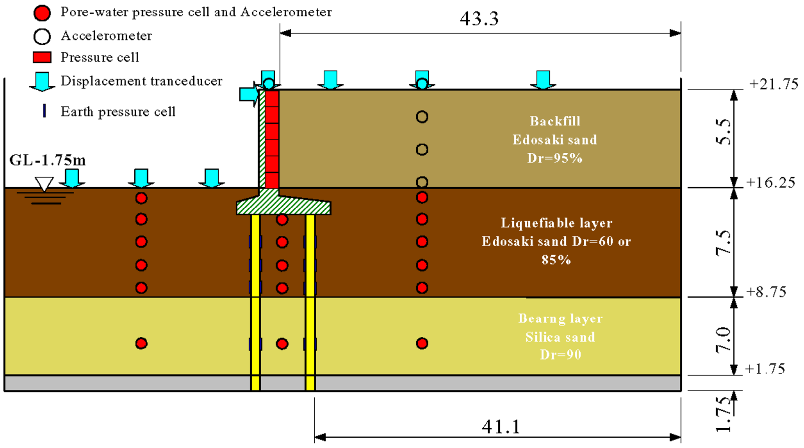
Table 1. Test conditions

Case	Foundation type	Top of the abutment	Thickness of liquefiable layer (mm)	Thickness of bearng layer (mm)	Relative density D (%)	
					Liquefiable layer	Bearng layer
1	Pile foundation	free	150	140	85	90
2	Pile foundation	free	150	140	60	90
3	Pile foundation	free	190	100	60	90
4	Spread foundation	free	150	140	85	90
5	Pile foundation	restrict	150	140	85	90
6	Pile foundation	restrict	150	140	85	90
7	Pile foundation	restrict	190	100	60	90
8	Pile foundation	restrict	150	140	60	90

to earth pressure from backfilling, it is required to stably maintain the load of the superstructure. Even after an earthquake, damaged bridge girders and piers can be repaired relatively easily, however, damaged bridge abutments are difficult to repair. Because of this, Japan’s seismic design specifications for highway bridges1) require that bridge abutments remain elastic, even during major earthquakes. There are many cases when the bridge abutments are constructed at the soft subsoil. Loose sandy soil may liquefy during earthquakes, and there is the possibility that earth pressure caused by lateral movements that are coincidental to subsidence of backfilling may come to bear on bridge abutments. There is a report of a case where, at a bridge abutment previously damaged by an earthquake, such liquefaction-induced lateral force caused another damage2). Many aspects of the mechanism that causes this liquefaction-induced lateral force have not been completely understood yet. There are many uncertaties regarding the mechanism that causes this lateral movement. Thus, it is necessary to understand the characteristics of seismic earth pressure that acts on the bridge abutment structure and to accurately evaluate these characteristics for rational seismic design of bridge abutments.

The authors conducted dynamic centrifuge tests using bridge abutment models on the liquefiable ground with pile foundations. This paper reports the relationship between earth pressure on the rear of the bridge abutment during earthquakes and ground liquefaction based on the experiment results. The paper also presents comparisons of these results with seismic earth pressure on the rear of bridge abutments as prescribed in the Japan’s seismic design specifications for highway bridges.



Unit: m (converted for prototype model)

Figure 2. Cross section of model

Table 2. Soil properties of sand

Properties	Silica sand	Edosaki sand
G_s	2.65	2.68
D_{50} *(mm)*	0.17	0.17
U_c	1.68	4.2
F_c *(%)*	4.0	11.0
e_{max}	1.63	1.52
e_{min}	1.24	1.15
F_{dmax} *(%)*	-	1.57
w_{opt} *(%)*	-	14.3

EXPERIMENTAL MODELS

The dynamic centrifuge tests were carried out in a total of eight "cases", in which constraint conditions were altered by ground density, thickness of liquefaction layer, and upper structure. A large geotechnical dynamic centrifuge with a radius of 6.6 m has been development at PWRI in 1997. For the purpose of the geotechnical earthquake studies, a powerful electro-hydrauric shaking table designed to work in the centrifuge has also been developed. This shaking table provides 40G shaking acceleration observed durng the 1995 Hyogo-ken Nanbu Earthquake for a model at 50G centrifugal acceleration field. As shown in **Figure 2**, 1:50-scale models of an inverted T-type abutment were used. As is shown in **Table 1**, two types of ground density were used: one for which liquefaction occurs easily (relative density of 60%) and one for which liquefaction does not occur easily (relative density of 85%). The relative density of the backfilling and that of the supporting layer directly below the layer of liquefaction were the same in all cases. In preparing the ground model, a supporting layer was created by compacting dry silica sand to the prescribed relative density (approximately 90%), on top of which a liquefaction layer was created by compacting Edosaki sand with a water content of 18% to the prescribed relative density (approximately 60% or 80%). **Table 2** shows the properties of the sand used in the experiments. After compacting backfilling soil onto the prepared liquefaction level, the completed soil models were put into a vacuum chamber. They were then saturated by passing an aqueous solution of Metolose from the bottom of the soil layers (in the centrifuge experiments, the chamber temperature was kept at 10℃ and a Metolose aqueous solution having a density of 1.8% was used) that was adjusted to 50 times the viscosity of water in order to satisfy the similarity law for permeation. Stainless steel was used in preparing the bridge abutment model, with lead being added to some areas to adjust the model's weight and center of gravity. The pile model was made of acrylic resin and fixed to the bottom of the bridge abutment with screws. The bottom tip of the pile was made free. In terms of restraint conditions caused by the upper structure, experimental cases were established whereby deformation in the forward direction was confined through impact with the end of the girder, and cases where the bridge abutment could transform freely without constraint. As a result, top of the abutment can be move for the elastic deformation of the rubber (approximately 30 cm if converted to 1:1 scale), even in the cases where the bridge abutment was fixed.

EXPERIMENTAL RESULTS

The experiments took place at a 50 G centrifugal acceleration field using equipment for load testing of dynamic centrifugal force. Because the model was built at a scale of 1:50, it was possible to reproduce stress conditions found in the actual ground by conducting the experiments under 50G. In saturating the ground, the groundwater level was raised to the ground surface. For this, water was extracted from the bottom soil layer when the centrifugal speed was brought up to 50 G. The groundwater level was brought to the prescribed position (1.75 meters below the surface of the front ground), and the dynamic loading experiments were begun. In the dynamic loading experiments, 20 cycles of sinusoidal shakings with a frequency of 100 Hz, and the input level at Step 1 was set at 12 G (approximately 250 gals when converted to 1:1 scale). In Step 2, the input level was set at 25 G (approximately 500 gals when converted to 1:1 scale). **Figure 3** shows the actual 1:1 conversion of the Step 1 pressure measured using load cells installed at the back of the bridge abutment. Also presented in **Figure 3** are calculations of active earth pressure during earthquakes by use of the Japan's seismic design specifications for highway bridges. Although there is amplification of earth pressure in the rear of the bridge abutment during earthquake in the Japan's seismic design specifications for highway bridges, there are many uncertainties concerning the characteristics of acceleration amplitude. Because, as is shown in **Figure 4**, seismic earth pressure was brought to bear on the wall of the bridge abutment using the same earthquake force. Earth pressure on the rear of the bridge abutment during earthquakes1) was calculated according to the following formula:

$$P_{EA} = \gamma \times x \times K_{EA} + q' \times K_{EA} \qquad (1)$$

Here,

P_{EA} : active seismic earth pressure (kN/m^2) at a depth of x (m)
K_{EA} : coefficient of active seismic earth pressure
When the backfilling consists of sand or gravel
$K_{EA} = 0.21 + 0.90\, k_h$
When the backfilling consists of sand or gravel
$K_{EA} = 0.24 + 1.08\, k_h$

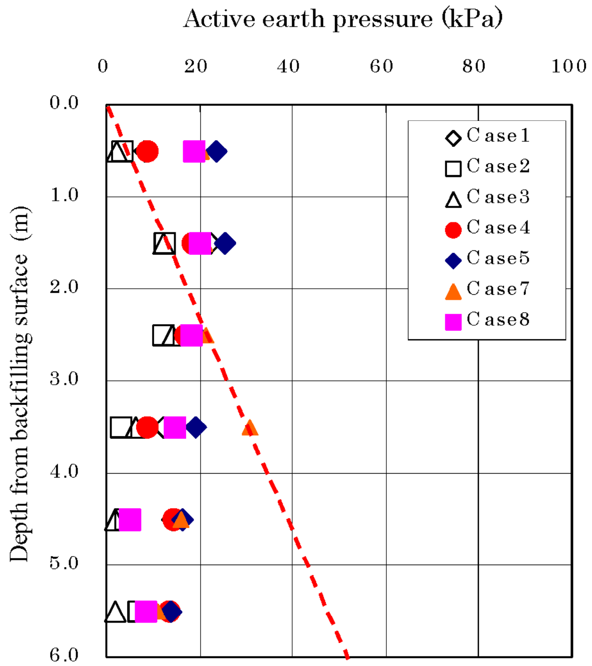


Figure 3. Active earth pressure (Step 1)

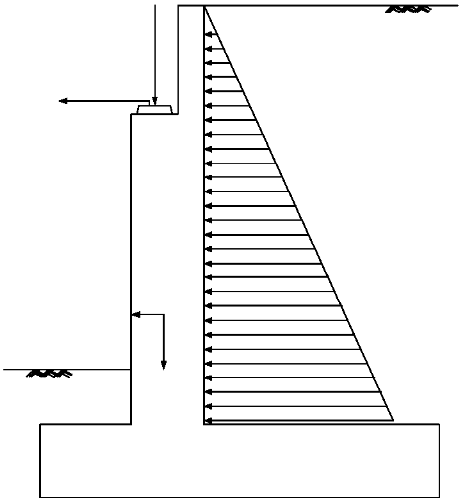
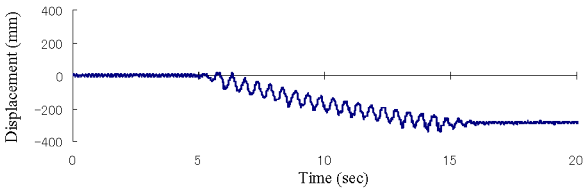
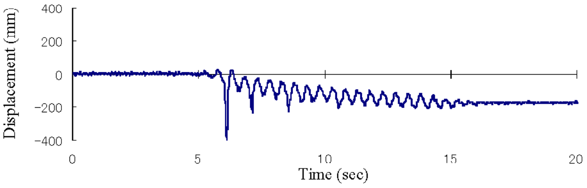


Figure 4. Active earth pressure



(a) case 2



(b) case 5

Figure 5. Displacement at top of the abutment (Step 1)

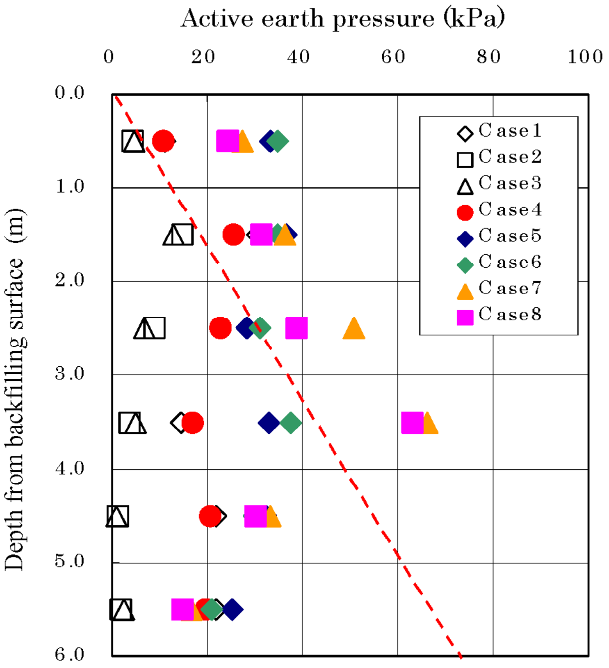
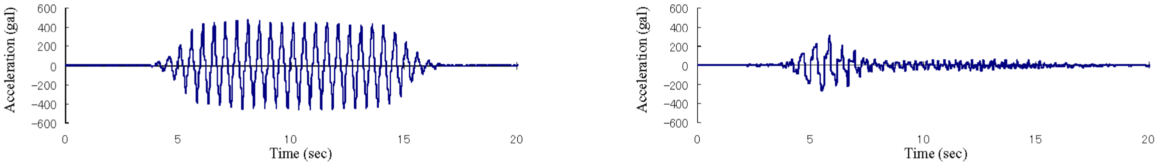


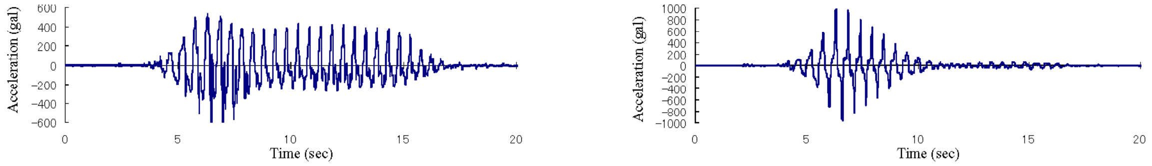
Figure 6. Active earth pressure (Step 2)

k_h : design horizontal seismic coefficient using calculation of earth pressure during an earthquake
y : unit weight of earth (kN/m^3)
q' : acting load at the surface of backfilling (kN/m^2)

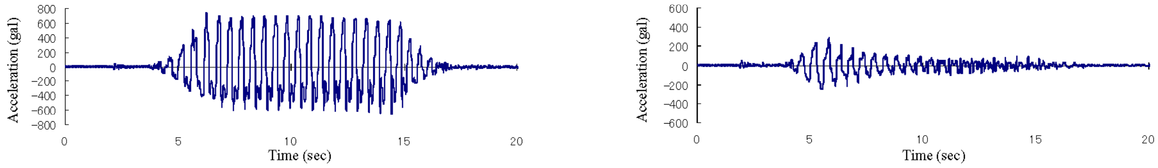
Comparing the cases 2, 3, 7, and 8, in which liquefaction occurred, and the cases 1, 4, and 5, in which liquefaction did not occur, a slightly greater amount of ground pressure was generated in the latter cases. Also, in the cases 5, 7, and 8, in which displacement of the top end of the bridge abutment was constrained, it was found that the calculated value of earth



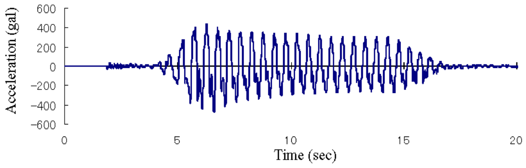
(a) bottom of container (case 2) (b) surface of the front-side ground (case 2)



(c) surface of the backfilling-side ground (case 2) (d) surface of the front-side ground (case 5)



(e) surface of the backfilling-side ground (case 5) (f) surface of the front-side ground (case 8)



(g) surface of the backfilling-side ground (case 8)

Figure 7. Response acceleration (Step 2)

pressure near the surface of the backfilling was higher. As is shown in **Figure 5**, this is attributed to a fact that displacement of the top end of the bridge abutment was confined through impact between the end of the girder and the abutment, and increased earth pressure on the rear side of the abutment. Accordingly, at the earth pressure increases where is low displacement confinement (Step 1, where input acceleration are low), this tendency was limited to a shallow range beneath the ground surface of the backfilling; however, it was recognized that ground pressure increased even at deeper levels when the displacement constraint becomes larger (Step 2, where input acceleration are high).

Next, **Figure 6** shows the results of Step 2, where the ground liquefied and the notable lateral movement in the backfilling occurred. In the same Figure, it can be seen that differences in displacement constraint conditions of the top end of the abutment had a larger influence than ground liquefaction. Looking at the cases 1, 2, 3 and 4, in which displacement of the top end of the abutment was not constrained, the calculation values were in general within the same range as those for Step 1. However, it was found that, in cases 5, 6, 7, and 8, in which displacement of the top end of the abutment was constrained, earth pressure far exceeded the calculation values. Although there was a reduction in transmission of acceleration due to liquefaction after the maximum acceleration of roughly 1,000 gals was reached on the front-side ground of the abutment (see **Figure** 7(d)) because the relative density of the layer of liquefaction was high in cases 1, 5, and 6, as is shown in **Figure** 7(e), it was not found that acceleration was reduced near the surface of the backfilling soil because of differences in effective constraining pressure. Thus, it was understood that the backfilling side ground underwent incomplete liquefaction. On the other hand, as shown in **Figures 7** (c) and (g), even the ground on the backfilling of the abutment underwent liquefaction in cases 2, 3, 7 and 8, and response acceleration near the surface was reduced. Because the ground had the same degree of liquefaction in these cases, the difference in earth pressure acting on the abutment was displacement of the top of the abutment. Even when comparing case 7 and case 8, where the thickness of the level of liquefaction was altered, a notable difference in earth pressure on the rear side of the abutment was not found. Accordingly, there was impact between the abutment and the end of the girder when the abutment underwent horizontal movement toward the bridge axis and when the laying gap between the girder ends shrank. It is considered that the effect of impact between the abutment and the end of the girder appeared sensitively. As a result, seismic earth pressure exceeded design values at the abutment.

CONCLUSION

We measured active seismic earth pressure that affects the abutment by centrifuge test. The following points were identified during the course of research.

1) Acceleration within the backfilling ground increased from the deeper regions toward the surface. Nearly uniform earth pressure acted on the abutment from the backfilling.
2) Until a depth of some 4 meters from the surface, seismic earth pressure that affected the backfilling of an abutment did not exceed the results of the formula indicated in the specifications for highway bridges when the abutment was free to move. However, if deformation of the upper part of the abutment was constrained through impact with girder end, earth pressure at the time of earthquake exceed the results of the formula, regardless of whether ground liquefaction occurred or not.
3) If deformation of the upper part of the abutment was constrained by impact with girder end, the backfilling of the abutment subsided when ground liquefaction occurred, which led to forward movement. As a result, lateral earth pressure acted on the abutment with lateral movement of the backfilling.

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