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Paper No. 252. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DYNAMIC RESPONSE ON A UNDERGROUND STRUCTURE IN PARTIALLY LIQUEFIED GROUND

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ABSTRACT

The objective of this research was to establish a method, for use in seismic-proof structural design, of calculating a underground structure's vertical direction when the soil in which it is located liquefies. This report shows the dynamic response of underground structures in partially liquefied ground by conducting three-dimensional FEM(finite element method) analysis based on experimental results. We conducted within a ground area measuring 240cm L × 40cm W × 60cm H, using a model structure measuring 220cm L × 10cm W × 6cm H. Tests were conducted in three ground configuration: when the entire underground structure was within the liquefaction layer; when one side of the underground structure was in the non-liquefaction layer; and when both sides of the underground structure were in the non-liquefaction layer. In all case, excitation was applied perpendicular to the axis of the underground structure.

KEYWORDS

Liquefied Ground; Dynamic Response; Underground Structure; Model Vibration test; Three-Dimensional FEM Analysis

INTRODUCTION

During earthquakes, underground structures, such as common utility ducts and shield tunnels, are subject to smaller acceleration than ground structures. Therefore, the influence of earthquakes on these structures is seldom studied. However, seismic-proof structural design calculations using the response displacement method are performed in cases where variable terrain or phase differences in earthquake motion are likely to influence soil composition(Japan road association 1986). This method is intended for ground that does not liquefy and is presumably unsuitable for liquefied ground. Some modified calculation methods for the response displacement method have been proposed, using a reduced soil constant depending the level of liquefaction(Yanagimoto et al., 1992). However, no established method for calculating seismic-proof designs has yet been developed. This study was intended to establish longitudinal seismic design and calculation methods for long underground structures in ground subject to liquefaction. This report presents the results from model vibration experiments and three-dimensional finite element analyses conducted to determine the effects of partially liquefied ground on underground structures(Kishishita et al., 1994, Saito et al., 1994, Kishishita et al., 1995).

OUTLINE OF EXPERIMENTS AND ANALYSES

Experimental Procedure

We conducted experiments using a steel vessel, 240 cm long, 40 cm wide and 60 cm high, which was filled with soil to a height of 50 cm (See Fig. 1). The soil material was standard Toyoura sand with a wet density of 1.93 gf/cm^3 and relative density of approximately 47% when saturated. We used 1 cm-thick acrylic resin rectangular plates to prepare an underground model structure, 10 cm wide, 6 cm high and 220 cm long. As the acrylic resin plates alone had a smaller apparent specific gravity than actual structures, we adjusted the model's specific gravity to 1.19 g/cm^3. Fig. 1 shows an arrangement of 3 accelerometers and 10 pore water pressure gauges (attached to the ground), and 5 accelerometers, 20 strain gauges, and 3 laser displacement gauges (attached to the model structure). Measurements were taken from the time that excitation began. The incident waves were white noise in a frequency range of 0 Hz to 30 Hz, multiplied by a form function. The maximum acceleration was 200 gal.

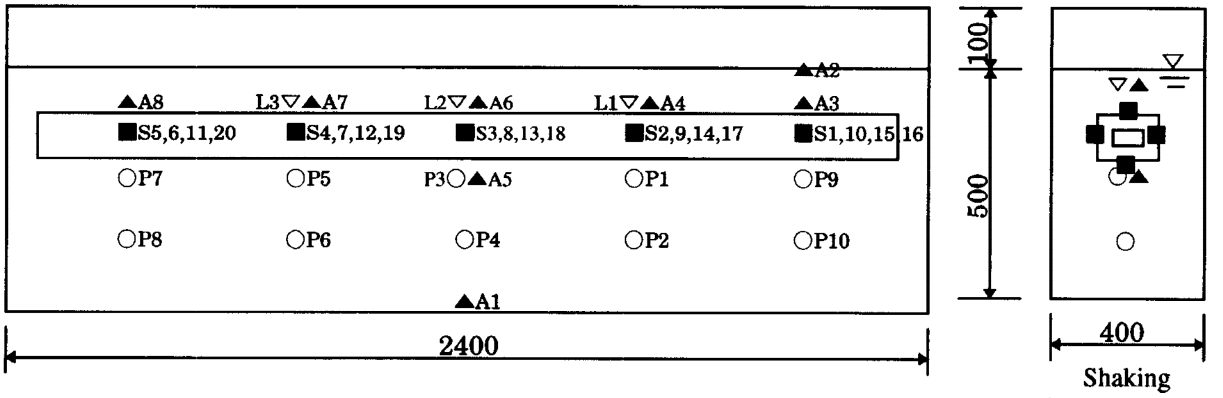


Fig. 1 Outline of experiment

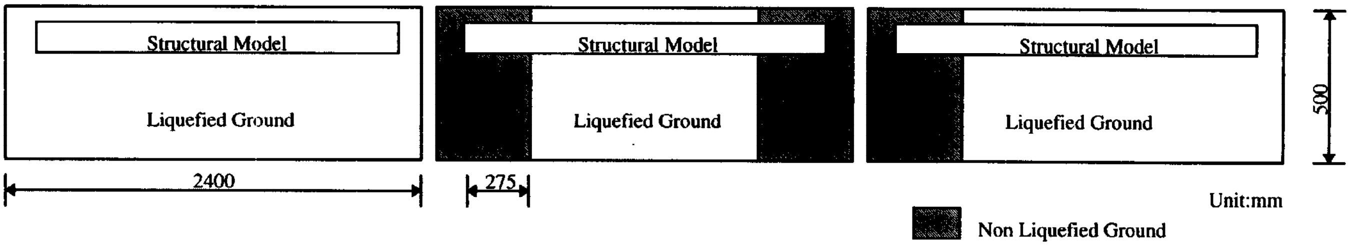
We tested three modes of liquefaction:

Mode 1: The entire structure was within a liquefied layer;

Mode 2: One side of the structure was within a liquefied layer; and

Mode 3: The structure's central portion was within a liquefied layer.

The structure was fixed in place by a steel fixture, located 27.5 cm away from one of its end.



a) Mode 1 b)Mode 2 c)Mode 3

Fig. 2 Test modes of liquefaction

Analytical Procedure

We analyzed the experimental results by the three-dimensional finite element method, using as incident waves the acceleration observed at the bottom of the vessel. Fig. 3 shows a meshed structure used in the analysis. Here, we assumed the underground model structure as a beam element. The interface between the vessel and soil was taken as stationary. Table 1 shows the parameters used in this analysis. The shear rigidity of the liquefied ground layer was assumed to be 1-1000th of the non-liquefied ground.

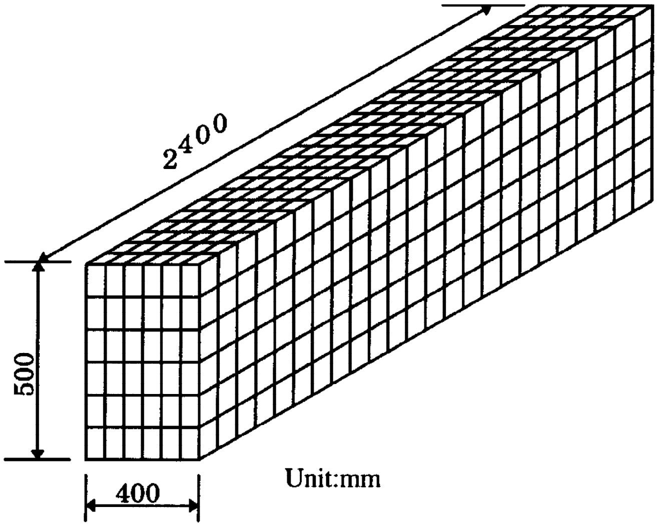


Fig. 3 Finite element model

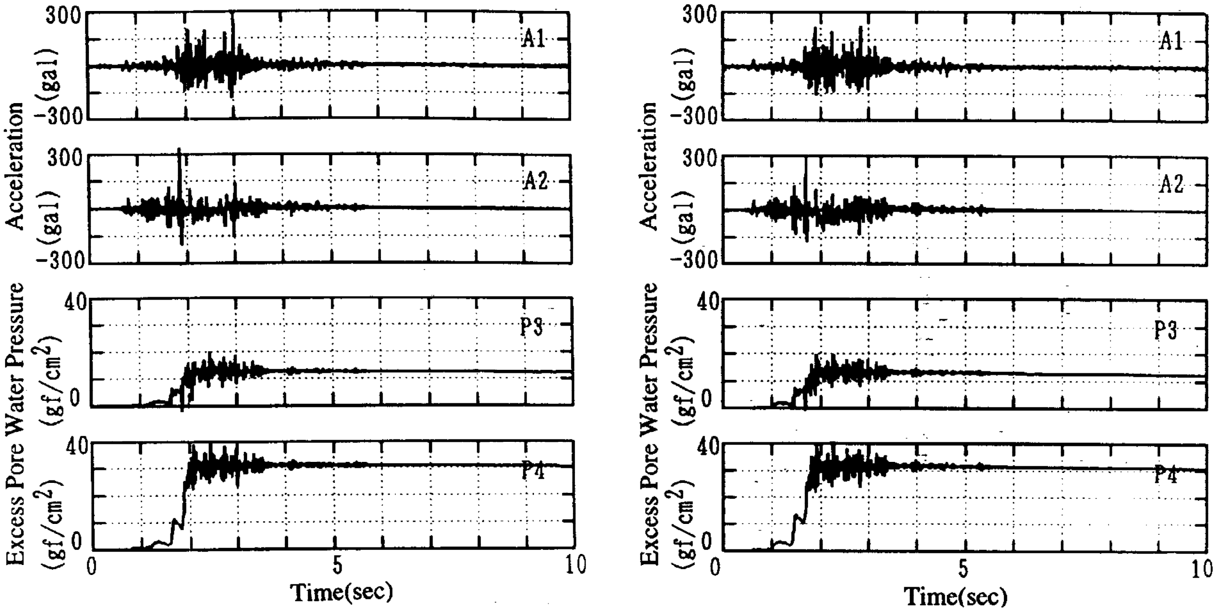
Table 1 The parameters of this analysis

	Unit weight (tf/m^3)	S wave (m/sec)	Damping ratio (%)
Non Liquefied Ground	1.80	300	10
Liquefied Ground	1.93	10	30
Structural Model	1.19	1000	5

EXPERIMENTAL RESULTS AND DISCUSSION

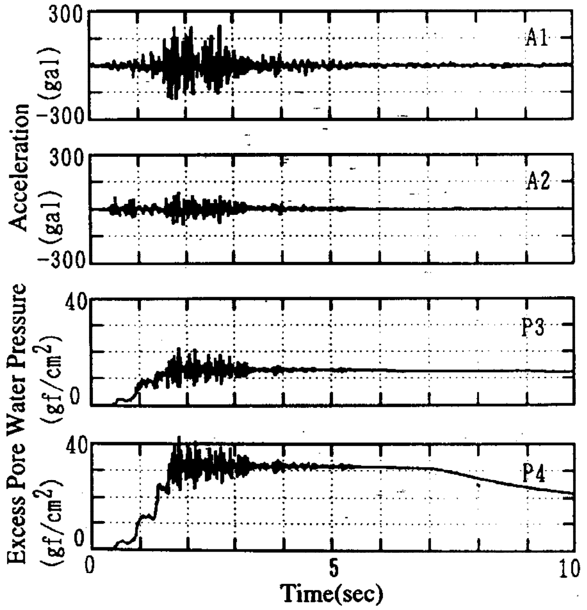
Acceleration Response of the Underground Structure

Fig. 4 shows the changes over time in acceleration response and excess pore water pressure for the three modes. This figure includes the following data: input acceleration at the vessel bottom (A1); acceleration response of ground at a point 2.0 cm below ground level. (A2); excess pore water pressure at a point 16.0 cm below ground level (P3); and excess pore water pressure at a point 34.0 cm below ground level (P4). In ground area close to the structure, the excess pore water pressure rose sharply about 0.5 second after excitation started. Within about two seconds, fully saturated liquefaction ($\Delta u/\sigma_{v0} = 1.0$) was attained, which remained for some time after excitation stopped. Input acceleration differed slightly from mode to mode. However, the state of liquefaction seemed similar in all cases, judging from the upward trends in acceleration response and excess pore water pressure.



a) Mode 1

b) Mode 2

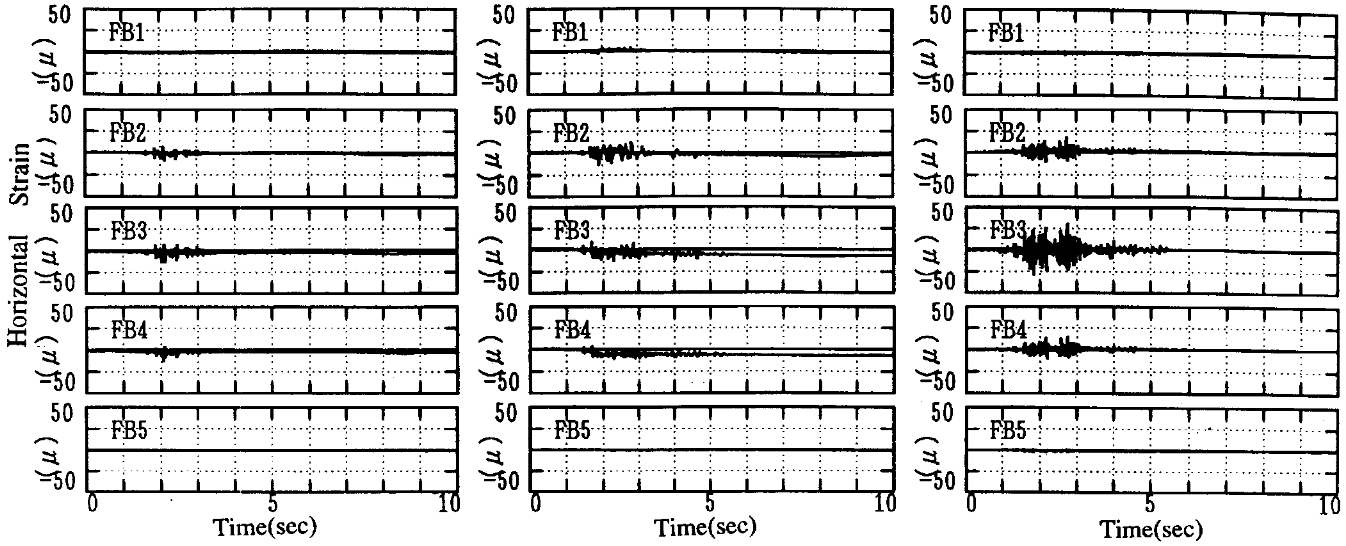


c) Mode 3

Fig. 4 Time histories for acceleration and excess pore water pressure

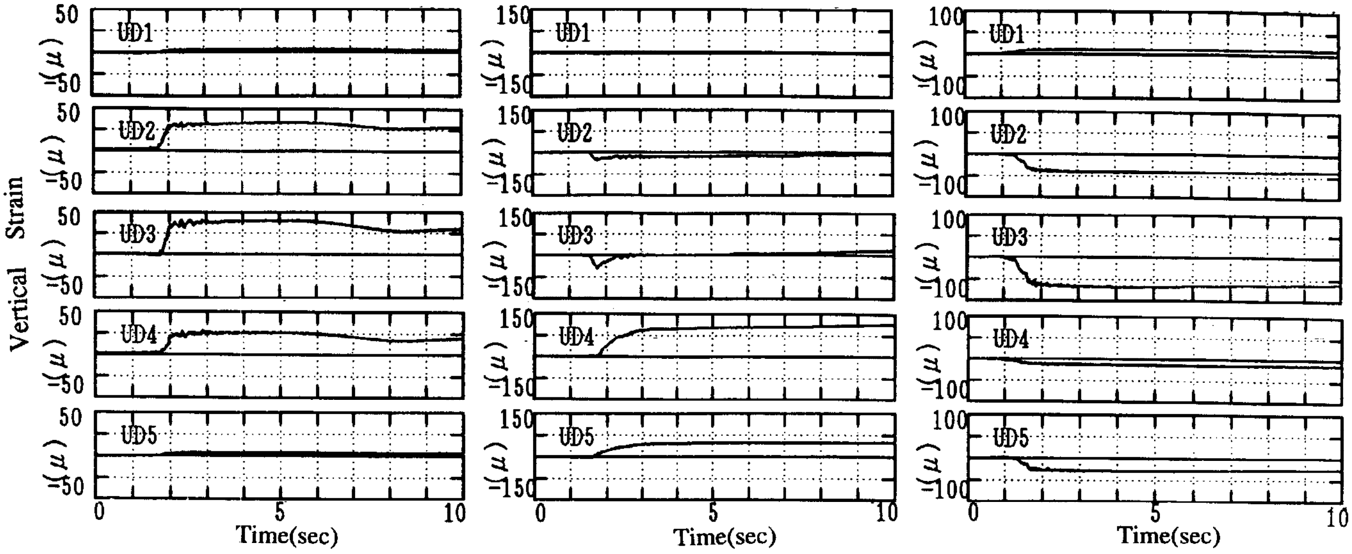
Strain on the Underground Structure

Fig. 5 shows the changes over time in horizontal strain on one side of a structure. Measurements were taken at distances of 210 cm, 160 cm, 110 cm, 60 cm, and 10 cm from the left end. For Mode 1 with both ends free, Mode 2 with one end fixed, and Mode 3 with both ends fixed, the horizontal strain tended to appear as the excess pore pressure rose and to vibrate substantially in the state of full liquefaction. This vibration seemed due to the lowered shear resistance of the ground around the structure, caused by softening after the rise in excess pore pressure. It was presumably independent of the ground response.



Mode 1 Mode 2 Mode 3

a) Horizontal strain



Mode 1 Mode 2 Mode 3

b) Vertical strain

Fig. 5 Time histories for strain

ANALYTICAL RESULTS AND DISCUSSION

In the experiment, the ground began to liquefy and the underground structure began to deform about 2 seconds after excitation started. These phenomena seemed to result from the lowered shear resistance of the ground around the structure, caused by softening after the rise in excess pore pressure. They were presumably independent of the behavior of the surrounding ground. The following analyses were based on an assumption that this portion of ground underwent full liquefaction, i.e., that shear rigidity was lower in this region.

Response of the Underground Structure

Fig. 6 shows a comparison between the experimental and analytical results for acceleration response at the center of the structure. In all modes of liquefaction, analyzed response was smaller than measured response until about 1.5 second after excitation started (i.e., before excess pore pressure appeared). After liquefaction began, there was good agreement in the response characteristics between the experimental and analytical results, though the analyzed values were slightly smaller than measured values. The lowered shear rigidity used in the analysis would thus seem to successfully explain the dynamic behavior of underground structures after the onset of liquefaction, though not such behavior prior to liquefaction.

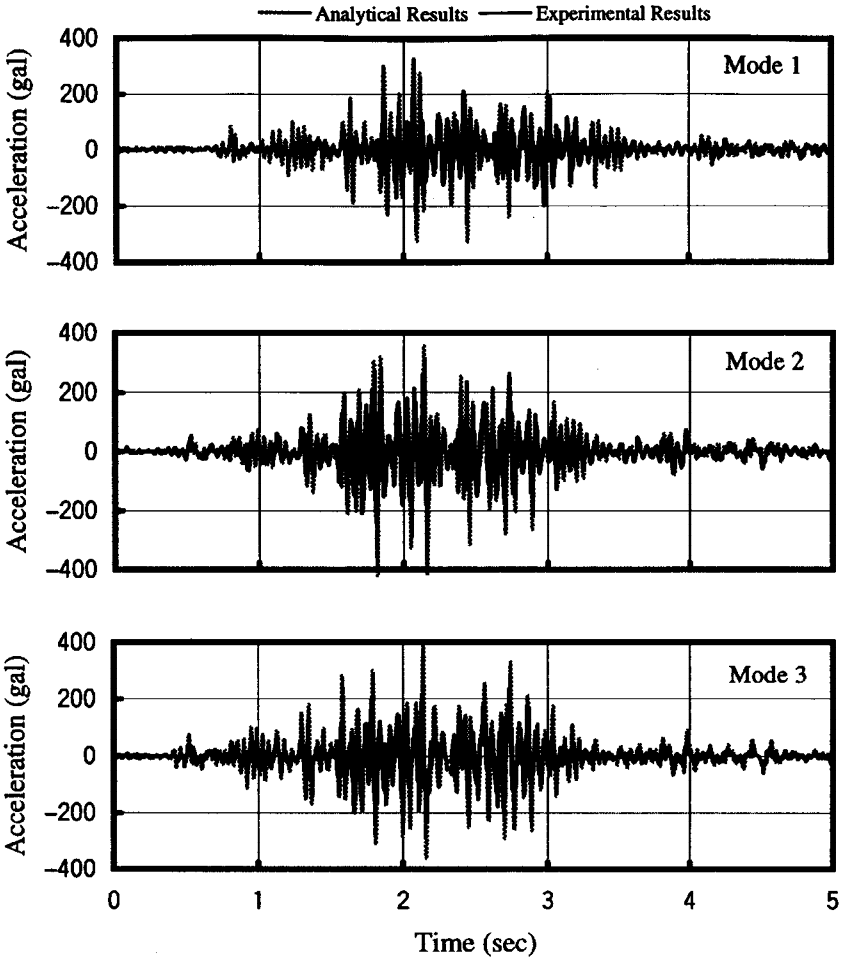


Fig. 6 Time histories for acceleration response at the center of the structure model

Maximum Bending Strain in the Underground Structure

Fig. 7 shows the experimental and analytical results for maximum bending strain in the underground structure once the ground had liquefied. In Mode 1, where the whole structure lay in the liquefied region, the two results agreed well. In Mode 2, where one end of the structure lay outside the region, and in Mode 3, where both ends were in non-liquefied regions, the measured maximum strain was larger than the analyzed maximum strain.

In the experiment, a non-liquefied ground layer was "expressed" or "replaced" by a steel fixture used to fix the model structure. In the analysis, the model structure lay partially within a non-liquefied ground layer and partially within a liquefied ground layer. This difference in constraint conditions may have led to the above disagreement. However, both the experimental and analytical results showed similar tendencies for strain distribution. The maximum bending strain generally seemed to agree fairly well. In particular, the analytical results for lower shear rigidity agreed well for the experimental results.

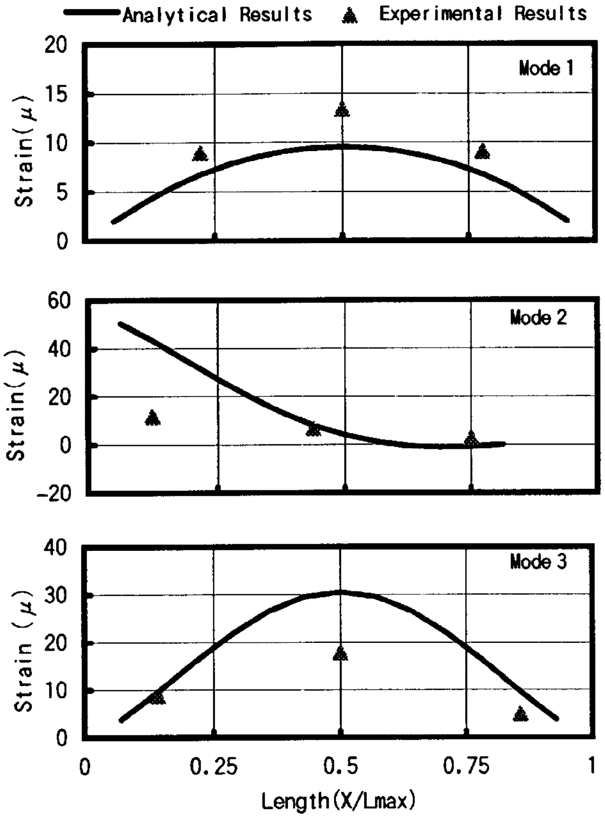


Fig. 7 Maximum bending strain in the underground structure

CONCLUSION

We conducted model experiments and dynamic analyses to establish longitudinal seismic design and calculation methods for underground structures in ground subject to liquefaction. The results we obtained are as follows:

(1) When the ground fully liquefied, the underground structure behaved independently of the surrounding

ground's behavior. This was because the surrounding ground softened and the shear resistance lowered as the excess pore pressure rose.

(2) By reducing shear rigidity, a dynamic analysis could be conducted of a underground structure lying in a liquefied region of ground.

(3) When a underground structure lay in a liquefied and non-liquefied region, it bent in the boundary region. The bending had no significant effect on the structure.

The present analysis employed a simplified model to characterize the liquefied or non-liquefied ground. It will be necessary in future experimental and analytical studies to find and use parameters with respect to the boundary, external force of an earthquake, etc.

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