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Centrifuge Model Tests of Embankment with a New Liquefaction Countermeasure by Ground Improvement Considering Constraint Effect

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ABSTRACT

In order to verify the effect of a liquefaction countermeasure for embankment foundation using a newly-developed ground improvement method considering constraint effect, two cases of centrifuge model tests of full section models were carried out. The centrifuge model tests were conducted in 70g of centrifugal acceleration and the depth of potential liquefaction layer was 10m. As a seismic motion, thirty sine waves with its half amplitude of 350gal were applied to the model. According to the result, the newly developed countermeasure considering constraint effect was effectively controlled the ground deformation and excess pore pressure. More discussions on deformation of embankment, response acceleration and excess pore pressure in sand layer will be presented in this paper.

Introduction

As one of the reliable countermeasures for the liquefaction, lattice shaped ground improvement method (TOFT method, Figure 1) has been adopted in Japan. Lattice shaped wall type stabilized bodies are constructed in this method and regarding the depth, whole liquefaction layer is solidified generally. For the spacing of the lattice, 1/2~1/3 of the thickness of liquefaction layer has been proposed in conventional design method to reduce the excess pore pressure inside the improvement effectively (Taya et. al. 2008). According to the result, the improvement ratio (area of the stabilized body divided by the area of structure) is around 50%. However, if the deformation control of the ground is the main purpose, suppressing excess pore pressure by conventional design spacing can be an overdesign. Larger spacing can be adopted for this purpose by considering the confining effect of the stabilized bodies against the unimproved ground (Miki et. al. 2011). This new ground improvement method considering confining effect is called CGI method. With this method, wider spacing of the lattice can be applied and liquefaction layer beneath the stabilized bodies can be left. According to the result, the cost of countermeasure can be reduced significantly.

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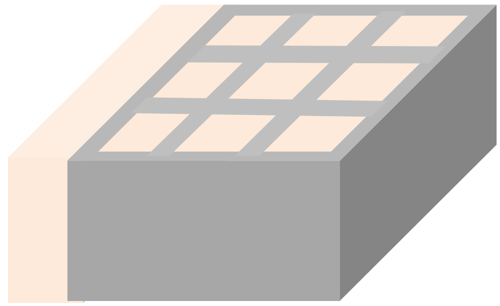


Figure 1. Image of latticed shaped ground improvement

The effect of enlarged spacing ground improvement for liquefaction countermeasure of collective housing has been verified by the authors (Okochi et. al. 2014). Since then, the authors tried to apply this method to embankment foundation problem. A series of centrifugal model tests (half section models) and their 3D FE analysis have been conducted to investigate the effect of the liquefaction countermeasure for embankment foundation using a newly-developed ground improvement method considering constraint effect (Sreng et al. 2014). By comparing with the conventional TOFT method, it was found that the newly developed countermeasure considering constraint effect was effectively controlled the ground deformation and excess pore pressure despite of enlarged spacing of the lattice compared to the conventional design. However, since the models used for the centrifuge model tests were half section models, it is considered that test results might influenced by the boundary conditions near the wall of rigid soil container. Therefore, full section models of centrifuge model tests should be carried out to clarify the effect of the countermeasure.

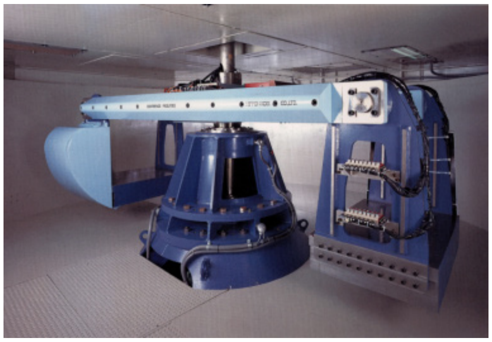
In this study, two cases of centrifuge model tests of full section models were carried out to verify the effect of the liquefaction countermeasure for embankment foundation using a newly-developed ground improvement method considering constraint effect. The first case was without countermeasure and the other case was with countermeasure using the ground improvement method considering constraint effect. The centrifuge model tests were conducted in 70g of centrifugal acceleration and the depth of potential liquefaction layer was 10m. As a seismic motion, thirty sine waves with its half amplitude of 350gal were applied to the model.

Centrifuge Model Tests

Test Apparatus

Centrifuge mode tests were carried out under centrifugal force field of 70g. The centrifugal model test system used in this study was a balanced beam type apparatus with 2.6m of effective radius which belongs to the Research and Development center of Nippon Koei Co. Ltd., Japan as shown in Figure 2. A shaking table as shown in Figure 3 was used to produce the earthquake motion to the model tests. The specifications of the shaking table are shown in Table 1.

In the model tests, the input earthquake motion of sine wave (30 waves) with frequency 2.0Hz and maximum acceleration 350gal (prototype scale) was applied after recognition of complete dissipation of excess pore pressure.



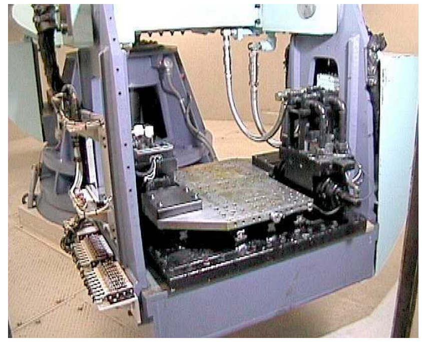


Figure 2. Centrifuge

Figure 3. Shaking table

Table 1. Specifications of shaking table

Item	Specification
Shaking Control System	Electro-hydraulic Servo Control
Max. Centrifugal Acceleration	100 G
Max. Shaking Acceleration	25 G (1/30 model 818gal)
Max. Payload	250kg
Max. Displacement	±3.0mm
Frequency Range	10 - 400Hz
Max Velocity	40 cm/s

Model preparation and measurements

Toyoura sand and Silica sand #3 were used in the tests. The main properties of these sands are summarized in Table 2. Toyoura sand was used for the liquefaction layer and Silica sand #3 was used for the foundation layer.

Table 2. Physical properties of test materials

Physical properties	Toyoura sand	Silica sand #3
Maximum grain size, D_{max} (mm)	0.425	2
Mean grain size, D_{50} (mm)	0.169	1.46
Uniformity coefficient, U_c	1.44	1.47
Coefficient of curvature, U_c’	0.974	0.975
Minimum dry density, ρ_{dmin} (g/cm^3)	1.343	1.490
Maximum dry density, ρ_{dmax} (g/cm^3)	1.649	1.673
Density of soil particles, ρ_s (g/cm^3)	2.641	2.636

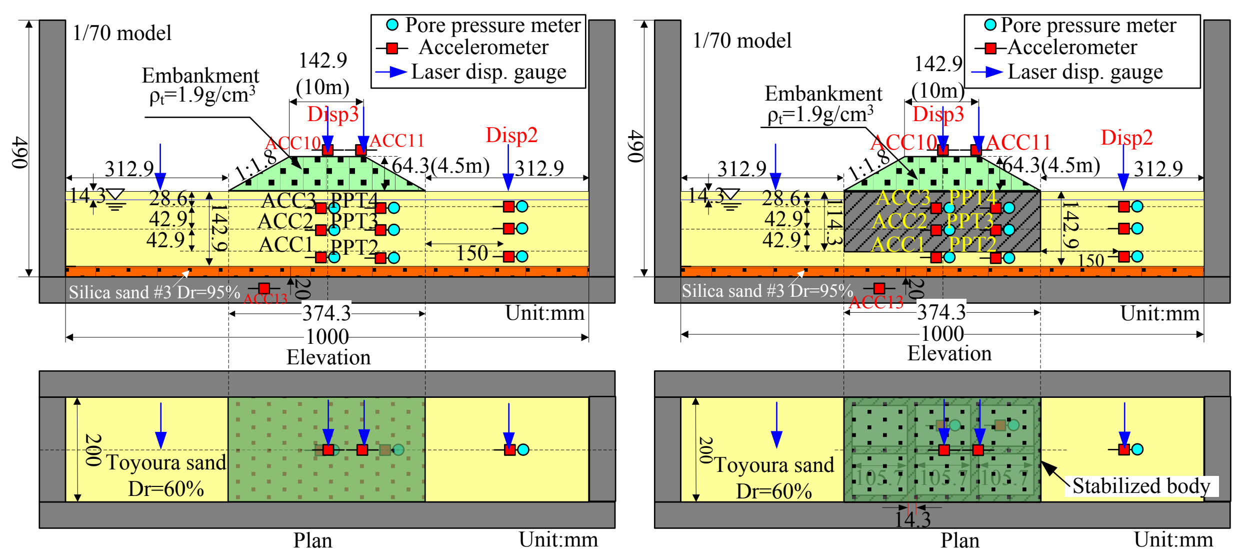
Two test cases; without countermeasure and CGI method are carried out and summarized in Table 3.

Table 3. Test cases (70g)

Test Case	Liquefaction counter measure
Case 1	Without countermeasure
Case 2	With countermeasure (CGI method)

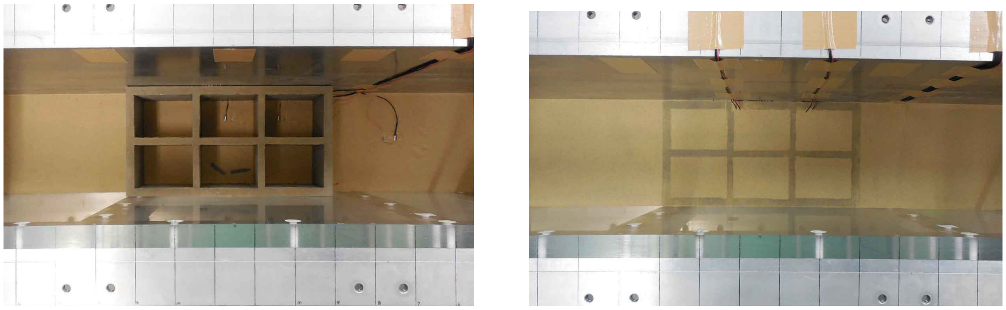
Figures 4 present the outline of the centrifuge model test (full model) in model scale. Depth of liquefaction layer corresponds to 10m. The model for stabilized bodies were made by mixing sand with cement then cured one week in the form aiming the target unconfined compression strength (q_u) 1000kN/m^2. Improvement ratio (area of the stabilized body divided by the area of embankment) in plan view was 33%. Model ground was prepared in a rigid soil container with dimensions of 1000×490×200 mm before set up to the centrifuge. The procedures for preparing the model ground are as follow. Firstly, foundation layer (Dr=95%) was prepared. Secondly, the stabilized body (latticed ground improvement) was installed (see Figure 5). Thirdly, Toyoura sand (Dr=60%) was prepared by an air pluviation method. The stabilized body of rectangular wall shape was set at specified depth during ground preparation. This shape express one block of continuous lattice. Detailed procedure is presented by Okochi et.al. 2013. The embankment was made by compacting the mixed material of Toyoura sand 80% and kaolin clay 20% into an embankment mold with its wet density 1.9g/cm^3 then frozen before mounted on the sand layer.

Model ground was saturated in a vacuum container by using silicone fluid which kinematic viscosity is 70mm^2/s. Groundwater level at the initial condition was 14.3 mm (1m in prototype scale) lower than ground level as shown in Figure 4.



(a) Without Countermeasure (Case 1)   (b) With countermeasure (CGI, Case 2)

Figure 4. Centrifuge model (Full section model)



(a) Before preparation of sand ground (b) After preparation of sand ground

Figure 5. Installation of latticed shaped ground improvement (Case2, CGI method)

Test Results

Response acceleration, excess pore pressure and vertical displacement

Figure 6 shows the comparison of time history of response acceleration of base (ACC13), top of embankment (ACC10) and top of slop (ACC11), respectively. Maximum acceleration of the base was 350gal. Response acceleration of the top of embankment (ACC10) and top of slop (ACC11) obtained from Case2 (CGI method) were larger than the case without countermeasure. This result is considered to be due to the effect of ground improvement. Figure 7 present the comparison of response accelerations of sand ground obtained from the two test cases. It is shown that the response acceleration of Case2 is larger than Case1, presents the same tendency with the response acceleration of embankment.

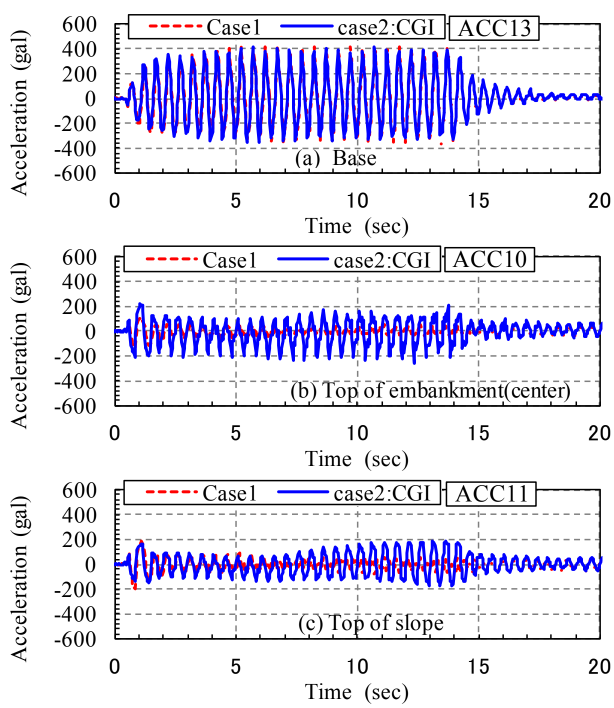


Figure 6. Response acceleration of base and embankment

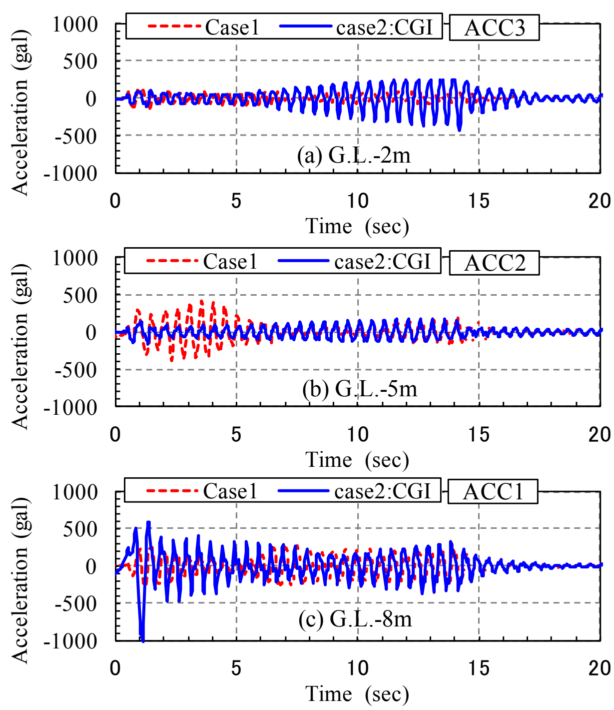


Figure 7. Response acceleration of sand layer (liquefaction layer)

Figure 8 shows comparisons of the relations between excess pore pressure and elapsed time obtained from case1 and case2. The excess pore pressure of countermeasure case (case2) is lower than that of the without countermeasure case (case1). This result indicated that the countermeasure method is effective for liquefaction control.

Figure 9 shows the comparisons of vertical displacement of embankment and sand ground obtained from the two cases. As shown in Figure 9(a), settlement of embankment of Case2 is smaller than Case1 (without countermeasure). Vertical displacement of sand ground (Figure 9(b)) of the case without countermeasure showed upheaval behavior caused by the embankment loading during shaking, however, displacement of Case2 was quite small and presented no upheaval phenomenon after the end of shaking. From these results it is revealed that the countermeasure method is effective for liquefaction countermeasure.

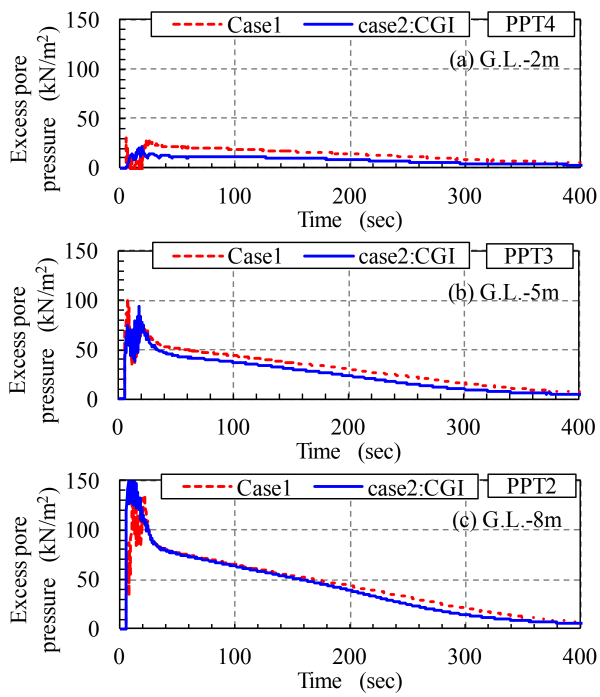


Figure 8. Excess pore pressure in sand layer (under embankment)

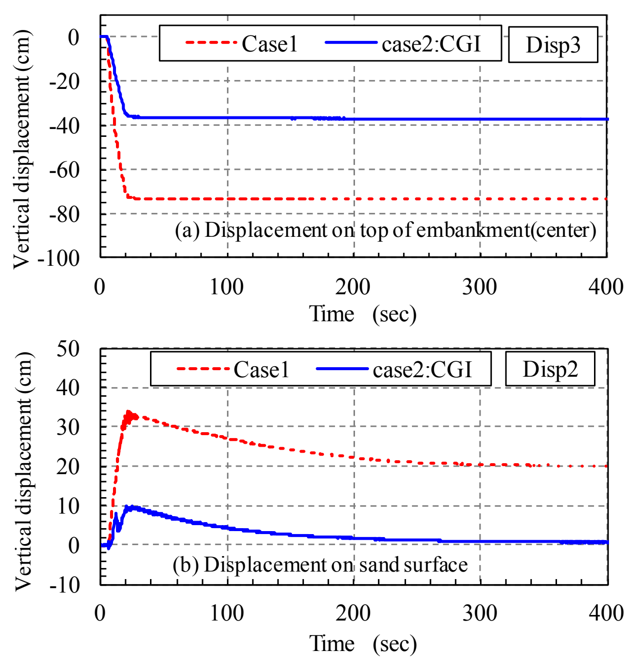
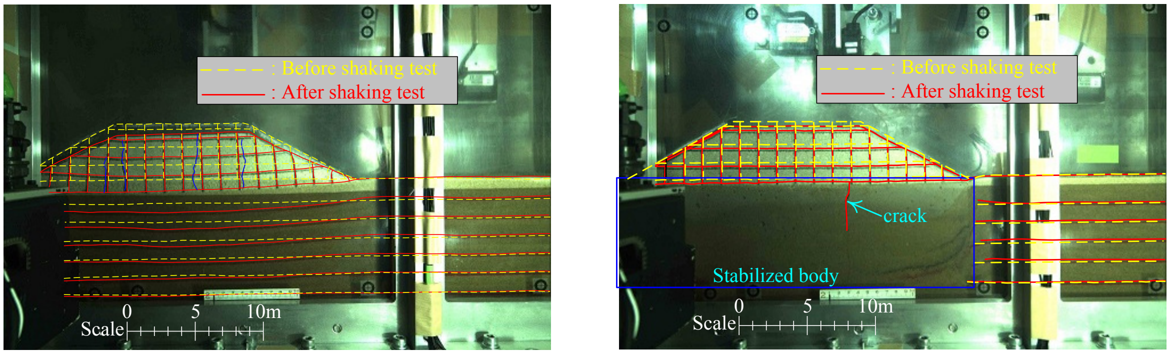


Figure 9. Vertical displacement

Deformation of ground and embankment before and after shaking tests

Figure 10(a), (b) show deformation of embankment and sand ground before and after shaking tests which is sketched from deformed photos of case1 and case2. It is found that due to the effect of ground improvement, deformation of case2 is smaller than that of case1.

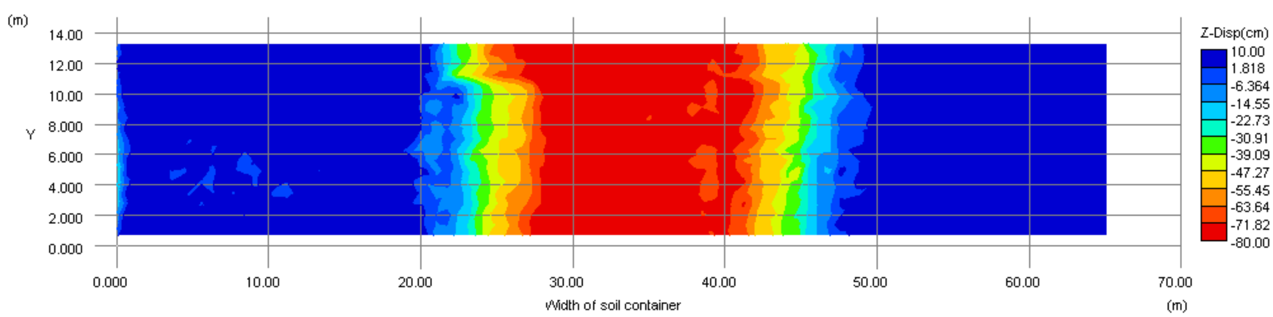


(a) Case1: without countermeasure (b) Case2: with countermeasure (CGI method)

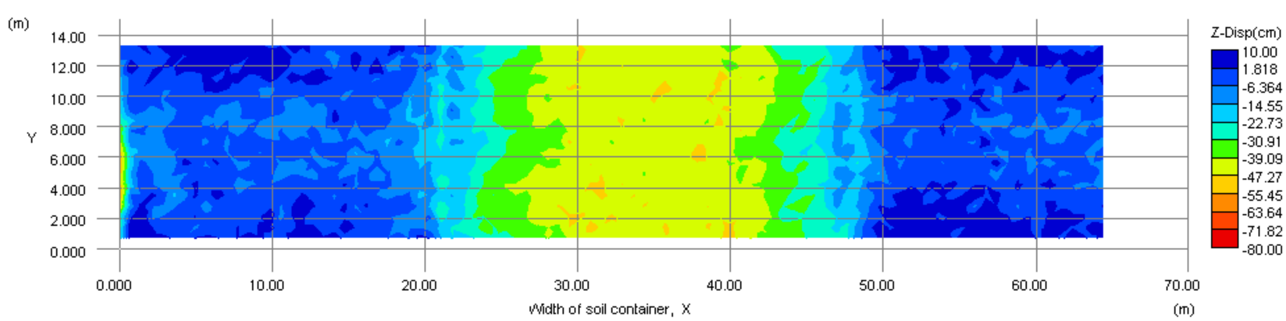
Figure 10 Deformation of embankment and sand ground before and after shaking tests

Vertical displacement distribution after shaking tests

Figure 11 shows the comparison of vertical displacement distribution of sand ground and embankment in plain view obtained from results of the measurement after dynamic centrifuge model tests. The vertical displacement of ground surface was measured by using a laser range meter from the top level of soil container before and after the shaking tests. The plus and minus value present upheaval and settlement of the ground respectively. Result of Case1 (without countermeasure) shows large settlement occurred especially on embankment and large upheaval occurred on sand ground. Vertical displacement of Case 2 (CGI method) is quite smaller than that of Case 1. This result indicates that the CGI method is effective for liquefaction control.



(a) Vertical displacement distribution of Case1 (without countermeasure)



(b) Vertical displacement distribution of Case2 (CGI method)

Figure 11. Vertical displacement distribution in plain view after shaking

Conclusions

In order to verify the effect of a liquefaction countermeasure for embankment foundation using a newly-developed ground improvement method (CGI method) considering constraint effect, two cases of centrifuge model tests were carried out. Results obtained from this study are summarized as follow.

(1) Response acceleration of embankment and ground of the CGI method was larger than the case without countermeasure. This result is considered to be due to the ground stiffness of the CGI method is larger than that of the case without countermeasure caused by the effect of ground improvement.
(2) Embankment settlement of CGI method was 50% smaller than the case without countermeasure. Moreover, vertical displacement of sand ground obtained from the case without countermeasure showed upheaval behavior caused by the embankment load due to shaking, however, displacement of the countermeasure case (CGI) was quite small and showed no upheaval after shaking.
(3) From results of displacement measurement of ground surface before and after shaking tests, it is shown that the vertical displacement after shaking obtained from CGI method is smaller than the case without countermeasure.

From these results, it is revealed that the proposed method is effective countermeasure for controlling liquefaction. Further studies on centrifuge model test of TOFT method and FE analysis should be carried out to compare and verify the CGI method.

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