Experimental study on compaction grouting method for liquefiable soil using centrifuge test and X-ray tomography

Etude expérimentale sur la CPG pour le sol liquéfiable par centrifugation et tomographie à rayons X

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ABSTRACT: Compaction grouting, an in-situ static compaction technique by means of grout injection, has been increasingly adopted for improving the liquefaction resistance of loose sandy ground in recent years. The surrounding ground's stress changes and densification induced by grout injection are considered to be an important cause for the stabilization effects. The present study investigates characteristic of ground deformation by simulating compaction grouting processes in micro focus X-ray tomography. 3D Volumetric Digital Image Correlation (V-DIC) techniques were applied to the tomographic images. V-DIC analysis of in-situ-acquired tomographic images provides a characterization of porosity, displacement and strain field of model ground. Additionally, simulation of ground injection and shaking table test was carried out in a geotechnical centrifuge to evaluate stress changes and liquefaction resistance of improved sandy soil.

RÉSUMÉ : Coulis compactage, une technique in-situ compactage statique à l'aide d'injection de coulis, a été de plus en plus adoptée pour améliorer la résistance à la liquéfaction du sable loos terrain ces dernières années. Changements de contrainte du sol environnant et de densification induite par injection de mortier sont considérées comme une cause importante pour les effets de stabilisation. La présente étude examine caractéristique de la déformation du sol en simulant les processus de compactage coulis au point tomographie à rayons X micro. 3D volumétrique Digital Image Correlation (V-DIC) techniques ont été appliquées aux images tomographiques. V-DIC analyse in-situ acquis par images tomographiques fournit une caractérisation de la porosité, de déplacement et champ de déformation du sol modèle. En outre, la simulation de l'injection de sol et de test table à secousses a été réalisée dans une centrifugeuse géotechnique pour évaluer les changements de résistance au stress et la liquéfaction de sol sablonneux améliorée.

KEYWORDS: compaction grouting, ground improvement, liquefaction, sand, full field measurement.

1 INTRODUCTION

In-situ static compaction by means of grout injection (CPG) is widely used as a countermeasure against liquefaction in loose sandy ground (e.g. Boulanger and Hayden 1995, Miller and Roycroft 2004). An increase in the liquefaction resistance of sand caused by compaction grouting is presumed to derive from three possible mechanisms. They are, (i) increase in the lateral confining stress, (ii) densification and (iii) reinforcement by hydrated and hardened grout piles. Especially, the surrounding ground's stress changes and densification induced by grout injection are considered to be an important cause for the stabilization effects. However, systematic studies of ground condition changes due to compaction grouting have been limited in number.

The author's research group has been studied about ground behavior due to grout injection especially focusing on stress change due to grout injection. The present study evaluate characteristic of ground deformation by simulating compaction grouting processes in 1g and centrifuge model test. In 1g test, the deformation process of the model ground by grout injection was visualized using X-ray computed tomography (XRCT). Moreover, 3D Volumetric Digital Image Correlation (3D V-DIC) techniques were applied to the x-ray tomographic images in order to discuss deformation of the ground quantitatively. 3D V-DIC analysis of in-situ acquired tomographic images provides a characterization of porosity, displacement and strain field of model ground. Additionally, simulation of ground injection and shaking table test was carried out in a geotechnical centrifuge to evaluate stress changes and liquefaction resistance of improved sandy soil.

2 SUMMARY OF TESTING

A microfocus X-ray tomographic scanner and a beam-type geotechnical centrifuge owned by Port and Airport Research Institute Japan were used in this study. Figure 1 illustrates a typical arrangement of grout piles with regular spacing in a triangular pattern. In order to simulate completion of this improvement arrangement in a physical modeling in laboratory, a cylindrical soil container with diameter of 60 mm (see Fig. 2) and hexagonal cylinder with diameter of 100 and 160 mm (see Fig. 3) are used for the XRCT test and the centrifuge test, respectively. The difference of diameter of soil container in centrifuge test presents the different pile spacing or improvement ratio and rigid wall of soil container simulates improved area by pre-injected grout piles. The ground was

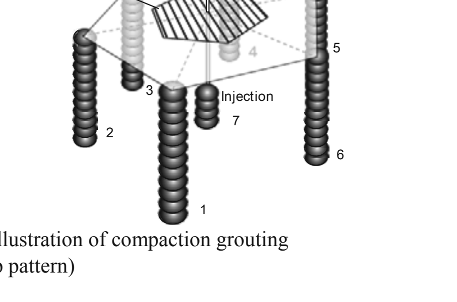


Figure 1. Illustration of compaction grouting (bottom-up pattern)

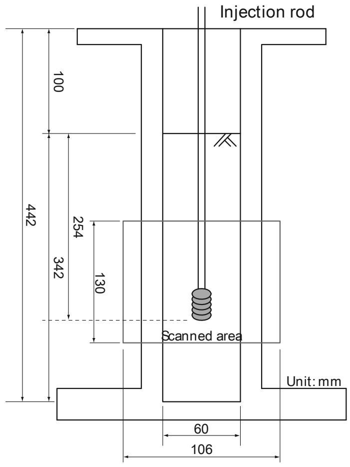


Figure 2. Schematic view of XRCT test setup

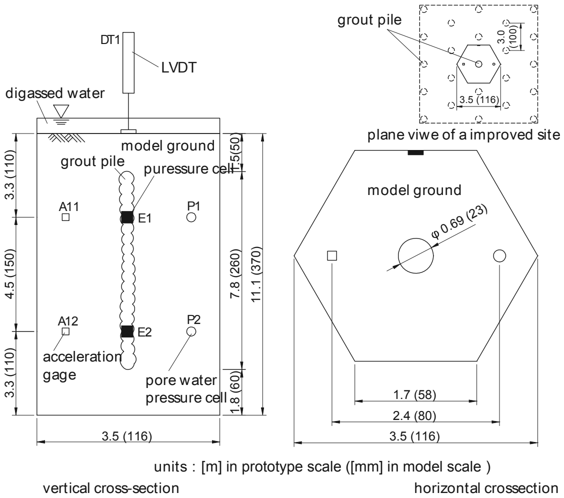


Figure 3. Schimatic view of test setup in centrifuge (CPGs30).

Table 1. properties of Soma Silica Sand #5

Soma Silica Sand #5			
Specific gravity, G_s	2.65	Median particle size, D_{50}	0.35 mm
Maxumum void ratio, e_{max}	1.115	Coefficient of uniformity, Uc	1.5
Minumum void ratio, e_{min}	0.71		
Shear resistance angle, φ' (from Dr=50 %)	36.1°		
Shear resistance angle, φ' (from Dr=90 %)	40.4°		

Table 2. List of test cases in centrifuge

Case	Improvement ratio (%)	Pile spacing (m)	Pile diameter (m)	Relative density (%)
CPGd18s	13.7	1.8	0.7	55
CPGd30n	-	-	-	41.3
CPGd30s	4.9	3	0.7	70.4

prepared by air-pluviation targeting the relative density of 50 % and Soma Silica Sand #5 is used as ground material. The properties of Soma Silica Sand #5 are shown in Table 1. The injected grout prepared mixing the Soma Silica Sand #5, the Kawasaki Clay, Portland cement and water at the ration of 40 %:60 %:12 %:50 % by weight.

As the procedure of XRCT test, the soil container was mounted on turn table of the XRCT scanner after preparing model ground and then grout pile was injected in a bottom-up sequence through the injection rod. All injection and CT scanning processes are carried out in-situ condition (in-situ meaning x-ray scanning at the same time as injection) and full volume of cross sectional images are recorded every two step of grout injection. The injected volume was controlled to make the grout pile diameter of 20 mm. The details of the injection system can be referred in Nishimura et al. 2012. In 1g model test using miniature model ground as XRCT test in this study, it was concerned that the uplifting deformation caused by grout injection will dominate because of lower effective confining pressure therefore densification effect will not be evaluated correctly. In order to avoid this effect, 10 kPa of overburden pressure was applied at tip of injection rod by filling up soil container above the model ground by stainless cubes with 2 mm of diameter. Reconstructed volume images were analyzed using 3D V-DIC in order to evaluate the deformation process during grout injection.

In centrifuge tests, the model ground was prepared as same procedure as CT test. All the test procedure, saturation of model ground, injection of grout pile and shaking table test were carried out under a centrifugal acceleration of 30 G. Viscous degassed fluid (30 mm^2/sec of dynamic viscosity) was used as pore water. The cross section of model ground presents shearing zone by one grout pile thus small diameter of container presents small pile spacing or large improvement ratio. Table 2 shows a list of test cases in centrifuge, in which case CPGd18sA and CPG30sB models 1.8 m and 3.0 m of pile spacing (in prototype scale) equivalent to 13.7 % and 4.9 % of improvement ratio and case CPG30nA models ground without grout injection, respectively. As a shaking condition, sinusoidal wave with 2 Hz of frequency (in prototype scale) and 50 waves are applied increasing the amplitude of vibration. During the shaking, horizontal earth pressure, response acceleration of ground and pore water pressure was measured.

3 RESULTS AND DISCUSSIONS

3.1 X-ray tomography

Figure 4 presents density distribution of the model ground at each scanning steps as a result of the x-ray tomography. After grout injection, the increase of ground density can be observed at the side of the grout piles with increase of 25 % of relative density thus densification effect may occur mainly at lateral side o grout piles. The distribution of vertical and horizontal displacement as results of DIC analysis is shown in Figure 5. The upper line of Fig. 5 presents incremental vertical displacement between initial-2^{nd} injection (Step A), 2^{nd}-4^{th} injection (Step B) and 4^{th}-6^{th} injection (Step C) and the lower line presents incremental horizontal displacement, respectively. Horizontal displacement is localized in the area around the grout pile through all the steps. On the other hand, vertical displacement beneath the grout pile can be observed at Step A injecting deeper position and the downward displacement is decrease with injecting position shallower. These features indicate that the mechanism of ground deformation caused by grout injection can be considered as a cavity expansion for deep injection and cone uplift for shallow injection. The map of maximum shear strain and volumetric strain calculated from DIC results are shown in Figure 6. The general tendency observed from Fig. 6 is that shear strain is localized around the

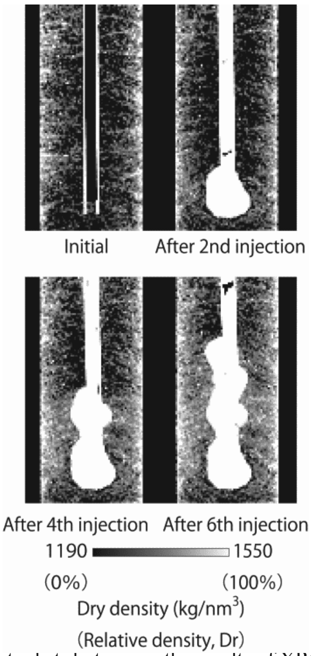


Figure 4. Density distributions as the results of XRCT scan

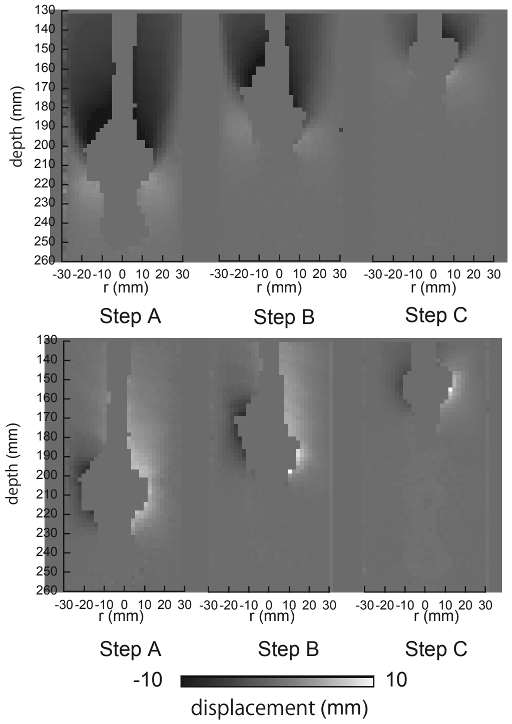


Figure 5. Vertical (upper line) and horizontal (lower line) incremental displacement.

grout pile and volumetric strain in this area shows contraction. Moreover, another localized area is also developed from the edge of grout pile to ground surface and it is indicating that upper ground of localized area is uplifted due to grout injection. Dark color in the map of volumetric strain presents volume contraction and this zone gradually decrease the injection depth becomes shallower. The average calculated volumetric strain is 5 % of contraction, 23.5 % of increase of relative density, in Step A, which agrees against the density map of tomography. Figure 7 shows the relationship between volumetric strain and maximum shear strain at the same pixel in Fig. 6. One of the features common to all the steps is that constrain volumetric strain mainly appears at small shear strain and expansion at

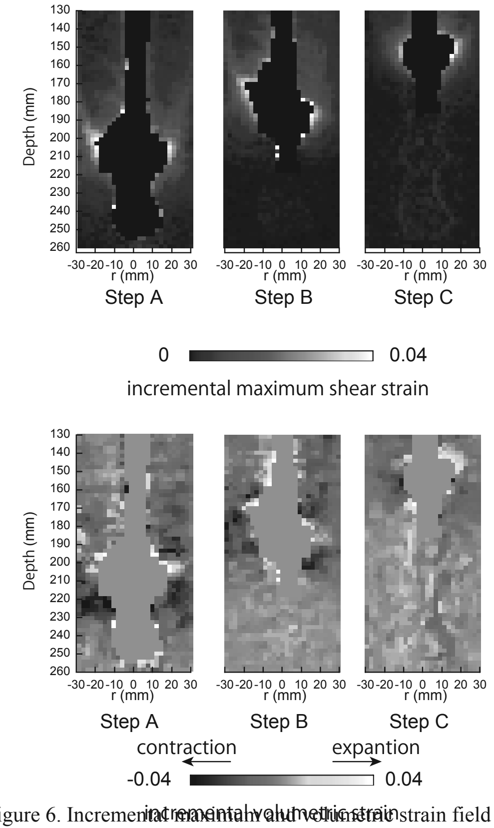


Figure 6. Incremental maximum and volumetric strain field

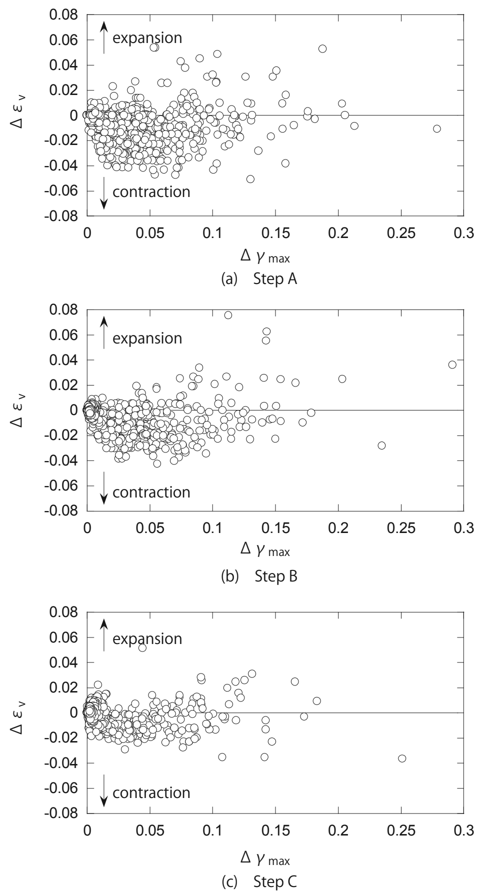
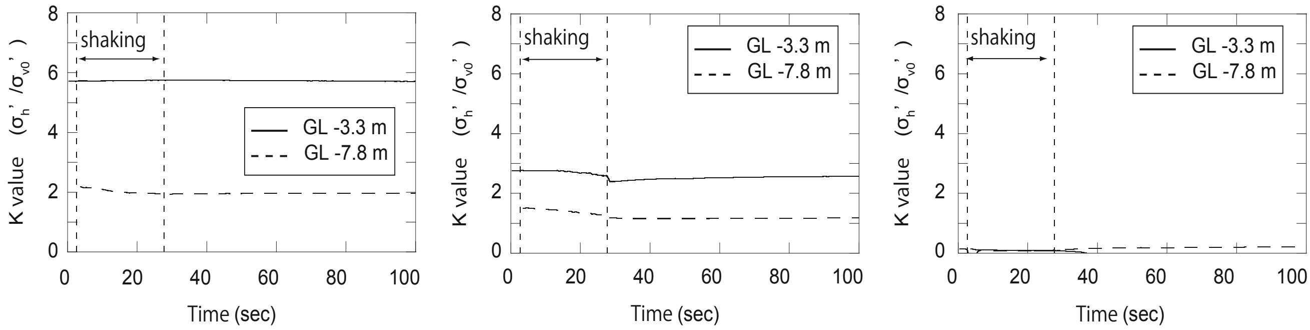
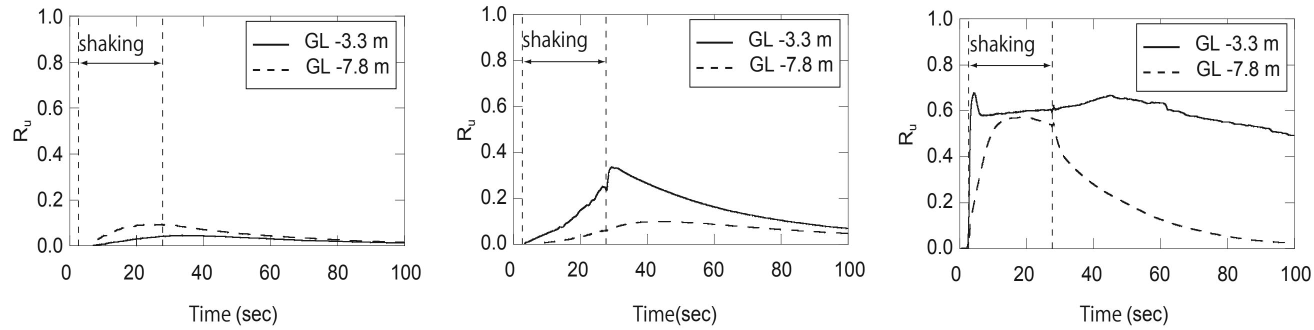


Figure 7. Relationship between volumetric strain and maximum shear strain.



(a) CPG18s (b) CPG30s (c) CPG30n

Figure 8. Time history of K values



(a) CPG18s (b) CPG30s (c) CPG30n

Figure 9. Time history of ratio of Ru

large shear strain. Especially in Step C, volumetric strain tends to expand with smaller shear strain compare to injection at deeper depth (Step A and Step B). This derive from failure mode at shallower depth tend to be uplift mode due to low confining pressure, thus it can be said that a certain grout pile diameter or injection volume is not largely contribute to densification especially at shallower depth.

3.2 *Centrifuge test*

Figure 8 presents the changes in horizontal stress recorded during shaking table test on centrifuge, expressed as K = (horizontal effective stress, σ'_h) / (initial vertical effective stress, σ'_{v0}). The results were fileted to remove the effect of variation due to shaking. The K value before shaking starts (0 sec ~ 3 sec) presents the value after grout injection. The influence of size of shearing area by one grout pile or improvement ratio is clear, with larger improvement ratio resulting in higher K value after grout injection. The residual K value after shaking test in Cases CPG18s and CPG30s keeps high K value even 250 m/s^2 of acceleration was applied to the ground. This feature indicates that the improved ground by CPG possibly to keep its improvement effect in terms of residual K value. Figure 9 shows time histories of ratio of excess pore water pressure, Ru = (excess pore water pressure Δu) / (initial vertical effective stressσ'_{v0}). Liquefaction was observed in Case CPG30n, without grout injection, from beginning of the dynamic loading. In contrast, the remarkable increase of Ru cannot be observed in the cases with grout injection even in the case CPG30s with lower improvement ratio. This is indicating that the increase of K value due to grout injection provides the increase of liquefaction resistance even in lower improvement ratio.

4 CONCLUSIONS

Ground behavior due to compaction grouting was studied by x-ray tomography and centrifuge tests, with particular interest in the density change and the increase of liquefaction resistance.

Density change and ground response due to grout injection were not only visualized by x-ray tomography but also discussed quantitatively based on results of image analysis, Volumetric Digital Image Correlation (V-DIC). The mechanism of ground deformation caused by grout injection can be considered as a cavity expansion for deep injection and cone uplift for shallow injection. The densification of ground was mainly observed in the area around the grout pile. However, it can be also said that a certain grout pile diameter or injection volume is not largely contribute to densification especially at shallower depth because of lower confining pressure.

The influence of the improvement ratio appeared in the residual K values after grout injection which was observed in centrifuge tests. As the results of shaking table test, the increase of K value due to grout injection provides the increase of liquefaction resistance even in lower improvement ratio of about 5 %.

5 REFERENCES

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