Geotechnical Aspects of Underground Construction in Soft Ground, Kastner, Emeriault, Dias, Guilloux (eds)
© 2002 Spécifique, Lyon. ISBN 2-9510416-3-2

Effect of Multiple Injection on Long-term Compensation Grouting – Laboratory and Numerical Studies

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ABSTRACT: Multiple injection tests were performed in the laboratory to examine the effect of nearby injections on the long-term efficiency of compensation grouting. The test result shows that nearby grout injection can improve the grout efficiency for normally consolidated and lightly overconsolidated clays. However, the grout efficiency of multiple injections decreases when injections are performed sequentially rather than simultaneously. Similar results were obtained from the finite element analysis of compensation grouting operation in typical field settings. The results of the grout injection tests and the finite element analysis show that OCR, grout spacing and injection methods are the critical parameters that affect the long term behaviour of compensation grouting.

1 INTRODUCTION

Compensation grouting is a technique to offset subsidence caused during bored tunnelling. The basic principle is that grouts are injected in the zone between the tunnel and overlying buildings to compensate for the ground loss and stress relief induced by underground excavation (Mair and Hight, 1994). A common form of compensation grouting involves injection of particulate grouts into the soil. Hydrofractures are formed during injection and the grout intrudes into the fractures, contributing to the heaving effect. Ground circumstances and grout rheology enable a compensation effect to be achieved in a limited number of hydrofractures.

A unique feature of compensation grouting is the use of multiple injections, in which large numbers of grout injections are carried out within a designated grouting zone. During each injection, soil around the injection port fractures and deforms plastically while excess pore pressures develop. In this study, it is hypothesised that, as more grout is injected into the ground, the injections influence each other and the soil deformation patterns and excess pore water pressure profiles around the injection points will be affected. This study therefore aims to investigate whether or not the spacing between injection ports and the sequence of injections influence the final grout efficiency after the excess pore pressures have dissipated. For the investigation, a series of multiple injections tests was performed in the laboratory on reconstituted clay specimens with different overconsolidation ratios. A practical implication of the findings from the laboratory experiments was examined by performing finite element analysis of selected field scenarios.

2 EFFECTIVENESS OF COMPENSATION GROUTING

The effectiveness of compensation grouting can be evaluated by the amount of soil heave obtained (compensation effect) for a given injected grout volume. Ideally, if injections were made quickly in clayey soil so that soil deformation occurs in undrained conditions, the amount of heave would be equal to the volume of injected grout. Assuming a representative element (e.g. a typical element size for numerical analysis) around grout injection points as shown in Figure 1, the grout efficiency (η) can be defined as the ratio of the increase in soil volume of the representative element (V_E) to the injected volume of grout (V_{inj}) (Soga et al., 1999).

$$\eta = V_E / V_{inj}$$

If η is equal to one, by definition, the grouting should be considered as perfect. However, this is not the case in practice. The expansion volume V_E is generally smaller than the injected volume V_{inj} (η<1) due to loss of fluid from the grout (bleeding) and escape of the grout from the designated area by migration along fractures. Even if a good compensation effect is achieved immediately after injection, η can

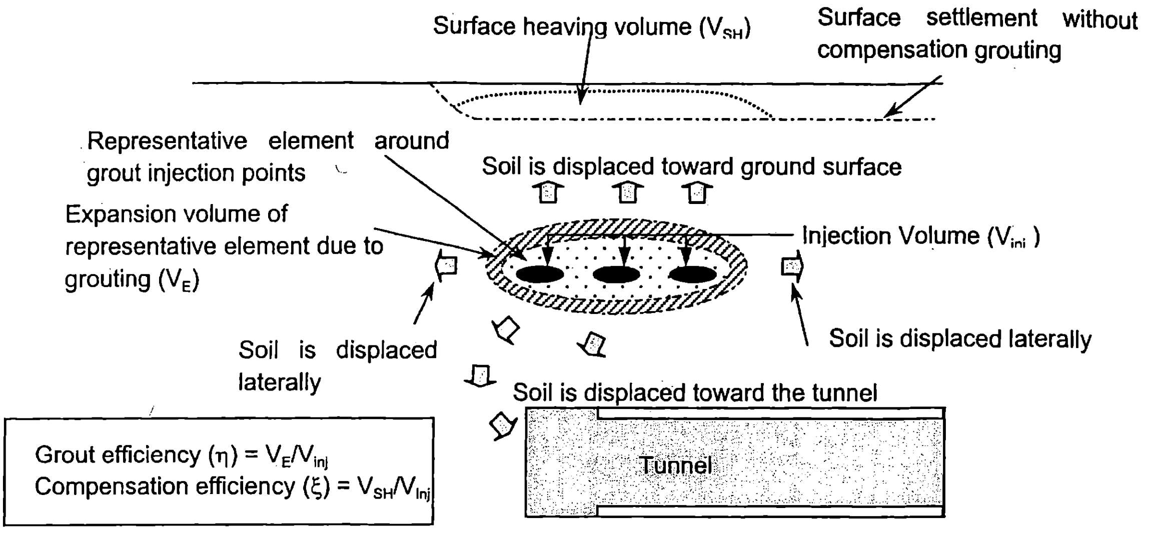

Figure 1. Grout efficiency and compensation efficiency

decrease with time. The clay around the grout will consolidate due to the dissipation of excess pore pressures generated during injection, which is the subject of this study.

In addition to the efficiency loss at the representative element level, the efficiency of compensation grouting (ξ in Figure 1) may be further reduced by geometry effects (i.e. lateral displacements produced by vertical fractures) and construction activity interaction effects (i.e. grout moving towards an underground opening) as shown in Figure 1. The assessment of this type of loss is a boundary value problem, which can be investigated by numerical analysis (see Komiya *et al.*, 2001).

In general, low compensation efficiencies are reported for soft clay conditions, whereas a better compensation efficiency is achieved in stiff clays. A field trial in Singapore soft clay reported by Shirlaw *et al.* (1999) showed that the heave obtained immediately after grout injection reduced with time due to soil consolidation associated with the dissipation of the excess pore pressures generated during injection. In some cases the surface level came back close to the original condition. Similar findings were obtained in the field trials reported by Ikeda *et al.* (1996) and by Komiya *et al.* (2001), addressing the undesirable long-term effect of grouting in soft clay for settlement control purposes. This study focuses on the long-term effect of compensation grouting in clays and extends the previous works reported in Soga *et al.* (1999) and Jafari *et al.* (2001).

3 LABORATORY INVESTIGATION

3.1 Testing method and materials

Grout injection tests were performed on laboratory reconstituted E-grade kaolin clay specimens prepared at different overconsolidation ratios. A schematic diagram of the experimental set-up is shown in Figure 2. A consolidometer of 100 mm diameter was modified and four injection tubes were placed at the base. A 4 mm OD and 3mm ID copper needle was used as an injection tube. The total length of the needle was 130 mm and the height above the bottom porous plate was 50 mm.

E-grade Kaolin (LL = 72, PL = 38) was used as an injected soil medium. Clay slurry was prepared by mixing dry E-grade kaolin powder with de-aired water under vacuum, giving a water content of 120%. The slurry was then placed in the consolidometer and the volume of slurry was determined based on the condition that the specimen height after consolidation will be approximately 100 mm. The samples were prepared at different overconsolidation ratios ranging from 1 to 10. The vertical effective stress at the injection stage was fixed at 140 kPa.

Two types of injection were performed; (a) injection of water or epoxy into a latex balloon attached

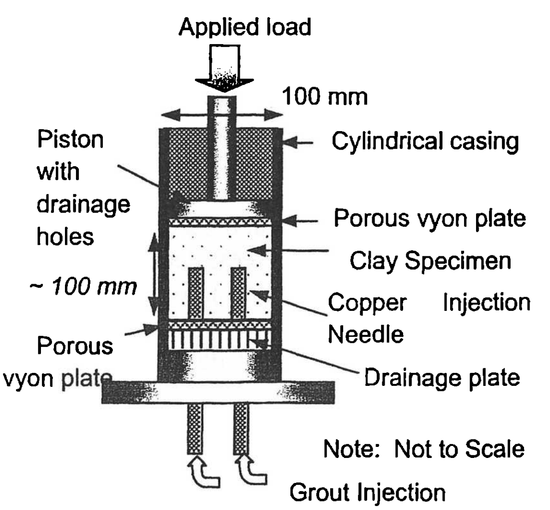

Figure 2. Grout injection consolidometer

at the tip of the injection point to simulate ideal compaction grouting, where no bleeding or penetration could occur, and (b) injection of epoxy resin to simulate fracture grouting. The purpose of using epoxy resin rather than a more realistic grout (such as cement bentonite mixtures) was to reveal the fracture patterns after the tests through hardened epoxy.

Injections were made using a pressure/volume controller, which can control the injection rate and volume. The injection rate of 500 mm^3/sec was selected so that the injection stage could be kept close to an undrained condition. Various pressure corrections for both balloon expansion and fracture grouting tests were based on calibrations. The surface displacement of the specimen during and after injection was measured using a LVTD.

The injection volume was 5 ml for most of the tests. This is to ensure that the grout will be contained within the specimen and will not migrate through fractures reaching the boundaries. However, because of this small amount of injection volume, the effect of compression of small air bubbles trapped in the system could not be neglected and great care was taken to remove these air bubbles as much as possible. Further experimental details can be found in Au (2001).

3.2 Test results

3.2.1 Single Injection or Multiple Injections

If a given volume of grout is injected over a fixed area for compensation purposes, it is possible to either use many injection points with small injection volumes, or conversely, fewer injection points with larger injection volumes. Simultaneous multiple injection tests were performed and the results were compared to the single injection test results.

For the multiple injection tests, four injection needles were placed in a square grid in the 100mm diameter consolidometer as shown in Figure 3. The diagonal distance between the injection points was 50 mm. For the single injection tests, the same 100 mm diameter consolidometer was used, but injection was made at the centre of the specimen. Water was injected into the latex balloons attached to the injection needles, simulating ideal compaction mode grouting. Therefore, the issue of grout bleeding is avoided. The single injection tests were carried out by injecting 20ml at one injection point, whereas the multiple injection tests were made by injecting 5ml for each needle, giving the total injection volume of 20 ml.

The measured grout efficiency-time curves of OCR = 1 and 1.5 specimens are shown in Figure 4. The initial efficiency losses were about 7 to 9 % in both types of tests. These initial losses are due to (1) partial consolidation near the injection point where the hydraulic gradient is very large, but more likely to be due to (2) compression of small air bubbles

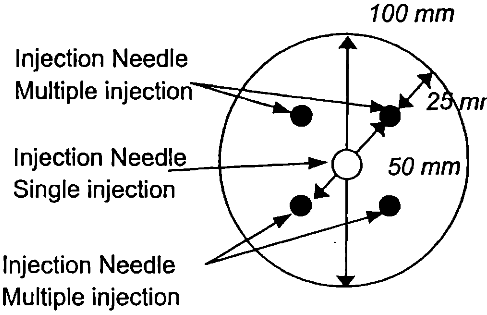

Figure 3. Injection locations

trapped inside the water and connections even though care was taken to remove any air bubbles during the set-up. The figure shows that, for a given OCR, the final grout efficiency of a single large injection is less than that of multiple simultaneous injections.

Assuming symmetry of the radially fixed outer boundary condition, the single injection test can be considered to be equivalent to injecting grout simultaneously with spacing of 113 mm as shown in Figure 5. When grouting is performed in a regular geometrical array with injections of the same volume at each port, the behaviour of any grouting unit should be similar to that of a single injection confined in an equivalent radial fixed boundary. This symmetry hypothesis for multiple simultaneous injections was confirmed experimentally by Au (2001).

The balloon expansion test results indicate that, for a given total volume of injection, more consolidation settlement is induced with larger spacing of larger injection than with closely spaced injections of small grout volume. This is primarily due to overlapping of excess pore pressure zones generated by each injection. For small spacing condition, an injection is influenced by the neighboring injections and the total amount of excess pore water pressure generated will be affected by this overlapping condition. The experimental data suggests that this overlapping suppressed the amount and extent of excess pore pressure generation, leading to less consolidation settlement and a better final grout efficiency for

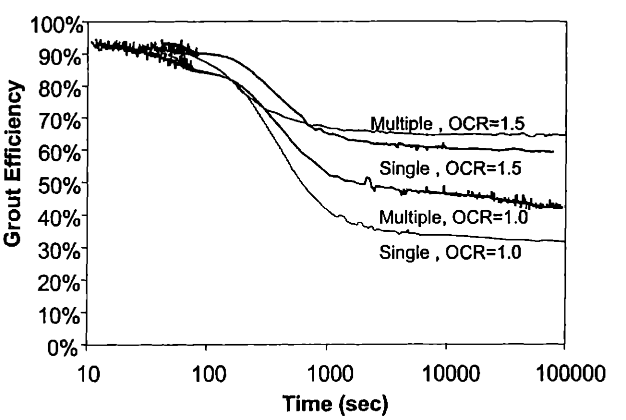

Figure 4. Multiple injections versus single injection

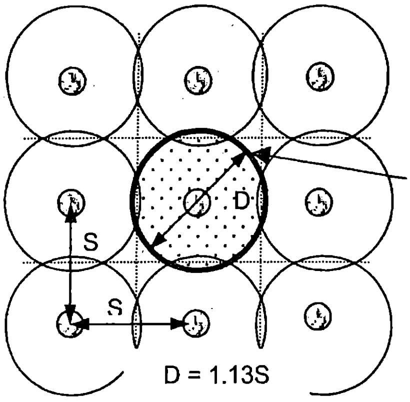

Figure 5. Multiple simultaneous injection

smaller spacing condition. This finding was also confirmed by performing coupled consolidation finite element analysis of multiple grout injections tests (Au, 2001).

3.2.2 Simultaneous or Sequential Injections

The simultaneous injection technique described in the previous section is not common in practice. The current compensation grouting technique is done using sequential injections at multiple points. A new series of tests was performed on both normally consolidated and overconsolidated clay specimens. The set-up of the sequential injection tests was the same as the simultaneous injection tests. There were four injection points and either a balloon was expanded or epoxy was injected in sequence. The duration between each injection was varied, but the sequence of injections was the same.

The measured grout efficiency against time from the balloon expansion tests on normally consolidated clay is shown in Figure 6. The peak efficiency decreased with the waiting period because the soil was consolidating during the waiting period. The figure also shows that the final grout efficiency after four injections decreased with the waiting period. When there was a longer waiting period, the excess pore pressures around the plastic zone dissipated. As a result, the overlapping of excessive pore water pressure zones was not as effective as that for the short waiting period test. The result suggests that shorter waiting periods can improve the grout efficiency by taking advantage of nearby injections.

The grout efficiency of the simultaneous epoxy grout injection test was also greater than that of the sequential injection test as shown in Figure 7. The fractures caused by the sequential epoxy injection were slightly inclined to the horizontal plane and many individual sub-fractures were formed off the surface of the main fracture. Therefore, the area of influence in the sequential injection case may be larger than that of the simultaneous injection case, resulting in larger zone of excess pore pressures and more consolidation effect.

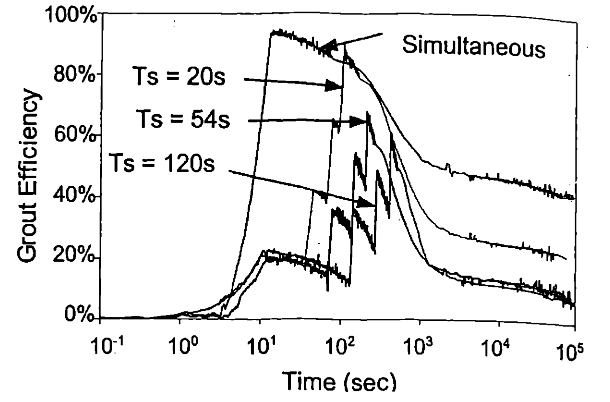

Figure 6. Effect of waiting period : Balloon expansion test

Two sequential injection tests were performed on OCR=5 specimens. The tests were compared with the simultaneous injection tests and the comparison of the grout efficiency-time curves is shown in Figure 8. The grout efficiency did not change in the consolidation phase. For highly overconsolidated clays (OCR = 5), the final grout efficiency was independent of the waiting period.

Comparison between Figures 6 and 7 shows that the final grouting efficiency for the epoxy injection test was 40% lower than that for the cavity expansion test. Although the amount of peak injection pressure in the epoxy injection test was similar to

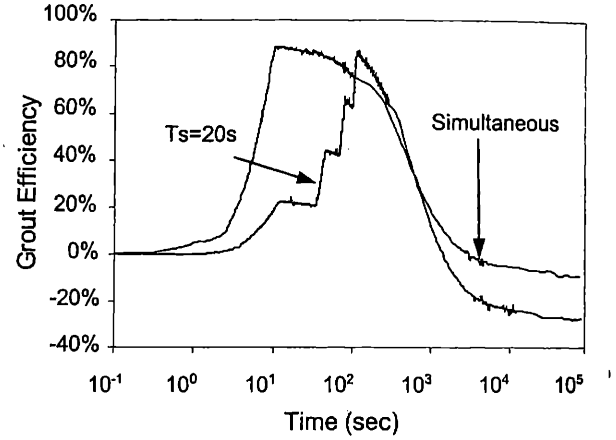

Figure 7. Simultaneous vs. Sequential : Epoxy injection

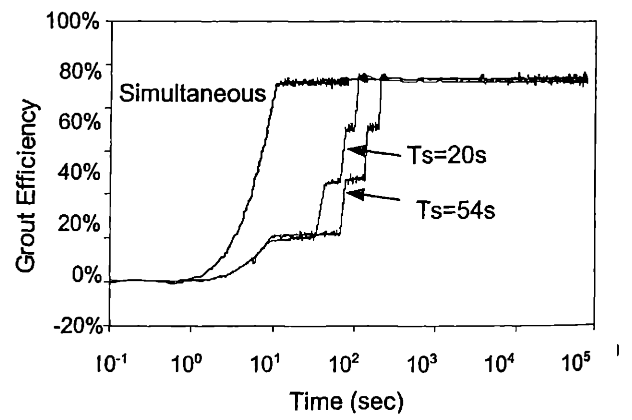

Figure 8. Effect of waiting period on grout efficiency for heavily overconsolidated (OCR = 5) specimens

that of the cavity expansion test, the amount of consolidation settlement for the epoxy injection was much higher than that of the cavity expansion test. This may be because the extent of excess pore pressure zone for the epoxy injection was higher than that for the cavity expansion test. It is also possible some epoxy penetrated into the soil pores.

4 NUMERICAL SIMULATION

The multiple grout injection tests showed that, for a given injection volume, the final grout efficiency can be improved by injecting grout with small spacing. The actual compaction grouting in the field involves a series of complex procedures and stages (e.g. drilling a borehole, installation of grouting tube and sealing the borehole with cement bentonite). The actual details of these procedures and stages are difficult to model. However, a simple cavity expansion model is introduced in this study to assess the feasibility of the multiple simultaneous injections for field conditions. An attempt is made here to apply this simple model in simulating the long-term behaviour in a typical site scale setting. The consolidation behaviour and variation of grout efficiency in different OCR soil conditions and in various relative radial boundary sizes were examined.

The axisymmetric finite element mesh used for the investigation is shown in Figure 9. The radial boundary size (R) was varied from 300mm to 20m; the cases of smaller R are for closely spaced simultaneous injections. The initial size of the injection cavity was assumed to be equal to the size of a typical injection tube. The injection depth was fixed as 5m below the ground surface. The grout injection volume was fixed at 30 litres to match the typical injection volume in the field. A uniform pressure was applied at the cavity boundary and the pressure was increased rapidly until the volume of the cavity became equal to 30 litres. The displacements of the cavity were then fixed and the excess pore pressures generated during the expansion were allowed to dissipate, leading to consolidation settlement.

A total of 28 finite element analyses were carried out with different sizes of spacing. The analyses were designed to examine the effect of OCR and relative radial boundary in ideal field scale conditions. Modified Cam-clay was used and two sets of material paramters were selected (LC and SC representing London Clay Singapore Marine Clay, respectively as shown in Table 1). A uniformly distributed load was applied at the ground surface to model the loading from buildings, creating different OCR conditions of the subsoil (i.e. smaller OCR means larger building surcharge). The self-weight and the variation of stress conditions (stresses, pore pressure and void ratio) of the soils were taken into account.

Figure 10 shows typical computed grout efficiency-time curves. The computed consolidation behaviours are similar to the ones observed in the labo-

Table 1. Camclay parameters

Soil Type	Singapore clay	London clay
λ	0.161	0.357
κ	0.074	0.062
M	0.772	0.89
Γ	4.46	2.75
ν	0.2	0.2
k (m/sec)	10^{-9}	10^{-9}

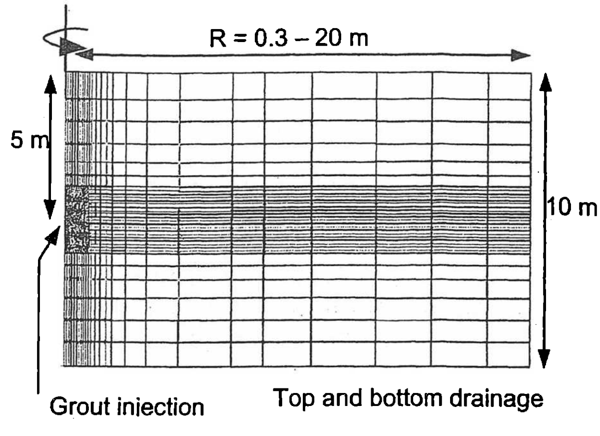

Figure 9. Finite element mesh for field case simulations

ratory tests, except the time of consolidation for laboratory tests are much shorter than that for field scale model. This is because the zone of excess pore pressure and therefore the drainage path are much larger in the field scale model than those in the laboratory tests.

The effect of radial boundary size at different OCRs is shown in Figure 11. Using the simultaneous injection hypothesis, the radial boundary size can be considered to be equivalent to a half of the grout spacing. In the figure, n-value is the radial boundary size (R) normalized by the cavity radius after grouting. The figure shows that the final grout efficiency increases with OCR but decreases with the increase in the n-value. The final grout efficiency levels off to a steady value when n is larger than 80 for the case of SC, OCR=1.2 and 40 for the

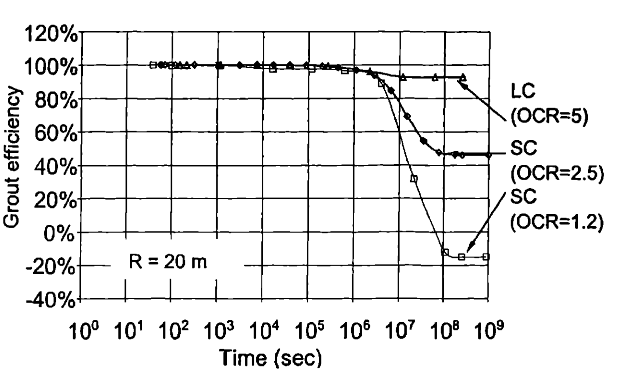

Figure 10. Computed grout efficiency time curves

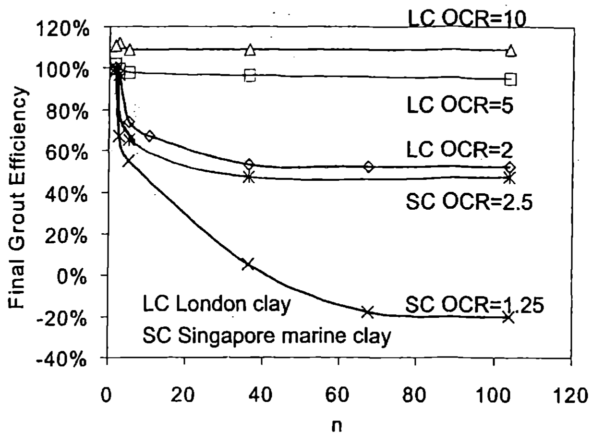

Figure 11. Final grout efficiency versus grout spacing

cases of SC OCR=2.5 and of LC OCR=2. It is surprising that the final grout efficiency can be a negative value when the clay is normally consolidated or lightly overconsolidated. This is primarily due to extensive shearing during the injection and the ultimate increase in mean effective pressure around the injection point caused by the injection pressure locked in when the grout solidified. Negative efficiencies were also measured in laboratory experiments reported in Jafari *et al.* (2001) and Au (2001). However, the efficiency of lightly overconsolidated clay dramatically increases when the spacing between the injection points decreases (smaller n value).

The radial boundary size has no effect when grout injection was performed in highly overconsolidated clays. A similar phenomenon has been observed in the laboratory tests. The positive efficiencies measured in the LC, OCR = 10 case is due to dilative behaviour of heavily overconsolidated clay after the clay is extensively sheared during injection. The numerical results show that pore water migrated from the positive excess pore pressure zone around the injection point to the negative zone some distance away from the injection point, during the consolidation stage. The compression near the injection point and swelling at some distance away from the injection point resulted in a negligible consolidation effect for heavily overconsolidated clays. The results clearly show that OCR and relative radial boundary (grout spacing for simultaneous injections) are the critical parameters that affect the long term behaviour of compensation grouting.

5 CONCLUSIONS

Multiple injection tests were performed to examine the effect of nearby injections on the long-term efficiency of compensation grouting. The test result shows that nearby grout injection can improve the grout efficiency for normally consolidated and lightly overconsolidated clays. However, the grout efficiency of multiple injections decreased when injections are performed sequentially rather than simultaneously. The final grout efficiency decreased with increase in the waiting period between the injections due to the partial consolidation occurring during the waiting period. The measured grout efficiencies of heavily overconsolidated clay were very close to one, indicating no long-term settlements induced by compensation grouting operation. A practical implication of this finding was examined by performing finite element analysis of compensation grouting operation in typical field settings. For lightly overconsolidated conditions, the increase in long-term grout efficiency was computed when the spacing between injection points was reduced. For heavily overconsolidated conditions, the long-term grout efficiency was independent of the grout spacing. The results of the grout injection tests and the finite element analysis show that OCR, grout spacing and injection methods are the critical parameters that affect the long term behaviour of compensation grouting.

ACKNOWLEDGEMENTS

The work was partially supported by the European Commission. The authors would like to thank Dr. Reza Jafari, who helped the experiments.

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