Factors Affecting Long-Term Efficiency of Compensation Grouting in Clays

S. K. A. Au[1]; K. Soga[2]; M. R. Jafari[3]; M. D. Bolton[4]; and K. Komiya[5]

Abstract: Compensation grouting has been attracting attention in recent years to control ground settlement caused by underground construction. A successful and effective application of compensation grouting depends not only on the use of a good monitoring system in the field but also on a fundamental understanding of grout behavior in soils. For compensation grouting in clay, there is a need to consider the long-term effectiveness of compensation grouting. Grout injection tests were conducted in the laboratory to examine soil fracturing patterns and consolidation effects in relation to compensation grouting. Both compaction and hydrofracturing modes of grouting were tested on kaolin clay specimens with different overconsolidation ratios. Finite-element analysis was also conducted to simulate the balloon expansion tests (ideal compaction grouting tests) and the results were compared with the data from the laboratory tests. Based on the research findings, new design criteria are proposed to improve the long-term efficiency of compensation grouting for clays.

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Introduction

In recent years, compensation grouting has become a popular method for settlement control during underground construction. The basic principle is that grout is injected in the zone between underground openings and building foundations to compensate for the ground loss and stress relief caused by the underground excavation. Grout injection is often undertaken simultaneously with construction in response to detailed observations so that settlement and distortions are limited to specified amounts. The use of real-time monitoring of settlement, such as by electrolevels attached to buildings, is the key to success for an effective compensation grouting operation (Mair and Hight 1994; Buchet et al. 1999; La Fonta 1999; Soga et al. 1999). In many cases, the information gathered from a real-time monitoring system has forced changes to the original grouting plan.

Successful applications of compensation grouting to tunneling are reported for the London Underground Jubilee Line extension project (Harris et al. 1996; Osborne et al. 1997; Harris et al. 1999), the Viennese subway project (Pototschnik 1992), the Saint Clair River tunnel project near the USA-Canada border (Dramer et al. 1994; Droff et al. 1995), the London Dockland extension project (Sugiyama et al. 1999; Essler et al. 2000) and the Lisbon underground line (Schweiger and Falk 1998). A summary of some of the past compensation grouting projects is listed in Table 1. The ''compensation efficiency'' in the Table 1 is defined as the ratio of the volume of heave obtained to the injected volume of grout. In general, low compensation efficiencies were calculated in soft clay conditions, whereas better compensation efficiencies were achieved in stiff clays. The 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.

Possible Mechanisms of Decreasing Compensation Efficiency

Fig. 1 shows the conceptual modeling of compensation grouting in clays. At the initial stage of compensation grouting, the grout pushes the soil outward and deforms plastically, forming a ball. As the grouting pressure increases, the size of the ball increases rapidly until the grout pressure builds up to the fracturing pressure and a plane of weakness is formed by hydraulic fracturing as shown in Fig. 1(b). As a result, the stress condition in the soil suddenly changes and the injection pressure drops. When grout with low viscosity and/or low solid content is used, it will intrude into planes of weakness to develop grout-filled fractures. When a grout with high viscosity and/or high solid content is used, the grout would not be able to penetrate into fractures and the grout ball simply continues to expand. In Europe, fracture grouting is often used in compensation grouting because it is possible to regrout from the same grouting port.

The effectiveness of compensation grouting can be evaluated by the amount of soil heave obtained (compensation effect) for a

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Table 1. Case Studies of Compensation Grouting

Project	Depth (m)	Soil type	Tunneling method	Grouting method	Grout type	Compensation efficiency	Results
Viennese Subway (Pototschnik 1992)	10	Soft clay	NATM[a]	Fracture grouting	Silica gel	3%	50% settlement was reduced.
Imperial Oil's research building St. Clair River (Droff et al. 1995)	7	Soft clay	EPB[b]	Fracture grouting	Cement bentonite PFA	N/A	Soil fracture grouting proved to be an effective means of protecting the research building. The predicted settlement was reduced from 120 mm to the actual settlement about 10 mm.
Waterloo Station, London (Harris et al. 1996)	5	Stiff clay	EPB[b]	Intrusion Grouting	Cement bentonite PFA	N/A	Compensation grouting proved to be very successful in limiting settlement from 40 mm to 20 mm.
Big Ben Clock Tower (Harris et al. 1999)		Stiff clay	Open face shield	Fracture grouting	Cement bentonite	N/A	Tilt of the tower has been controlled within very fine tolerances.
Docklands Light Railway Lewishm Extension (Essler et al. 2000)	6.5	Stiff clay	EPB[b]	Fracture grouting	Cement bentonite, PFA, Silica gel	20%	Maximum settlement (predicted) was reduced from 30 mm to 0 mm (actual). Overlying structure has been protected.
Japanese Storehouse (Ikeda et al. 1996)	11	Soft clay	EPB[b]	Fracture grouting	Silica gel	3%	Compensation grouting undertaken from inside of the tunnel had been proven to be very effective in limiting settlement. The settlement was reduced from 60 mm to 14 mm heave.
Grouting trial in Singapore marine clay (Shirlaw et al. 1999)	7	Soft clay	No tunneling	Fracture grouting	Cement bentonite, PFA, Silica gel	−5%	Compensation grouting as a building protection measure within Singapore marine clay is unlikely to be successful.

[a]NATM indicates new Austrian tunneling method.

[b]EPB indicates Earth pressure balance machicne.

[c]PFA indicates pulverized fuel ash.

[d]N/A indicates not applicable.

given injected grout volume. Ideally, if an injection is rapid so that soil deformation is occurring in an undrained condition, the amount of heave is equal to the injected volume. However, this is often not the case in the field due to (1) increased deformation towards the excavation; (2) lateral subsurface displacements due to vertical fractures resulting in surface heave outside the designated compensation area; and (3) escape of the grout through extended fractures. Even if a good compensation effect is achieved immediately after injection, the effectiveness can decrease with time. The clay around the grout will consolidate due to the dissipation of excess pore pressures generated during injection [Fig. 1(c)] and the constituents of the grout can migrate into soil pores (bleeding and solid penetration).

The aim of this research was to investigate the factors affecting the long-term efficiency of compensation grouting. Grout injection tests were performed in the laboratory to examine soil fracturing patterns and consolidation effects in relation to compensation grouting. Both compaction and hydrofracturing modes of grouting were tested. During injection, the volume expansion of the specimen and the injection pressure were measured. Postinjection settlement was recorded to assess the magnitude of the consolidation effect. The factors varied in the laboratory testing program were the overconsolidation ratio (OCR) of the clay, grout materials, and the injection method (regrouting and grout spacing).

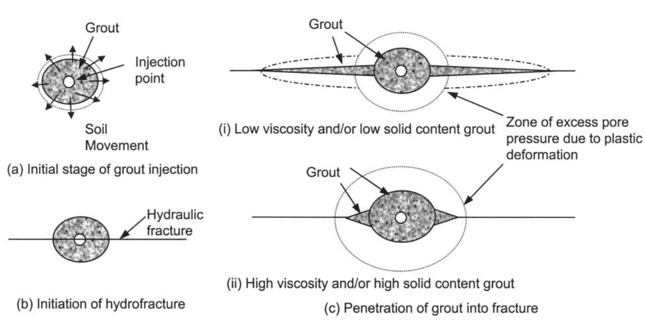

Fig. 1. Conceptual modeling of compensation grouting process

Experimental Investigation

The experimental layout of the laboratory grout injection tests is shown in Fig. 2. E-grade kaolin was consolidated in a modified consolidometer with an injection needle incorporated into the base. Two modified consolidometers with different diameters (50 cm or 100 cm) were employed. A 4 mm outer diameter (OD) and 3 mm inner diameter (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 [see Fig. 2(a)]. In order to prevent the grout from leaking down the sides of the injection needle, a 40 mm long 4.5 mm ID copper tube was used as a retaining collar around the injection tube. As shown in Fig. 2(b), injection was made using a GDS Pressure/Volume Controller, which can control the injection rate and volume. A pressure interface chamber (PIC) was used to transmit the pressure from the hydraulic fluid in the GDS Controller to the grout during injection. Injection pressures were measured using a pressure transducer positioned between the PIC and injection needle, while surface displacements of the specimen during and after injection

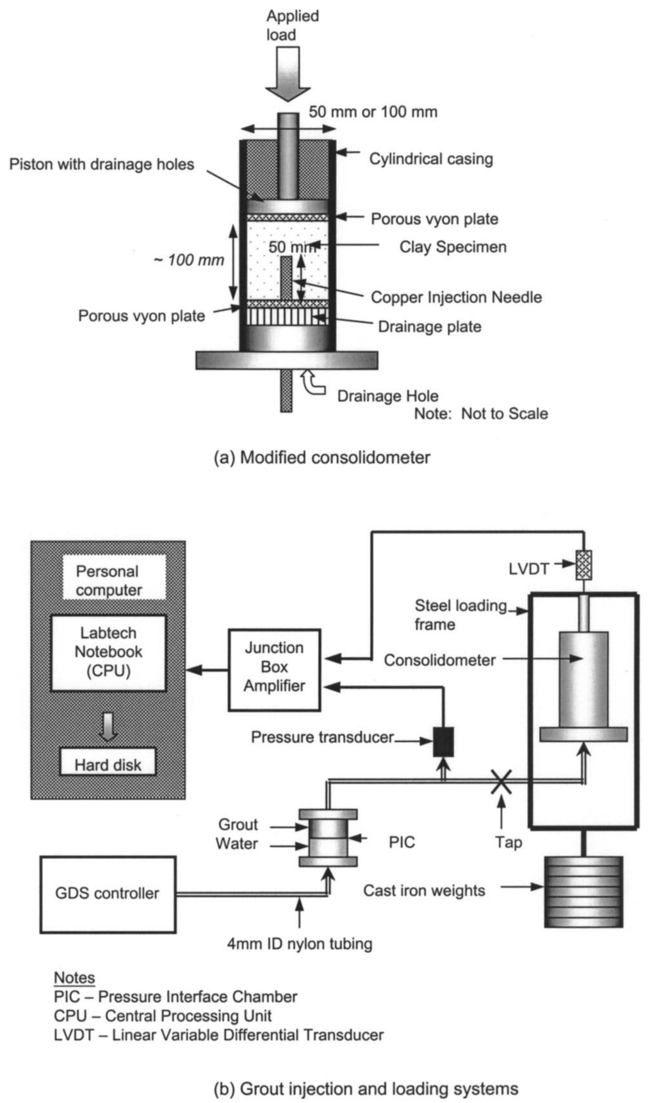

Fig. 2. Experimental setup for grout injection tests

were measured using a linear variable differential transducer attached to the top plate of the consolidometer.

In order to investigate the compensation effect under different stress histories, clay specimens were prepared at different OCR's ranging from 1 to 10. Clay slurry was made by mechanically mixing dry E-grade kaolin powder with de-aired water under a vacuum, giving a water content of 120%. The slurry was placed in a consolidometer and the volume of slurry was determined based on the condition that the specimen height before injection will be approximately 100 mm. The vertical effective stress during the injection stage was fixed to be 140 kPa.

Different injection materials were used to investigate the effect of grout bleeding and solid penetration on the long-term efficiency of compensation grouting: (1) Deaired water: Water will fracture the clay but can drain out from the fractures with time (large bleeding effect). (2) Epoxy resin: The epoxy resin used is manufactured by Sempol Surfaces Ltd. A ratio of 10:6 of resin and hardener by weight was selected to obtain the highest strength of epoxy resin. Epoxy resin does not bleed (no water), but can penetrate into clay fissures before hardening. The use of epoxy resin allowed the examination of the fracture pattern by washing the soil away after the test. (3) Laponite water mixture: Laponite is a colloidal synthetic layered silicate manufactured by Laporte Industries Ltd. A typical Laponite crystal is negatively charged and is about an order of magnitude smaller than a typical clay particle. Mixing of gel-grade Laponite with water forms a highly thixotropic gel with high viscosity at low shear. In this study, Laponite grout was prepared by mixing 3% by weight of gel-grade RD Laponite powder in 200 g de-aired water dyed red. The lack of setting properties and the small particle size mean that both bleeding of water and migration of the Laponite particles into the clay pores can occur. (4) Cement bentonite: A mixture of ordinary Portland Cement, bentonite, and water was adopted based on the grout mix used in current compensation grouting practice. The size of all of the solids is considered to be larger than the clay pores; hence, no solid penetration is expected. However, the water can bleed out from the grout with time. In order to examine the magnitude of the bleeding effect, tests were performed using three different water/cement ratios (w/c):$w/c = 0.6$, 1, and 3. Due to large wall friction through the piping, the GDS pressure controller could not inject cement bentonite grout with a water/cement ratio lower than 0.6. 3% bentonite by weight of cement was added to the mixture to increase the workability of the grout. (5) Balloon expansion: A latex balloon was placed at the tip of the injection needle and either water or epoxy was injected into the balloon to simulate an ideal compaction grouting model, where no bleeding or solid penetration could occur.

The injection volume of grout was fixed to be 5 ml. This was to ensure that the grout will be contained within the specimen and will not migrate through fractures reaching the boundaries. It was found from the preliminary tests using the smaller 50 mm diameter consolidometer that, if the grout volume is larger than 5 ml, the grout would escape from the testing boundaries through fractures, resulting in an artificial reduction in grouting efficiency. A series of regrouting tests were also conducted to investigate the effect of time lag between two injections and to find out which injection method would give the best long-term compensation effect.

Effect of Overconsolidation Ratio

The effect of OCR on grouting efficiency is shown in Fig. 3(a) for the balloon expansion tests using the 100 cm diameter consolidometer. The rate of injection was 500 mm^3/s. The grout efficiency (η) is defined as the ratio of heaved volume to the initial injection volume. The initial part of the curves immediately after injection implies that the injection process is not completely undrained. If the injection was performed in undrained conditions without grout permeation into the soil pores, the heaved volume should be equal to the injected volume resulting in 100% grout efficiency. However, it was common that the measured initial grout efficiencies (η_i) after the injection were slightly less than 100% even when the injection was done in a relatively small duration of about 10 s. This is thought to be due to the compression of tiny gas bubbles trapped in the grout materials and in the connections leading to the injection needle. Since the injection volume was only 5 ml, the effect of the compression of the air bubbles could not be neglected. In general, the amount of the initial efficiency loss was about 5% to 10% in most of the injection tests. Nevertheless, the outcome of Fig. 3(a) is clear. For the normally consolidated clay sample, negative grout efficiency was measured at the end of the consolidation stage. The final grout efficiency dramatically increased when the OCR increased from 1 to 2 and reached almost 100% for the heavily overconsolidated clay of OCR=5.

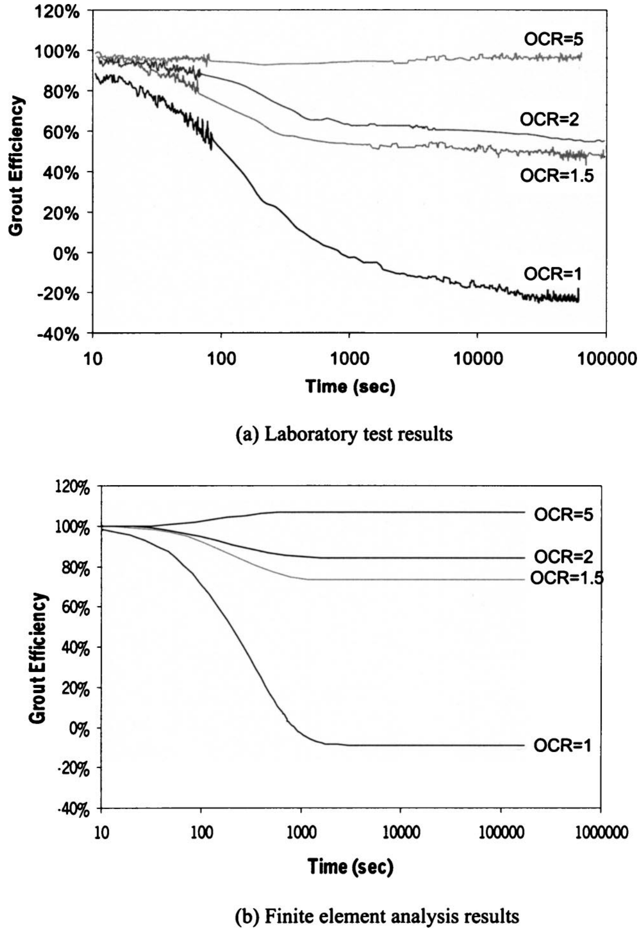

Fig. 3. Grout efficiency–time curves of balloon expansion tests

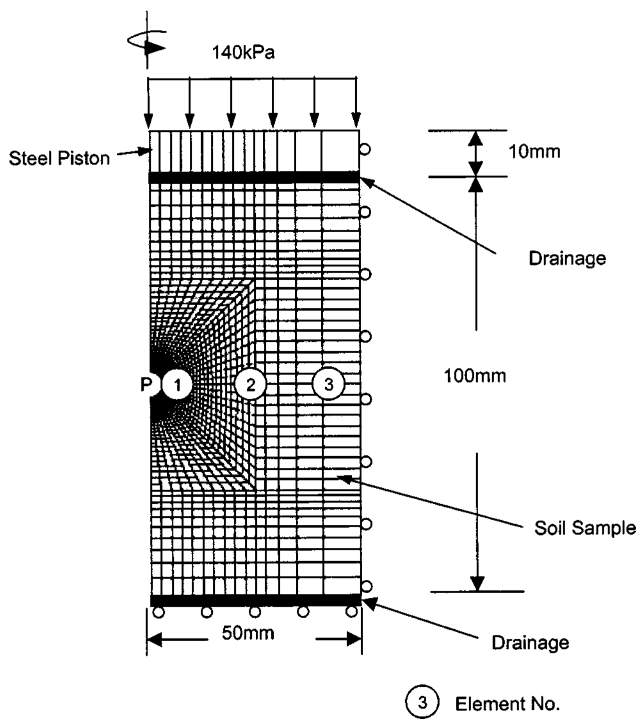

Fig. 4. Axisymmetric finite-element mesh

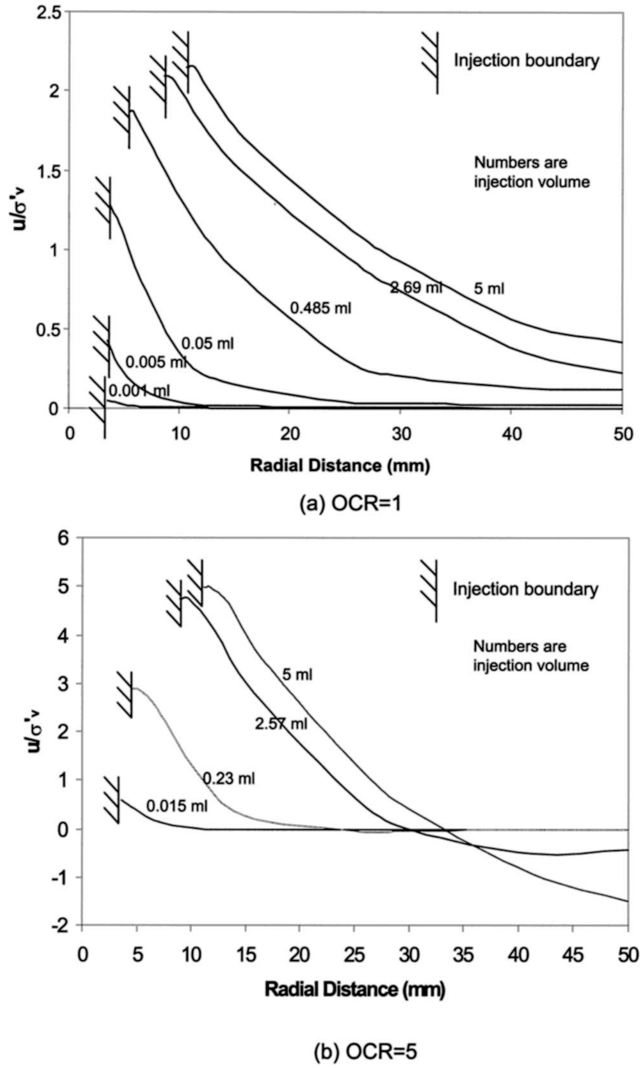

Fig. 5. Computed normalized excess pore pressure distribution within a clay specimen

Finite-element analysis of the balloon expansion tests was performed using *ABAQUS* version 5.8 with consolidation elements (HKS 1998). The axisymmetric finite-element mesh used is shown in Fig. 4. The radius of the initial cavity was assumed to be the radius of the latex balloon. The pressure was applied in the cavity until the cavity volume expanded by 5 ml. After fixing the displacements at the cavity boundary, the soil was allowed to consolidate. The modified Cam-clay model was used to simulate the deformation behavior of E-grade kaolin and the input parameters were $\lambda=0.13$, $\kappa=0.03$, $M=1.05$, $\Gamma=2.65$, $\upsilon=0.2$ and $k=2\times10^{-9}$ m/s. The details of the analysis are described in Au (2001).

The computed grout efficiency time curves with different OCR's are plotted in Fig. 3(b). Since the initial efficiency loss observed in the experiments does not exist in the finite-element analysis, the computed final grout efficiencies are consistently 10–20% higher than the experimental test results. When this initial loss is taken into account, the finite-element analyses gave good agreement with the experimental results.

The computed excess pore pressures during the injection stage along the horizontal direction from the injection point are shown in Figs. 5(a and b) for OCR=1 and 5, respectively. The computed excess pore pressures are normalized by the initial vertical effec-

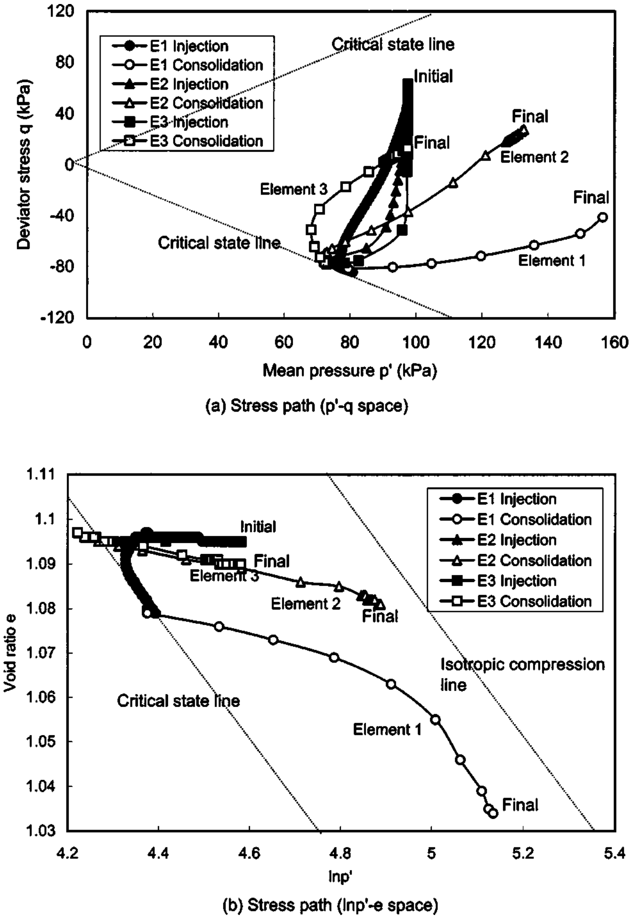

Fig. 6. State paths of selected elements for overconsolidation ratio=1 case

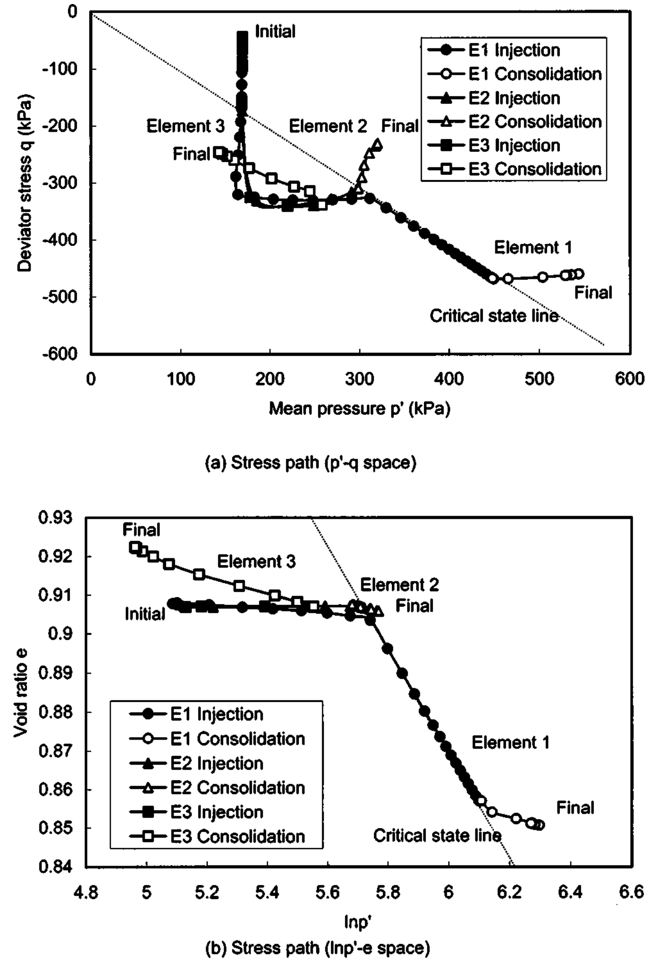

Fig. 7. State paths of selected elements for overconsolidation ratio=5 case

tive stress ($\sigma_v' = 140$ kPa). In both normally consolidated and overconsolidated clay cases, the magnitude of the excess pore pressure around the injection point increased with the volume of injection.

For the normally consolidated clay, the computed excess pore pressures were all positive as shown in Fig. 5(a). Hence, the large decrease in grout efficiency with time for the normally consolidated clay specimen is due to dissipation of the positive excess pore pressures generated during injection. Fig. 6 shows the stress paths (in p'-q-e space) of the elements identified in Fig. 4. In Fig. 6, $p'(=(\sigma_v' + \sigma_r' + \sigma_\theta')/3)$ is the mean effective pressure, $q = \sigma_v' - \sigma_r'$ is the deviator stress, e is the void ratio, σ_v', σ_r', and σ_θ' are the vertical, radial, and circumferential effective stresses, respectively. The shear stress (τ_{vr}) was computed to be very small at these elements. The stress paths show that elements 2 and 3 were close to the undrained condition during the injection stage (solid symbols in Fig. 6). Element 1, which is adjacent to the injection boundary, showed partial drainage during the injection due to the large computed hydraulic gradient. During the postinjection stage (open symbols in Fig. 6), a large decrease in volume occurred due to the increase in mean effective pressure as the excess pore pressures dissipated.

For the overconsolidated clay case, the excess pore pressure was positive at the injection boundary, but it was negative at the outer boundary due to dilative behavior of the clay, as shown in Fig. 5(b). Fig. 7 shows the stress paths of the elements selected in Fig. 4. Element 1, which is adjacent to the injection boundary, decreased in volume during the injection stage along the critical state line (solid circles in Fig. 7). This is due to partial drainage caused by the large hydraulic gradient in the element. During the consolidation stage, the negative pore pressures that were generated some distance away from the injection point compensated for the excess positive pore pressures around the injection point. This resulted in a decrease in volume of element 2 (open triangles in Fig. 7) and swelling in element 3 (open squares in Fig. 7). As the excess pore pressures dissipated, the clay deformed elastically leading to a small loss in the grout efficiency as shown in Fig. 3(b).

Effect of Bleeding and Solid Penetration

The effect of bleeding and solid penetration on grout efficiency was investigated by injecting different types of grouts. The injection rate was kept as 500 mm^3/s. The 100 mm diameter consolidometer was used for the investigation.

The measured changes in the grout efficiency with time for various grouts injected into normally consolidated clay specimens are shown in Fig. 8. The injection of water resulted in the smallest final efficiency of -120%, whereas expansion of a latex balloon gave the largest final efficiency of -20%. The measured final grout efficiencies for different OCR's and different grouts are

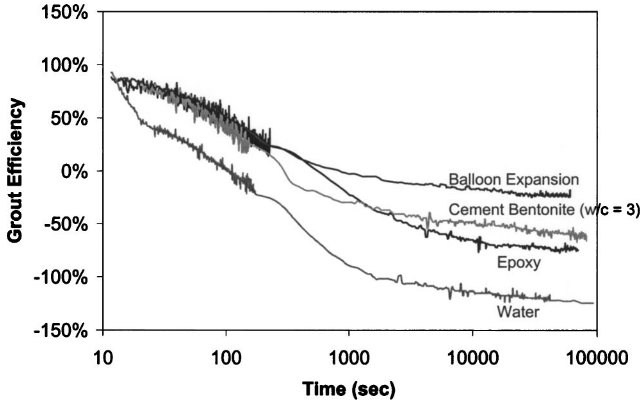

Fig. 8. Effect of grout material on grout efficiency–time curves for overconsolidation ratio=1

summarized in Fig. 9. The final grout efficiency improved dramatically when the OCR changed from 1 to 2.

The decrease in grout efficiency with time in the balloon expansion was mainly due to soil consolidation associated with excess pore pressures generated around the balloon. For the cement bentonite injection case, an additional decrease in the efficiency was caused by the bleeding of the water from the grout. From the field test result reported by Shirlaw (1990), the typical value of the w/c ratio in a fracture is about 0.3. McKinley (1994) performed laboratory tests to examine the consolidation of filter cake under the filtration pressure ranging between 5–60 kPa and found that the moisture content of the hardened grout fracture was approximately 0.35 for ordinary Portland cement. Hence, it was reasonable to assume the bleeding had occurred in the current experiments.

In order to confirm the bleeding effect, additional injection tests with different w/c ratio grouts were conducted using the 50 mm diameter consolidometer. Fig. 10 shows that the final grout efficiency increased when the w/c ratio decreased from 3 to 0.6. Hence, a high solid content grout will give good final grout efficiency owing to less bleeding effect.

Visual examination of the sectioned samples after injection indicated that the extent and thickness of fracture were different for different OCR's. Fig. 11(a) shows that a thick localized spherical ball was formed in the OCR=1 specimen. On the other

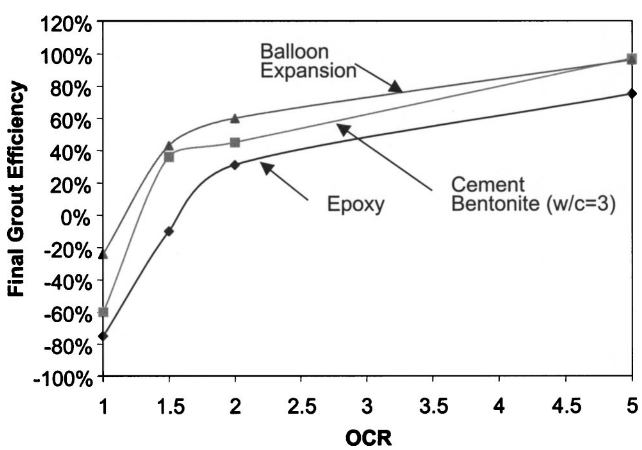

Fig. 9. Effect of grout material and overconsolidation ratio on final grout efficiency

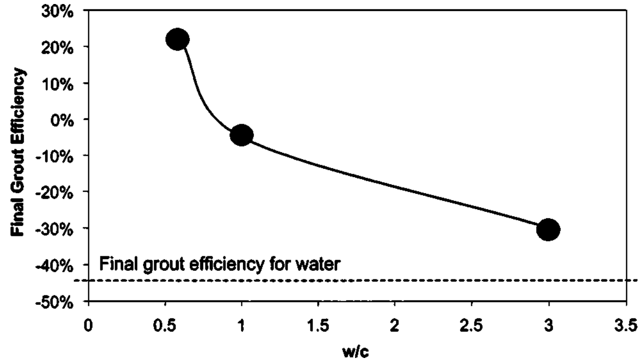

Fig. 10. Effect of water cement ratio on final grout efficiency for overconsolidation ratio=1

hand, Fig. 11(b) shows that the grout injection in the OCR=5 specimen formed a horizontal fracture. When low solid content cement bentonite grout $(w/c=3)$ was injected in an OCR=1 specimen, a thin horizontal fracture was formed across the sample as shown in Fig. 11(c). This suggests that the fracture initiation and propagation were also influenced by grout bleeding. When a grout material contains a higher solid content, filter cake is

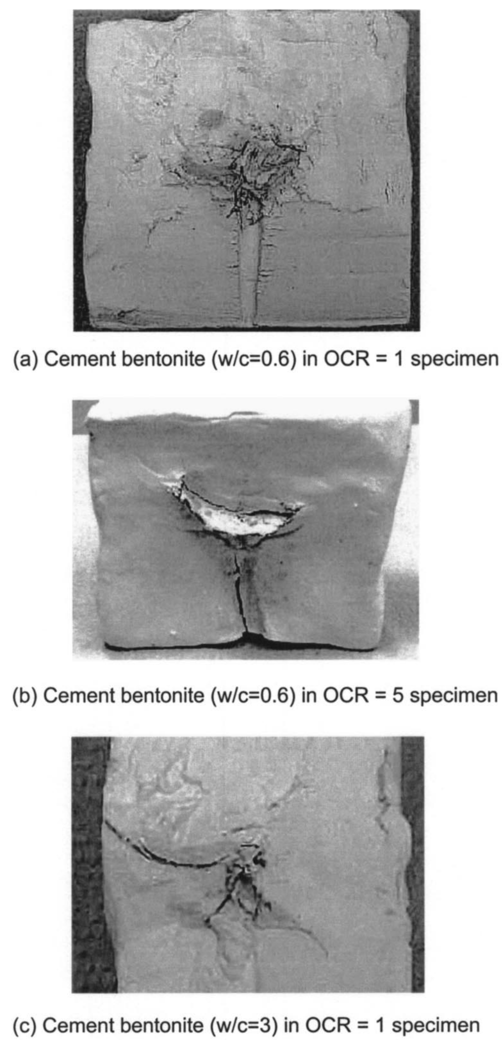

Fig. 11. Behavior of cement bentonite grout in overconsolidation ratio=1 and 5 specimens

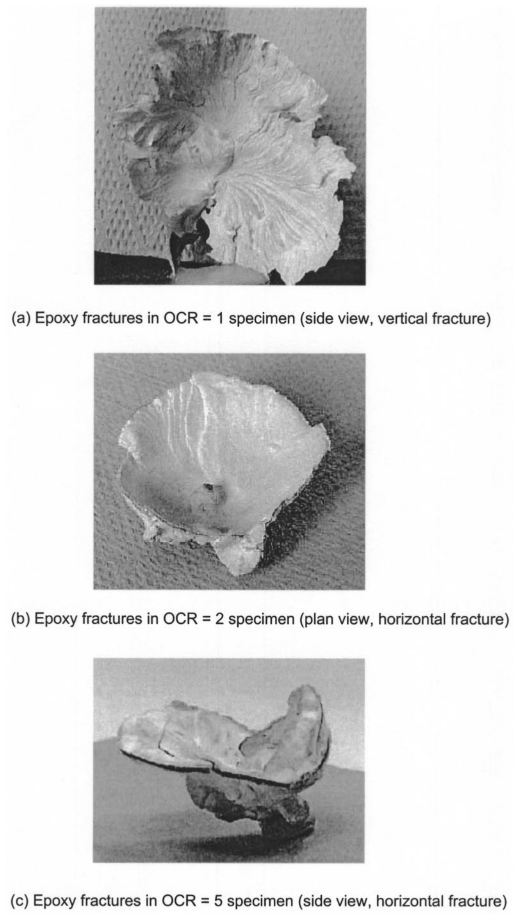

Fig. 12. Fracture patterns of epoxy injection in overconsolidation ratios=1, 2, and 5 specimens

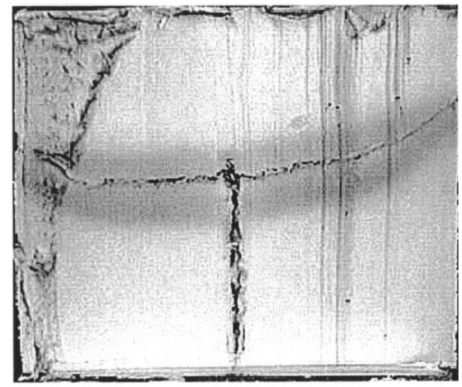

Fig. 13. Horizontal fractures by Laponite grout. Dyed Laponite grout penetrated from the fractures into the soil.

formed rapidly around the cavity during the injection stage to block the minute cracks which developed around the injection cavity. Since the penetration of grout into fractures is less likely to occur by this blockage, further grout injection leads to shear failure around the injection cavity, similar to the balloon expansion tests.

When epoxy resin was injected into OCR=1 specimens, the fractures were thin and widespread, propagating to form a vertical fracture as shown in Fig. 12(a). Excess pore pressures were generated in a larger area, which resulted in a large decrease in grout efficiency with time. On the other hand, horizontal fractures were formed when epoxy was injected in overconsolidated clay specimens as shown in Figs. 12(b and c) for the OCR=2 and 5 specimens, respectively.

Laponite–water mixtures also resulted in low grout efficiency for normally consolidated clay specimens due both to bleeding and the solid penetration effect. The fracture generated in the OCR=1 specimen is shown in Fig. 13. The zone around the fracture was red indicating that bleeding and penetration of the grout occurred from the fracture. The injected water extensively sheared the OCR=1 specimens, creating a large zone of excess pore pressures. The large decrease in grout efficiency is due to the drainage of the injected water and the dissipation of the excess pore pressures. The post-test examination showed that the fractures propagated in different directions.

Effect of Boundary Condition

The interaction of a single-grout injection and the outer rigid boundary of the modified consolidometer is analogous to the injection of grout simultaneously at multiple points in a closely spaced grid, as shown in Fig. 14. The effect of the radial boundary condition was examined by injecting 5 ml of grout into modified consolidometers with different diameters (50 mm versus 100 mm). Fig. 15 shows that, for a given volume of grout, the reduction in the radial boundary size (i.e., grout spacing) was able to improve the final grout efficiency significantly when the OCR of the clay was between 1 and 2.

Finite-element simulations of balloon expansion tests were performed at two different radial size boundaries and Fig. 16 shows the comparison of final grout efficiencies calculated by finite element to those obtained in the experiments. Since the initial grout efficiency loss due to compression of tiny air bubbles does not occur in the finite-element analysis, the final grout efficiencies calculated by the finite-element analysis were consistently higher that the experimental data by about 10 to 20%.

Fig. 17 shows the computed excess pore pressures distributions along the horizontal line from the injection boundary for the 50 mm diameter and 100 mm diameter cases. The result indicates that a close radial boundary can limit the magnitude and extent of excess pore pressures zone effectively in normally consolidated or

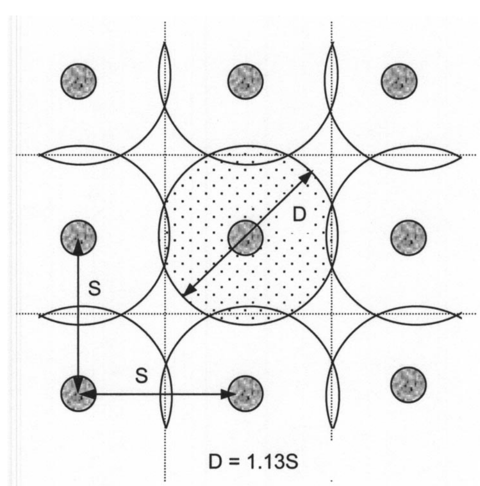

Fig. 14. Single injection with radial boundary condition

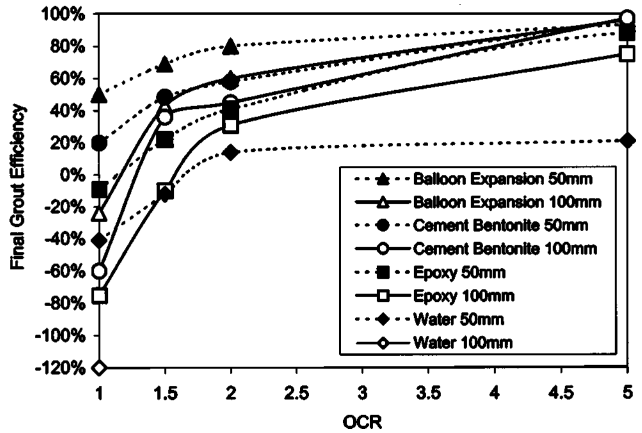

Fig. 15. Effect of radial boundary size on final grout efficiency

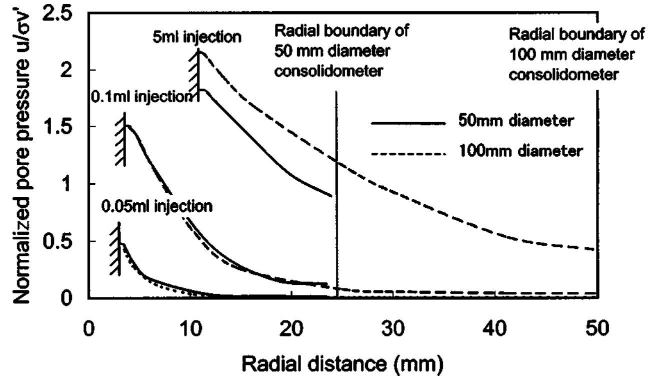

Fig. 17. Effect of radial boundary on excess pore pressure distribution

lightly overconsolidated clays which, in turn, increases the final grout efficiency. As a separate study, experiments to investigate the boundary effect as well as multiple grouting effect were performed and the discussion on these test results can be found in Au (2001).

Effect of Regrouting

It is common practice in compensation grouting to use a tube-a-manchette, which allows grout to be injected many times from the same port. If a given volume of grout is injected over a fixed area, it is possible to either regrout many times at the same point with small injection volumes, or conversely, perform a smaller number of regrouting processes but with larger injection volumes. Three tests were undertaken in normally consolidated clay specimens to investigate the effect of a waiting period on long-term grout efficiency after the regrouting process. In the experiment, an injection of 5 ml for each injection was made four times for the regrouting injection tests. The duration between each injection was varied ($T_s = 2$ min or 120 min). The test results were compared to the result of a single-injection test, which was carried out by injecting 20 ml at once. The rate of injection was fixed at 500 mm^3/s.

Fig. 18 shows that the single injection with large injection volume resulted in the best final grout efficiency. When regrouting was made, the behavior of the first injection was similar to the comparative part of the original injection. During the waiting period, consolidation occurred and more excess pore pressure was generated in the subsequent injections due to the previous consolidation effect. Therefore, the regrouting process resulted in smaller grout efficiency than for the single injection.

Conclusions

Laboratory grout injection tests were carried out to examine the effect of consolidation and grout properties on long-term grouting efficiency. The test results showed that the grout efficiency dramatically reduced with time for normally consolidated or lightly overconsolidated clays 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. For heavily overconsolidated clays, on the other hand, 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 effect of bleeding and solid penetration on long-term consolidation was examined by injecting different types of grouts.

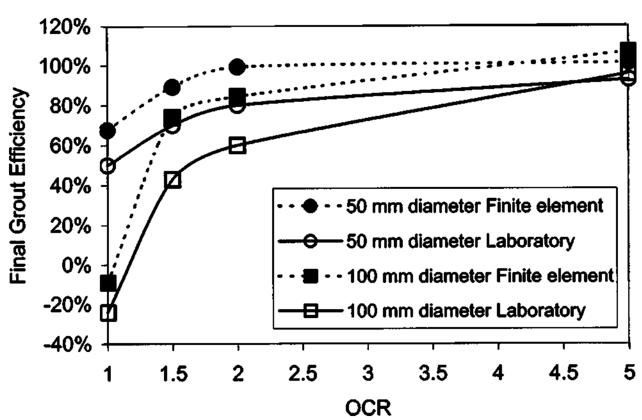

Fig. 16. Comparison of final grout efficiency computed by finite-element to that from the experiments

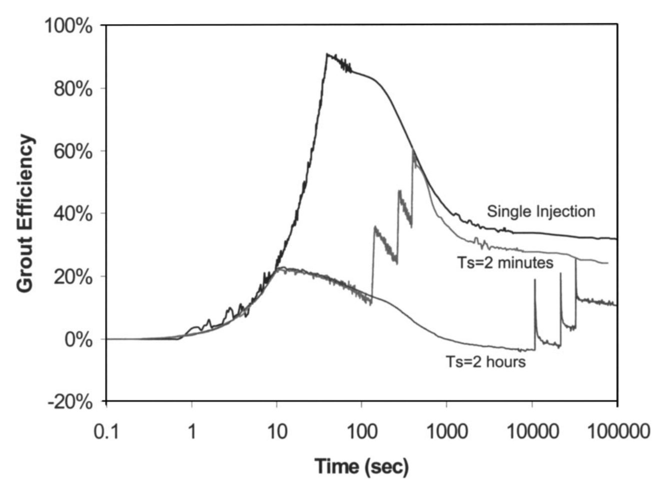

Fig. 18. Effect of waiting period (T_s) on grout efficiency

Water injection gave the lowest grout efficiency due to the drainage of the injected water as well as extensive positive pore pressures generated during the injection stage. The ideal compaction grouting tests (balloon expansion tests) resulted in the highest grout efficiency because of no bleeding/solid penetration effect. Hydrofracture grouting resulted in grout efficiency less than the balloon expansion tests due to the extensive shearing of the soil occurring around the fractures and various degrees of bleeding and solid penetration depending on the grout properties.

The effect of partial consolidation during the injection stage was examined by performing regrouting tests. The test results show that regrouting is not as effective as injecting the whole volume of grout in one effort due to extra consolidation effects. The grout efficiency increased when a smaller diameter consolidometer was used. This is because the outer radial boundary suppressed the magnitude and extent of excess pore pressure generation in the soil. This result suggests that grout efficiency can be improved if the spacing between injection ports were closer.

Although the tests identified some factors that affect the long-term efficiency of compensation grouting, the interpretation of the test data is limited by the scale of the laboratory tests. Further field trials are needed to examine the applicability of the findings to field scale conditions.

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