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Laboratory investigation of multiple grout injections into clay

K. SOGA*, S. K. A. AU†, M. R. JAFARI‡ and M. D. BOLTON§

Compensation grouting is a multiple injection process in which large numbers of grout injections are carried out in a designated grouting zone. Each injection alters the in-situ stress state at the site of neighbouring injections, influencing the grout behaviour as well as the deformation of the surrounding soil. In this study, multiple grout injection tests were performed in the laboratory on clay specimens prepared at different overconsolidation ratios ranging from 1 to 10. Two types of grouting mode for compensation grouting were examined: (a) facture grouting by injecting epoxy resin, and (b) compaction grouting by expanding a latex balloon placed inside the soil specimen. The sequence of multiple injections was also varied by injecting either simultaneously or sequentially with different waiting periods. For highly overconsolidated clay the grout efficiency, defined as the ratio of the volume of heave achieved to the injected grout volume, was close to 1 irrespective of grout spacing and injection sequence. For normally consolidated and lightly overconsolidated clays the grout efficiency increased when the separation in space and time between the injections was reduced. A better grout efficiency was obtained in compaction grouting than in fracture grouting. The results from finite element analyses of the laboratory tests show that the magnitude and extent of excess pore pressure reduce when many closely spaced simultaneous injections are performed. A few non-simultaneous injections create large stress concentrations around the injection points, leading to larger soil consolidation.

KEYWORDS: grouting; tunnels; settlement; clays; consolidation

La cimentation de compensation est un processus à injections multiples dans lequel de grands nombres d'injections de ciment sont effectués dans une zone de cimentation désignée. Chaque injection change l'état de contrainte in-situ à l'endroit des injections voisines, influençant le comportement du ciment ainsi que la déformation du sol aux alentours. Dans cette étude, des tests d'injections multiples ont été réalisés en laboratoire sur des spécimens d'argile préparés à divers taux de surconsolidation, allant de 1 à 10. Nous avons examiné deux types de modes de cimentation pour la cimentation de compensation : (a) une cimentation de fracture en injectant de la résine époxyde et (b) une cimentation de compaction en gonflant un ballon de latex placé à l'intérieur du spécimen de sol. La séquence des injections multiples a également été variée en faisant les injections soit simultanément, soit les unes à la suite des autres, avec diverses périodes d'attente. Pour l'argile très surconsolidée, l'efficacité de la cimentation, définie comme le rapport entre le volume de rejet obtenu et le volume de ciment injecté, était proche de 1, quels que soient l'espacement du ciment et la séquence d'injection. Pour des argiles normalement surconsolidées et des argiles légèrement surconsolidées, l'efficacité de la cimentation augmente lorsque la séparation dans l'espace et dans le temps entre les injections est réduite. On obtient une meilleure efficacité avec la cimentation de compaction qu'avec la cimentation de fracture. Les résultats des analyses d'éléments finis des essais de laboratoire montrent que la magnitude et l'étendue de la pression interstitielle excessive baissent lorsque l'on effectue beaucoup d'injections simultanées très rapprochées dans l'espace. Quelques injections non simultanées créent de grandes concentrations de contrainte autour des points d'injection, ce qui donne une consolidation du sol plus grande.

INTRODUCTION

Compensation grouting is a technique to offset subsidence caused during underground excavation and 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 & Hight, 1994). A common configuration of the compensation grouting operation is a fan array of grouting holes radiating horizontally from a vertical shaft as shown in Fig. 1. Grout injection is usually undertaken contemporaneously with tunnelling in response to detailed monitoring, so that settlements and distortions are limited to specified amounts.

A common form of compensation grouting involves injection of low-viscosity particulate grouts into the soil, creating hydrofractures (termed *fracture grouting*). The grout intrudes into the fractures, and the introduction of solids enables a compensation effect to be achieved in a limited number of fractures. Grout injection is commonly achieved through the use of a sleeved tube known as a *tube à manchette* (TAM). A TAM is a plastic or steel tube with pairs of holes drilled at intervals of 0·3–1·0 m along the length of the tube, each pair being covered by a tight rubber sleeve. These ports act as one-way valves. The TAMs allow re-injection of grout from the same port; appropriate amounts of grout are injected at the right place and time. Successful applications of fracture grouting for compensation grouting are reported for the Viennese subway project (Pototschnik, 1992), the Saint Clair River tunnel project near the USA–Canada border (Kramer *et al.*, 1994; Drooff *et al.*, 1995), the Jubilee Line Extension project in London (Linney & Essler, 1994; Harris *et al.*, 1996, 1999; Osborne *et al.*, 1997), the Dockland Extension Project in London (Sugiyama *et al.*, 1999) and the Lisbon underground line (Schweiger & Falk, 1998).

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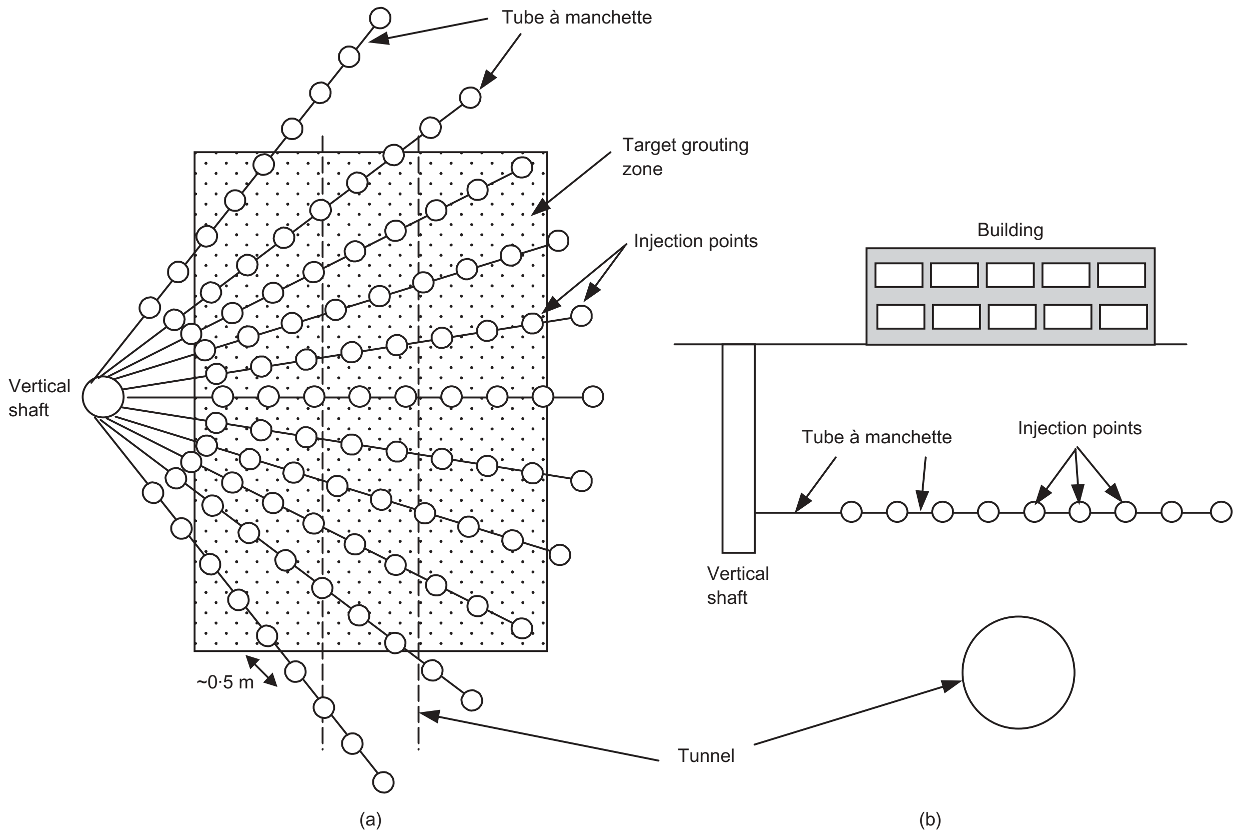

Fig. 1. Conceptual diagram of fan array grouting points for compensation grouting: (a) plan; (b) section

However, the high mobility and low viscosity of the grout can cause difficulties in controlling grout locality. The major limitations are the uncertainty in the orientation of fractures, the lack of control over the extent and frequency of fractures, and difficulty in predicting the amount and thickness of grout within the fractures. Hence fracture grouting may become unacceptable for compensation grouting when grout needs to be injected close to an excavation.

Compaction grouting avoids hydrofracturing by using grouts with high solid content, and has been used successfully as a method of compensation grouting in tunnel construction of the Northwest Line of the Baltimore Region Rapid Transit System (Zeigler & Wirth, 1982; Graf, 1992), the Washington Light Rail Transit tunnel in Seattle (Critchfield & MacDonald, 1999) and the Tunnel and Reservoir Plan (TARP) system in Evanston, Illinois (Scherer & Gay, 2000). Compaction grouting displaces and compacts soil without permeation (Warner, 1992; Graf, 1992), and the uplift displacement contributes to the compensation effect of ground settlement associated with underground excavation. The major disadvantage of compaction grouting for settlement control is that regrouting at the same point of injection becomes difficult as the set grout is effectively unbreakable, preventing any immediate action should further settlement occur. High injection pressure is needed to overcome the large tube friction between the grout tube and the highly viscous grout. 'Squeezing' may then occur, where water is prematurely forced out of the grout during high-pressure injection (Essler *et al.*, 2000), causing the tube to plug.

GROUT EFFICIENCY AND COMPENSATION EFFICIENCY

In this paper, both fracture grouting and compaction grouting are examined as methods for compensation grouting. The effectiveness of compensation grouting can be evaluated by the amount of soil heave (or of volume compensated) for a given injected grout volume. Ideally, if injections are made quickly in clayey soil so that soil deformation occurs in undrained conditions, the amount of heave will be equal to the volume of injected grout. Assuming a volume element local to grout injection points, as shown in Fig. 2, the grout efficiency, η, can be defined as the ratio of the increase in soil volume of the element, V_E, to the injected volume of grout, V_{inj} (Soga *et al.*, 1999).¶

$$\eta = \frac{V_E}{V_{inj}} \tag{1}$$

If η is equal to 1 then, by definition, the grouting should be considered as perfect. This does not occur in practice. The expansion volume, V_E, is generally smaller than the injected volume, V_{inj} ($\eta < 1$), owing 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 tends to decrease with time. Excess water trapped in a slurried grout will tend to bleed into the ground as the grout itself shrinks. This potential source of inefficiency can be prevented either by using sufficiently low water contents or by suppressing the rate of bleeding during the setting period through the use of polymer additives. Furthermore, if the surrounding soils are susceptible to swelling, the bleed water can be retained and this source of grouting inefficiency is largely eliminated. However, long-term grout inefficiency still applies when any clay soils surrounding the grout consolidate, owing to the dissipation of positive excess pore pressures generated during injection. Hence η is both grout dependent

¶The injected volume is the sum of the volumes of solids, fluids and additives in this case. Different definitions of grout efficiency are available in practice: for example, the ratio of heaved volume to the solids volume of the grout.

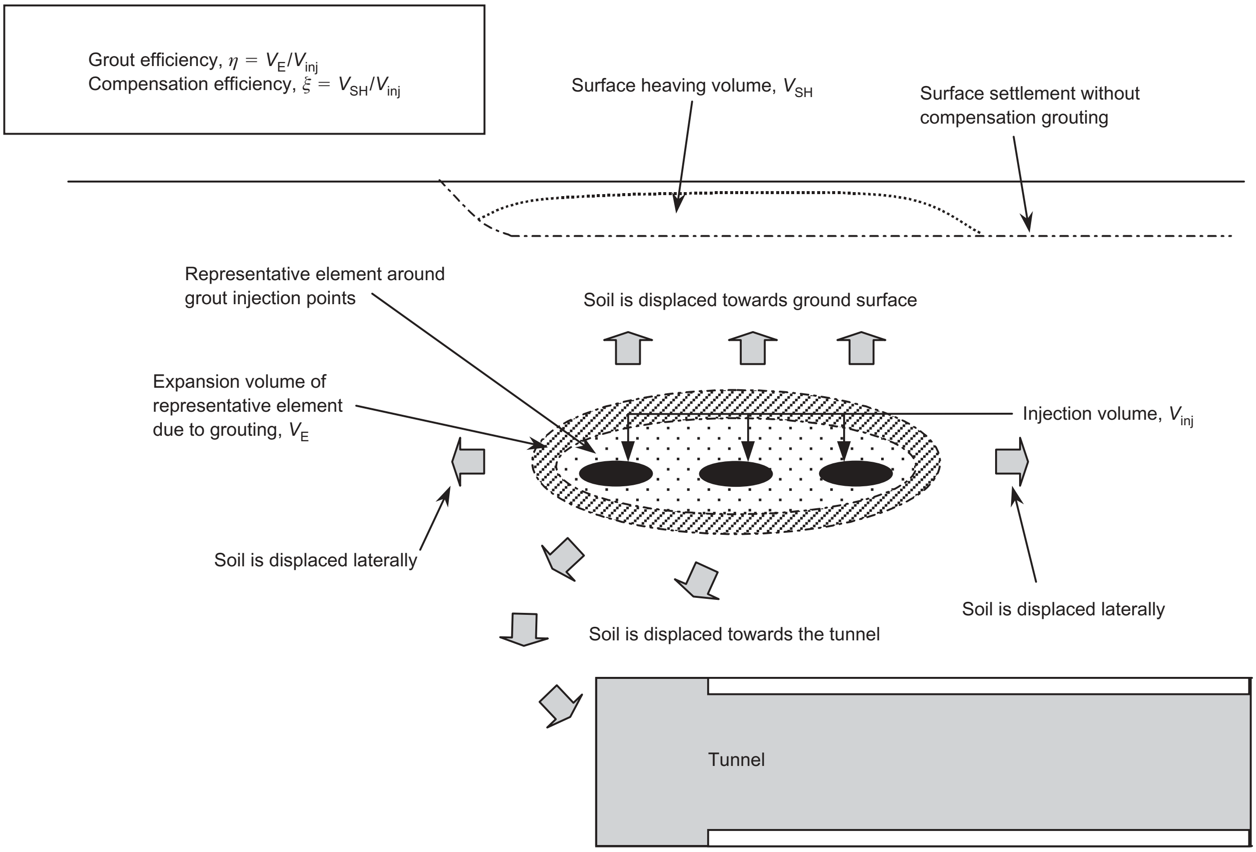

Fig. 2. Soil displacements by compensation grouting

and soil dependent. This paper will focus on the problem of soil consolidation, which will always be an influence, even when grout bleed has been eliminated.

In addition to the efficiency loss at the local level, the efficiency of compensation grouting (ξ in Fig. 2) may be further reduced by far-field 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 Fig. 2. The assessment of this type of loss is a boundary value problem, which can be investigated by numerical analysis coupled with the use of an appropriate value of η at the point of injection (e.g. Buchet *et al.*, 1999; Komiya *et al.*, 2001). In all cases of grouting in clays, therefore, it is essential to know what value of η to assume to account for soil consolidation effects local to a grout injection.

MULTIPLE GROUT INJECTION FOR COMPENSATION GROUTING

The effectiveness of compensation grouting is a function of ground conditions, grout rheology and injection methods. Although Au *et al.* (2003) showed that fracture initiation/propagation and grout efficiency, η, are largely influenced by grout rheology (e.g. viscosities, solid contents, hardening time, bleeding characteristics), this study examines the significance of ground conditions (OCRs) and injection method (spacing and timing) on the soil consolidation effect associated with dissipation of excess pore pressures generated during injection.

In compensation grouting large numbers of grout injections are carried out within a designated grouting zone, as shown in Fig. 1. During each injection, soil around the injection port fractures and/or deforms plastically while excess pore pressures develop. It is a conjecture of this study that, as the injection volume increases, the movement of the soil starts to be affected by the spacing of nearby injections, and that the pattern and magnitude of excess pore pressure generation will correspondingly be different from that of a single injection of the equivalent volume. This study therefore aims to investigate whether or not the spacing between the injection ports and the sequence of injections influence the grout efficiency. As most of the previous laboratory tests are reported for a single injection (e.g. Jaworski *et al.*, 1981; Mori & Tamura, 1987; Panah & Yanagisawa, 1989; Lo & Kaniaru, 1990; Mori *et al.*, 1990; Lefebvre *et al.*, 1991; Mhach, 1991; Andersen *et al.*, 1994; Yanagisawa & Ali, 1994), a series of multiple injection tests as well as single injection tests were performed in the laboratory.

TESTING APPARATUS AND METHODS

A schematic diagram of the experimental set-up is shown in Figs 3 and 4. The investigation can be categorised into two types of test: (a) grout injection tests using a consolidometer with four injection points (*multiple injection test*; see Fig. 3(c)); and (b) grout injection tests using different diameter consolidometers (50 or 100 mm diameter) with a single injection point (*single injection test*; see Fig. 3(b)). As shown in Fig. 5, the interaction of the single injection and the outer rigid boundary is analogous to injecting grout simultaneously in a closely spaced grid, which will be discussed later on.

Two types of injection mode were performed: (a) injection of liquid into a latex balloon attached 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 was to reveal the fracture patterns in the hardened resin after the tests through hardened epoxy. A

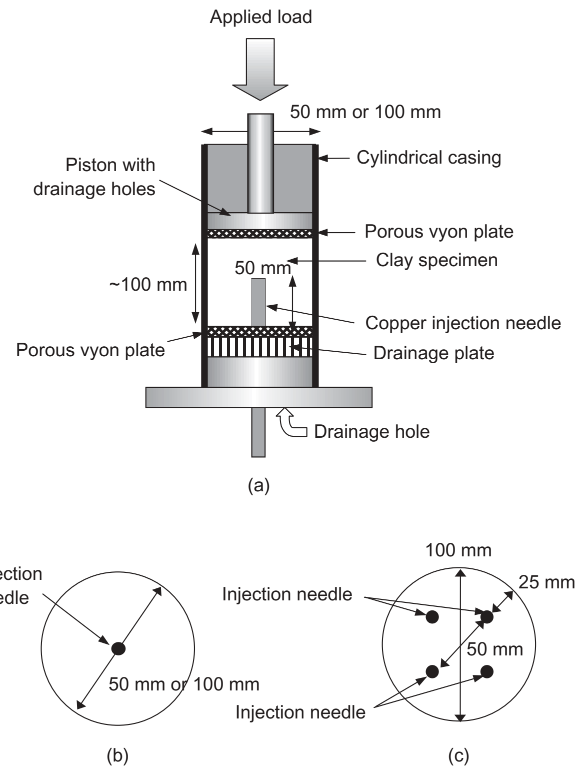

Fig. 3. Modified consolidometer for grout injection test (not to scale): (a) side view; (b) plan view (single injection); (c) plan view (multiple injection)

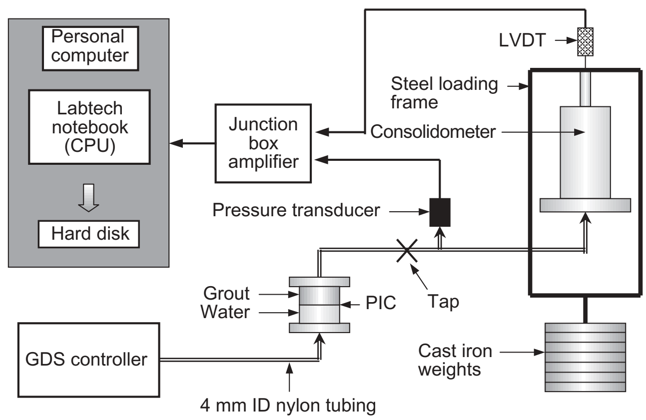

Fig. 4. Grout injection experimental layout: PIC, pressure interface chamber; CPU, central processing unit; LVDT, linear variable differential transducer

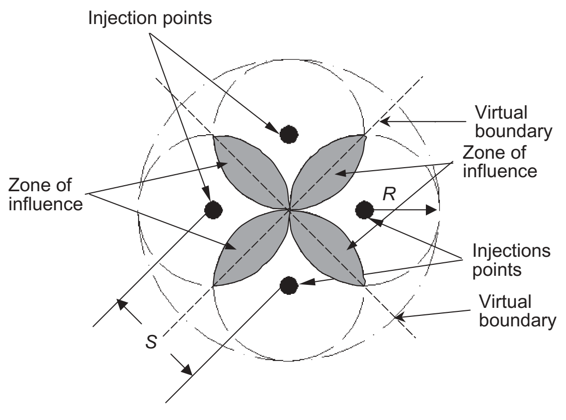

Fig. 5. Interaction of grout injections in multiple injection tests

ratio of 10 : 6 of resin and hardener by weight was used to obtain the highest strength of epoxy resin. Au *et al.* (2003) showed in their single injection testing that the fracture patterns produced by epoxy resin injection were similar to those of cement–bentonite mixtures of a high water/cement ratio ($w/c = 3$).

A 4 mm OD and 3 mm 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. 3). The specimen height was approximately 100 mm, and hence the injection was made at the mid-height of the specimen. In order to prevent grout from leaking down the sides of the injection during epoxy injection, a copper tube 40 mm long and 4·5 mm internal diameter was used as a retaining collar around the injection tube.

Injections were made using a pressure/volume controller, which can control the injection rate and volume. The injection rate of 3×10^{-5} m^3/min was selected for the experiment so that the injection stage could be kept close to undrained conditions. When epoxy resin was injected, a pressure interface chamber (PIC) was used to transmit the pressure from the hydraulic fluid in the pressure/volume controller to the grout during injection, as shown in Fig. 4. Injection pressures were measured using a pressure transducer positioned between the PIC and the injection needle. Various pressure corrections for both balloon expansion and fracture grouting tests were based on calibrations. The surface displacement of the specimen was measured using a linear variable differential transducer (LVDT).

Injection volumes (5–20 ml) were selected to ensure that the grout would be contained within the specimen and would not migrate through fractures reaching the test boundaries. The preliminary experiments showed that, when grout escaped from test boundaries through fractures, an artificial reduction in grouting efficiency was measured. As the injection volumes were small, there was the possibility of errors in the test data due to compression of tiny air bubbles trapped in the system. Great care was therefore taken to remove these air bubbles as much as possible.

The grouts were injected into specimens of E-grade kaolin (LL = 72, PL = 38). For sample preparation, clay slurry was prepared by mechanically mixing dry E-grade kaolin powder with de-aired water under vacuum, giving a water content of 120%. The slurry was placed in a consolidometer, and different consolidation pressures (140–1400 kPa) were applied to the specimens. After initial consolidation, the vertical effective stress was brought to 140 kPa and, before injection, the specimens had different overconsolidation ratios ranging from 1 to 10. During the consolidation of the slurry it was necessary to prevent leakage of the slurry from the consolidometer through the injection needle. A 2·8 mm diameter steel rod with a 0·3 mm thick latex coating was placed into the needle during the consolidation stage and was taken away before the injection stage. Further experimental details can be found in Au (2001).

MULTIPLE INJECTIONS VERSUS SINGLE INJECTION

If a given volume of grout is injected over a fixed area for compensation purposes, it is possible either to use many injection points with small injection volumes or, conversely, fewer injection points with larger injection volumes. In order to examine whether grouting efficiency can be improved by changing the distance between the injection points, single and multiple injection tests were performed on OCR = 1 and 1·5 specimens. For the multiple injection tests four injection needles were placed in a square grid in the 100 mm diameter consolidometer, as shown in Fig. 3(c). 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, as shown in Fig. 3(b). Compaction grouting was simulated by injecting water into the latex balloons attached to the injection needles. The single injection tests were carried out by injecting 20 ml of water at one injection point, whereas the multiple injection tests were carried out by injecting 5 ml of water for each needle, giving a total injection volume of 20 ml.

The curves of measured grout efficiency against time are shown in Fig. 6. The initial efficiency losses were about 7–9% in both types of test. These initial losses are primarily due to (a) partial consolidation near the injection point, where the hydraulic gradient is very large, and (b) compression of small air bubbles trapped inside the water and connections, even though care was taken to remove any air bubbles during the set-up. For a given OCR, the final grout efficiency of a single large injection was somewhat less than that of multiple simultaneous injections, as shown in Fig. 6.

Figure 7 shows the measured normalised pressure–volume curves for OCR = 1 specimens in the single and multiple injection cases. At the beginning of the tests the initial injection pressures were about the same, and the two curves almost coincided. However, the peak pressure for single injection was slightly higher than that for multiple injection, indicating that the excess pore pressures would be smaller for multiple injection.

In summary, the test data demonstrated that, for a given total injection volume, an improved grout efficiency can be obtained by injecting small amounts of grout from multiple locations rather than by injecting the whole volume from a single location. In order to find the relationships between grout spacing and grout efficiency, further laboratory injection tests were performed for both compaction and fracture grouting modes, as described in the following sections.

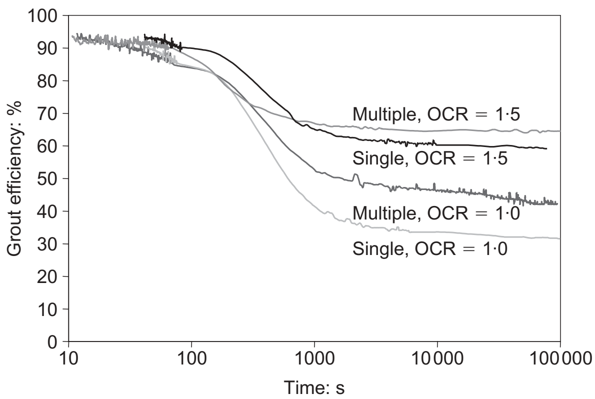

Fig. 6. Grout efficiency of single and multiple simultaneous balloon expansion tests

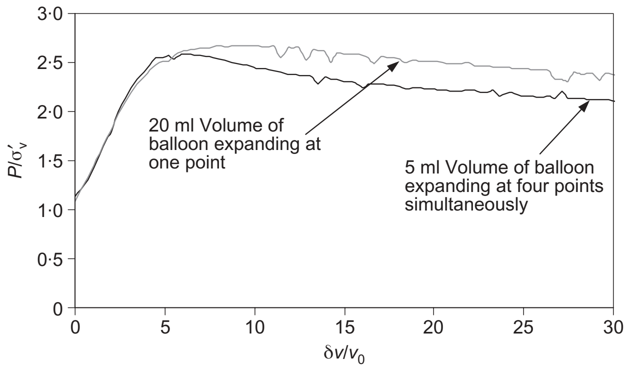

Fig. 7. Pressure–volume curves of single and multiple simultaneous balloon expansion tests on specimens with OCR = 1

EQUIVALENT SINGLE INJECTION HYPOTHESIS FOR MULTIPLE SIMULTANEOUS INJECTION

Proposed hypothesis

When grouting is performed in a regular (arranged in a specific array, e.g. triangular or rectangular) and symmetrical (same volume of injection in each port) condition, the behaviour of any one grouting unit should be identical to the others. If this hypothesis is correct, a simultaneous multiple injection can be simulated by a single injection confined within an equivalent radial fixed boundary, as shown in Fig. 8.

In order to validate the proposed hypothesis, injections were made simultaneously from four needles placed on the 100 mm diameter consolidometer, and the amount of injection for each needle was 5 ml. The test result was then compared with that of the equivalent single 5 ml injection in a 50 mm diameter consolidometer. Both balloon expansion test and epoxy injection test were conducted.

Compaction grouting mode

The final grout efficiencies of the multiple simultaneous balloon expansion tests are compared with those of the equivalent single balloon expansion tests in Fig. 9. The behaviour of the multiple simultaneous injection tests was quite similar to the results of the single injection tests, validating the proposed symmetry hypothesis. The final grout efficiency increased dramatically when the OCR increased from 1 to 2, and reached almost 100% for the heavily overconsolidated clay of OCR = 5.

Fracture grouting mode

Simultaneous multiple injections of epoxy grout were conducted on OCR = 1 and 1·5 specimens, and the test results were compared with those of the equivalent single injection tests, as shown in Fig. 10. The consolidation behaviour was very similar for both single and multiple injections for OCR = 1. However, for OCR = 1·5, the amount of consolidation settlement for multiple injection was more than that for single injection. The epoxy injection resulted in lower grout efficiencies than the balloon expansion, possibly because of the larger volume of excess pore pressure generation created by the extended fractures.

When the proposed hypothesis is applied in the fracture grouting mode, the fracture initiations for all the injections are assumed to occur at the same time, and if fractures occur in the horizontal direction, they have to merge into one plane. The fracture patterns for the two multiple epoxy injection tests are shown in Fig. 11(a) and (b) for OCR = 1 and 1·5, respectively. It was found that most of the fractures for OCR = 1 were merging together. On the other hand a large fracture, which did not merge with the other fractures, was clearly visible for OCR = 1·5. These additional fractures may have created an extra amount of excess pore pressure in the soil during the injection process, resulting in smaller grout efficiency.

In summary, contrary to compaction grouting, the proposed symmetry hypothesis may not be so easily applicable for fracture grouting. However, it was considered that simple single injection tests with a confined radial boundary could still provide a useful upper limit of grout efficiency for the actual multiple injections of fracture grouting.

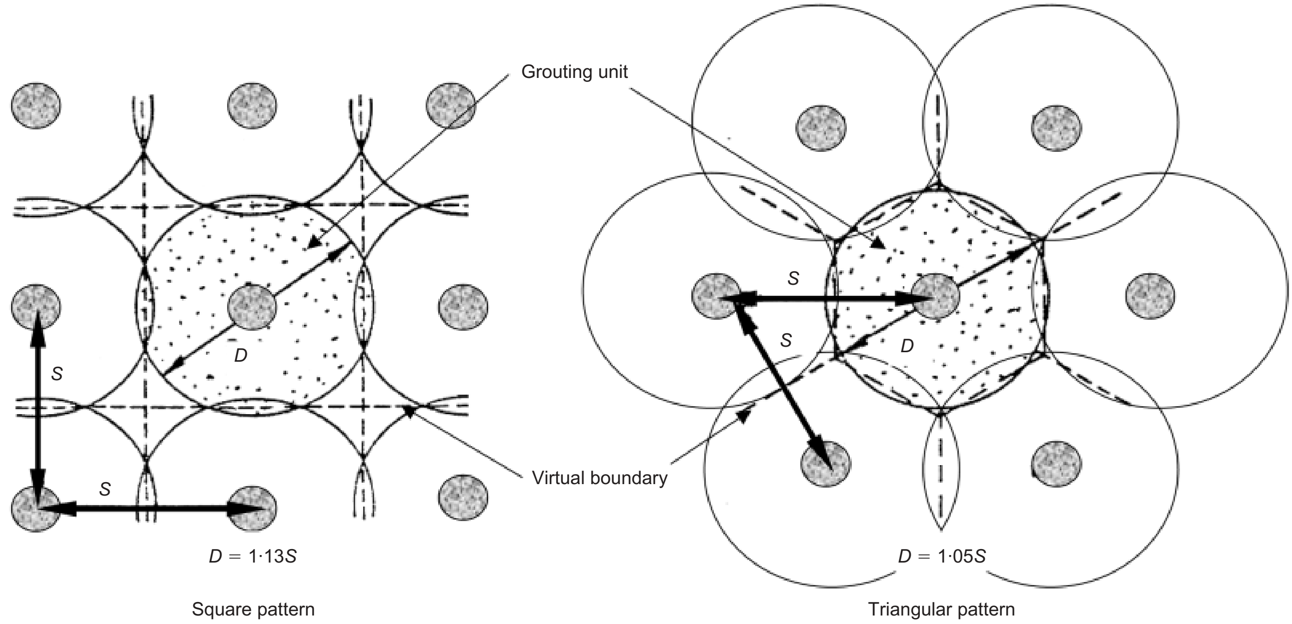

Fig. 8. Multiple simultaneous symmetrical injection hypothesis. $R_e = K_r S$, where R_e is equivalent radial boundary radius ($D = 2R_e$) and K_r is the injection array constant

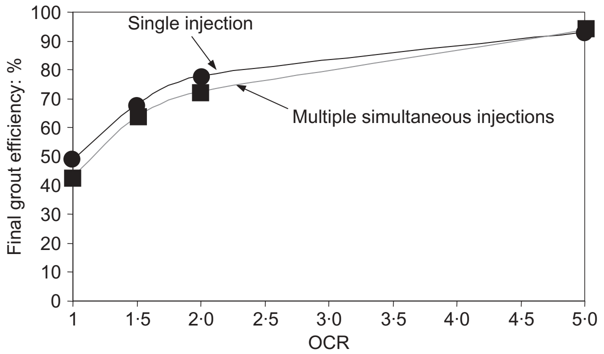

Fig. 9. Final grout efficiencies of single and multiple simultaneous balloon expansion tests

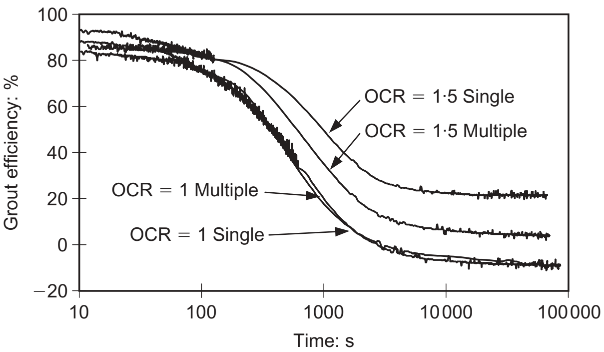

Fig. 10. Curves of grout efficiency against time for single and multiple injections for epoxy injection

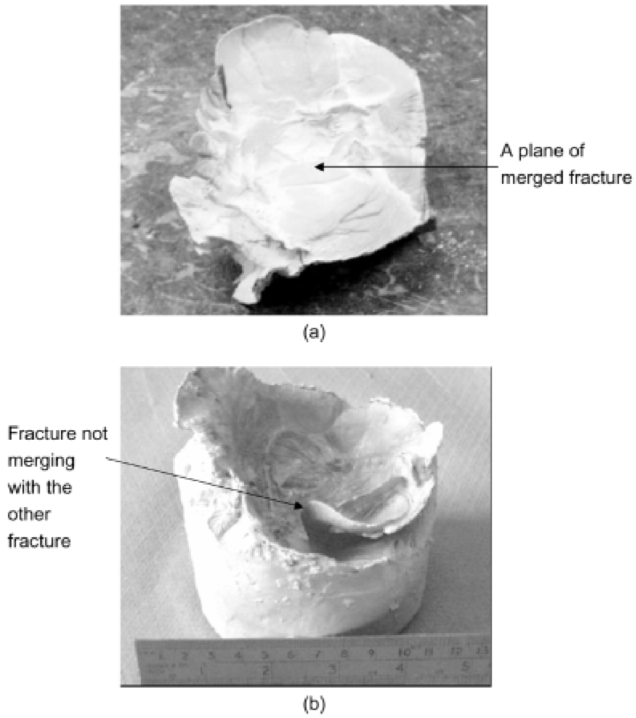

Fig. 11. Fracture patterns of multiple simultaneous epoxy injections: (a) OCR = 1; (b) OCR = 1·5

GROUT SPACING EFFECT ON GROUT EFFICIENCY

The foregoing results show that a single injection test with confined radial boundary can be used to simulate the behaviour of a simultaneous multiple grout injections. A smaller radial confinement implies closer injection spacing.

Effect of outer boundary distance

In order to demonstrate the effect of radial boundary distance (or grout spacing based in the proposed hypothesis) on grout efficiency, 5 ml of grout was injected into the 50 and 100-mm diameter consolidometers for both compaction and fracture grouting modes. Although the measured grout efficiencies were always low for normally consolidated clays, a better grout efficiency was obtained when the outer rigid boundary was close to the injection point, as shown in Fig. 12. The data consistently show that, for a given injection volume of grout, a reduction of the radial boundary size was able to improve the final grout efficiency significantly within the range of OCR = 1–2. However, the advantage of this reduction was not obvious for highly overconsolidated clays.

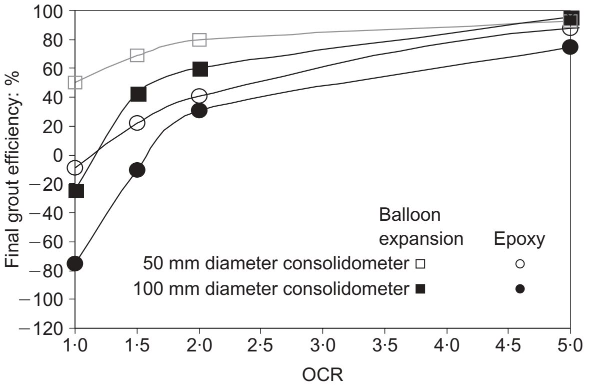

Fig. 12. Effect of radial boundary size, grout material and OCR on final grout efficiency

It appears that the interaction between the confined radial boundary and injected grout affected the magnitude and extent of excess pore pressures generated during the injection for normally consolidated clay or lightly overconsolidated clay. As a separate study, coupled consolidation finite element analyses were performed to simulate the balloon expansion tests (Au, 2001; Au *et al.*, 2003). Using the modified Cam-clay model, injections in normally consolidated clay specimens placed in two different sizes of consolidometer (50 and 100 mm in diameter) were simulated. Fig. 13 shows the computed excess pore pressures at different injection volumes along the horizontal line from the injection point. The result indicates that the closer radial boundary of 50 mm diameter can limit the magnitude and extent of the excess pore pressure zone, which results in a better grout efficiency after soil consolidation. On the other hand, a few non-simultaneous injections create large stress concentrations around the injection points, leading to larger soil consolidation.

As shown in Fig. 12, negative grout efficiencies were recorded for normally consolidated clay specimens. This implies that the overall soil volume after grout injection was smaller than before; a large soil consolidation occurred as a result of the injection process. Au *et al.* (2003) showed from their finite element study that the grout efficiency of normally consolidated and lightly overconsolidated clays can dramatically reduce with time, owing to (a) soil contraction by extensive shearing during the injection, and (b) soil compression by the ultimate increase in mean effective pressure around the injection point caused by the injection pressure locked in when the grout solidified. This in turn results in a negative grout efficiency for normally consolidated clays. Similar very low efficiencies have been reported in field trials of compensation grouting in soft clays (Shirlaw *et al.*, 1999; Komiya *et al.*, 2001).

For heavily overconsolidated clays, on the other hand, pore water migrates during the consolidation stage from the positive excess pore pressure zone around the injection point to the negative zone some distance away from the injection point. Soil compression near the injection point tends to cancel with swelling at some distance away from the injection point, resulting in a negligible overall consolidation effect for heavily overconsolidated clays.

Normalised effect of grout spacing

As demonstrated above, a better grout efficiency was obtained when the symmetry boundary affected the injection process. More interaction is expected when a larger volume is injected for a given spacing, or when injections are performed at closer spacing for a given injection volume. In order to normalise the radial boundary size and injection volume for possible field application, a dimensionless number n, which is the ratio of the radial boundary size to the equivalent grout radius, is introduced in this study;

$$n = \frac{R}{r_g} \tag{2}$$

where R is the size of the radial boundary, r_g, is the equivalent grout radius, calculated from

$$r_g = \left(\frac{3V_{inj}}{4\pi}\right)^{1/3} \tag{3}$$

and V_{inj} is the injected grout volume. R should be related to the arrangement of grouting points. For instance, utilising the commonly used theory for vertical drains, $R = 0{\cdot}565S$ for a square grid pattern and $R = 0{\cdot}527S$ for a triangular grid pattern, where S is the spacing between the nearest injection points, as shown in Fig. 8. When n is small, the spacing between the injections is close for a given injection volume and more interaction effect is expected. An injection in an infinitely extended soil space is at $n = \infty$.

In order to examine the effect of n on grout efficiency, η, different volumes of grout were injected in different-diameter consolidometers. The measured final grout efficiencies with different n values are plotted in Fig. 14. For normally consolidated clay or lightly overconsolidated clay specimens,

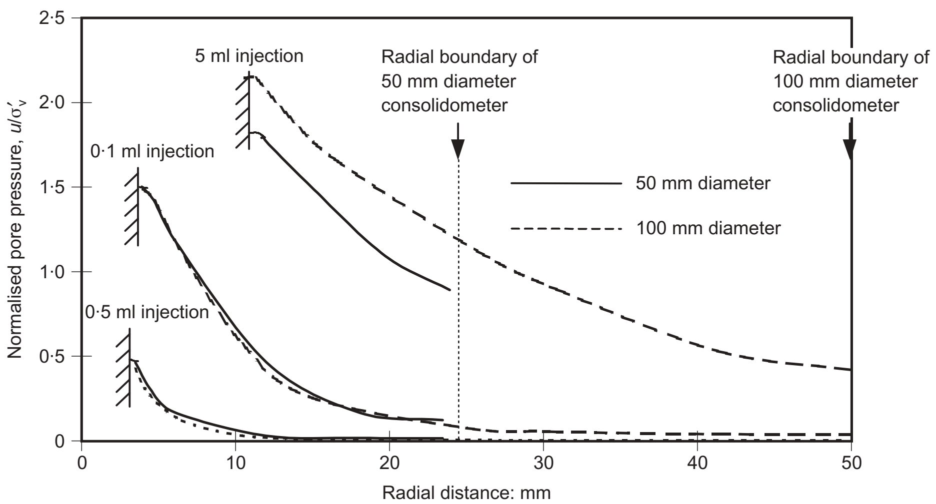

Fig. 13. Effect of radial boundary on excess pore pressure distribution (Au *et al.*, 2003)

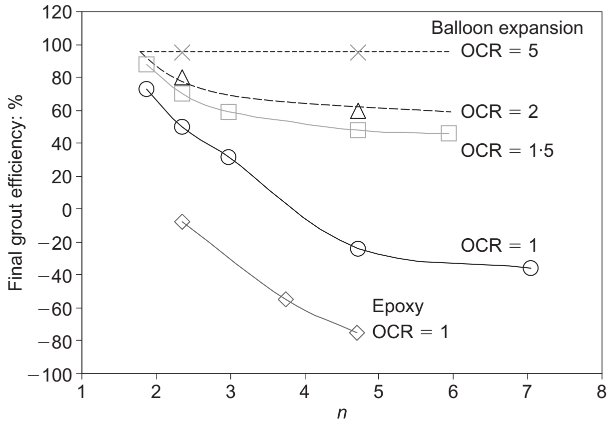

Fig. 14. Relative radial boundary effect on final grout efficiency

the final grout efficiency improved greatly by decreasing the n value (or decreasing the injection spacing) for both balloon expansion and epoxy injection tests. For overconsolidated clay specimens, the final grout efficiency was independent of n.

Finite element analysis of compaction grouting was performed at different values of n, and the computed final grout efficiencies are plotted against n in Fig. 15. The results of the numerical simulations are seen to be consistently higher than the experimental data by about 10%. This discrepancy is attributed to the initial loss of grout efficiency observed in the experiments: the numerical analysis showed 100% grout efficiency immediately after the injection. When the initial loss is taken into account, the experimental data are in good agreement with the simulations. The analyses showed that radial confinement suppressed the amount and extent of excess pore pressure generation for normally consolidated and lightly overconsolidated clays.

SIMULTANEOUS VERSUS SEQUENTIAL INJECTION

The simultaneous injection technique performed in the previous test series is not common in practice. Compensation grouting is currently done using sequential injections at multiple points. In order to investigate this current technique, 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 for 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.

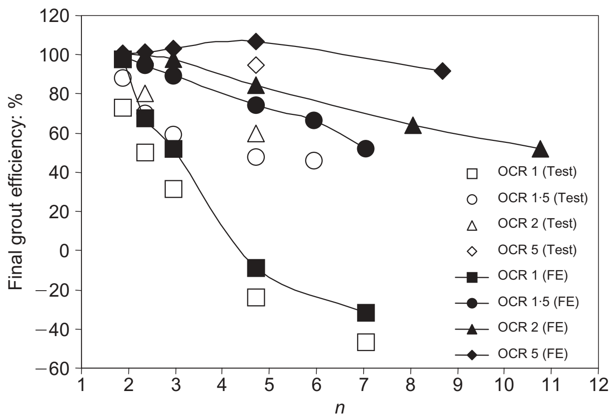

Fig. 15. Comparison of final grout efficiency between finite element results and laboratory test data

Compaction grouting mode

The measured grout efficiency against time from the balloon expansion tests on normally consolidated clay is shown in Fig. 16. 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 suppression of excessive pore water pressure was not as effective as that for the short waiting period test. For large waiting periods the final grout efficiency was similar to that with injection at large spacing (i.e. large n in Fig. 15). The result suggests that shorter waiting periods can improve grouting efficiency by taking advantage of nearby injections.

The measured pressures also showed the effect of neighbouring injections. The normalised pressure–volume curves of each balloon expansion when the waiting period (T_s) was equal to 20 s are shown in Fig. 17. The peak pressure decreased with subsequent injections: it dropped in the second and third injections and levelled off to a steady value after the third injection. As the waiting period prior to each injection was very short, only a small amount of excess pore pressure dissipated around the neighbouring injection points. As the zone of excess pore pressures was still extensive and the effective stresses were reduced, the peak injection pressure decreased in the following injections.

When a longer waiting period ($T_s = 54$ s) was employed, the opposite trend was observed, as shown in Fig. 17. For a given volume of injection, the pressure for the first injection

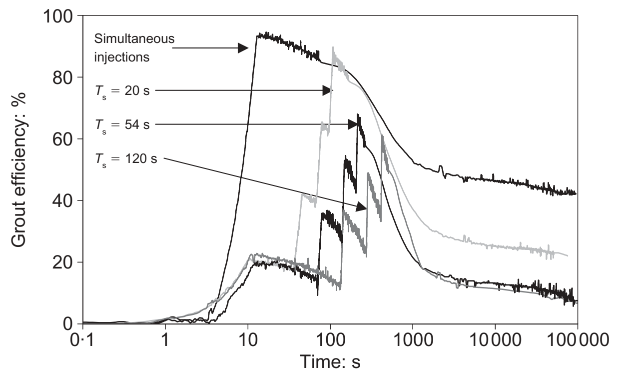

Fig. 16. Effect of waiting period, T_s, on grout efficiency (balloon expansion, OCR = 1)

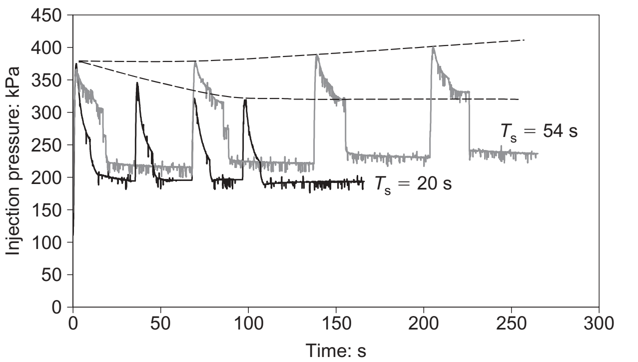

Fig. 17. Curves of pressure against time for multiple sequential balloon expansion tests

was slightly smaller than that of the others. As the waiting period (T_s) between each injection was long enough for a certain amount of excess pore pressure to dissipate, partial consolidation occurred and the peak injection pressure increased in the subsequent injection. Hence different degrees of consolidation created by different waiting periods resulted in a complicated pattern of injection pressures.

Fracture grouting mode

The grouting efficiency of the simultaneous epoxy grout injection test was also greater than that of the sequential injection test, as shown in Fig. 18. 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, as shown in Fig. 19. Therefore the area of influence for sequential injection may be larger than that for simultaneous injection, resulting in a larger zone of excess pore pressure and more consolidation effect.

Two sequential injection tests were performed on specimens with OCR = 5. The tests were compared with the simultaneous injection tests, and the curves of grout efficiency against time are shown in Fig. 20. 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.

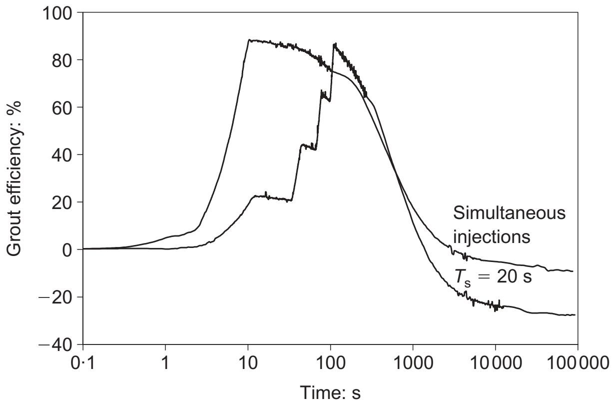

Fig. 18. Effect of waiting period, T_s, on grout efficiency (epoxy injection, OCR = 1)

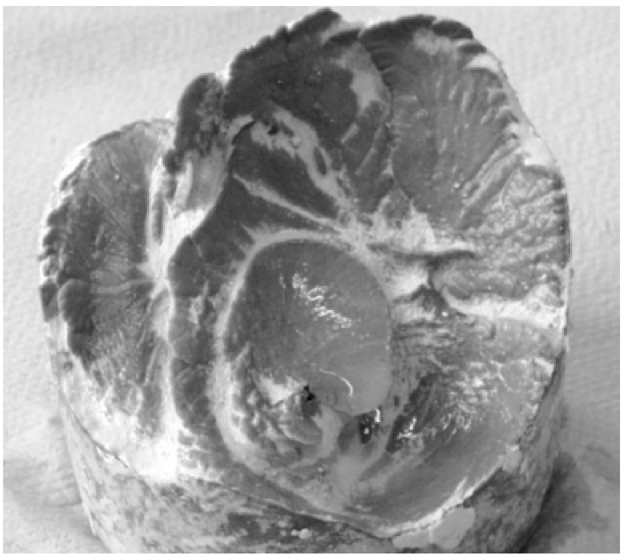

Fig. 19. Sequential injections by epoxy resins (T_s = 20 s)

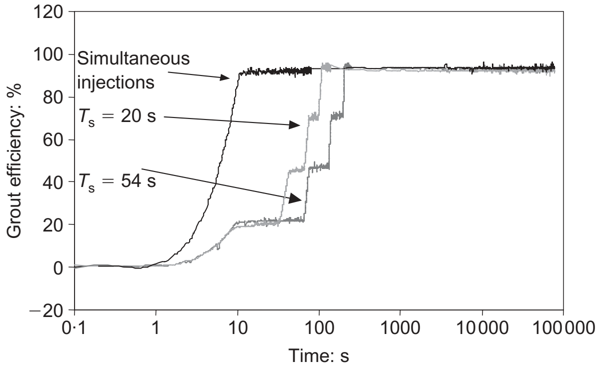

Fig. 20. Effect of waiting period, T_s, on grout efficiency (balloon expansion, OCR = 5)

CONCLUSIONS

The effect of injection spacing and timing on grout efficiency was examined by performing both multiple grout injection tests and single grout injection tests with confined radial boundary. Both balloon expansion tests (simulating compaction grouting) and epoxy injection tests (simulating fracture grouting) were performed on E-grade kaolin specimens with different OCRs. Although the epoxy injection resulted in lower grout efficiencies than the balloon expansion, owing to the larger volume of excess pore pressure generation created by the extended fractures, both grouting modes showed a similar trend with regard to injection spacing and timing effect. For a given injection volume of grout, a reduction of the radial boundary size was able to improve the final grout efficiency significantly for soils within the range of OCR = 1–2. However, the advantage of this reduction was not obvious for highly overconsolidated clays.

A finite element study confirmed that the grout efficiency of normally consolidated and lightly overconsolidated clays can reduce dramatically with time, owing to (a) soil contraction by extensive shearing during the injection, and (b) soil compression by the ultimate increase in mean effective pressure around the injection point caused by the injection pressure locked in when the grout solidified. However, when closely spaced injections occur simultaneously, the local severity of the excess pore pressures zone is much reduced, leading to a better grout efficiency in normally consolidated and lightly overconsolidated clays. On the other hand, a few non-simultaneous injections create large stress concentrations around the injection points, leading to larger soil consolidation.

For heavily overconsolidated clays, the 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. Soil compression near the injection point and swelling at some distance away from the injection point resulted in a negligible overall consolidation effect for heavily overconsolidated clays.

Grout efficiency decreases when injections are performed sequentially in normally consolidated clay. The final grout efficiency decreased with increase in the waiting period between the injections owing to the partial consolidation that occurred during the waiting period. This result suggests that shorter waiting periods can improve grout efficiency by taking advantage of nearby injections. For highly overconsolidated clays, the final grout efficiency was independent of the waiting period.

Although the tests identified some factors that affect the efficiency of compensation grouting, the interpretation of the test data is limited by the scale of the laboratory tests. It can also be argued that fissuring and layering observed in natural clays may affect the soil–grout behaviour, and different grout efficiencies can be expected in the field compared with the data for reconstituted clay specimens reported in this paper. Further field trials are needed to examine the applicability of the current findings to field conditions.

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REFERENCES

Andersen, K. H., Rawlings, C. G., Lunne, T. A. & Trond, H. (1994). Estimation of hydraulic fracture pressure in clay. *Can. Geotech. J.* **31**, 817–828.

Au, S. K. (2001). *Fundamental study of compensation grouting in clay.* PhD thesis, University of Cambridge.

Au, S. K. A., Soga, K., Jafari, M. R., Bolton, M. D. & Komiya, K. (2003). Factors affecting long-term efficiency of compensation grouting in clays. *J. Geotech. Geoenviron. Engng* **129**, No. 3, 254–262.

Baker, W. H., Cording, E. J. & MacPherson, H. H. (1983). Compensation grouting to control ground movements during tunnelling. *Underground Space* **7**, 205–212.

Buchet, G., Soga, K., Gui, M. W., Bolton, M. D. & Hamelin, J. P. (1999). COSMUS: new methods for compensation grouting. *Proceedings of the AFTES international conference on underground works: ambitions and realities*, *Paris* pp. 131–137

Critchfield, J. W. & MacDonald, J. R. (1999). Seattle Bus Tunnel construction. *Proc. Rapid Excavation and Tunneling Conf.,* 1999.

Drooff, E. R., Travares, P. D. & Forbes, J. (1995). Soil fracture grouting to remediate settlement due to soft ground tunnelling. *Proc. Rapid Excavation and Tunnelling Conf 1995.*, 21–40.

Essler, R. D., Drooff, E. R., & Falk, E. (2000). Compensation grouting, concept, theory and practice. In *Advances in grouting and ground modification* (eds R. J. Krizek and K. Sharp), ASCE Geotechnical Special Publication No. 104, pp. 1–15. Reston, VA: American Society of Civil Engineers.

Graf, E. D. (1992). Compaction grout. In *Grouting, soil improvement and geosynthetics*, ASCE Geotechnical Special Publication No. 30, Vol. 1, pp. 275–287. Reston, VA: American Society of Civil Engineers.

Harris, D. I., Pooley, A. J., Menkiti C. O. & Stephenson, J. A. (1996). Construction of low level tunnels below Waterloo Station with compensation grouting for Jubilee Line Extension. In *Geotechnical aspects of underground construction in soft ground* (eds R. J. Mair and R. N. Taylor), pp. 361–366. Rotterdam: Balkema.

Harris, D. I., Mair, R. J., Burland, J. B. & Standing J. R. (1999). Compensation grouting to control tilt of Big Ben Clock Tower. In *Geotechnical aspects of underground construction in soft ground* (eds O. Kusakabe, K. Fujita and Y. Miyazaki), pp. 225–232. Rotterdam: Balkema.

Jaworski, G. W, Duncan, M. J. & Seed, H. B (1981). Laboratory study of hydraulic fracturing. *J. Geotech. Div., ASCE* **107**, No. GT6, 713–732.

Komiya, K., Soga, K., Akagi, H., Jafari, M. R. & Bolton, M. D. (2001). Soil consolidation associated with grouting during shield tunnelling in soft clayey ground. *Géotechnique* **51**, No. 10, 835–847.

Kramer, G. J. E., Tavares, P. D. & Droof, E. R. (1994). Settlement protection works for new St Clair River rail tunnel. *Canadian Tunnelling*, 291–302 BiTech Proc.

Lefebvre, G., Bozozuk, M., Philibert, A. & Hornych, P. (1991). Evaluating K_0 in Champlain clays with hydraulic fracture tests. *Can. Geotech. J.* **28**, 365–377.

Linney, L. F. & Essler, R. D. (1994). Compensation grouting trail works at Redcross Way, London. In *Grouting in the ground* (ed. A. L. Bell), pp. 313–326. London: Thomas Telford.

Lo, K. Y. & Kaniaru, K. (1990). Hydraulic fracture in earth and rock-fill dams. *Can. Geotech. J.* **27**, 496–506.

Mair, R. J. & Hight, D. W. (1994). Compensation grouting. *World Tunnelling*, 361–367.

Mori, A. & Tamura, M. (1987). Hydrofracturing pressure of cohesive soil. *Soils Found.* **27**, No. 1, 14–22.

Mori, A., Tamura, M. & Fukui, Y. (1990). Fracturing pressure of soil ground by viscous material. *Soils Found.* **30**, No. 3, 129–136.

Mhach, H. K. (1991). *An experimental study of hydraulic fracture and erosion*. PhD thesis, City University, London.

Osborne, N., Murry, K., Chegini, A. & Harris, D. I. (1997). Construction of Waterloo Station upper level tunnels, Jubilee line extension project. *Proc. Tunnelling 97, London*, 639–666.

Panah, A. K. & Yanagisawa, E. (1989). Laboratory studies on hydraulic fracturing criteria in soil. *Soils Found.* **29**, No. 4, 14–22.

Pototschnik, M. J. (1992). Settlement reduction of soil fracture grouting. *ASCE Geotechnical Special Publications*, Vol. 1, No. 30, pp. 398–409.

Scherer, S. D. & Gay, R. L. (2000). Compaction grouting: three midwest case histories. In *Grouting, soil improvement and geosynthetics*, ASCE Geotechnical Special Publication No. 30, Vol. 1, pp. 65–81. Reston, VA: American Society of Civil Engineers.

Schweiger, H. F. & Falk, E. (1998). Reduction of settlement by compensation grouting: numerical studies and experience from Lisbon Underground. *Proc. World Tunnel Cong. '98 on Tunnel and Metropolises, Sao Paulo* **2**, 1047–1052.

Shirlaw, J. N., Dazhi, W., Ganeshan, V. & Hoe, C. S. (1999). A compensation grouting trial in Singapore marine clay. *Geotechnical aspects of underground construction in soft ground*, pp. 149–154. Rotterdam: Balkema.

Soga, K., Bolton, M. D., Au, S. K. A., Komiya, K., Hamelin, J. P., Van Cotthem, A., Buchet, G. & Michel, J. P. (1999). Development of compensation grouting modelling and control system. In *Geotechnical aspects of underground construction in soft ground* (eds O. Kusakabe, K. Fujita and Y. Miyazaki), pp. 425–430. Rotterdam: Balkema.

Sugiyama, T., Nomoto, T., Nomoto, M., Ano, Y., Hagiwara, T., Mair, R. J., Bolton M. D. & Soga, K. (1999). Compensation grouting at the Docklands Light Lewisham Extension project. In *Geotechnical aspects of underground construction in soft ground* (eds O. Kusakabe, K. Fujita and Y. Miyazaki), pp. 319–324. Rotterdam: Balkema.

Warner, J. (1992). Compaction grout; rheology vs. effectiveness. In *Grouting, soil improvement and geosynthetics*, ASCE Geotechnical Special Publication No. 30, Vol. 1, pp. 229–239. Reston, VA: American Society of Civil Engineers.

Yanagisawa, E. & Ali, K. P. (1994). Two-dimensional study of hydraulic fracturing criteria in cohesive soils. *Soils Found.* **30**, No. 1, 1–9.

Zeigler, E. J. & Wirth, J. (1982). Soil stabilization by grouting on Baltimore Subway. *Proceedings of the conference on grouting in geotechnical engineering*, New York, pp. 576–590.