Geomechanics and Engineering, *Vol. 10, No. 3 (2016) 335-355*
DOI: http://dx.doi.org/10.12989/gae.2016.10.3.335

Experimental study on the performance of compensation grouting in structured soil

Gang Zheng [1,2,3], Xiaoshuang Zhang [1,2], Yu Diao [*1,2] and Huayang Lei [1,2]

[1] *School of Civil Engineering, Tianjin University, Tianjin 300072, China*
[2] *Key Laboratory of Coast Civil Structure Safety, Tianjin University, Ministry of Education, China*
[3] *State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China*

(*Received July 18, 2015, Revised December 28, 2015, Accepted December 29, 2015*)

Abstract. Most laboratory test research has focused on grouting efficiency in homogeneous reconstituted soft clay. However, the natural sedimentary soils generally behave differently from reconstituted soils due to the effect of soil structure. A series of laboratory grouting tests were conducted to research the effect of soil structure on the performance of compensation grouting. The effects of grouting volume, overlying load and grouting location on the performance of compensation grouting under different soil structures were also studied. Reconstituted soil was altered with added cement to simulate artificial structured soil. The results showed that the final grouting efficiency was positive and significantly increased with the increase of stress ratio within a certain range when grouting in normally consolidated structured clay. However, in the same low yield stress situation, the artificial structured soil had a lower final grouting efficiency than the overconsolidated reconstituted soil. The larger of normalized grouting volume could increase the final grouting efficiency for both reconstituted and artificial structured soils. Whereas, the effect of the overlying load on final grouting efficiencies was unfavourable, and was independent of the stress ratio. As for the layered soil specimens, grouting in the artificial structured soil layer was the most efficient. In addition, the peak grouting pressure was affected by the stress ratio and the overlying load, and it could be predicted with an empirical equation when the overlying load was less than the yield stress. The end time of primary consolidation and the proportion of secondary consolidation settlement varied with the different soil structures, grouting volumes, overlying loads and grouting locations.

Keywords: grouting efficiency; soil structure; grouting volume; overlying load; grouting location; primary consolidation

1. Introduction

Compensation grouting has been widely adopted in recent years to control the settlements caused by tunnelling and underground construction. The basic principle of compensation grouting is to inject grout into the zone between the tunnel and overlying buildings to compensate for the ground loss and stress relief induced by excavation (Mair and Hight 1994). Successful cases of compensation grouting have been reported (Schweiger and Falk 1998, Harris *et al*. 1994 and Sun

*Corresponding author, Lecturer, E-mail: yudiao@tju.edu.cn

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

et al. 2010), and analyses (Zhang *et al*. 2011), field tests (Liao *et al*. 2011 and Yi *et al*. 2009) and numerical methods (Schweiger *et al*. 2004 and Wisser *et al*. 2005) have also been conducted.

A laboratory test can study the fundamental behaviours of compensation grouting by focusing on a single influence factor such as overconsolidation ratio, grout material or injection method (Au *et al*. 2003). Most laboratory test research has focused on grouting efficiency in homogeneous reconstituted soft clay (Au *et al*. 2003, Komiya *et al*. 2001, Soga *et al*. 2005 and Akira and Masahito 1987). However, it is widely recognised that natural sedimentary soils generally behave differently from reconstituted soils due to the effect of soil structure (Hong *et al*. 2012, Leroueil *et al*. 1979, 1985, Schmertmann 1991 and Chen *et al*. 2014a). To date there have been few studies on the relationship between soil structure and compensation grouting performance. Thus, it is necessary to investigate the effect of soil structure on the performance of compensation grouting.

It is more common in practice to find heterogeneous soils with layers differing either in texture or structure (Xie *et al*. 2002, Kumar and ISH 1999 and Parsa-Pajouh *et al*. 2014), and as a result, performance of compensation grouting varies with grouting locations in different layers. Essler *et al*. (2000) proposed that the relative tunnel position of compensation grouting zone must be considered when designing compensation grouting scheme. However, grouting locations are typically selected through practical engineering experience. The influence of grouting locations and the properties of adjacent soil layers on performance of compensation grouting has been rarely studied. Therefore, selecting a grouting location requires more theoretical guidance in order to gain a better grouting effect.

Grouting volume is an important parameter in compensation grouting design schemes and always becomes the terminal criterion in grouting engineering or tests (Komiya *et al*. 2001 and Zhang *et al*. 2012). However, grouting volumes calculated from theoretical formulas have always differed from those in practice. In addition, Ni and Cheng (2010) noted that the efficiency of compensation grouting was a function of building weight, injection method and ground conditions. The case history reported by Xu *et al*. (2013) also showed that a heavy building could barely be lifted by grouting but a lighter building could be lifted when there was a soft clay soil layer under the building foundation. Thus, further study is warranted on the effects of grouting volume and overlying load (building weight) on performance of compensation grouting for reconstituted and structured soils.

This paper develops a set of laboratory experiments for studying compensation grouting. A series of laboratory grouting tests were performed to evaluate the influence of soil structure on the performance of compensation grouting. Other factors varied in the laboratory grouting tests were the grouting volume, the overlying load and the grouting location for both reconstituted and structured soils. The experimental results were examined in terms of the effect on grouting efficiency, grouting pressure, the end time of primary consolidation and the proportion of secondary consolidation settlement.

2. Laboratory investigations

2.1 Experimental setup

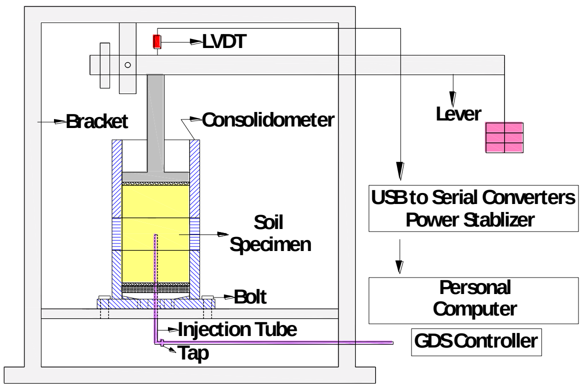
To investigate the factors affecting the performance of compensation grouting in structured soil, a set of test equipment used for compensation grouting was processed. The experimental setup is shown in Fig. 1.

As shown in Figs. 1(a)-(b), a 100-mm diameter modified consolidometer supplied the confining boundary condition. The thickness of consolidometer was 15 mm, which ensured that any deformation of the consolidometer could be ignored. The consolidometer was composed of three parts that were connected by 10-mm diameter bolts and fixed on a bracket. The height of these three parts from top to bottom was 120, 50 and 90 mm and the total height of the soil specimen was 150 mm. Porous discs and filter papers were placed on the top and bottom of the soil specimen. The overlying load was supplied by a lever. The loading arm of the lever was connected to the guide lid on top of the soil specimen. The load ratio of the lever was 1:24.686.

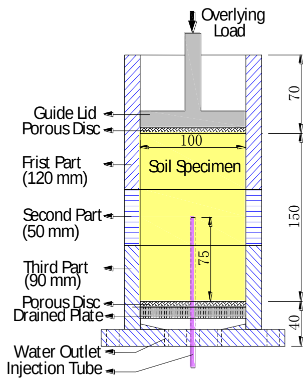
As shown in Figs. 1(b)-(c), a 6-mm outer diameter and 4-mm inner diameter stainless steel needle was used as an injection tube. The total length of the needle was 200 mm and was inserted 75 mm into the soil. The tip of the needle had four uniformly distributed 2-mm diameter holes covered by an expandable latex balloon. Water was injected into the latex balloon to simulate an ideal compaction grouting (Soga *et al*. 2005 and Wang *et al*. 2009, 2013) where no bleeding or solid penetration could occur. Before preparing the soil specimen, the leakproofness of injection system was checked by injecting 1.0 mL water into the latex balloon, and the leakproofness of injection system was regarded as in a good condition if the pressure after injecting remained constant in 2.0 minutes. After that, the injection water was discharged by GDS controller.

As shown in Fig. 1(a), a Geotechnical Digital Systems (GDS) controller was used to control the grouting rate and the volume of water injected through the injection tube. The grouting pressure was also measured by the GDS controller.

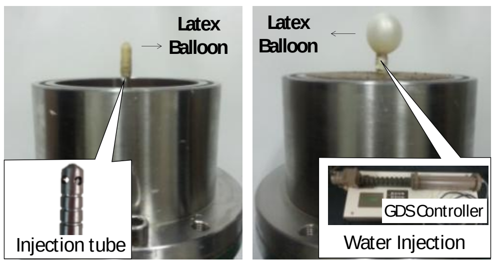
As shown in Fig. 1(a), the surface displacements of the specimen during and after grouting



(a) Grouting injection and loading systems



(b) Schematic of modified consolidometer



(c) Modelling of ideal compaction grouting

Fig. 1 Laboratory experimental setup (unit: mm) were measured by a linear variable differential transducer (LVDT) attached to the guide lid. The LVDT had a total stroke of 10 mm and a sensitivity of 0.001 mm. Automatic data recording was accomplished with a computer program.

2.2 Specimen preparation and testing

2.2.1 Homogeneous soil specimen

Tianjin silty clay (alluvium) was used as the soil medium for the test series. The soil was reconstituted to provide a reference (Burland 1990). Liu and Carter (2000), Lorenzo and Bergado (2004) and Lei *et al*. (2013) noted that the essential compression behaviour of cemented clay was similar to that of natural structured clay. Therefore, reconstituted soil with added cement was adopted to simulate the structured soil. Specimens with cement contents of 1%, 2%, 3%, 4% and 6% by weight (cement to dry silty clay) were prepared in this study for artificial structured soil specimens.

The soil slurry was prepared by mixing the dry silty clay with distilled water in a mechanical mixer, giving a water content of 70%, which was approximately 1.4 times the liquid limit (Fearon and Coop 2000). Portland cement was added to the soil slurry for the artificial structured soil specimen. The retarder was also added to the soil slurry to control the hardening time and gain a similar initial void ratio with the reconstituted soil under an overlying load of 50 kPa. After the mixing was completed, the soil slurry was spooned into the modified consolidometer for consolidation. The inner surface of the consolidometer was initially lubricated with Teflon tape and grease to reduce friction.

Based on the prior experience of different trial tests, the initial height of the specimens must be determined accurately to consolidate the specimen to a 150-mm height before grouting.

The overlying loads were applied using a lever system to consolidate the specimens. The soil specimen was prepared when the settlement rate was less than 0.002 mm/h, indicating that consolidation was completed and a steady state was reached. The total time for preparing the artificial structured soil specimens was approximate 120 hours.

When considering of the effect of overlying load, the artificial structured soil specimens were consolidated under an overlying load of 50 kPa for approximately 105 hours, and then the overlying loads were increased to the target load. The soil specimens reached a steady state in approximately 120 hours in several trial tests.

The overconsolidated soil specimens initially reached a steady state with greater overlying loads (75, 100 and 150 kPa), and the overlying load was then fixed to 50 kPa to reach a steady state again before grouting.

2.2.2 Layered soil specimen

Fig. 2 shows the profile of the layered soil specimens, with each layer consolidated to 50 mm under 50 kPa. The preparation of each layer was similar to the homogenous soil specimen mentioned in Section 2.2.1. It is worth noting that filter papers were placed on the top and bottom of the artificial structured soil layer to prevent the infiltration of cement into the adjacent layers.

2.2.3 Test procedure

Water was injected into the injection tube at a rate of 0.5 mL/s. The tap attached to the injection tube was closed after reaching the target volume to prevent water from flowing back into the injection system. The test completed when the settlement rate was less than 0.002 mm/h and the

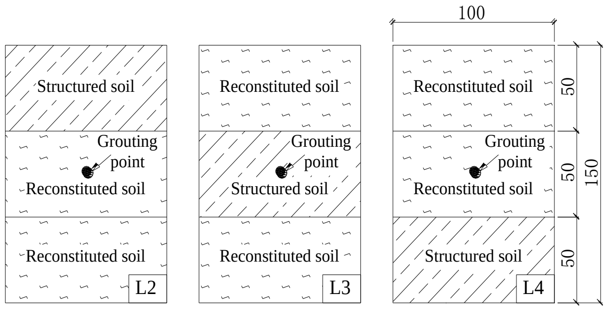


Fig. 2 Schematic diagram of different layered soil specimens (unit: mm)

total time for the continued consolidation was approximate 24 hours, meaning that the primary consolidation was completed and a steady state of soil specimen was reached.

2.3 Experimental conditions

2.3.1 Properties of soils

The parameters of both the reconstituted and artificial structured soils are shown in Table 1. The soil specimen was prepared under a vertical stress of 50 kPa, and then the test samples were cut from the soil specimen to conduct parameter tests. Thus, all test samples had a preconsolidation pressure of 50 kPa.

Consolidated drained direct shear tests were employed to obtain the friction angle at critical state and cohesion. The permeability coefficient was measured using a seepage test. An oedometer test was conducted to obtain one-dimensional compression parameters. As shown in Table 1, the differences in water content, void ratio and density between the different soils were extremely small and can be ignored, and the differences in other parameters were primarily caused by soil structure.

Fig. 3 shows the relationship between the void ratio and the vertical stress. The preconsolidation pressure was 50 kPa. In Fig. 3, the compression curve of the reconstituted soil was a straight line when the vertical stress was greater than the preconsolidation pressure. However, the compression curves of the artificial structured soil crept slowly downward before significantly dropping when the vertical stress was greater than the preconsolidation pressure. The compressive behaviour of the artificial structured soil agreed well with the deformation mode of the natural structured soil reported by Hong *et al*. (2012). The results further evidenced the similarity of soil structure between the artificial structured and natural soils.

As shown in Fig. 3, the yield stress (σ_y) can be calculated by the double logarithmic coordinate method of ln(1+*e*)-lg*p* proposed by Butterfield (1979). The equivalent vertical stress (σ_e^*) was defined as the vertical stress when the void ratios of reconstituted and artificial structured soils were identical (Cotecchia and Chandler 1997), and this value was found to be 50 kPa in this study. The stress ratio σ_y/σ_e^* reflects the magnitude of the strength of the structure of artificial structured soil compared to the reconstituted soil (Cotecchia and Chandler 1997). A greater stress ratio indicates a greater structural strength. Summaries of the yield stress and stress ratios are listed in Table 2. As shown in Fig. 4, the stress ratio increased nonlinearly with increasing cement content. The stress ratios rose slightly when the cement content was less than 2% and increased dramatically afterwards. In conclusion, the stress ratio was equal to 1.00 for the reconstituted soil

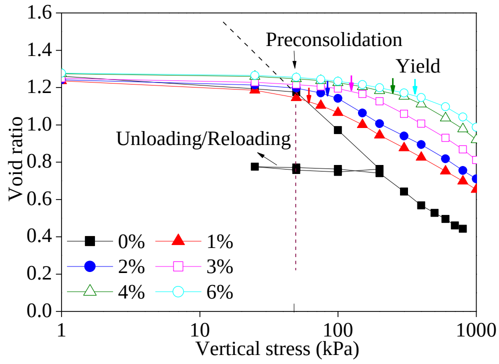


Fig. 3 One-dimensional compression behaviour of soils with different cement contents

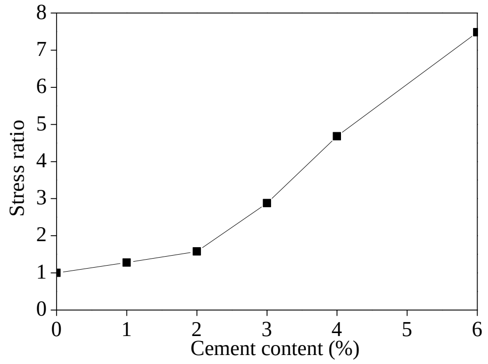


Fig. 4 Stress ratio of soil versus cement content

Table 1 Physical and mechanical parameters of soil

Cement content	Water content (%)	Void ratio	Density (g/cm^3)	Friction angle at critical state (°)	Cohesion (kPa)	Permeability coefficient (m/s)
0%	46	1.26	1.7	17.2	0.0	1.0×10^{-9}
1%	46	1.24	1.8	26.9	4.1	1.3×10^{-9}
2%	46	1.24	1.8	28.8	8.4	1.7×10^{-9}
3%	48	1.25	1.8	30.5	11.8	2.3×10^{-9}
4%	49	1.27	1.8	32.0	19.9	3.2×10^{-9}
6%	50	1.28	1.8	33.1	29.6	4.4×10^{-9}

Table 2 Yield stress and stress ratios of soils with various cement contents

Cement content	0%	1%	2%	3%	4%	6%
Yield stress σ_y (kPa)	50	64	79	144	234	374
Stress ratios σ_y/σ_e^*	1.00	1.28	1.58	2.88	4.68	7.48

and greater than 1.00 for the artificial structured soils in this study.

2.3.2 Test program

Grouting test series of SS0-SS6 were carried out to study the effect of soil structure on the performance of compensation grouting, and the parameters are listed in Table 3.

In addition, grouting test series of V1-V9 were conducted to consider the grouting volume as an affecting factor, and the test series of SS0, SS3 and SS4 were used as references to consider the various soil structures.

Similarly, grouting test series of O1-O6 were conducted to consider the overlying load as an influencing factor, and the test series of SS0 and SS4 were used as references.

Finally, additional grouting test series of L2-L4 and SO1-SO3 were conducted to study the effect of the grouting location and the overconsolidation ratio (OCR) on grouting efficiency, respectively, and both used the test of SS0 as a reference.

Table 3 Parameters for the tests

Test No.	Cement content (%)	Overlying load (kPa)	Grouting volume (mL)	Stress ratio σ_y/σ_e^*	OCR	Soil condition
SS0	0	50	10	1.00	1	H
SS1	1	50	10	1.28	1	H
SS2	2	50	10	1.58	1	H
SS3	3	50	10	2.88	1	H
SS4	4	50	10	4.68	1	H
SS6	6	50	10	7.48	1	H
V1	0	50	5	1.00	1	H
V2	0	50	15	1.00	1	H
V3	0	50	20	1.00	1	H
V4	4	50	5	4.68	1	H
V5	4	50	15	4.68	1	H
V6	4	50	20	4.68	1	H
V7	3	50	5	2.88	1	H
V8	3	50	15	2.88	1	H
V9	3	50	20	2.88	1	H
O1	0	75	10	1.00	1	H
O2	0	100	10	1.00	1	H
O3	0	200	10	1.00	1	H
O4	4	75	10	4.68	1	H
O5	4	100	10	4.68	1	H
O6	4	200	10	4.68	1	H
L2	0 & 4	50	10	1.00&4.68	1	L(L2)
L3	0 & 4	50	10	1.00&4.68	1	L(L3)
L4	0 & 4	50	10	1.00&4.68	1	L(L4)
SO1	0	50	10	1.00	1.5	H
SO2	0	50	10	1.00	2	H
SO3	0	50	10	1.00	3	H

* Note: H represents homogeneous soil specimen; L represents layered soil specimen

2.4 Definitions

The concepts involved in this paper are defined as follows:

- Soil structure denotes the bonding of soil constituents that causes different mechanical behaviours from those of corresponding reconstituted soil (Liu and Carter 2000).
- The grouting efficiency is defined as the ratio of heaved volume to the initial grouting volume (Au *et al*. 2003).
- The peak grouting pressure is equal to the difference between the maximum pressure during the grouting process and the maximum pressure during leakproofness checking.

- The end time of primary consolidation is determined by a graphic method proposed by Casagrande and Fadum (1940). The end time of primary consolidation reflects the time required to complete the primary consolidation settlement after the completion of grouting.
- The influence of secondary consolidation settlement was caused widely attention (Wang *et al*. 2010 and Chen *et al*. 2014b). The secondary consolidation refers to the creep deformation of the soil skeleton caused by the deformation of bonding water film around soil grains and the rearrangement of the soil grains. The proportion of secondary consolidation settlement is defined as the ratio of secondary consolidation settlement to the total consolidation settlement. It typically takes a very long time to complete the secondary consolidation stage. Thus, studying the proportion of secondary consolidation settlement aids in predicting the final long-term settlement based on the primary consolidation settlement after the grouting is completed.

3. Experimental results

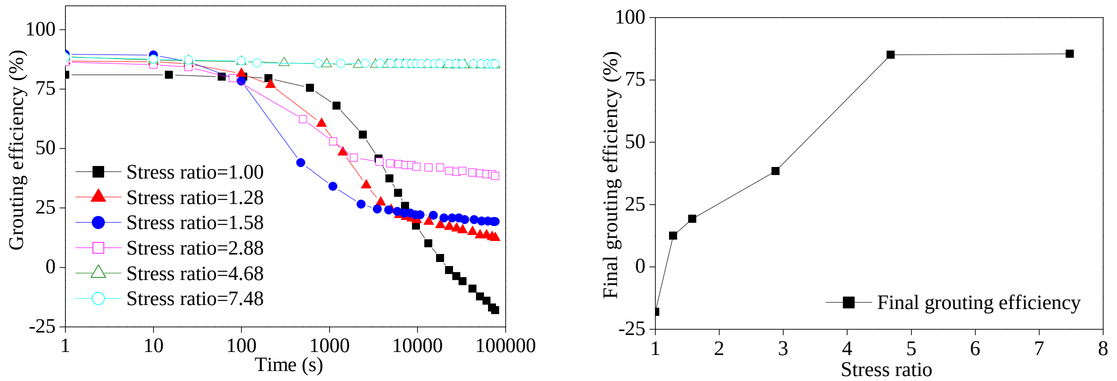
3.1 Effect of soil structure

The effect of the soil structure on grouting efficiency is shown in Fig. 5. If the entire grouting process occurs in an undrained condition, then the uplift volume should be equal to the grouting volume and the grouting efficiency would be 100% in an ideal situation. However, it was found that the initial measured grouting efficiencies were slightly less than 100%. In general, the initial efficiency loss was approximately 10% to 13% in most of the grouting tests. Au *et al*. (2003) noted that this initial efficiency loss could be caused by the compression of tiny gas bubbles and was acceptable. In addition, the compression of tiny gas bubbles had little influence on consolidation after the grouting was completed, which was the focus of this study.

As shown in Fig. 5(a), the grouting efficiency decreased sharply over time and gradually reached stability when the stress ratio was less than 4.68. However, the grouting efficiency remained nearly stable over time when the stress ratio was 4.68 and 7.48. The decreasing rate of grouting efficiency for the reconstituted soil was obviously lower than that of the artificial structured soil in prior period, and then gradually exceeded in later period when the stress ratio was less than 4.68.

As shown in Fig. 5(b), the grouting in the reconstituted soil resulted in the lowest final grouting efficiency, which negative grouting efficiency was measured at the end of the consolidation stage. Conversely, positive grouting efficiency was recorded for the artificial structured soil, which significantly improved from 12.47% to 84.99% when the stress ratio changed from 1.28 to 4.68 and then had almost no change when the stress ratio was greater than 4.68.

These results indicate that soil structure could effectively improve the impact of grouting from negative to positive, as the final grouting efficiency increased with the increase of the stress ratio within a certain range. For grouting in normally consolidated soil, Au *et al*. (2003) showed a typical stress path that the soil approached to yield at the critical state during the injection stage and then was compressed under the increasing mean effective pressure due to the excess pore pressure dissipation during the consolidation stage. Compared to the reconstituted soil, the artificial structured soil had a smaller range of disturbance due to the higher yield stress (see Fig. 3) in the injection stage, and a lower volume loss due to the lower compressibility in the consolidation stage, resulting in a higher final grouting efficiency. A greater stress ratio creates a more obvious advantage of the soil structure's effect on grouting efficiency. Similar phenomena



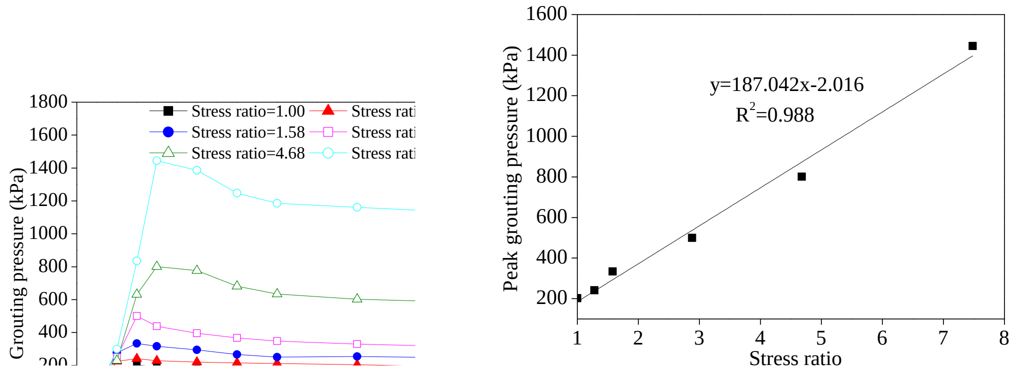
(a) Grouting efficiency versus time (b) Final grouting efficiency versus stress ratio

Fig. 5 Effect of soil structure on grouting efficiency

have been reported in compensation grouting tests and practical engineering applications of grouting uplift (Shirlaw *et al*. 1999 and Harris *et al*. 1996).

Fig. 6 shows the effect of soil structure on grouting pressure. Grouting pressure increased significantly over time, and then decreased slightly until reaching a stable state as shown in Fig. 6(a). Au *et al*. (2006) also reported the similar trend. In Fig. 6(b), the peak grouting pressure grew linearly with an increasing stress ratio. This was because higher grouting pressure was required to expand the balloon when the soil around the grouting point had a greater stress ratio (yield stress). The lowest peak grouting pressure was 202 kPa for grouting in the reconstituted soil, which was approximately four times higher than the overlying load. It meant that the pressure in the grouting pump was considerably higher than the vertical stress of the soil around the grouting point in practical engineering. Similar conclusions have been achieved in prior field grouting tests and practical engineering applications (Zhang *et al*. 2013 and Marchi *et al*. 2014).

As shown in Fig. 7, the end time of primary consolidation for the reconstituted soil was approximately 3~10 times longer than that of the artificial structured soil. The end time of primary



(a) Grouting pressure versus time (b) Peak grouting pressure versus stress ratio

Fig. 6 Effect of soil structure on grouting pressure

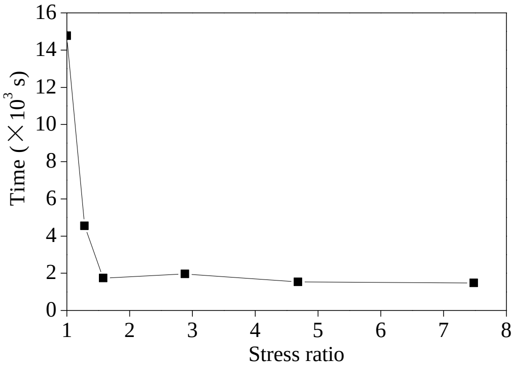


Fig. 7 End time of primary consolidation versus stress ratio

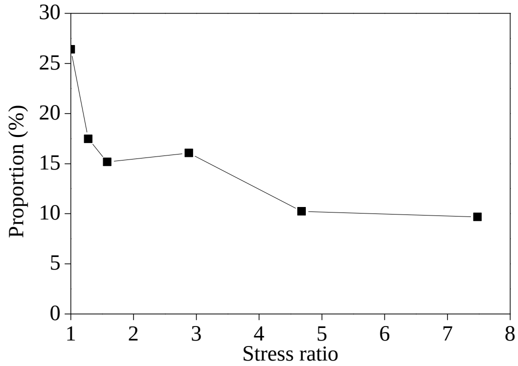


Fig. 8 Proportion of secondary consolidation settlement versus stress ratio

consolidation for the artificial structured soil decreased with slight fluctuations as the stress ratio increased. In other words, the heave obtained after grouting in the reconstituted soil gradually reduced over a longer time period. The pores between the soil grains in the reconstituted soil were consistently very small because of the weak bond between the soil grains. However, due to the effect of the structure, the pores of the artificial structured soil sustained by soil grains in a cemented state were generally much larger than the reconstituted soil, and these larger pores were protected from damage during the grouting process. Therefore, the permeability coefficient of the artificial structured soil was greater than reconstituted soil of the same porosity. The excess pore pressure generated during the grouting process dissipated more quickly resulting in a relative reduction in the end time of primary consolidation for the artificial structured soil, and the advantage induced by soil structure improved with the increased stress ratio overall. The changing trends of the end time of primary consolidation were similar to field measurements. The dissipation of the pore pressure was rapid, reverting to original values within 14 days after grouting in stiff clay, and approximately 1000 days were required to completely dissipate excess pore pressure after grouting in soft clay (Essler *et al*. 2000).

The proportions of secondary consolidation settlement for various stress ratios are shown in Fig. 8. The proportion of secondary consolidation settlement showed an overall declining trend with the increase of stress ratio. The proportion of secondary consolidation settlement for the artificial structured soil ranged between 17.5% and 10.2%, visibly lower than that of the reconstituted soil, which reached 26.4%. This may be because the cementation bond between the soil grains resisted the creep deformation of the soil grains in the artificial structured soil. The grains of the reconstituted soil were easily moved and rearranged due to the weak bond. Moreover, the secondary consolidation settlement obviously increased the consolidation settlement for reconstituted soil, contributing to the negative grouting efficiency (see Figs. 5(a) and 8). Therefore, the secondary consolidation settlement should be given significant attention because of the higher proportion in reconstituted soil.

3.2 Effect of grouting volume

To study the effect of grouting volume on the performance of compensation grouting, twelve grouting tests were conducted (see Table 3). The overlying load was 50 kPa.

The normalized grouting volume is defined as the volume ratio of grout to soil specimen. As shown in Fig. 9, a better final grouting efficiency was obtained when the normalized grouting volume was increased from 0.42% to 1.70%. The increment of normalized grouting volume could dramatically improve the final grouting efficiency for both reconstituted soil and artificial structured soil with a lower stress ratio of 2.88. The higher normalized grouting volume actually meant closer boundary. Numerical analysis by Au *et al*. (2003) showed that the closer boundary diameter could reduce the magnitude of the excess pore pressure zone, resulting in the reduction of consolidation settlement and improvement of the final grouting efficiency. However, the effect of this increment was not obvious in the artificial structured soil with a greater stress ratio of 4.68. This may be because the higher yield stress played a boundary role.

The relationship between the end time of primary consolidation and the normalized grouting volume is shown in Fig. 10. When the normalized grouting volume increased, the end time of primary consolidation markedly increased for the reconstituted soil and slightly increased for the artificial structured soil with a stress ratio of 2.88. The magnitude and extent of the excess pore pressures zone increased with the increase of normalized grouting volume. Thus, more time is required to dissipate the excess pore pressure for greater normalized grouting volumes under similar permeability coefficients of the soil specimens.

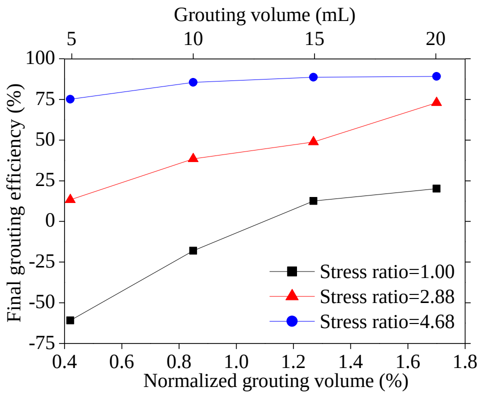


Fig. 9 Effect of grouting volume on grouting efficiency

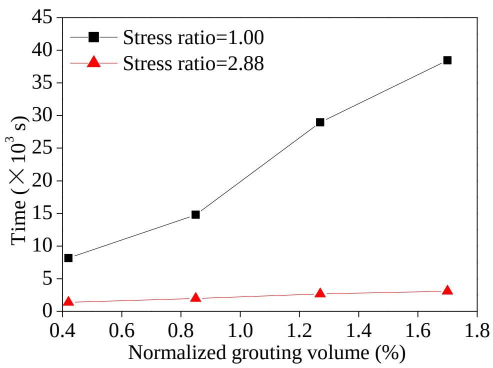


Fig. 10 End time of primary consolidation versus normalized grouting volume

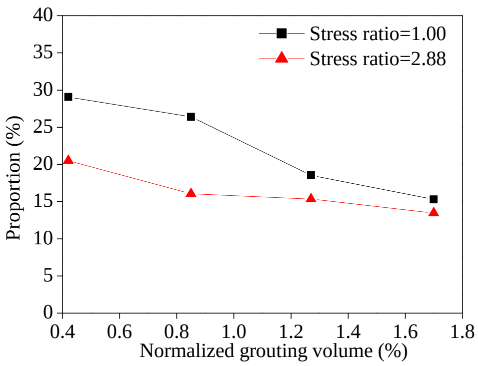


Fig. 11 Proportion of secondary consolidation settlement versus normalized grouting volume

As shown in Fig. 11, the proportion of secondary consolidation settlement showed a similar trend for reconstituted soil and artificial structured soil with a stress ratio of 2.88, obviously decreasing with the increased normalized grouting volume. The expansion distance of latex balloon increased with the increase of normalized grouting volume, resulting in a greater disturbed range around the grouting point. The greater disturbed range caused more damage of soil structure and hence an easier rearrangement of soil grains. In addition, it is worth noting that the proportion of secondary consolidation settlement was approximately 30% at the normalized grouting volume of 0.42% for the reconstituted soil, meaning that additional settlement measured during the stage of secondary consolidation was very large.

3.3 Effect of overlying load

To study the effect of the overlying load on the performance of compensation grouting for reconstituted and artificial structured soils, eight grouting tests were conducted. The grouting volume was 10 mL.

As shown in Fig. 12, the final grouting efficiencies for the reconstituted soil and artificial structured soil with a stress ratio of 4.68 showed a similar tendency and were nearly parallel as a whole, with both notably decreasing when the overlying load increased. For each given stress ratio, the same change of overlying load nearly caused an equal variation in the final grouting efficiency, indicating that the effect of the overlying load on grouting efficiency was nearly independent of the stress ratio. In this study, the structured soil with different stress ratios had a same corresponding reconstituted soil, resulting in same intrinsic properties (Burland 1990). The effect of overlying load on grouting efficiency was mainly related to the intrinsic properties. For a given overlying load, the final grouting efficiency in the artificial structured soil was significantly higher than the reconstituted soil, which changed from positive to negative.

A case history of Tianjin Metro Line 3 (Xu *et al*. 2013) also showed a similar trend. Compensation grouting was adopted to control the subsequent settlement of a historic building while tunnelling beneath it. The tunnel stopped and maintained the face pressure because of the large settlement. The regrouting was conducted in the soft clay between the building and the tunnel. The cover depth of the grouting point was 1.6 m from the building foundation. As shown in Fig. 13, the vertical displacement of the six-story historic building (the vertical stress of the grouting

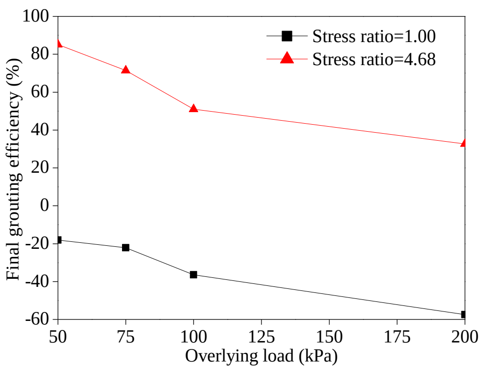


Fig. 12 Effect of overlying load on grouting efficiency

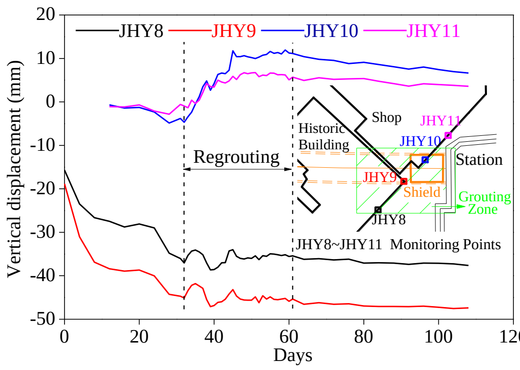


Fig. 13 A case history of the Tianjin Metro Line 3 (Xu *et al*. 2013)

point was approximately 160 kPa) decreased significantly after each stage of grouting, and the decreasing rate of vertical displacement was finally reduced. The vertical displacement of the one-story shop (the vertical stress of the grouting point was approximately 60 kPa) decreased slightly after each stage of grouting, and the shop was finally uplifted. The results showed that the grouting effect for light building was better than that of heavy building, indicating that the final grouting efficiency decreased with the overlying load as shown in Fig. 12.

Therefore, when a heavy building can barely be lifted by grouting in a soft clay soil layer, the advance reinforcement of the soft clay is essential for improving the effect of grouting.

The peak grouting pressures in the reconstituted and artificial structured soils showed a similar trend, increasing linearly with the increase of overlying load as shown in Fig. 14. The peak grouting pressure for the artificial structured soil was higher than that of the reconstituted soil at the same overlying load. However, the increasing rate of peak grouting pressure showed the opposite tendency. During grouting in reconstituted soil, the increasing rate of peak grouting pressure was approximately 3.25 times higher than that in artificial structured soil. Because the reconstituted soil lacked cemented bond between the soil grains, the peak grouting pressure was 0 kPa when the overlying load was 0 kPa. However, 724 kPa was required to overcome the soil structure around the grouting point when the overlying load was 0 kPa for the artificial structured soil.

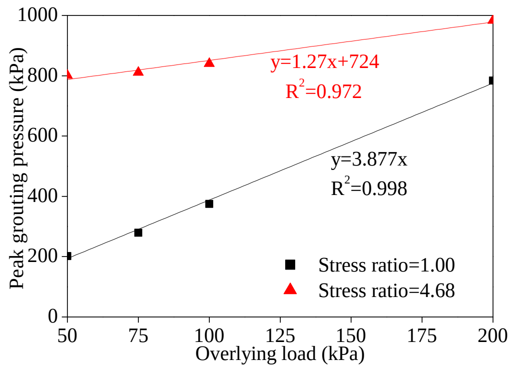


Fig. 14 Peak grouting pressure versus overlying load

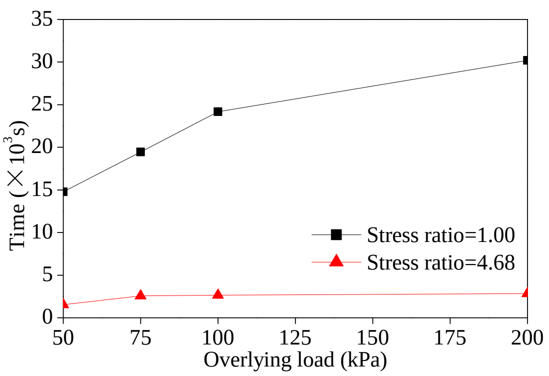


Fig. 15 End time of primary consolidation versus overlying load

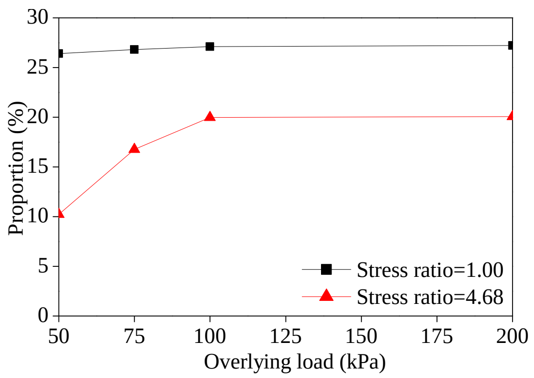


Fig. 16 Proportion of secondary consolidation settlement versus overlying load

For a given overlying load, the end time of primary consolidation for the reconstituted soil was far longer than that of the artificial structured soil, as shown in Fig. 15. The end time of primary consolidation rose significantly with the increase in overlying load for the reconstituted soil. However, the influence of the overlying load on the end time of primary consolidation was slight for the artificial structured soil. The void ratio decreased significantly in the reconstituted soil with an increase of overlying load from 50 to 200 kPa (see Fig. 3). The pore compression decreased the permeability coefficient, resulting in slowing the dissipation speed of the excess pore pressure. In addition, a greater overlying load increased excess pore pressure. Therefore, the overlying load has a significant influence on the end time of primary consolidation. By contrast, the change of void ratio for the artificial structured soil was not obviously benefitting from the cemented bond, resulting in a similar permeability coefficient. Therefore, the increasing rate of the end time of primary consolidation was lower than that of the reconstituted soil.

As shown in Fig. 16, the proportion of secondary consolidation settlement for the reconstituted soil was greater than that of the artificial structured soil under the same overlying load, and both increased with the increase of overlying load as a whole. However, when the overlying load exceeded 100 kPa, the increment of the proportion of secondary consolidation settlement was obviously reducing. In addition, the increasing rate of the proportion of secondary consolidation settlement for the reconstituted soil is significantly lower than that of the artificial structured soil when the overlying load was less than 100 kPa. This may be because the greater total settlement led to the lower increasing rate of the proportion of secondary consolidation settlement for the reconstituted soil.

These results indicate that the overlying load has a greater impact on both the end time of primary consolidation for the reconstituted soil and the proportion of secondary consolidation settlement for the artificial structured soil.

3.4 Effect of grouting location

The grouting location is an important parameter, particularly when a soft clay soil layer is located under buildings or underground structures. Four grouting tests were conducted to study the effect of grouting location on performance of compensation grouting. The first condition, marked as L1, represented grouting point selected in the homogeneous reconstituted soil. The other three soil specimens were layered and contained reconstituted soil layer and artificial structured soil layer as shown in Fig. 2. The second, third and fourth conditions, marked as L2, L3 and L4, respectively, represented grouting points located below, inside and above the artificial structured soil layer. The stress ratio of the artificial structured soil layer was 4.68 and the grouting volume was 10 mL.

The effect of grouting location on grouting efficiency is shown in Fig. 17. The lowest final grouting efficiency was -18.04% for the L1 condition, where the grouting point was selected in homogeneous reconstituted soil. The final grouting efficiencies for the L4 and L2 conditions, where the grouting points were located above and below the artificial structured soil layer, were higher than that of L1 condition. Grouting in the artificial structured soil layer obtained the highest final grouting efficiency, reaching 44.74% for the L3 condition.

These results indicate that the presence of artificial structured soil layer can effectively improve grouting efficiency, and grouting in artificial structured soil is the most efficient. In addition, the properties of upper soil layer have a greater influence on grouting efficiency than those of the lower soil layer. Therefore, the grouting should be conducted in the soil layer with higher yield stress or improved soil layers in practice.

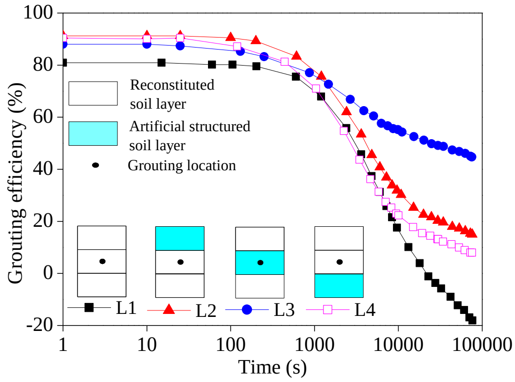


Fig. 17 Effect of grouting location on grouting efficiency

For layered soil specimens, the properties of the soil around the grouting point had a significant influence on the peak grouting pressure, as shown in Fig. 18. The peak grouting pressures ranged from 202 to 324 kPa when the grouting points were located in the reconstituted soil layer. However, the peak grouting pressure reached 833 kPa during grouting in the artificial structured soil layer, which was approximately 2.5~4.0 times higher than grouting in the reconstituted soil layer.

As shown in Fig. 19, the end time of primary consolidation was the longest for the L1 condition at 14780 s, where the grouting point was selected in homogeneous reconstituted soil. The end time of primary consolidation for the L2 condition was shorter, followed by the L4 condition. The end time of primary consolidation for the L3 condition was the shortest at 8620 s, where the grouting point was located in the artificial structured soil layer. In addition, the proportion of secondary consolidation settlement was the highest for the L1 condition at 26.4%. The relative differences in the proportion of secondary consolidation settlement between the L2, L3 and L4 conditions were slight, and all were lower than the L1 condition. These results indicate that the presence of artificial structured soil layer can effectively shorten the end time of primary consolidation and decrease the proportion of secondary consolidation settlement.

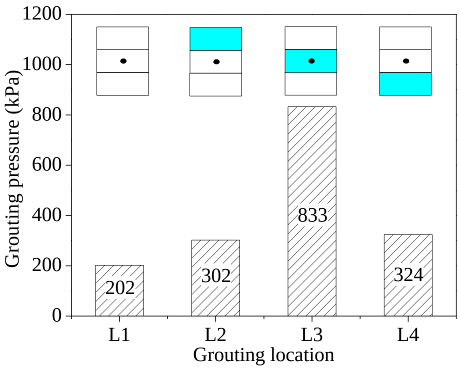


Fig. 18 Relationship between peak grouting pressure and grouting location

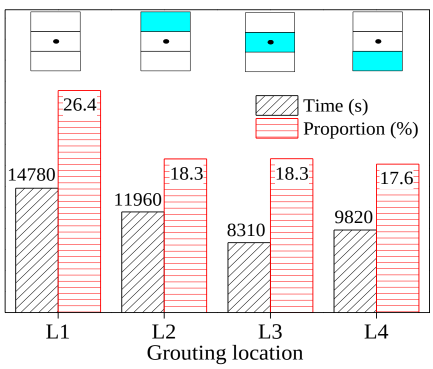


Fig. 19 Relationship between the end time of primary consolidation, the proportion of secondary consolidation settlement and grouting location

4. Discussion

4.1 Final grouting efficiency

To compare the effects of soil structure and overconsolidation on the long-term efficiency of compensation grouting, grouting test series of SO1-SO3 were conducted. For the overconsolidated reconstituted soil, its yield stress was identical to the preconsolidation pressure, which was the product of the overlying load and the OCR in these tests.

As shown in Fig. 20, the final grouting efficiency showed a similar trend for artificial structured and overconsolidated reconstituted soils, which was significantly improved and then reached a limit of approximately 85% in this study when the yield stress increased.

Furthermore, the overconsolidated reconstituted soil had a lower yield stress reaching the limit of final grouting efficiency than the artificial structured soil. Au *et al*. (2003) pointed that the overconsolidated reconstituted soil deformed elastically in the consolidation stage. In other words, the compressibility of the overconsolidated reconstituted soil was related to the unloading-reloading behaviour. In contrast, the compressibility of the artificial structured soil was mainly controlled by virgin compression in consolidation stage. As shown in Fig. 3, the artificial structured soil with low yield stress had higher compressibility than the overconsolidated reconstituted soil in unloading-reloading curve. Therefore, in the same low yield stress situation, the artificial structured soil had a lower final grouting efficiency than the overconsolidated reconstituted soil.

4.2 Peak grouting pressure

The aforementioned results illustrate that the peak grouting pressure was affected by the stress ratio and the overlying load (see Figs. 6 and 14). Hence, the peak grouting pressure could be divided into two parts: the peak grouting pressure affecting by overlying load (P_0) and the peak grouting pressure affecting by soil structure or overconsolidation effect (P_y), which was expressed by Eq. (1) as follows

$$P = P_0 + P_y \tag{1}$$

P_0 could be calculated by the correlation between the peak grouting pressure and the overlying

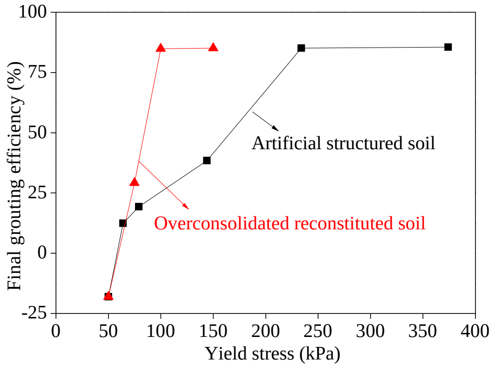


Fig. 20 Comparison of the effects of yield stress on final grouting efficiency for artificial structured and overconsolidated reconstituted soils

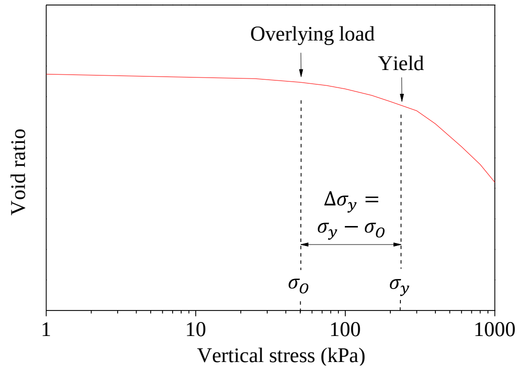


Fig. 21 Schematic of the effective yield stress $\Delta\sigma_y$

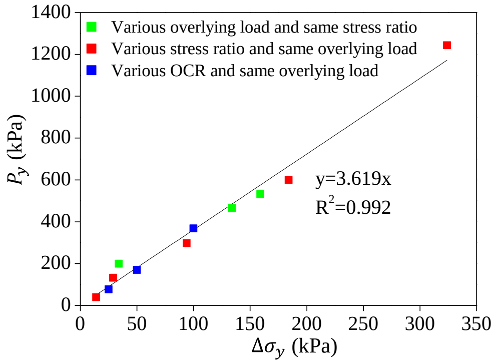


Fig. 22 Peak grouting pressure related to soil structure P_y versus the effective yield stress $\Delta\sigma_y$

Table 4 Summary of measured and calculated peak grouting pressures

Overlying load (kPa)	Yield stress (kPa)	Stress ratio	Peak grouting pressure (kPa)		$\frac{\lvert P_m - P_c \rvert}{P_m} \times 100$ (%)
			Measurement P_m	Calculation P_c	
50	50	1.00	202	193.85	4.03
75	75	-	279	290.78	4.22
100	100	-	375	387.70	3.39
200	200	-	784	775.40	1.10
50	234	4.68	801	859.75	7.33
75	234	4.68	811	866.20	6.81
100	234	4.68	840	872.65	3.89
200	234	4.68	983	898.45	8.60
50	64	1.28	241	244.52	1.46
50	79	1.58	334	298.80	10.54
50	144	2.88	500	534.04	6.81
50	374	7.48	1445	1366.41	5.44
50	75 (OCR = 1.5)	-	279	284.33	1.91
50	100 (OCR = 2)	-	372	374.80	0.75
50	150 (OCR = 3)	-	570	555.75	2.50

load (σ_0) for the normally consolidated reconstituted soil as follows

$$P_0 = k_0 \sigma_0 \tag{2}$$

where k_0 was the proportional coefficient of P_0 and σ_0. In this study, k_0 was equal to 3.877 as shown in Fig. 14.

P_y could be calculated by the effective yield stress ($\Delta\sigma_y$), which is defined as the difference between σ_0 and σ_y for the artificial structured or overconsolidated reconstituted soil when the overlying load was less than the yield stress, as shown in Fig. 21. The relationship between P_y

and $\Delta\sigma_y$ is shown in Fig. 22. In this study, it was found that P_y linearly increased with the increase of $\Delta\sigma_y$, and as a result, P_y was given by

$$P_y = k_y \Delta\sigma_y \ (\sigma_O < \sigma_y) \tag{3}$$

where k_y was the proportional coefficient of P_y and $\Delta\sigma_y$. In this study, k_y was equal to 3.619 as shown in Fig. 22.

Therefore, the Eq. (1) was expressed as follows

$$P = P_o + P_y = k_O\sigma_O + k_y\Delta\sigma_y \qquad (\sigma_O < \sigma_y) \tag{4}$$

The comparison of the peak grouting pressure measured and calculated by Eq. (4) is shown in Table 4. Most of the differences between measurement and calculation were less than 7%, and only one value exceeded 10%. Thus, Eq. (4) can be used to predict the peak grouting pressure when the overlying load is less than the yield stress.

5. Conclusions

A series of laboratory grouting tests were performed to examine the influence of soil structure on the performance of compensation grouting. The effects of grouting volume, overlying load and grouting location on the performance of compensation grouting under various soil structures were also studied. The following conclusions may be drawn from the results:

- The soil structure could effectively improve the impact of grouting from negative to positive, as the final grouting efficiency increased with the increase of the stress ratio within a certain range. As the stress ratio increased, the peak grouting pressure grew linearly, and both the end time of primary consolidation and the proportion of secondary consolidation settlement showed an overall declining trend.
- The increment of normalized grouting volume was able to improve the final grouting efficiency for both reconstituted soil and artificial structured soil with lower stress ratio. However, the effect of this increment was not obvious for artificial structured soil with a higher stress ratio.
- The final grouting efficiencies notably decreased with the increasing overlying load for both reconstituted and artificial structured soils, and the effect of the overlying load on final grouting efficiency was independent of the stress ratio. However, the peak grouting pressures increased linearly with increasing overlying load. The overlying load had a greater impact on both the end time of primary consolidation for the reconstituted soil and the proportion of secondary consolidation settlement for the artificial structured soil, which increased with the increase of overlying load as a whole.
- For the layered soil, grouting in artificial structured soil layer was the most efficient. Therefore, the grouting should be conducted in the soil layer with higher yield stress or improved soil layers in practice. However, the soil structure could increase the peak grouting pressure and appropriate device should be chosen correspondingly.
- For both artificial structured and overconsolidated reconstituted soils, the final grouting efficiency was significantly improved and then reached a limit of approximately 85%. In the same low yield stress situation, the artificial structured soil had a lower final grouting

efficiency than the overconsolidated reconstituted soil.

- The peak grouting pressure was affected by the yield stress and the overlying load, and could be predicted with an empirical equation when the overlying load was less than the yield stress.

Although the results in this study played a guidance role on compensation grouting, the test data was not directly applied in practical engineering due to the scale effect. It is necessary to conduct field trials to verify the applicability of the findings to field scale conditions.

Acknowledgments

This research was funded by the National Basic Research Program of China (973 Program) under Grant No. 2010CB732106, the Tianjin Construction and Communication Council Project (2012-3 & 2012-5), the National Natural Science Foundation of China under Grant No. 51308389. Their financial support is gratefully acknowledged.

References

Akira, M. and Masahito, T. (1987), "Hydrofructuring pressure of cohesive soil", *Soil. Found.*, **27**(1), 14-22.

Au, S.K.A., Soga, K., Jafari, M.R., Bolton, M. and Komiya, K. (2003), "Factors affecting long-term efficiency of compensation grouting in clays", *J. Geotech. Geoenviron. Eng.*, **129**(3), 254-262.

Au, A.S.K., Yeung, A.T. and Soga, K. (2006), "Pressure-controlled cavity expansion in clay", *Can. Geotech. J.*, **43**(7), 714-725.

Burland, J.B. (1990), "On the compressibility and shear strength of natural clays", *Geotechnique*, **40**(3), 329-378.

Butterfield, R. (1979), "A natural compression law for soils (an advance on e-log p')", *Geotechnique*, **29**(4), 469-479.

Casagrande, A. and Fadum, R.E. (1940), "Notes on soil testing for engineering purposes", *Soil MechanICS SERIES*, **8**, 36-39.

Chen, B., Xu, Q. and Sun, D.A. (2014a), "An elastoplastic model for structured clays", *Geomech. Eng., Int. J.*, **7**(2), 213-231.

Chen, X.P., Luo, Q.Z. and Zhou, Q.J. (2014b), "Time-dependent behaviour of interactive marine and terrestrial deposit clay", *Geomech. Eng., Int. J.*, **7**(3), 279-295.

Cotecchia, F. and Chandler, R.J. (1997), "The influence of structure on the pre-failure behaviour of a natural clay", *Geotechnique*, **47**(3), 523-544.

Essler, R.D., Drooff, E.R. and Falk, E. (2000), "Compensation grouting, concept, theory and practice", *Geotechnical Special Publication*, No. 104, American Society of Civil Engineers, pp. 1-15.

Fearon, R.E. and Coop, M.R. (2000), "Reconstitution: What makes an appropriate reference material?", *Geotechnique*, **50**(4), 471-477.

Harris, D.I., Mair, R.J., Love, J.P., Taylor, R.N. Henderson, T.O. (1994), "Observations of ground and structure movements for compensation grouting during tunnel construction at Waterloo station", *Geotechnique*, **44**(4), 691-713.

Harris, D.I., Pooley, A.J., Menkiti, C.O. and Stephenson, J.A. (1996), "Construction of low level tunnels below Waterloo Station with compensation grouting for Jubilee line extension", *Geotechnical Aspects of Underground Construction in Soft Ground*, Balkema, Rotterdam, The Netherlands, pp. 361-366.

Hong, Z.S., Zeng, L.L., Cui, Y.J., Cai, Y.Q. and Lin, C. (2012), "Compression behaviour of natural and reconstituted clays", *Geotechnique*, **62**(4), 291-301.

Komiya, K., Soga, K., Akagi, H., Jafari, M.R. and Bolton, M.D. (2001), "Soil consolidation associated with grouting during shield tunnelling in soft clayey ground", *Geotechnique*, **51**(10), 835-846.

Kumar, C.P. and ISH, M. (1999), "Evaporation from shallow water table through layered soil profiles", *Indian Soc. Hydraul. J. Hydraul. Eng.*, **5**(2), 65-75.

Lei, H.Y., Zhang, W.Z., Ding, X.D., Wang, X.C., Chen, L. and Huang, M.S. (2013), "Experimental study on secondary consolidation considering structural strength of clay", *Chinese J. Geotech. Eng.*, **35**(7), 1221-1227.

Leroueil, S., Tavenas, F. and Brucy, F. (1979), "Behavior of destructured natural clays", *J. Geotech. Eng. Div., ASCE*, **105**(6), 759-788.

Leroueil, S., Tavenas, F. and Locat, J. (1985), "Correlations between index tests and the properties of remolded clays", *Géotechnique*, **34**(2), 223-226.

Liao, S.M., Shen, M.L., Zhou, L. and Shao, W. (2011), "In-situ experimental study on SDC grouting in Shanghai saturated soft clay", *Geotechnical Special Publication*, 2504-2513.

Liu, M.D. and Carter, J.P. (2000), "Modelling the destructuring of soils during virgin compression", *Geotechnique*, **50**(4), 479-483.

Lorenzo, G.A. and Bergado, D.T. (2004), "Fundamental parameters of cement-admixed clay-New approach", *J. Geotech. Geoenviron. Eng.*, **130**(10), 1042-1050.

Mair, R.J. and Hight, D.W. (1994), "Compensation grouting", *World Tunnel Superf. Excavat.*, **8**, 361-367.

Marchi, M., Gottardi, G. and Soga, K. (2014), "Fracturing pressure in clay", *J. Geotech. Geoenviron. Eng.*, **140**(2), 04013008.

Ni, J.C. and Cheng, W.C. (2010), "Monitoring and modeling grout efficiency of lifting structure in soft clay", *Int. J. Geomech.*, **10**(6), 223-229.

Parsa-Pajouh, A., Fatahi, B., Vincent, P. and Khabbaz, H. (2014), "Analyzing consolidation data to predict smear zone characteristics induced by vertical drain installation for soft soil improvement", *Geomech. Eng., Int. J.*, **7**(1), 105-131.

Schmertmann, J.H. (1991), "The mechanical aging of soils", *J. Geotech. Eng., Proc. Am. Soc. Civ. Engrs.*, **117**(9), 1288-1330.

Schweiger, H.F. and Falk, E. (1998), "Reduction of settlement by compensation grouting numerical studies and experience from Lisbon underground", *Proceedings of the World Tunnel Congress '98 on Tunnel and Metropolises*, Sao Paulo, Brazil, April.

Schweiger, H.F., Kummerer, C., Otterbein, R. and Falk, E. (2004), "Numerical modelling of settlement compensation by means of fracture grouting", *Soil. Found.*, **44**(1), 71-86.

Shirlaw, J.N., Dazhi, W., Ganeshan, V. and Hoe, C.S. (1999), "A compensation grouting trial in Singapore marine clay", *Geotechnical Aspects of Underground Construction in Soft Ground*, Balkema, Rotterdam, The Netherlands, 149-154.

Soga, K., Au, S.K.A., Jafari, M.R. and Bolton, M. (2005), "Laboratory investigation of multiple grout injections into clay", *Geotechnique*, **55**(3), 257-258.

Sun, F., Zhang, D.L., Wang, C., Fang, Q. and Li, B. (2010), "Analysis of raising pipeline by fracture grouting and its application", *Rock Soil Mech.*, **31**(3), 932-938.

Wang, S., Chan, D. and Lam, K.C. (2009), "Experimental study of the effect of fines content on dynamic compaction grouting in completely decomposed granite of Hong Kong", *Construct. Build. Mater.*, **23**(3), 1249-1264.

Wang, Z., Wong, R.C.K. and Heinz, H. (2010), "Assessment of long-term behaviour of a shallow tunnel in clay till", *Geomech. Eng., Int. J.*, **2**(2), 107-123.

Wang, S.Y., Chan, D.H., Lam, K.C. and Au, S.K.A. (2013), "A new laboratory apparatus for studying dynamic compaction grouting into granular soils", *Soils Found.*, **53**(3), 462-468.

Wisser, C., Augarde, C.E. and Burd, H.J. (2005), "Numerical modelling of compensation grouting above shallow tunnels", *Int. J. Numer. Anal. Method. Geomech.*, **29**(5), 443-471.

Xie, K.H., Xie, X.Y. and Jiang, W. (2002), "A study on one-dimensional nonlinear consolidation of double-layered soil", *Comput. Geotech.*, **29**(2), 151-168.

Xu, Z.M., Han, Q.H. and Zheng, G. (2013), "Field monitoring and analysis of effects of metro tunnels under historic buildings", *Chinese J. Geotech. Eng.*, **32**(2), 364-374.

Yi, X.M., Zhang, D.L. and Pang, T.Z. (2009), "Practice and monitoring analysis of building lifting due to grouting", *Rock Mech*., **30**(12), 3776-3782.
Zhang, M., Wang, X.H. and Wang, Y. (2011), "Mechanism of grout bulb expansion and its effect on ground uplifting", *J. Central South Univ. Technol*., (English Edition), **18**(3), 874-880.
Zhang, M., Wang, X.H. and Wu, Y. (2012), "Numerical evaluation of uplifting effect for upper structure by grouting", *J. Central South Univ. Technol*., (English Edition), **19**(2), 553-561.
Zhang, D., Fang, Q., Hou, Y., Li, P. and Yuen Wong, L.. (2013), "Protection of buildings against damages as a result of adjacent large-span tunneling in shallowly buried soft ground", *J. Geotech. Geoenviron. Eng*., **139**(6), 903-913.

CC