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The differences between soil grouting with cement slurry and cement-water glass slurry

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Abstract. Cement slurry and cement-water glass slurry are the most widely applied for soil grouting reinforcement project. The viscosity change of cement slurry is negligible during grouting period and presumed to be time-independent while the viscosity of cement-water glass slurry increases with time quickly and is presumed to be time-dependent. Due to the significantly rheology differences between them, the grouting quality and the increasing characteristics of grouting parameters may be different, such as grouting pressure, grouting surrounding rock pressure, i.e., the change of surrounding rock pressure deduced by grouting pressure. Those are main factors for grouting design. In this paper, a large-scale 3D grouting simulation device was developed to simulate the surrounding curtain grouting for a tunnel. Two series of surrounding curtain grouting experiments under different geo-stress of 100 kPa, 150 kPa and 200 kPa were performed. The overload test on tunnel was performed to evaluate grouting effect of all surrounding curtain grouting experiments. In the present results, before 240 seconds, the grouting pressure increases slowly for both slurries; after 240 seconds the increase rate of grouting pressure for cement-water glass slurry increases quickly while that for cement slurry remains roughly constant. The increasing trend of grouting pressure for cement-water glass is similar to its viscosity. The setting time of cement-water glass slurry obtained from laboratory test is less than that in practical grouting where grout slurry solidifies in soil. The grouting effect of cement-water glass slurry is better than that of cement slurry and the grouting quality decreases with initial pressure.

1. Introduction

Collapses, instability and inrush of clay and water often occur during the construction of tunnel, mining or hydropower engineering caused by soil which has poor strength or permeability. Grouting reinforcement is a useful technique to improve soil properties, specifically to increase strength and durability or to reduce permeability [1-4]. It is a procedure in which grout slurry is injected into soil.

Various grout slurries are used for Grouting reinforcement, which one of them could be used for specific project depending on the purpose of grouting and the properties of the soil. They may range from cement-based grout slurry such as cement slurry, cement-water glass slurry to chemical slurry such as lignin, acrylic, and urea or epoxy resins [5-9]. Although Chemical grout has adjustable gel time, good permeation and flexibility after solidification, it does not have wide applications due to its expensiveness, lower solid strength, and low durability [10]. Furthermore, they could do harmful to surroundings. Cement slurry and cement-water glass slurry are the two most common grout slurries used in soil grouting projects due to their inexpensiveness, wide raw material sources, high solid strength, good durability and well compatible with surroundings.

The rheological characteristics of cement slurry and cement-water glass slurry are remarkably different. The viscosity change of cement slurry during grouting period is not large enough to affect other parameter obviously such as grouting pressure, grout slurry space distribution, so the viscosity of cement slurry is assumed to be time-independent [11]. It will be supposed that viscosity of cement slurry maintains constants throughout the grouting process. However, the viscosity of cement-water glass slurry increases with time quickly and can be adjusted by controlling the constituents [12]. Its time-dependent viscosity has significant effect on other parameters obviously such as grouting pressure; grout slurry space distribution [13].LI shucai et al. [12] studied the rheological behaviour of cement-water glass slurry under different volume ratios between cement slurry and water glass. Based on the results he proposed that the setting process of cement-water glass slurry could be divided into three stages, the low viscosity stage, increase stage and solidify stage. In the initial of mixture, the viscosity increase is relatively slow and remains small, and then the viscosity increased quickly, and fluidity decrease quickly, at last the Cement-water glass slurry solidified and lost fluidity gradually.

Uniaxial compression on grouted cylindrical specimen is probably the most widely performed test on soil used to study the effect of grouting parameters such as soil character, grout slurry, grouting pressure on soil grouting effect. Lohrasb Faramarzi [14] using uniaxial and biaxial compressive test on specimens injected with cement slurry or modified cement slurry with urea-formaldehyde resin as additive to study the effectiveness of grouting on improving the strength characteristics and hydraulic properties of alluvial formation at different curing ages. Anagnostopoulos C A [15] also using uniaxial and biaxial compressive test on specimens of granular soil injected with cement slurry or cement slurry modified with acrylic resin or methyl methacrylate as additives. The experimental results reveal that the addition of latexes in thick pure cement grouts improves substantially the physical and mechanical properties of the injected soil.

Scientific and reasonable theoretical model used to study the grouting reinforcement mechanism of soil have not been successfully proposed because the property of grout slurry and soil and their interaction are complex. However, grouting simulation test has gradually been one of the most important methods in the research of grouting because it can well simulate the complex condition of practical gutting project and the research results is well fitted to practical gutting project. Zhang Z M et al. [16] developed a grouting simulation test device and studied the generation and development of grout balls and fractures in clay with cement slurry. Their result proposed that the fracture grouting in the clay can be divided into three stages: grout ball stage, first fracture surface stage, and following fracture surface stage; every fracture occurs in the weakest surface. LIPENG et al. [17] designed a large-scale test device to simulate the process of splitting grouting in fault fracture zone. According to the experimental study, the grouting splitting process of soil are divided into three stages including the energy accumulation, soil fracturing and slurry energy transfer from the perspective of energy dissipation based on the grouting pressure versus time curves.

These previous studies were mainly focused on mechanical parameters of grouted soil specimens injected with cement based slurries or diffusion characteristic of cement based slurries injected into soil; however, few studies have been performed on the effects of on cement slurry or cement-water glass slurry on grouting pressure, grouting surrounding rock pressure (i.e., variation of surrounding rock pressure by grouting) or grouting quality, nor the comparison between them. All of them are important factors for design of grouting plan, especially for evaluating the effect of grouting quality.

In this paper, a large-scale 3D grouting simulation device was developed to simulate the grouting process. Two series of surrounding curtain grouting experiments under different geo-stress of 100 kPa, 150 kPa and 200 kPa were performed. One of the series of grouting experiments injects cement slurry and another series injects cement-water glass slurry. After seven days of solidification of grouting slurry, a tunnel was excavated. Then an overload test was performed in order to investigate the grouting quality. Based on the grouting pressure, grouting surrounding rock pressure obtained during grouting, the effect of viscosity on them was analysed. Based on the tunnel deformation obtained from the overload test, comparison of grouting quality between the two slurries was also analysed.

2. Grouting experiment design

2.1. Grouting device

To simulate the grouting process, a large-scale 3D grouting simulation device was developed which is shown in Figure 1. This device includes two parts: hydraulic servo controlled loading system with a maximum load capacity of 500 kPa and maximum load trip of 25 cm and grout box with Internal dimensions of 120cm in length, 60cm in width and 100 cm in height. The load steel plate used to compact the soil directly is 159.5cm long, 59.5cm wide and 2cm thickness. A hole of 20cm in diameter drilled in the front and back wall of the soil box serving as the tunnel entrance and tunnel exit respectively. Both of the holes are situated in the middle of the walls and 20cm from the bottom of the soil box. They are covered by a steel plate until the tunnel excavation starts. A hand fork lifter is needed for moving the grout box during grouting experiments.

The data acquisition system and grouting system is needed for the experiments. The data acquisition system includes grouting pressure sensors, surrounding rock pressure sensors, and tunnel displacement sensors and data acquisition instrument. Those dates are recorded by a computer in interval of 0.5 s. One thing should be noted is that the magnitude of surrounding rock pressure obtained is only caused by grouting pressure, i.e., not including the initial surrounding rock pressure induced by the initial pressure and gravity. Grouting system includes a manual double liquid grouting pump, grouting pipes and some valves.

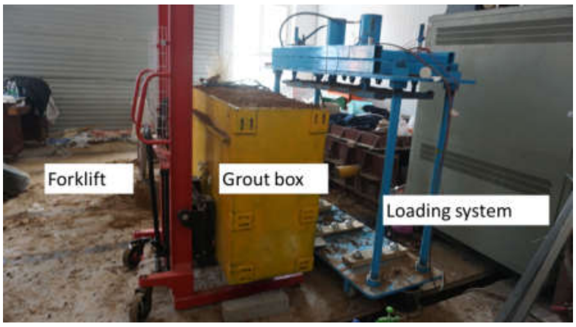

Figure 1. Grouting device

2.2. Grouting experiment cases

The Buried depth in grouting box is far less than the tunnel buried in test case is far less than the actual grouting project. It is difficult to achieve higher geo-stress level and soil compaction degree only by test soil self-gravity. Therefore, the stress levels in the actual stratum are simulated by applying a certain vertical pressure on the test soil using the ground stress system, and the test soil with larger density is obtained. Soil density is the key factor influencing the grouting effect. In most cases, grouting effect increases with increasing the soil density. In order to make the experiment universal, three kinds of ground stress levels, 100kPa, 150kPa and 200kPa, are used to simulate the strata with different density. Table 1 shows the soil density under different geo-stress.

Table 1. Soil density under different geo-stress

Geo-stress(kPa)	void ratioe	dry densityρd (g/cm3)
100	1.01	1.34
150	0.94	1.39
200	0.88	1.43

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Under the condition of each geo-stress level, there are two grouting cases including injecting cement slurry and cement water glass grout. All the grouting cases apply the same grouting slurry volume and grouting rate. The grouting case number and grouting parameters are shown in Table 2.

Table 2. Test case number and its specific parameters

Case number	Geo-stress P_0/ kPa	Grouting volume/ L	Single hole grouting capacity /L	Average grouting rate q /((L/min)
SN-100	100	64	8	2.6
CS-100	100	64	8	2.6
SN-150	150	64	8	2.6
CS-150	150	64	8	2.6
SN-200	200	64	8	2.6
CS-200	200	64	8	2.6

Note: In the case number, "SN" means the cement slurry grout is injected; the "CS" indicates the injection of cement-water glass grout

2.3. Test material

2.3.1. Test soil, the test soil was taken from a Construction pit in Shandong University Jinan City, Shandong Province, China. Impurities such as broken stones and hard soil blocks were removed out by sieving the test soil before used to improve its homogeneity. Clay content is 42.9%, powder content is 38.9%, sand content is 18.2%, control particle size d60=0.0125mm, effective particle size d10=0.0009mm and d30=0.0035mm, uneven coefficient Cu=13.8, curvature coefficient Cc=1.1. The soil is well graded clay. Figure 2 shows the grain grading curve of the soil. The basic properties of the soil are tabulated in Table 3.

Table 3. Basic physical properties of test soil

parameter	unit	value
specific gravity	g/cm_3	2.6
maximum dry density	g/cm_3	1.6
optimum moisture	%	18
plastic limit	%	16
liquid limit	%	40.8
plastic index	%	22.3
moisture content	%	20.1

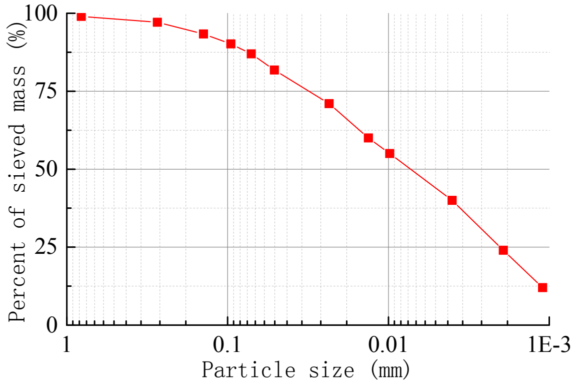


Figure 2. Soil particle gradation curve

The moisture content of the test soil is 23.1% by the drying method. The liquid plastic limit test of the test soil was carried out by the combined liquid plastic limit tester. The liquid limit of the test soil was w_L=40.8%, the plastic limit was w_p=22.3%, and the water content was 20.1.

2.3.2. Grouting slurry, (1) Cement slurry, locally available Portland cement was used to prepare cement grout. The cement was mixed with water at a water/cement weight ratio of one. As its viscosity variable quantity are so small during injecting that it can be seen as a constant in most cases. The properties of the cement grout material are tabulated in Table 4. The mechanical parameters of the cement slurry were determined at seven days setting period in natural conditions, which was the same with the Cement-water glass slurry.

Table 4. Basic properties of cement material

Parameter	Unit	Value
Water cement ratio in weight	1	1
Density	g/cm^3	1.5
Initial setting time	h	14
Final setting time	h	25
Apparent viscosity	mPa.s	19
Uniaxial compressive strength	Mpa	5.9
Young's modulus	Gpa	0.41
Poison's ratio	1	0.24

(2) Cement-water glass slurry

Cement-water glass slurry is a mixture of cement slurry and water glass in the certain proportion. Cement slurry and water glass usually begin to be mixed together in the injection pipe or rock. The volume ratio of cement slurry to water glass is one. The property of cement slurry used in Cement-water glass slurry is listed in Table 5, the Baume degree of water glass is 38 and the apparent viscosity versus time curve is shown inFigure 3. The mechanical parameters of the Cement-water glass slurry were determined at a setting period of seven days in natural conditions which was the same with the cement slurry.

Table 5. Basic properties of cement-water glass slurry

parameter	unit	value
uniaxial compressive strength	Mpa	6.2
Young's modulus	Gpa	0.39
Poison's ratio	1	0.25

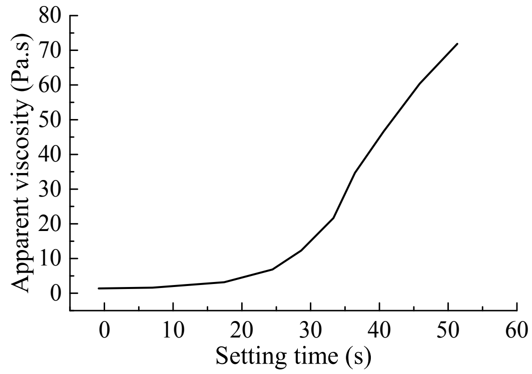


Figure 3. Viscosity versus time curve of Cement-water glass slurry

2.4. Grouting plan

The prefabricated eight grouting mesh tubes are pushed into the soil interior in turn after finishing filling soil and applying geo-stress. Grouting rate, grouting end pressure and grouting slurry volume are important parameters for controlling grouting. Considering the reality of grouting simulation test, the constant grouting rate and constant grouting slurry volume for each mesh tube was adopted.

Considering the fact that jump hole grouting is often used, and the distance between grouting holes is larger, the possibility of grouting between different grouting holes is less. As the grouting time for single grouting hole is long, the grout injected in the pre-grouting hole is in the initial solidification or solidification state when the next grouting hole starting grouting. For better close to the engineering practice, jump hole grouting is adopted; the interval time between adjacent order mesh tubes is greater than the initial setting time of grouting slurry. Cement grout initial setting time is about 14h, cement water glass slurry solidification time for a few seconds to a few minutes. Figure 4 shows the number and order of grouting mesh holes.

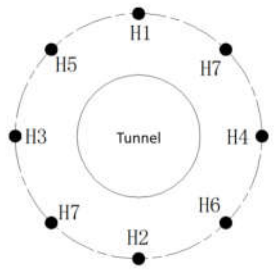


Figure 4. Sketch map of grouting mesh holes

2.5. Tunnel excavation plan

The tunnel was excavated with full face excavation method when the setting time of slurries in the test soil was seven days. The whole tunnel length was divided into six sections and these sections were excavated in turn.

2.6. Data monitoring plan

2.6.1. Grouting pressure and grouting rock pressure, It' s known that grouting rock pressure which was induced by grouting pressure is closely related to monitor positon. In the present grouting experiments, the grouting surrounding rock pressure of the tunnel center was most likely largest and could reflect grouting compaction more reasonable. So there are two surrounding rock pressure sensors Imbedded in the position. The mean values of the results were calculated as surrounding rock pressure (see Figure 5).

Figure 5. Imbedded grouting rock pressure sensors

2.6.2. Tunnel deformation plan, Tunnel deformation can be a better response to the strength of grouting reinforced soil. Smaller tunnel deformation inductees better effect of grouting. Four monitoring point was designed, and the specific location and identification number of each monitoring point is shown in Figure 6. Two deformation sensors in the front and back of the tunnel were used for monitoring horizontal deformation and two deformation sensors in the middle of the tunnel were used for monitoring vertical displacement.

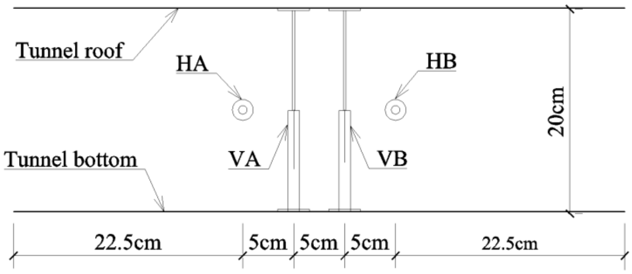


Figure 6. Arrangement and number of Displacement sensor

2.7. Overload test plan

The overload test of the tunnel was started after the variation of each deformation sensor is less than 0.1mm/min. The overload test applies step loading method and the loading step is approximate 10 *kPa*. If the variation of each deformation sensor is less than 0.1mm/min, the deformation of the tunnel is considered as stable and then applies the next level of load. This procedure is repeated until the overload reaches 80 *kPa*. The deformations of the tunnel and the corresponding overload during the overload test were recorded automatically by computer.

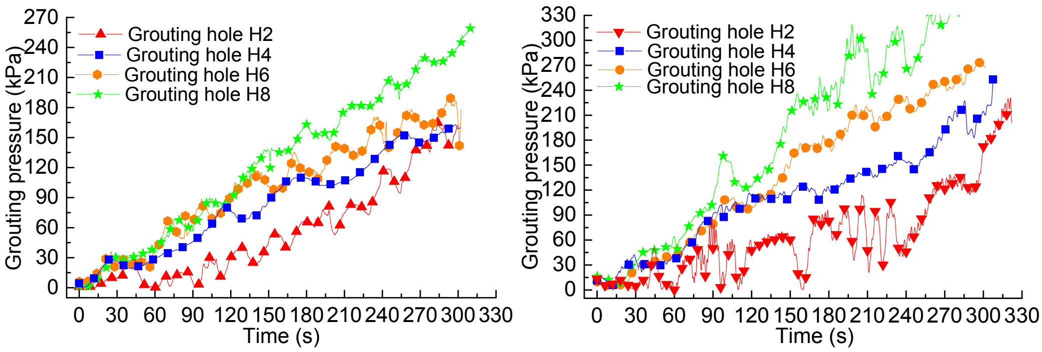
3. Experiment data analysis

3.1. Grouting pressure

The curves grouting pressure versus time under different geo-stress are shown in Figure 7. The values and increase tendency of grouting pressure for both cement slurry and cement-water glass slurry are similar before around 240 seconds, while they are significant difference after 240 seconds. Before 240 seconds, the grouting pressure increases slowly for both slurries. After 240 seconds, the increase rate of grouting pressure for cement-water glass slurry increases quickly while that for cement slurry remains roughly constant.

During flowing of grouting slurry into soil, the grouting pressure roughly equals to the sum of flow resistance caused by the viscosity of grouting slurry and soil resistance existing in grouting front and caused by splitting the soil off. As stress concentration exists in the grout front, smaller pressure can split the soil off. This kind of pressure remains roughly constant, which is closely related with surrounding rock stress and less related with the rheological property of grouting slurry under splitting condition. Hence soil resistance cannot result in remarkable deviation between the two grouting pressures. Considering that the viscosity of cement slurry remains roughly constant while the viscosity of Cement-water glass slurry increased quickly after some certain time during grouting period, the difference of viscosity between the two grouting slurries could attributed to remarkable difference between grouting pressure of the two grouting slurries.

By comparing the curves of grouting pressure versus time in Figure 7 and the curve of viscosity versus time curve of Cement-water glass slurry in figure 3, it can be concluded that their variation trend is similar. The threshold time after which viscosity increases quickly is around 30 s while that for grouting pressure is around 240 seconds. This apparent difference could indicate that the setting time obtained from laboratory test is less than that in practical grouting environment where the grout slurry components are mixed in soil.



(a) SN-150 (b) CS-150

Figure 7. Grouting pressure curves

3.2. Features of slurry diffusion

Figure 8 and Figure 9 shows the features of slurry veins and bulbs of grouted soils with cement slurry and Cement-water glass slurry under initial presser of 150 kPa respectively. The other two groups under geo-stress of 100 and 150 kPa were not shown here and they have similar features of space distribution of grouting slurry solid with the initial pressure of 150 kPa. As it can see from Figure.9 and Figure.10 that the interface between the soil and grouting slurry solid is clear and distinct and no obvious signs of permeation of grouting slurry were observed. According to this it can be concluded that the cement based grouting slurries used here mainly enter into soil by means of splitting or compacting soil rather than permeating due to that the porosity size of the test soil is not big enough for cement particles to enter into.

(a) Slurry veins in tunnel (b) Slurry veins around grouting hole H2

Figure 8. Cement slurry diffusion (SN-150)

(a) Slurry veins in tunnel (b) Slurry veins nest to grouting hole H2

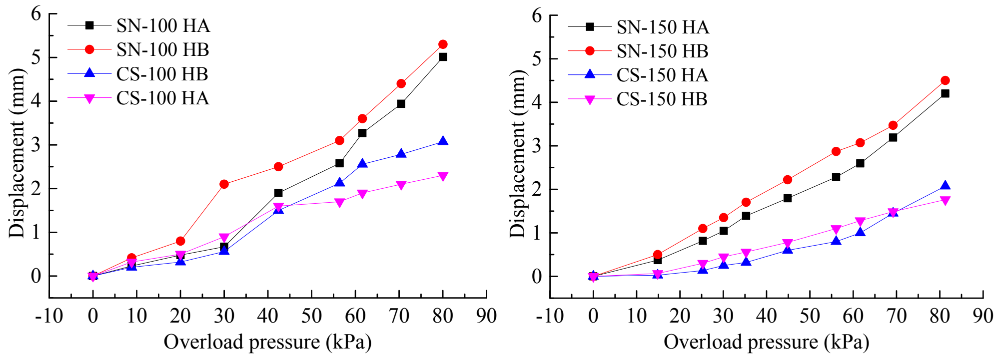
Figure 9. Cement-water glass slurry diffusion (CS-150)

3.3. Tunnel deformation

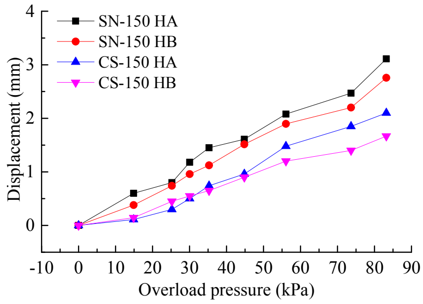
There are mainly two ways to determine the mechanical parameter improvement of grouting soil. One way is using laboratory tests such as uniaxial compression test, triaxial compression test or direct shear test to determine unconfined compressive strength, elasticity modulus, poison ratio, internal friction angle ratio or cohesion of specimens drilled out or cut from the grouted soil; the other way is analysing the deformation of the surrounding rock. The former is quantitative precise. As the tested volume of specimen is far less than that of grouted soil, it may cause larger discreteness of the experimental data due to the inhomogeneity of the grouting soil. Consequently, laboratory tests results could not reflect the mechanical parameter improvement of grouting soil properly. The latter is qualitative but can well reflect the relative mechanical parameter improvement of grouted soil. So the deformation of the surrounding rock is very useful for comparative purposes, for example, checking the grouting reinforcement effect.

The curves of horizontal displacement of tunnel versus overload pressure under different geo-stress were shown in Figure 10 and the curves of vertical displacement of tunnel versus overload pressure were shown Figure 11.From both Figure 10 and Figure 11, it can be concluded that the vertical and horizontal displacements of grouted soil with cement slurry is larger than that of grouted soil with Cement-water glass slurry and decrease with initial pressure.

It is known that soil structure is a main factor influencing its strength. When the soil structure is disturbed by grouting, the grouting soil strength has a tendency to decrease. When grouting slurry enters into soil by splitting or compaction, it is inevitable to disturb the soil structure. Consequently, the extension of grouting slurry implies the degree of disturbing the soil structure. Furthermore, larger degree of grouting compaction indicates less degree of disturbing the soil structure or larger degree of extension of grout slurry indicates larger degree of disturbing the soil structure. This could be the reason that grouting reinforcement quality for cement silicate slurry is better than that of cement slurry. With the increasing of overloading pressure, the degree of soil structures increases and more difficulty to compact. This could be one of the reasons that grouting reinforcement effect decreases with geo-stress.

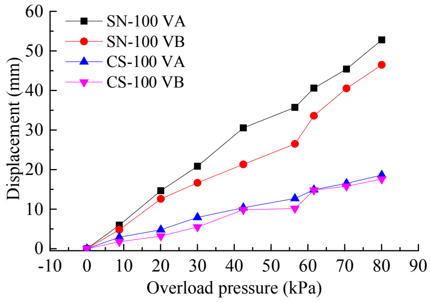


(a) Geo-stress 100kPa (b) Geo-stress 150kPa

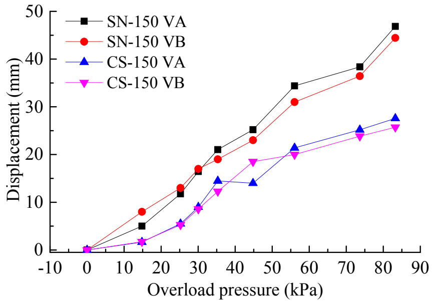


(c) Geo-stress 200kPa

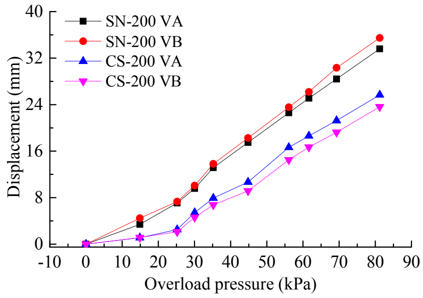
Figure 10. The relationship between horizontal displacements and overload pressure



(a) Geo-stress 100kPa



(b) Geo-stress 150kPa



(c) Geo-stress 200kPa

Figure 11. The relationship of vertical displacement to overload pressure

4. Conclusion

To investigate the grouting quality and the increasing characteristics of grouting parameters of cement slurry and cement-water glass, a large-scale 3D grouting simulation device was developed. The device can perform surrounding curtain grouting for a tunnel to obtain grouting pressure, grouting surrounding rock pressure data during grouting period.it can also preform overload test for a tunnel to evaluate the grouting quality. From the present results of grouting reinforced soil with cement slurry and cement-water glass slurry under different initial pressure of 100 kPa, 150 kPa and 200 kPa, the following conclusions can be summarized:

(1) Before four minutes, the grouting pressure increases slowly for both slurries; After four minutes the increase rate of grouting pressure for cement-water glass slurry increases quickly while that for cement slurry remains roughly constant. The increasing trend of grouting pressure for cement-water glass is similar to its viscosity trend.

(2) The cement based grouting slurries used here mainly enter into soil by means of splitting or compacting soil rather than permeating due to that the porosity size of the test soil is not big enough for cement particles to enter into.

(3) Before around 2 minutes, the grouting rock pressure for cement slurry and Cement-water glass slurry are nearly zero; after around two minutes, they increase quickly. But the increase rate of grouting pressure for cement-water glass slurry increases quickly while that for cement slurry remains roughly constant.

(4) The grouting quality of cement-water glass slurry is better than that of cement slurry and the grouting quality decreases with initial pressure. This could be attributed to soil structure.

(5) The setting time of cement-water glass slurry obtained from laboratory test is less than that in practical grouting environment where the grout slurry solidifies in soil.

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