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TECHNICAL NOTE

Kai Fang,[1] *Zhongmiao Zhang,*[1] *Jian Zou,*[2] *and Zhijie Wang*[1]

Laboratory Studies on Pressure Filtration in Post-Grouting of Drilled Shaft Tips in Clay

ABSTRACT: Practice has proved that significant tip capacity improvement can be realized through pressure grouting for drilled shaft tips in clay. A comprehensive series of laboratory model experiments were conducted in order to study the influence of pressure filtration on tip improvement and provide an insight into the influence factors of pressure filtration. The fundamental variables that could affect pressure filtration behavior, including filtration pressure P, water cement ratio w_i, and clay thickness H were studied in these experiments. Results indicate that the velocity of pressure filtration is determined by the velocity of water through clay. The final water cement ratio of grout is maintained at about 0.3 after the pressure filtration process regardless of the initial water content under the pressures of 75–225 kPa. Atomic absorption spectrometry and scanning electron microscopy were used to study the mechanism of exchange of cations. The analyses reveal that the Ca^{2+} ions from cement grout exchange with Na^{+} and K^{+} adsorbed in clay particles. The separated clay particles become more close to each other after the exchange of cations. In addition, the results of laboratory direct shear tests show that the shear strength of the clay after pressure filtration is also increased due to the compression of the clay and the exchange of cations.

KEYWORDS: pressure filtration, post-grouting, model experiment, clay

Introduction

Pressure grouting the shaft tip after its construction has been successfully employed throughout the world. It has been a common practice when the shafts are designed to carry a significant end-bearing load. After the concrete in the shaft has cured, the cement grout can be transported to the region around the shaft tip, which both densifies the in situ soil and compresses any debris left by the drilling process. Practice has proved that significant tip capacity improvement can be realized through pressure grouting (Dapp and Mullins 2002; Fu and Zhou 2003; Mullins and Winters 2004).

Pressure filtration or so-called dehydration or bleeding from grout is exudation of water from grout during pressure grouting. When the grain size of the cement is greater than the opening size of the soil, water is squeezed out from pores between cement particles into the ground (see Fig. 1). It will greatly influence the behavior of the grouted shaft, especially the reinforcement of the shaft tip. Therefore, it is necessary to have a fundamental understanding of the pressure filtration in post-grouting of drilled shaft tips and its factors.

Much effort has been made to account for the pressure filtration in sand (Bezuijen et al. 2007; Bezuijen et al. 2009; Gafar and Soga 2006; Khodaverdian and McElfresh 2000; Kleinlugtenbelt 2005; Mollamahmutoğlu et al. 2007; Zebovitz et al. 1989). However, the pressure filtration in sand is different from that in clay. Since the pressure filtration in sand is relatively simple and basic and the permeability of clay is much lower than that of sand, the results of cement grout in sand cannot be simply applied to that in clay.

In this paper the results of load test conducted on grouted shaft and ungrouted shaft tipped in clay are presented at first. The performance of end-bearing was compared to show the effectiveness of the grouting. Then a comprehensive series of laboratory model experiments was conducted in order to provide an insight into the influential factors of pressure filtration. In addition, the influence of the squeezed water on the clay strength was also considered by a series of experiments.

Case Study—Grouted Shaft in Clay

The mechanism and the affecting factors of the improved capacity of the post-grouted drilled shafts have drawn geotechnical engineers' attention in the past decades (Bruce 1986; Fleming 1993; Mullins and Winters 2004). Analysis on case histories indicated that post-grouting can effectively increase bearing capacity and reduce head settlements for the drilled shaft in gravel and sand. But few of them focused on the grouted shaft in clay. Therefore, a case study is selected to examine the behavior of grouted shaft tipped in clay.

The shafts with a diameter of 1000 mm and length of 68 m were located at a test site in Wenzhou, China. Maintained load tests were carried out on test piles S1 (conventional pile) and S2 (grouted pile with cement consumption of 1200 kg and grouting pressure of 1.5 MPa), and loading and unloading requirements were based on the typical criteria recommended by the Chinese

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[1]Institute of Geotechnical Engineering, Zhejiang Univ., Hangzhou 310058, China.
[2]Fujian Electronic Power Survey and Design Institute, Fuzhou 350003, China.

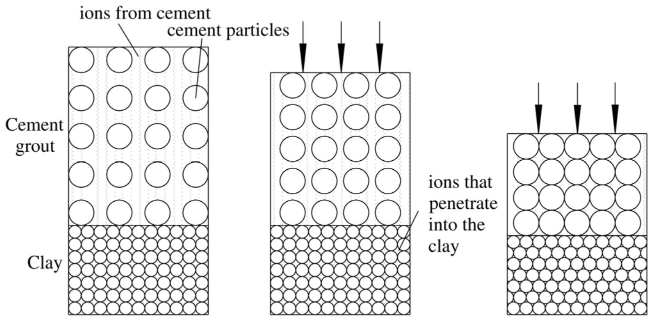

FIG. 1—*Schematic of pressure filtration.*

Technical Code for Testing of Building Foundation Piles. The results are shown in Fig. 2.

As shown in Fig. 2, the shaft S1 fails by the tip punching into the bearing layer with a settlement of 113 mm when the applied load reaches 11 000 kN. So its ultimate capacity can be assumed to be 10 000 kN. For grouted shaft S2, the accumulated head settlement is only 25 mm at the applied load of 12 000 kN, and its ultimate capacity is at least 20% larger than that of the conventional shaft.

The tip load-displacement curves of the two shafts are shown in Fig. 3. It can be found that the base stiffness of the shaft increases after grouting, such that significant tip capacity improvement can be realized within the service displacement, as the studies in sand (Mullins et al. 2000). It indicated that the grout compacted and split the surrounding soil to strengthen them under pressure. However, due to the differences in permeability, the grout cannot permeate into the clay and only water is removed from the fresh cement suspension by pressure filtration. In order to analyze the pressure filtration of cement grout against clay, model experiments were designed and performed.

Model Experiments

Experiment Apparatus

The experiments were similar to consolidation tests with bottom drainage only. Figure 4 gives the apparatus of the experiments of

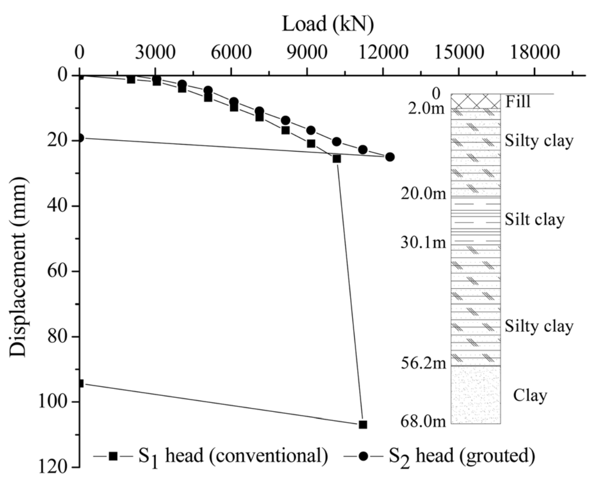

FIG. 2—*Load displacement behaviors of shafts with and without post-grouting.*

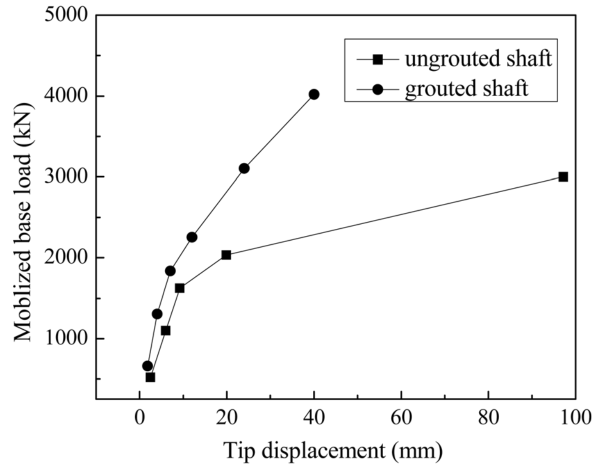

FIG. 3—*Load-displacement curves of the shaft tip.*

pressure filtration. A cylinder container with an inner diameter of 0.1 m and a height of 0.2 m was used for the experiments. As shown in Fig. 4, the water can be drained from the bottom of the apparatus. The cement grout was loaded using air pressure and a PVC plate was placed on the top of the fresh cement grout to prevent uneven displacement of cement grout. Rubber seal and Vaseline were used to prevent the cement grout from escaping through the contact between the container and the PVC plate.

The cement used in the experiments was normal 32.5 R Portland cement (PC). Table 1 contains the typical chemical compositions by weight and the physical properties of PC, based on the manufacturer's data.

The clay used in the experiments was from the Xiaoshan brick factory, so-called Xiaoshan clay, which was coastal sedimentary soil. Tables 2 and 3 provide the physical properties, chemical properties and mineral constituents of Xiaoshan clay, respectively.

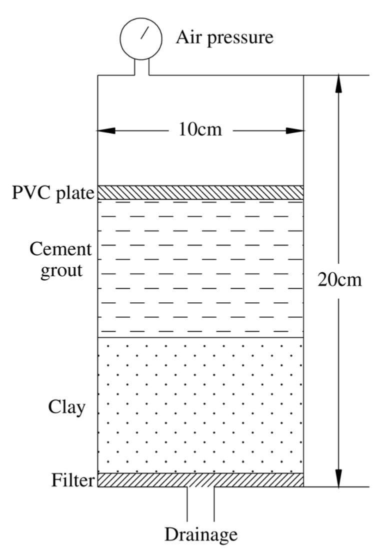

FIG. 4—*Experiment apparatus.*

TABLE 1—*Typical chemical and physical properties of PC.*

Cement	SiO_2, %	Al_2O_3, %	Fe_2O_3, %	CaO, %	MgO, %	SO_3, %	Surface Area, m^2/kg
PC	21.50	5.88	3.67	60.20	1.82	2.46	378

Experimental Procedures

First, a porous stone was placed at the bottom of the container. Then, a certain amount of clay, depending on the required thickness, was placed into the container and was densified in layers to natural density. The amount of soil mass for each layer was weighed before being placed in the container to achieve the required natural density. After that, enough water was added to the container to make sure the clay was in a nearly saturated condition. In this way all the squeezed water could be collected and measured during the course of experiment. Moreover, the permeability of the soil was measured approximately after its saturation using the experiment apparatus to guarantee the consistency of the soil for different experiments. Then a certain amount of mixed cement grout was transferred into the container and covered with the PVC plate. The rest of the apparatus was then assembled. During the process of pressure filtration, the amount of squeezed water was measured. The experiments stopped when there was no more squeezed water from the bottom drain of the container within 5 min. The finish time of the experiment can be defined as the duration of the drainage.

Experiment Results and Analysis

When the air pressure was exerted on the PVC plate, the water, which was transparent and colorless with a density of 1.01 g/cm^3, drained out of the hole in the bottom. It also can be observed that no cement particles existed in the clay.

The fundamental variables that could affect pressure filtration behavior, including filtration pressure p, water cement ratio w_i, and initial clay thickness H were studied by experiments. Table 4 shows the test parameters and results of the experiments. Where Q_f is the final amount of the squeezed water, H' is the final thickness of the clay layer, L is the grout thickness, w_f is the final water cement ratio of the grout, and t_f is the finish time of experiment.

Typical Filtration Curve

Figures 5 and 6 present the filtration curves for various initial water cement ratios and various clay thicknesses. They show that the amount of squeezed water Q increases with time up to the peak value Q_f and maintains at this value. At the initial stage of the pressure filtration, the curves are nearly linear. The nonlinearity part can be contributed by the decrease of clay permeability during consolidation.

It can be found from the two figures that the velocity of pressure filtration depends on the clay thickness and is independent of the water cement ratio of the grout. This means the velocity of pressure filtration is dominated by the velocity of water through clay, i.e., the permeability of the clay. These observations appear to be consistent with Gustin's conclusion that the velocity depends on the permeability of the filter (Gustin et al. 2007).

In order to study the influence of initial water cement ratio and pressure, the results in Table 4 are selected for comparison in Figs. 7 and 8.

Figure 7 shows that the final water cement ratio of the grout is maintained at about 0.3 after pressure filtration regardless of the initial value. Similar results were found in the research conducted by Bolton and Mckinley (1997), who reported a mean value 0.35 for ordinary Portland cement. Another conclusion that can be drawn from Fig. 7 is that the finish time increases with increasing initial water cement ratio. It indicates that the extra water is squeezed by pressure filtration until the water cement ratio reaches about 0.3.

Grouting pressure has a significant influence on the interaction between the grout and soil (Mullins et al. 2005; Yin and Zhou 2009). Figure 8 shows the influence of filtration pressure on the final water cement ratio and finish time. It can be found from Fig. 8 that the filtration pressure cannot change the final water cement ratio, which also stabilized at about 0.3. But the finish time can be affected by filtration pressure. That is, the pressure filtration process can be sped up under high pressure.

In Fig. 9 the void ratio e after pressure filtration under various filtration pressures is presented. As the filtration pressure increases, the void ratio decreases. It shows that the gout can compact and consolidate the soil under pressure, which is one explanation for improvement in base stiffness.

Microstructure Analysis of Clay Strength Improvemets By Pressure Filtration

The main constituents of common Portland cement are tricalcium silicate ($3CaO{\cdot}SiO_2$), dicalcium silicate ($2CaO{\cdot}SiO_2$), tricalcium

TABLE 3—*Chemical properties and mineral constituents of Xiaoshan clay.*

Soil	Organic Matter Content, %	PH	Main Clay Minerals Content, % Montmorillonite	Illite	Kaolinite
Xiaoshan clay	0.6	7.79	10	15	10

TABLE 2—*Physical properties of Xiaoshan clay.*

Soil	Natural Density, $\rho/(g \cdot cm^{-3})$	Natural Water Content, w/%	Specific Weight, G_S	Liquid Limit, w_L/%	Plastic Limit, w_P/%	Particle Composition, % Clay	Silt	Sand
Xiaoshan clay	1.76	41.3	2.72	52.7	26.3	57	35	8

TABLE 4—*Details and results for the filtration experiments.*

Test	w_i	w_f	P, kPa	H, cm	H', cm	L, cm	t_f, s	Q_f, g
T01	0.6	0.276	150	4	3.57	6	330	146
T02	0.6	0.287	150	5	4.47	6	420	141
T03	0.6	0.283	150	6	5.45	6	440	143
T04	0.6	0.267	150	7	6.32	6	490	150
T05	0.6	0.259	150	8	7.29	6	560	154
T06	0.6	0.265	150	9	8.19	6	630	151
T07	0.6	0.287	75	6	5.81	6	680	141
T08	0.6	0.267	100	6	5.70	6	510	150
T09	0.6	0.261	125	6	5.54	6	470	153
T10	0.6	0.263	175	6	5.36	6	380	152
T11	0.6	0.305	200	6	5.29	6	310	133
T12	0.6	0.294	225	6	5.25	6	300	138
T13	0.7	0.301	150	6	5.43	6	480	158
T14	0.8	0.288	150	6	5.40	6	660	231
T15	0.9	0.309	150	6	5.41	6	720	267
T16	1.0	0.304	150	6	5.42	6	750	313
T17	0.6	0.267	150	6	5.45	5	400	125
T18	0.6	0.300	150	6	5.43	7	580	180
T19	0.6	0.292	150	6	5.41	8	620	185
T20	0.6	0.307	150	6	5.40	9	720	198

aluminate ($3CaO{\cdot}Al_2O_3$), and calcium ferrite aluminate ($4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$), among which $3CaO{\cdot}SiO_2$ and $2CaO{\cdot}SiO_2$ consist up to 65–85%. When the Portland cement is mixed with water, hydrolysis and hydration reaction take place, and subsequently a large amount of Ca^{2+} ions are generated.

During the pressure filtration process, the Ca^{2+} ions spread with the squeezed water into the clay. Higher valence cations can easily replace lower valence cations, then the Ca^{2+} ions exchange with Na^{+} and K^{+} adsorbed in clay particles. Because the absorbed layer of water would be thinner when the valence of the cation is larger (Ranjan and Rao 2005), the thickness of the electric layer can be reduced and the soil particles can move close to each other.

In order to confirm this mechanism, atomic absorption spectrometry (AAS) and scanning electron microscopy (SEM) were used to conduct further research.

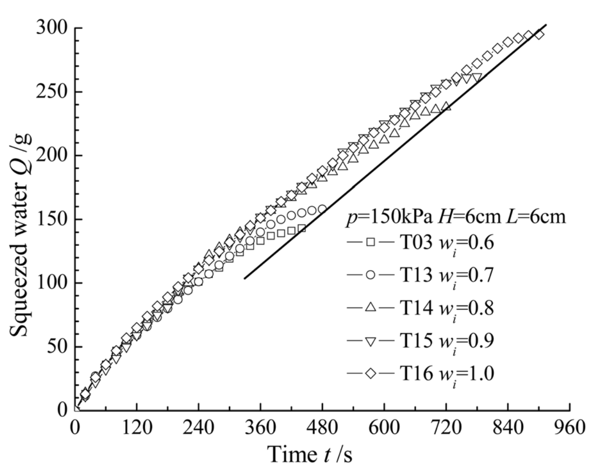

FIG. 5—*Filtration curves in various initial water cement ratio* w_i.

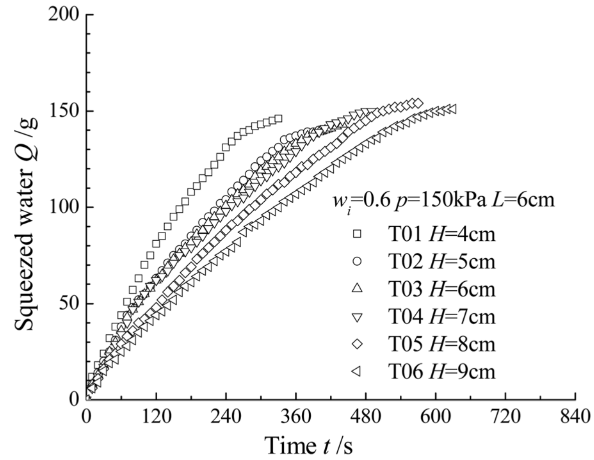

FIG. 6—*Filtration curves in various clay thickness* H.

Results of AAS Tests

The squeezed water (collected from test T03) and the filtered cement solution (water cement ratio 0.6) were analyzed by AAS tests. The results showed that the Ca^{2+} ions concentration decreased from 1836 mg/l in the filtered cement solution to 567.6 mg/l in the squeezed water, while the K^{+} ions increased from 294.5 to 1160.4 mg/l. So it proved that the Ca^{2+} ions had exchanged with K^{+} and other ions adsorbed in clay particles.

Results of SEM Tests

Three samples, natural Xiaoshan clay, consolidated Xiaoshan clay (at the pressure of 150 kPa), and pressure filtrated Xiaoshan clay (from test T03) were analyzed by SEM tests.

Figure 10 shows the SEM image of natural Xiaoshan clay with 1000-fold magnification. It can be seen in Fig. 10 that the natural Xiaoshan clay is of flocculent structure, and the soil is deposited in a loose state.

Figure 11 shows the SEM image of consolidated Xiaoshan clay with 1000-fold magnification. It can be seen in Fig. 11 that the porosity between the clay particles is significantly reduced after consolidation. However, the connection are still not tight

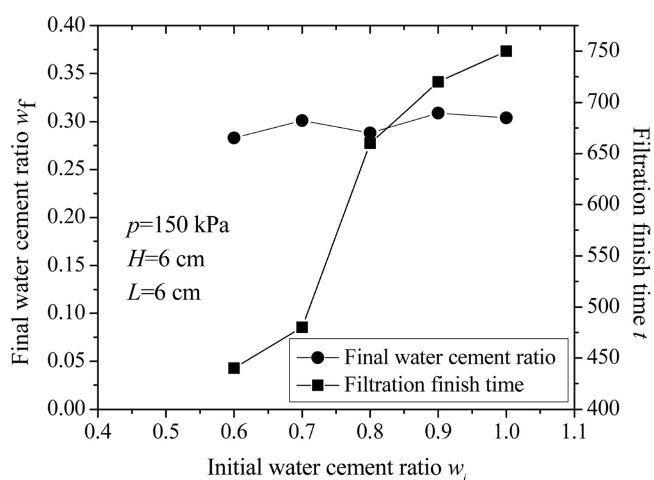

FIG. 7—*Plot of* w_i *against* w_f *and* t.

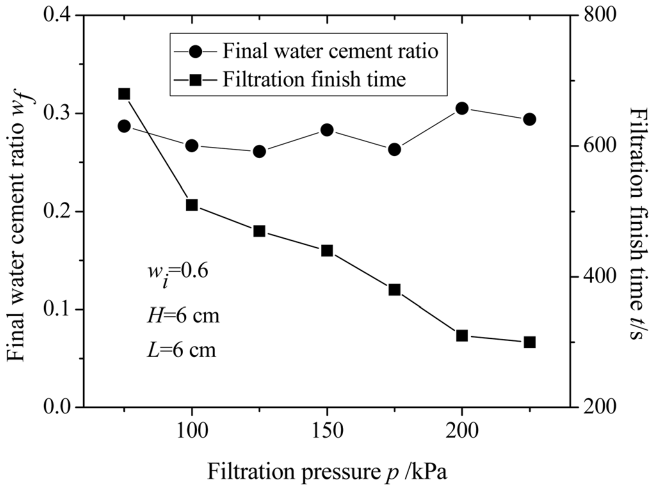

FIG. 8—*Plot of p against* w_f *and t.*

enough, for the shapes of most clay particles can be clearly distinguished.

Figure 12 shows the SEM picture of pressure filtrated Xiaoshan clay with 1000-fold magnification. It can be seen in Fig. 12 that the separated clay particles become more close to each other and form clay agglomerates after pressure filtration, which can improve the soil strength further.

Shear Strength of Clay After Pressure Filtration

In order to further study the influence of pressure filtration on the strength improvement of the clay, a series of laboratory direct shear tests without vertical pressure were conducted on the clay after pressure filtration under different filtration pressure. In addition, other experiments with cement grout replaced by water were conducted to examine the effect of the exchange of cations. The amount of the water used in the experiment was equal to the squeezed water of cement grout. The shear strength of the clay after pressure filtration with water was also obtained by the direct shear tests. The results are shown in Fig. 13.

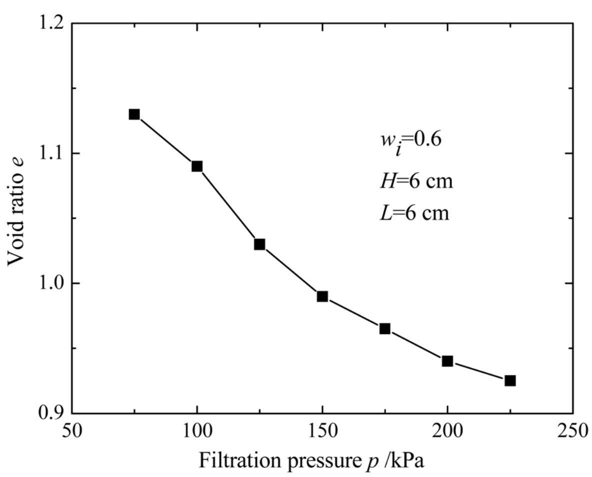

FIG. 9—*Plot of p against e.*

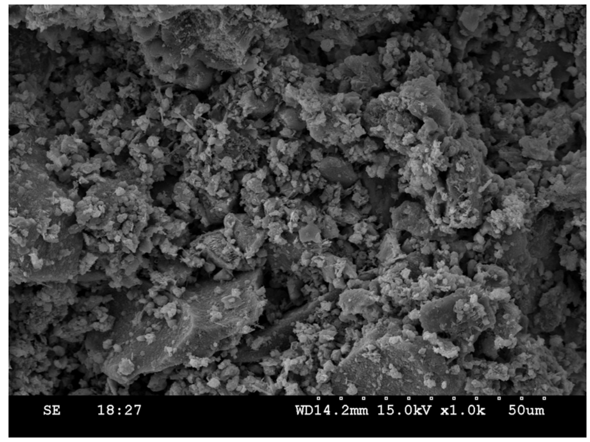

FIG. 10—*Flocculent structure of natural Xiaoshan clay.*

It can be noted from Fig. 13 that shear strength of clay increases with the increasing filtration pressure. This is not surprising in view of the fact that the clay can be precompressed during the process of pressure filtration. It also can be found that the shear strength of the clay after pressure filtration with cement grout is higher than that with water. The difference is particularly significant under higher pressure. It indicates that the strength improvement due to the exchange of cations is more pronounced under high pressure.

Discussion

The grout is injected at high pressure to densify the soil around the shaft tip. When the grouting pressure is equal to the soil split pressure, the grout splits or fractures the surrounding soils and mixes with the soil to strength them. As indicated in the preceding sections, the pressure filtration of grout can compact and consolidate the soil. However, for fracture grouting, the fracture length is particularly affected by pressure filtration for it is one cause for stagnation of the fracture propagation (Murdoch 2002; Bezuijen et al. 2007). In addition, the residual pressures locked in at the shaft base during grout process, which is beneficial to the

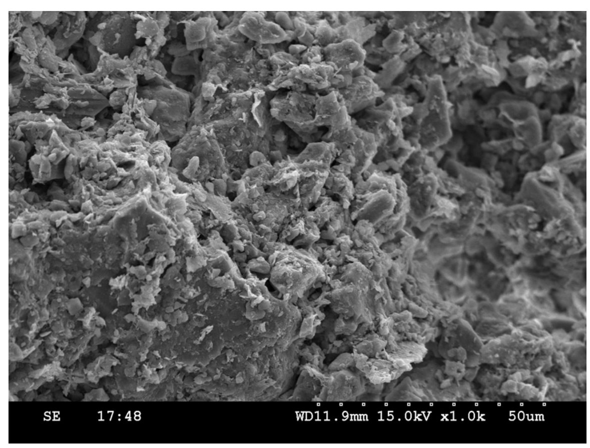

FIG. 11—*Flocculent structure of consolidated Xiaoshan clay.*

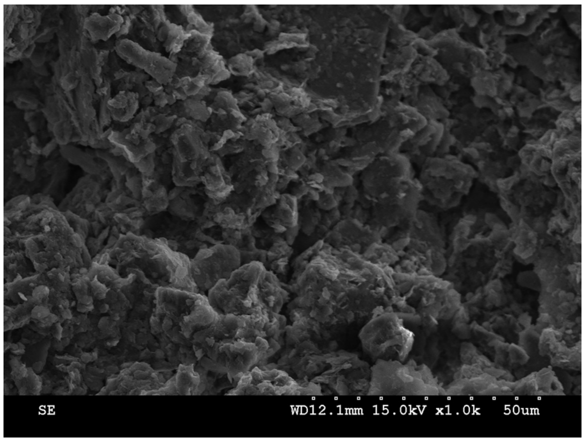

FIG. 12—*Agglomerate structure of pressure filtrated Xiaoshan clay.*

improvement of shaft stiffness (Fleming 1993), will reduce gradually due to the pressure filtration.

The grout with higher water cement ratio will more easily find planes of weakness in the ground and will then cause hydrofracture (Fleming 1993). So it is suggested that grout with high water cement ratio should be used in the initial stage of grouting process. However, in order to minimize the volume loss of grout, the water content should be reduced as much as tolerably possible at the end of the grouting period.

As the grouting pressure increases, the soil is more likely to be split and compacted by the grout. And the strength improvement due to the exchange of cations is more pronounced. Then better reinforcement effect can be achieved for the shaft base. It is considered necessary to conduct further research on the relationship between grouting pressure and end-bearing improvement. In addition, grout with high water cement ratio is suggested to be used in the condition of high grouting pressure, for pressure filtration may be sped up to cause the stagnation of the fracture propagation.

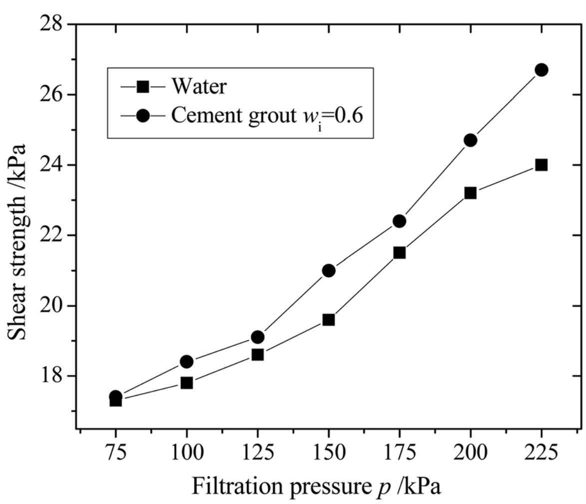

FIG. 13—*Shear strength of clay after pressure filtration under different filtration pressures.*

Conclusion

This paper reports a series of laboratory studies on the pressure filtration in post-grouting of drilled shaft tips in clay. The main conclusions that have been drawn from this study are summarized as below.

(1) The velocity of pressure filtration is determined by the velocity of water through clay.
(2) The final water cement ratio of the grout is maintained at about 0.3 after the pressure filtration process regardless of the initial water content under the laboratory pressures of 75–225 kPa.
(3) The Ca^{2+} ions from cement grout exchange with Na^+ and K^+ adsorbed in clay particles during the process of pressure filtration. The separated clay particles become closer to each other and form clay agglomerates after pressure filtration.
(4) The shear strength of clay increases with the increasing filtration pressure. The strength improvement due to the exchange of cations is more pronounced under high pressure.

Acknowledgments

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