Experimental Study on the Strength of the Side Bored Pile After Post Grouting

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Abstract. Due to different soil strengths, drilled bored piles and slurry-supported bored piles affect the side friction. Through the application of post grouting technology, the friction resistance and bearing capacity of piles can be improved. In this paper, an analysis was conducted on the strength increasing rule of the side drilled bored hole and the side slurry-supported bored pile after post grouting at different ages, by means of chemical reinforcement. The results show that: the post grouting technology has better effect on the slurry-supported bored piles, especially in poor ground conditions, and that the strength on the 120th day can be used as the design strength. Our research achievements can provide a theoretical basis for the post-grouting technology in engineering work.

1. INTRODUCTION
Among the various types of bored piles, drilled bored piles and slurry-supported bored piles are the most widely used(Zhang 2009, Zhang 2013). The pile hole of drilled bored piles is fixed up manually or by machine rather than by slurry or casing. The reinforcement cage is installed, and the grouting material is concrete(Yang 2014, Ma 2006). The slurry-supported bored piles can simultaneously reduce formation pressure and maintain the stability of hole wall, lest the hole collapses or shrinks in size(Mollamah 2010, Akbulut 2002). As the mud cake has high moisture content, high compressibility, and low shear strength, the initial characteristics of pile-soil interaction will change, and the physical and mechanical properties of soil are hardly reflected(Deng 2013, Huang 2008, Huang 2010). Besides, it restricts the development of side friction(Li 2005, Mullins 2001, Yang 2012).

In order to measure the effect of post grouting technology on the bearing capacity of the drilled bored pile and the slurry-supported bored pile, the authors conduct shear tests to analyze the strength increasing rule of the side bored piles after post grouting at different ages, which provides scientific basis for determining the strength of bored piles after post grouting at different ages(Wei 2010, Wang 2008, Qiao 2014).

2. TEST SURVEY
2.1 Test Scheme
The authors prepare four types of soil samples to analyze the working principle and characteristics of the post grouted drilled bored piles and slurry-supported bored piles. The size of soil specimens is determined by using cutting rings whose height is 20 millimeters and diameter is 61.8 millimeters, as
shown in Figure 1. The ratios of soil material and cement mortar are: ① 1/2 soil and 1/2 cement mortar, ② 3/4 soil and 1/4 cement mortar, ③ 1/2 mud and 1/2 cement mortar, ④ 3/4 mud and 1/4 cement mortar, as shown in Table 1. The shear strength of the soil specimens at different ages is measured in shear tests at 3d, 7d, 28d, 60d, 90d, 120d, 150d, and 180d, respectively. Then, we further analyze the strength increasing rule of the side bored piles after post grouting.

![Image](a) Sample of soil and cement mortar  (b) Sample of mud and cement mortar

Figure 1. Finished sample

| Number | Sample Description | Cement: Water: Sand | Detection method | Notes |
|--------|--------------------|---------------------|-----------------|-------|
| T1/2   | Soil 1/2 and Cement mortar 1/2 | 1:0.5:0.4 | shear plane is the strength of interface | The temperature and humidity remain unchanged |
| T3/4   | Soil 3/4 and Cement mortar 1/4 | 1:0.5:0.4 | shear plane is the strength of soil |
| N1/2   | Mud 1/2 and Cement mortar 1/2 | 1:0.5:0.4 | shear plane is the strength of interface |
| N3/4   | Mud 3/4 and Cement mortar 1/4 | 1:0.5:0.4 | shear plane is the strength of cement mortar |

2.2 Make sample and maintain

The cement mortar is prepared by adding 40g sand to 100g 32.5R ordinary Portland cement. The water-cement ratio is set as 0.5 to prevent the solidified pure cement slurry from cracking.

The clay for test use has the features of fast hydration, strong mud-making ability, and high viscosity. Moisture content and other indexes of the clay are shown in Table 2. The preparation steps are: weigh a right amount of clay, dry it in the air, smash it in pieces and filter it through the 0.5mm sieve, mix it well with 23% water, seal and humidify it in buckets for 24 hours. After clay preparation, the T1/2, T3/4 samples can be prepared accordingly. As a mixture of clay and water, the mud is used to protect the hole wall from collapsing and cool the drilling tool when boring holes. 48% water is added to the mud to prepare N1/2, N3/4 samples, at the particle proportion of 1.25.

In preparing the sample of soil and cement mortar, smear a layer of Vaseline on the inner wall of the cutting ring first. Then, the handler filled the sample in the surplus space of the cutting ring in which there is a piece of organic glass whose diameter is 5 and 10mm smaller than the inner diameter.
of the cutting ring, and spray water on the sample by the same drop height and drop number (15). Next, remove the organic glass and spread the cement mortar evenly in the cutting ring. Finally, the sample was cured in the moisturized ware. In preparing the sample of mud and cement mortar, replace compacted soil with mud and repeat the above steps. It should be guaranteed that the plane of shear fracture is directly above the interface between soil and cement mortar or between mud and cement mortar, because the smoothness of interface is the main factor affecting the test results of T1/2, N1/2 samples.

We observe the sample frequently and spray water timely lest the sample cracks due to water shortage, or else the test results will be unsatisfactory.

2.3 Process of direct shear test
The shear test is carried out in accordance with geotechnical testing rules. Apply 100kPa, 200kPa, 300kPa, 400kPa vertical pressure on T1/2, T3/4 samples. Apply 12.5kPa, 25kPa, 37.5kPa, 50kPa vertical pressure on N1/2, N3/4 samples with higher moisture content, in order to avoid overload failure.

3. RESULT OF DIRECT SHEAR TEST
The shear strengths of the specimen at different ages are obtained from shear tests, as shown in Figure 2 and Figure 3.

![Figure 2. the increasing rule of cohesion at different ages](image1)

![Figure 3. the increasing rule of internal friction angle at different ages](image2)

Initial state (0d): the shear strength of T1/2, T3/4 samples is equal to the shear strength of compacted soil according to Figure 2 and Figure 3. The moisture content of N1/2, N3/4 samples is higher, and the shear strength is zero.

The cohesion and internal friction angle of T1/2, T3/4 samples show an increasing trend from the first day to the 180th day, with only a minor fluctuation. As it is difficult for the minerals in diffused cement to hydrate or hydrolyze with active material in soil, there are relatively few crystals of chemical products. The cohesion and internal friction angle of T1/2, T3/4 samples increase at a stable rate from the first day to the 120th day and reach the peak. The increasing trend is unapparent, so that the state is steady in the first 120 days.

The cohesion of N1/2, N3/4 samples grows faster in the first 90 days than in the next 30 days. The internal friction angle of T1/2, T3/4 samples inclines rapidly during the first day and the 7th day, reaches a maximum value during the 7th day and the 120th day, and maintains steady in the following 60 days. Under the effect of hydration and hydrolysis, the mud and cement are aggregated in a mass with the formation of cementation connection, causing the increase of cohesion and internal friction angle for the mud. As the process of hydration and hydrolysis is slowed down, the increasing amount of cohesion and internal friction angle becomes less from the 90th day to the 120th day, marking the beginning of the transition period.

The cohesion and internal friction angle of N1/2, N3/4 samples increase greater than the T1/2, T3/4 samples from the first day to the 180th day. The reason for this phenomenon is that the soil in the T1/2,
T3/4 samples has higher compactness and lower moisture content, making it different for cement minerals to hydrate and hydrolyze with active materials in soil by diffusion, so that the increase of shear strength for soil is smaller than that for mud in N1/2, N3/4 samples. Meanwhile, the test results also show that the hydration and hydrolysis reactions between cement minerals and active soil materials by diffusion are more and more intensified in the areas closer to the interface, so that the shear strength becomes higher in areas with shorter distance from the interface.

4. THE RESULTS OF SAMPLE COMPACTNESS AT DIFFERENT AGES

The soil sample can be divided into two parts: outside of the interface and inside the interface which is perpendicular to the shear plane. The corresponding compactness at different ages are obtained and listed in Table 3.

Table 3. The results of sample compactness (%) at different ages

| Sample type | 0d  | 3ds | 7ds | 28ds | 60ds | 90ds | 120ds | 150ds | 180ds |
|-------------|-----|-----|-----|------|------|------|-------|-------|-------|
| T1/2 outside | 23.0 | 22.9 | 22.9 | 22.7 | 22.4 | 22.3 | 22.1 | 22.0 | 22.5 |
| T1/2 inside  | 23.0 | 22.8 | 22.1 | 21.6 | 20.0 | 19.8 | 19.6 | 19.4 | 20.8 |
| T3/4 outside | 23.0 | 23.0 | 22.8 | 22.6 | 22.5 | 22.4 | 22.2 | 22.1 | 22.5 |
| T3/4 inside  | 23.0 | 22.6 | 22.4 | 21.7 | 20.6 | 20.0 | 19.7 | 19.6 | 21.0 |
| N1/2 outside | 48.0 | 47.9 | 47.6 | 47.8 | 47.6 | 47.5 | 47.4 | 47.0 | 47.7 |
| N1/2 inside  | 48.0 | 47.2 | 46.5 | 41.8 | 37.2 | 36.5 | 36.3 | 36.0 | 39.6 |
| N3/4 outside | 48.0 | 48.0 | 47.7 | 47.6 | 47.5 | 47.3 | 47.2 | 47.1 | 47.5 |
| N3/4 inside  | 48.0 | 47.6 | 46.8 | 42.3 | 37.5 | 37.0 | 36.7 | 36.5 | 40.4 |

As shown in Table 3, the decrement in inside compactness of N1/2 sample is larger than the T1/2 sample’s in 180ds, and the result is the same when comparing N3/4 sample with T3/4 sample. The reason is that the soil in the T1/2, T3/4 samples has higher compactness and lower requirement for water than the mud samples do, making it different for cement minerals to hydrate and hydrolyze with active materials in soil by diffusion, which causes smaller change in shear strength.

All samples become less compact with less water required in the decelerated reactions of hydration and hydrolysis during the first 120 days, and the compactness remains the same when the reaction is nearly completed with barely no water consumed during the 120th day and the 180th day.

5. ANALYSES OF STRENGTH INCREASING RULES

After the undisturbed soil is compacted, soil particles are realigned into compact structure with less space between them, as shown in Figure 4 and Figure 5. Obviously, the mud has higher moisture content before compaction.
There is crystalline hydrate on the surface of soil particles and in the pores of T1/2 sample, but the soil structure is unchanged, so that the increase of shear strength is slight in 28ds, as shown in Figure 6. The hydration and hydrolysis reactions between cement minerals and active soil materials by diffusion in 28ds are shown in Figure 7. Most of the flocculent or fibrous crystalline hydrates appear in mud, leading to the interaction between neighboring soil particles. However, as mud particles are loosely distributed, the pore between mud particles is easy to see, which means that the mud sample can easily fail under pressure in the shear test. For these reasons, the shear strength of the mud samples increases within a limited range.

The T1/2 soil particles are surrounded by crystalline cement hydrate in 120ds, which is shown in Figure 8. Although the pores between soil particles are not filled with cement hydrate, the cementation connection is formed and the shear strength of the prepared soil is somewhat higher than that of undisturbed soil. The crystalline cement hydrate is widespread in the T1/2 mud particles of all sizes and among pores on the 120th day (as shown in Figure 9). In addition, as the pores between soil particles are full of cement hydrate, the pore size is declined, with small particles overlapping with each other, which helps mud particles aggregate up to form a stronger coupled structure. Compared with undisturbed mud, great changes have taken place in the microstructure of prepared mud, and the shear strength of the prepared mud is improved substantially.
On the 180th day, the T1/2 soil particles are surrounded by crystalline cement hydrate and become less angular, as shown in Figure 10. However, as the microstructure of soil changes little compared with that on the 120th day, the increment in the soil’s shear strength is insignificant. The crystalline cement hydrate is widespread in the T1/2 mud particles and among pores on the 180th day (as shown in Figure 11). In addition, the large pores are filled with crystalline cement hydrate, accelerating the cementation and cohesion of soil particles. After 120ds, the hydration and hydrolysis reactions between cement minerals and active soil materials by diffusion continue, but the reaction rate is much lower than before and the microstructure feature of N1/2 mud barely change. Consequently, the change of shear strength of the prepared mud is less in 180ds than in 120ds.

6. CONCLUSIONS

(1) As the age is extended, the shear strength of the side bored pile after post grouting is growing, remaining stable on the 120th day. Therefore, the shear strength on the 120th day can be used as the design strength (while the usual design strength is 90 days)

(2) Compared with drilled bored piles, the side bored pile becomes much more strengthened when the post grouting technology is applied in the slurry-supported bored piles, especially in poor ground conditions.

(3) The influence of post-grouting technology on the increase of shear strength of the side bored pile is less significant as the distance from the grouting position is further. In practical engineering work, we should choose appropriate position of grouting in poor ground conditions to obtain better reinforcement effect and economic benefit.

(4) Through SEM test, it can be seen that the cement hydrate increases in amount with the extension of age. As they fill in the gaps between soil particles, the originally loose soil particles aggregate up to form strong grouted stone structure with less and smaller pores. As a result, the strength of the side bored pile is improved dramatically.
(5) The analysis process of the strength increasing rule of side bored piles after post grouting at different ages can be used inversely to analyze the chemical reinforcement characteristics of cement hydration and hydrolysis, aggregation and coagulation reaction.

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