Application of Controllable Splitting Grouting Technology in Loess Foundation Reinforcement

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Abstract. Taking the foundation settlement accident of a large heating boiler foundation in a city in collapsible loess area as an example, controllable splitting grouting can be achieved by controlling the grouting pressure, grouting pipe opening form, grouting volume and grouting method etc., so as to stabilize foundation settlement and improve foundation bearing capacity, for the boiler with large uneven settlement, for boilers with large uneven settlement, quicklime piles are used to jack up the foundation after splitting grouting to stabilize the foundation, the foundation is lifted with quicklime piles after splitting grouting to stabilize the foundation. The results show that the grouting amount of soil is within the design range, the grout splits in the soil several times to form a slurry vein, the settlement is stable after boiler reinforcement, the quicklime method can jack up the foundation and reduce the uneven settlement of the foundation, and the use of controllable splitting grouting can basically eliminate the slight collapsibility grade loess, which provides a new idea for solving the similar problem of uneven settlement of collapsible loess foundation buildings.

Keywords. Uneven settlement; foundation reinforcement; split grouting; quicklime pile.

1. Introduction

Due to soil structure problems, collapsible loess is prone to collapse and deform under water immersion, resulting in uneven settlement of the foundation [1-2], which affects the safety of buildings. Among the existing loess foundation reinforcement methods, grouting technology has the advantages of convenient construction, short period, small disturbance to surrounding buildings, and significant reinforcement effect have been widely used in various fields such as tunnels, highways, railways, and coal mines and other fields [3-6]. For grouting on loess, controlling grouting pressure can effectively realize compaction grouting and splitting grouting in loess area [7], so as to strengthen soil mass.

However, most of the grouting design is blind at present, some grouting parameters rely on experience, and the control of the grouting process is not mature enough. which can not ensure the grouting effect, but also hinder the further promotion of splitting grouting for splitting grouting engineering. Scholars have studied more grouting diffusion theory in rock mass [8-10], and less research on the diffusion of grouting in loess. Under various factors, it is difficult to find the law of slurry diffusion in loess. Slurry may diffuse too far in a crack, resulting in slurry waste and affecting the grouting effect. The spread of grout veins in the soil greatly affects the grouting effect, controls the distribution of grout veins in the soil layer, and forms a controllable splitting grouting technology, which can greatly improve the bearing capacity of the foundation after grouting.

Therefore, in this paper, the controllable splitting grouting technology is used for the loess foundation where the boiler foundation of a northwest project has produced uneven settlement, and the
grouting is achieved by controlling the grouting pressure, the opening form of the grouting pipe, by controlling the grouting pressure, grouting pipe opening form, grouting volume and grouting mode, the slurry pulse can be controlled and the foundation bearing capacity can be improved.

2. Overview of Controllable Split Grouting

2.1. Mechanism of Splitting Grouting to Reinforce Loess

At present, with the maturity of split grouting technology and its construction technology, and there are many successful cases in the reinforcement of collapsible loess foundation. The research shows that the reinforcement effect of split grouting on soil mainly includes extrusion and slurry vein skeleton [11-12].

At the initial stage of slurry diffusion, the forms of filling, infiltration and extrusion occur, which relies on its own flow to spread in the soil layer, which will squeeze the soil, fill the overhead voids in the soil and compact the pores of the surrounding loess.

When the grouting pressure reaches the splitting pressure, the grout will split in the loess. Zhou Mingru et al. [13-14] used the hole expansion theory to divide the soil around the grouting hole into elastic and plastic zones, and deduced the prediction formulas of vertical and horizontal pressure of loess under undrained conditions:

\[
P_{uv} = \left( \sigma_r - \sigma_0 \right) \left( \frac{q_p}{G\sqrt{k+2}} \right) + \sigma_0
\]

\[
P_{uh} = (1+\eta) \left[ \left( \sigma_r - \sigma_0 \right) \left( \frac{q_p}{G\sqrt{k+2}} \right)^{1/(\eta/(\eta-1)/(\eta+1))} \right] + 2\left[ \eta(\nu+1)+\nu-1 \right]
\]

where: \( P_{uv} \) is the vertical splitting grouting pressure, \( P_{uh} \) is the horizontal splitting grouting pressure, \( r_p \) is the final reaming pressure of the plastic zone, \( k \) is the coefficient, \( \eta \) and \( \sigma_0 \) are the soil strength parameters, \( \sigma_0 = \sigma_0 \). When the grouting pressure is exceeded, the soil splitting effect occurs. At this time, the soil will be continuously sheared by the slurry to form cracks. The grout is filled in the fissures and hardened to form grout veins. The slurry veins under different grouting holes are staggered to form a network skeleton. The strength of the composite soil formed by the slurry veins and the soil is significantly increased, thereby strengthening the soil.

2.2. Controllable Split Grouting Technology

The controllability assumption is to control the spacing, length and width of slurry vein formed by splitting grouting within the allowable error range of design value. By realizing the controllable slurry pulse, the slurry pulse around the grouting hole is "branch" with the solid in the grouting hole as the "axis" after grouting to form the branch controllable splitting grouting pile, which forms the controllable splitting grouting pile composite foundation together with the soil to improve the foundation bearing capacity.

3. Project Overview

The project is a large-scale heating boiler reconstruction project in the central urban area of a city. The boiler room is in the form of frame structure. There is a concrete retaining wall in the East and buildings in the other sides. There are three heating boilers in the boiler room. The east side of the boiler is near the retaining wall, and the plane size of the foundation is 5.24×11.33 m, the buried depth is 0.6 m, about 3 m on the side of the boiler foundation close to the retaining wall is placed in backfill, and the west side is placed in undisturbed soil (figure 1). The top 1m of backfill soil is 3:7 lime soil, and about 6m below lime soil is plain soil backfill. Class I self weight collapsible loess of boiler site, with the maximum collapsible depth of 7.8 m.
According to the field survey, the foundation settlement of boiler 1 and boiler 2 is small, the foundation of boiler 3 has a large uneven settlement, and the foundation on the backfill side is settling at a relatively obvious speed. There are two reasons for the large uneven settlement of the boiler foundation. One is that 3m from the east of the three heating boiler foundations are placed on the backfill, as shown in figure 2, the foundation structure on the east and west sides of the boiler foundation exists large differences, insufficient compaction of the backfill, and low foundation bearing capacity. Second, there are many buildings around the site and the drainage is inconvenient. The construction is in the rainy season. After several heavy rainfalls, a lot of rainwater will collect on the ground. It infiltrates along the periphery of the foundation, and finally flows into the ground. Due to the collapsibility of the site, the backfill soil inside the boiler foundation is soaked and collapsed, resulting in uneven settlement of the boiler foundation.

4. Treatment Plan and Implementation

In order to allow the heating boiler to operate safely and stably in the future, the main purpose of reinforcement is to stabilize the settlement of the boiler foundation, improve the bearing capacity of the boiler foundation, and jack up the foundation with large uneven settlement. The boiler foundation reinforcement this time mainly includes the following three items:

- Controllable splitting grouting technology is adopted on both sides of the foundation of the three boilers to stabilize the foundation settlement and improve the foundation bearing capacity;
- Compaction grouting shall be carried out for the soil outside the boiler foundation to strengthen the soil;
- Both sides of boiler 3 Foundation adopt quicklime pile expansion jacking equipment foundation.

4.1. Split Grouting

To realize the controllability of split grouting, not only depends on the existing theory, but also needs to improve the process control in the grouting construction. From these aspects, try to control the pulse pulse.

4.1.1. Grouting Material. The commonly used grouting material in Loess grouting is cement, and the grouting water cement ratio is 0.6-1.2. In this grouting, the water-cement ratio is selected as 0.8. The water-cement ratio has properties such as viscosity, stone rate, stone body strength, etc. can ensure a better grouting effect. The grouting material is made of composite Portland cement and ordinary tap water.

4.1.2. Grouting Pressure. According to the previous grouting test, the grouting opening pressure of loess is about 0.4M Pa, and the soil parameters are taken into equation (1) and equation (2) to calculate
that the vertical crack opening pressure of the split grouting is 0.42 MPa. The horizontal opening pressure is 0.513 MPa, assuming that this test is a vertical slurry pulse, in order to prevent the slurry from spreading too far in the crack due to excessive pressure, the slurry pressure needs to be controlled to be slightly greater than 0.42 MPa, it is necessary to control the slurry pressure slightly greater than 0.42 MPa, when the pressure is too high, the grouting pressure shall be controlled by limiting flow and reducing pressure.

4.1.3. Grouting Pipe. The grouting pipe is connected by three steel flower pipes with a length of 2.5 m, and the diameter of the steel flower pipe is 79 mm. The bottom section of the grouting pipe is sealed, and the grouting port is 300 mm away from the bottom of the pipe, on both sides of the pipe wall, 8mm grouting holes are drilled every 0.8 mm, there are 6 grouting holes arranged in a cross-penetration pattern. The upper steel flower pipe is not provided with slurry outlet holes.

4.1.4. Grouting Design. The amount of grout required for grouting Q is calculated according to the formula, including the amount of grout Q1 required for grouting holes and the amount of grout Q2 required for cracks. The amount of grout required for grouting holes is calculated according to the formula:

\[ Q = Q_1 + Q_2 = \alpha \beta \pi R^2 L / m + 2n \beta b l h / m \]  

where: \( Q_1 \) is the amount of grout required for the grouting hole, \( Q_2 \) is the amount of grout required for the crack, \( \alpha \) is the grout filling coefficient, \( \beta \) is the grout loss coefficient, \( R \) is the radius of the grout hole after the grout is squeezed out of the grouting hole wall, and \( L \) is The length of the grouting section, \( m \) is the rate of grout stones, \( n \) is the number of layers of grout veins, \( b \) is the thickness of the cracks, \( l \) is the length of grout diffusion, and \( h \) is the thickness of grout veins.

According to the designed grouting pipe, \( \alpha \) Take 0.8, \( \beta \) Take 1.3, \( R \) take 1.2 (1.5 times the diameter of grouting pipe), it is estimated that the number of grouting veins \( n \) is 8 layers and the slurry diffusion length \( L \) is 1 m. According to equation (3), the grouting amount required for a single grouting hole is 0.44 m³.

4.1.5. Grouting Hole Layout. The grouting depth is 6m (according to the depth of the soil layer that needs to be reinforced on site). The grouting holes are arranged in a plum blossom pattern with a hole distance of 800 mm, the hole location is shown in figure 3. In order to ensure that the slurry can split and enhance the reinforcement effect at the bottom of the boiler foundation smoothly during the split grouting construction, the grouting holes are distributed on both sides of the boiler foundation, with three rows on each side, and the design length is 6 m, 5.2 m and 5 m, the inclination angles are 50°, 45° and 40° respectively, as shown in figure 4.

![Figure 3. Hole location plan.](image-url)
4.1.6. **Grouting Method.** Segmented grouting divides the whole grouting section into multiple grouting sections, and grout is poured respectively. In segmented case, repeated grouting can be realized for a certain layer of soil, and the grouting amount and grouting pressure can be controlled, which can better solve the problem of uneven slurry diffusion in the whole section of grouting [15].

The grouting process is carried out in three stages, and the grouting amount in each stage is 0.15 m$^3$. The grouting process is divided into three sections, and the grouting amount of each section is 0.15 m$^3$. The bottom section grouting shall be carried out first, and the bottom end grouting shall be carried out upward after completion. Since the diameter of the grouting pipe is slightly smaller than the diameter of the soil borehole, the slurry is easy to flow out from the pores between the grouting pipe and the soil, resulting in pressure loss and affecting the grouting effect. In order to solve this problem, the self-set underground hole sealing device (as shown in figure 5) is used to seal the holes at the sections in the segmented grouting process. The device can control the slurry to split the soil below the depth of the underground hole sealing device to form a slurry vein, and the slurry will not emerge, so as to ensure that there is large pressure in the grouting hole and realize split grouting.

4.1.7. **Grouting Step.**

1. Loess drilling. Drill holes according to the required hole position and angle, and adjust the grouting parameters when encountering more complicated geology to ensure the grouting quality.

2. Grouting. We configure the grout according to the design requirements, and use a hydrometer to test the mixing ratio of the grout. The grout is stirred many times during the configuration and use, and the grouting is carried out in sequence and segmented backwards from the outermost hole. If any abnormal situation is found during the grouting process, it should be timely such as pressure sudden rise, slurry overflow, etc. need to be adjusted according to the site in time. When grouting, grouting should be done at intervals to prevent the occurrence of collapsed holes and grouting from series holes.

3. Replenish the slurry. After the grouting pipe is pulled out, the grout must be added immediately. Pay attention to the amount of grout in the hole during the subsequent construction, and do multiple grout refills to prevent the phenomenon of grouting forming solid cavities.

4.2. **Compaction Grouting.**

The bearing capacity of the original backfill soil on the east side of the boiler equipment foundation, that is, the side close to the concrete retaining wall, is low and soaked and collapsible, which has a great impact on the boiler foundation. In order to improve the bearing capacity of the soil on this side, eliminate the collapsibility of the soil and improve the impermeability of the soil, the method of compaction grouting is adopted for reinforcement, and thicker slurry is selected to inject into the soil. The slurry can reinforce the backfill through compaction and infiltration in the soil. The compaction
grouting holes are arranged as plum blossom piles along the inner side of the retaining wall and 20 cm away from the retaining wall. The hole spacing is 1 m, the diameter is 100 mm, the depth is 6 m and the hole position arrangement is shown in figure 3.

4.3. Quicklime Pile
The quicklime pile is mainly used to strengthen the soil through physical and chemical reinforcement [16-17]. The expansion process of the quicklime pile is obvious, which can lift the soil and eliminate the collapsibility of loess. For the foundation that is undergoing uneven settlement, first use Splitting grouting stabilizes the settlement of the foundation, and then uses quicklime piles to lift the foundation to reduce the uneven settlement of the foundation.

The lime pile construction is carried out after ensuring the final setting of the splitting grouting slurry to ensure the compaction effect of the quicklime pile. The quicklime piles are arranged according to plum blossom piles, the pile distance is 800 mm, and the pile diameter is 100 mm. The pile position is shown in figure 3. The quicklime pile holes are distributed on both sides of the boiler foundation, with three rows on each side. The design lengths are 5.5 m, 5.8 m, and 6.5 m from the inside to the outside, and the inclination angles are 40°, 45°, and 50° respectively, as shown in figure 6.

![Figure 6. Section of quicklime pile.](image)

![Figure 7. P-Q-T relation curve.](image)

5. Analysis of Reinforcement Effect
5.1. Time history Analysis of Grouting Pressure and Flow
During the grouting process, the time spent on pipe extubation and hole sealing is not included in the test record, so the P-Q-T relationship curve diagram drawn is continuous and uninterrupted. The variation curve of grouting pressure and grouting amount with time is shown in figure 7. It can be seen from the figure that after grouting starts, the grouting rate is maintained at 1L/s, the pressure rises rapidly, and when the time is 40 seconds, the grouting pressure reaches 0.38MPa. At this time, the slurry mainly compresses the soil and compacts the pores of the soil. Since then, the pressure has remained above 0.38 Mpa, during which there are 6 pressure peaks, which may be the multiple splitting of the soil. After that, the pressure remained above 0.38MPa, during which there were 6 pressure peaks, which may be the multiple splitting of the soil. When the pressure exceeds 0.46 MPa, reduce the flow rate to 0.8 L/s to prevent the slurry from spreading too far in the crack due to excessive pressure. When the grouting amount reaches 0.15m³, the first section of grouting is completed and the second section of grouting is started. This process is repeated. After the grouting time is about 480 s, the soil begins to emit slurry. At this time, the grouting amount of the third section is only 0.122 m³. This shows that after the new underground hole sealing device is used to seal the hole, the slurry pressure can be continuously maintained at a high level to ensure the air tightness in
the grouting hole, but the grouting amount in the uppermost section cannot be guaranteed, and the hole sealing measures at the surface need to be improved.

Figure 8. Variation of cumulative settlement of boiler foundation 1 and 2 with time.

Figure 9. Variation of cumulative settlement of boiler foundation 3 with time.

5.2. Settlement Monitoring

In order to understand the effect of reinforcement, a structural monitoring system was established before and after construction. Two settlement observation points and two datum points are set at the bottom of boiler foundation on the backfill side of boiler 1, 2 and 3 Foundation. During and after construction, the same instruments and equipment shall be used for observation for several times.

The relationship of the cumulative settlement of boilers 1 and 2 with splitting grouting reinforcement over time is shown in figure 8. The foundation of boilers 1 and 2 was the split grouting construction stage in the first 10 days. At this time, the settlement increment of boiler foundation is large. This is because the original soil mass is settling and the water in the slurry seeps into the soil mass during grouting construction, and the soil mass is collapsing, resulting in an obvious increase in settlement, with the maximum settlement of about 14mm. After the split grouting construction, the slurry coagulates and hardens in the soil to form a solid body, which bears the upper load together with the soil. The settlement increment of the boiler foundation is significantly reduced, and the settlement is less than 1mm after about two weeks, indicating that the settlement has been basically stable.

The cumulative settlement before and after the construction of boiler 3 is shown in figure 9. The settlement increment of boiler 3 Foundation has gradually decreased from the end of grouting to the formal construction of quicklime pile, indicating that the subsequent construction of quicklime pile is carried out after the foundation settlement is basically stable. The strength of the boiler foundation is increased after grouting and compaction, and the porosity is reduced. The subsequent expansion and jacking of the lime pile overcomes the earth pressure after compacting the less pores to lift the foundation. The jacking amount of the lime pile is very small during construction. After the construction, the lime pile fully absorbs the water in the soil. After about two months, the jacking amount reaches the maximum value, and the maximum jacking amount is 25.1 mm, which reduces the uneven settlement of boiler foundation to a certain extent.

5.3. Collapsibility Detection

After the reinforced soil is sampled and tested by the indoor collapsibility test, the variation curve of the collapsibility coefficient of the foundation soil with depth under the pressure of 0.2 MPa is shown in the figure 10, which is similar to that of the natural foundation $\delta_{0.2}$ the maximum value is 0.026, less than 0.03. The site is only slightly collapsible, and the soil within the treatment range of splitting grouting $\delta_{0.2}$ is less than 0.015, and the collapsibility is basically eliminated, indicating that splitting
grouting can basically eliminate the collapsibility of slightly collapsible loess.

![Figure 10. Variation of collapsibility coefficient with depth under 0.2MPa pressure.](image)

### 6. Conclusion

This article proposes the use of controllable split grouting technology for the boiler foundation that has uneven settlement in the collapsible loess area, and draws the following conclusions:

1. By controlling the grouting pressure, grouting pipe opening form, grouting amount and grouting method, the grouting amount of soil can be ensured to be within the design range, making the slurry split many times in the medium soil to form a slurry vein, so as to realize controllable splitting grouting. However, due to the limitation of conditions, the size of slurry vein cannot be verified.

2. The controllable splitting grouting technology is used to strengthen the foundation, and the boiler foundation basically no longer settles, which proves that this method can obviously stabilize the settlement of the soil and improve the bearing capacity of the foundation.

3. After splitting grouting to stabilize the foundation, the quicklime pile was used to lift the foundation, the result showed that the boiler foundation was lifted to a certain extent, which reduced the uneven settlement of the foundation.

4. Controllable split grouting can basically eliminate the collapsibility of slightly collapsible grade loess, but further research is needed for the more severe collapsible loess.

### References

[1] Wang G B, Zhao J C and Lei Y X 2020 Differential settlement of collapsible loess foundation: deformation law of masonry structure foundation *Science Technology and Engineering* **20**(25) 10422-10427

[2] Hu Y D, Yao J T, Han X L and Wang Y 2012 Mechanism analysis of uneven settlement of an accident building in Loess Area *Journal of Xi’an University of Architecture and Technology (NATURAL SCIENCE EDITION)* **44**(03) 345-350

[3] Zhang D L, Sun Z Y and Chen T L 2019 Composite grouting technology and its engineering application in subsea tunnel *Chinese Journal of Rock Mechanics and Engineering* **38**(06) 1102-1116

[4] Wang A H, Ding X M and Zhang D W 2017 Grouting treatment technology for uneven settlement of soft foundation of expressway in service *Journal of Southeast university (Natural Science Edition)* **47**(02) 397-403

[5] Geng L C, De G, Wei S W and Yao J P 2020 Research status and development trend of grouting technology in railway engineering *Railway Engineering* **60**(10) 89-93

[6] Kang H P 2020 70 year development and prospect of surrounding rock control technology of coal mine roadway in China *Chinese Journal of Rock Mechanics and Engineering* 1-30
[7] Ma L S, Wang T, Zhou M R and Zhu D M 2018 Study on crack propagation model of loess split grouting soil Journal of Underground Space and Engineering 14 (04) 962-967
[8] Sun F, Chen T L, Zhang D L, Zhang Z J and Li P F 2009 Study on splitting grouting mechanism of subsea tunnel based on Bingham slurry Chinese Journal of Underground Space and Engineering 33 (04) 1-6
[9] Li S C, Zhang W J, Zhang Q S, Zhang X, Liu R T, Pan G M, Li Z P and Che Z Y 2014 Study on dominant splitting grouting mechanism and grouting control method in Fushui fault zone Rock and Soil Mechanics 35 (03) 744-752
[10] Zhang Q S, Lianzhen Z, Xiao Z, Rentai L, Mingting Z and Dongzhu Z 2015 Grouting diffusion mechanism of horizontally fractured rock mass based on temporal and spatial variation of slurry viscosity Chinese Journal of Rock Mechanics and Engineering 34 (06) 1198-1210
[11] Zhang J X 2016 Study on the mechanism of power-law fluid splitting grouting Journal of Yangtze River Scientific Research Institute 33 (12) 113-118
[12] Zhu M T, Zhang Q S, Li S C, Li W, Sui H T and Yang H L 2018 Simulation test on main control factors of soil splitting grouting reinforcement Journal of Zhejiang University (Engineering Science) 52 (11) 2058-2067
[13] Zhou M R, Chen Z C, Luo X B, Zhou G K, Lu C G 2017 Mechanism of cement slurry grouting reinforcement in collapsible loess Journal of Architecture and Civil Engineering 34 (06) 65-70
[14] Zhou M R, Zhang J B, Lu G W, Chao X and Chen J X 2018 Application of reaming theory in splitting grouting of unsaturated loess Journal of Building Structures 39 (S1) 368-378
[15] Tan W Y 2016 Test and detection of segmented grouting technology of steel flower pipe Construction Technology 45 (06) 122-128
[16] Zhu Y P and He Y Q 2006 Mechanism and experimental study on deviation correction of inclined buildings in collapsible loess area by expansion method Journal of Lanzhou University of Technology 03 (03) 108-111
[17] Han X L, Ma C G and Cui G Q 2011 Experimental study and engineering application of quicklime pile strengthening collapsible loess foundation of existing buildings Engineering Investigation 39 (07) 32-36