Field Test Research on Film Bag Grouting in Strongly Weathered Stratum Overlying Subway

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Abstract. A strongly weathered stratum needs to be reinforced by grouting before tunnel excavation due to its poor self-stability. This work studied the law of surface uplift caused by grouting in a strongly weathered stratum overlying a subway. A strongly weathered stratum overlying a subway section was taken as the research object, and the field test method was used to reveal the time and space variation characteristics of the surface uplift with grouting reinforcement. Then, the influence of the grouting reinforcement technology, quantity, and material on the maximum surface uplift value in the practical grouting process was analyzed. The results show the following. Regardless of whether film bag grouting is used or not, the uplift value of the monitoring points is directly proportional to time, and the growth rate of the uplift value tends to accelerate. The spatial distribution of the surface uplift is mainly related to its distance to the grouting point. In addition, the maximum uplift value of the film bag grouting technology is 32.1% lower than that of the ordinary grouting technology; given the same grouting materials and technology, the grouting amount increases by 50%, and the surface uplift value increases by 121%. Moreover, the C-S slurry exhibits rapid setting, a small diffusion range, and a large thickness of the grouting vein; the surface uplift value of the C-S slurry is 3.08 times that of the cement slurry. The field test research conclusion is applied to practical engineering, where the final uplift value is 1.8 to 2.5 cm, and the average permeability coefficient of the inspection hole is 3.52×10⁻⁷ cm/s, which reflects a good engineering governance effect.

Keywords: Subway tunnel; Strongly weathered stratum; Film bag grouting; Surface uplift; Field test

1. Introduction

The structure of a strongly weathered stratum is mostly broken; thus, it is difficult to maintain its stability. In the construction of urban subway tunnels, grouting [1-3] is often used to strengthen the soft stratum in front of the tunnel face to ensure safe excavation. However, the buried depth of urban subway tunnels is usually shallow, and grouting will cause surface uplift above the target grouting area. Roads or pipelines distributed above the tunnel will also affect the road traffic safety and municipal
pipeline safety above the tunnel\textsuperscript{[4,5]}. Therefore, studying the law of surface uplift caused by grouting in strongly weathered strata is of great significance for the safety control of grouting in tunnels. Scholars from various countries have conducted studies relevant to the surface deformation above grouting areas caused by grouting. Gollegger\textsuperscript{[6]} studied an analytical solution to the displacement field caused by compensation grouting. Based on the above research results, Tang et al.\textsuperscript{[7,8]} simulated the influence of grouting uplift on underground pipelines through the numerical software FLAC3D; Zhang et al.\textsuperscript{[9]} derived a theoretical calculation formula and a simplified form of the surface lifting deformation of multiple slurry bubbles under uniform and non-uniform expansion modes according to random medium theory and the linear superposition principle; Zhang et al.\textsuperscript{[10]} performed a simulation test of surface deformation caused by grouting in the sand layer of a tunnel, and they analyzed the variation law of the formation pressure and displacement during the surface uplift process. However, the existing research lacks grouting cases of strongly weathered strata, and most of them focus on static theoretical and simulation test research. During the research process, surface uplift is considerably simplified, and there is a lack of field test research. Ordinary grouting technology is used to control surface uplift, and no new grouting technology is being applied. Thus, existing research results cannot effectively provide guidance for actual grouting projects. A field test of the law of surface uplift caused by grouting in a subway tunnel grouting reinforcement project was conducted in this paper to study the law of surface uplift caused by grouting. The field test results were applied to the reinforcement of strongly weathered rock strata, and good results were obtained.

2. Engineering situation and difficulties

2.1. Engineering situation

The hydrogeology of the tunnel in this project is complex. The buried depth is shallow and varies at different parts of the tunnel. The elevation of the top of the tunnel is between minus 10.8 m and minus 20.7 m. The excavation section of the tunnel is 12 m wide and 8 m high, and the tunnel face is arched. The interval stratum distribution, as shown in Figure 1, is as follows: artificial filled soil from 0 to minus 3.5 m, marine swamp soil mainly from minus 3.5 to minus 6 m, organic silty clay and alluvial silty clay mostly from minus 6 to minus 8 m, strongly weathered granite mainly between minus 8 and minus 20 m, 2–3 m-thick intermediary weathered granite, and slightly weathered granite distributed in the underside of the intermediary weathered granite. The tunnel is covered with strongly weathered granite that is broken and incomplete. The groundwater at the site is mainly phreatic water, with a buried depth of minus 1.8 m. The water supply is pore fissure water, and the overburden of the tunnel is a water-rich area with strong water permeability.
The pipelines above the tunnel are densely distributed. There are power, communication, water supply, rainwater, gas, and other pipelines successively distributed from a buried depth of minus 1 to minus 4 m. The minimum distance between the φ 110 gas pipeline and the tunnel vault is only 6.8 m. This is the biggest potential safety hazard of the treatment project.

2.2. **Engineering difficulties**

The difficulties of grouting reinforcement in this section mainly include the following aspects.

(1) Geological complexity: The tunnel crossing strata and overlying stratum have poor self-stability, low strength, and complex surrounding rock properties. They can easily collapse under the influence of excavation disturbance in the process of tunnel excavation, resulting in the instability of the working face. Therefore, the grouting reinforcement effect needs to be enhanced.

(2) Heavy traffic: There is heavy traffic in the excavation section and the interaction between the surface traffic and grouting. A large amount of grouting will cause an uneven uplift of the surface and increase the danger of driving.

(3) Surface uplift: The interval pipeline is highly dense and close to the surface; hence, it can be easily damaged by the impact of surface uplift. Damage to the underground pipeline will increase construction difficulty and repair cost, and the repair pipeline will disturb the tunnel excavation. Therefore, the monitoring of the surface and the pipeline should be strengthened during construction to ensure that the clear distance between the grouting pipe and the pipeline is not less than 1.5 m, and the surface uplift shall be strictly controlled \(^{[11]}\).

3. **Grouting reinforcement treatment plan**

3.1. **Grouting reinforcement treatment ideas**

Progressive grouting was used to prevent the collapse of holes in weak strata after drilling \(^{[12]}\). The reinforcement was from shallow to deep strata. The grouting reinforcement range was 5 m from the upper part to the vault, 1 m from the lower part to the intermediary weathered granite, and 5 m from both sides of the tunnel to the tunnel contour line. Due to the limited construction environment in the tunnel, vertical surface drilling grouting was adopted. Schematic diagrams of the section and section grouting reinforcement are shown in Figures 2 and 3.
3.2. Drilling design

The vertical surface drilling method was adopted. The horizontal and vertical spacing of the grouting holes was 1.5 m, and the number of holes in each row was 13. A total of 238 rows of holes were arranged, and the total number of holes was 3094. Figure 4 shows the layout of the grouting holes.

3.3. Film bag grouting technology

Given the strong weathering of the stratum and poor hole wall integrity, the film bag grouting process was used to block the steel casing from the borehole wall, thereby increasing its ability to resist the upward return of slurry. Therefore, film bag grouting can limit the influence of grouting on the surface deformation and effectively avoid slurry lose. Grouting sections 1 and 2 were designed to reinforce the reinforcement area section by section, as shown in Figure 5 (b).
The diameter of the surface hole was 127 mm. The grouting process was divided into two sections, and their grouting reinforcement lengths were 8 m and 12 m. The film bag used a polyester material with a width of 1 m and a length of 2.2 m. A single-hole support bag consumable was controlled to 2.2 m². The elongation at break was greater than 30%, and the elongation was about 25%. The film bag had corrosion resistance, and the inside was coated with a 2 mm polyurethane material that swells when contacting water and thus stops water. The maximum resistance to water pressure was greater than 1.5 MPa.

During the operation, the film bag and a rubber band were first used to wrap the slurry outlet on the outer tube. The sleeve valve tube was placed into the grouting hole, and water was injected to react with the polyurethane. Grouting was conducted in stages after the polyurethane had completely solidified.

3.4. Grouting parameter design
The grouting material used cement slurry and C-S slurry. The Portland cement slurry water–cement ratio was equal to 1, and the volume ratio of the cement to the water glass of the C-S slurry was equal to 1.25. The modulus of the water glass, which means the ratio of SiO₂ to Na₂O in its molecular formula NaO₂·nSiO₂, was from 2.6 to 3.4. The concentration of the water glass was from 30 to 40 Bé. The initial setting time of the C-S double slurry project site was from 40 to 50 seconds.

The grouting volume of a single hole and a single section was from 0.5 to 1.5 m³, which was adjusted according to the grouting reinforcement effect and surface uplift.

The grouting amount and grouting pressure were used to control the end grouting standard. Grouting was finished when the single-hole grouting volume reached the designed grouting volume or the grouting pressure remained 1.5 MPa for 5 minutes.

3.5. Control ideas for difficult points of grouting process
There were problems on surface uplift and pipeline safety control in the grouting treatment of strongly weathered strata in this project. The solutions are as follows.

Film bag grouting technology was used to explore the time and space changes in the surface uplift with grouting reinforcement. A reduction in surface uplift would be convenient for a targeted adjustment of grouting schemes. Finally, film bag grouting was compared with the traditional grouting method.

Inflatable film bags can resist the upward movement of slurry and theoretically exert a certain control effect on the surface uplift, but their applicability under this working condition merits further study. The amount of single-hole and single-section grouting determines the total amount of slurry injected into the reinforcement area, thus influencing the surface uplift and the effect of grouting reinforcement.
Exploring this impact of grouting volume on the surface uplift is of great significance for practical engineering. The spreading range of the slurry should be prevented from becoming too large, which would result in repeated grouting. Two kinds of slurry can be mixed to control surface uplift, and the influence of single slurry and double slurry on the surface uplift can be explored.

4. Monitoring scheme design

4.1. Layout of monitoring points for surface uplift

Monitoring points were established in the field test to monitor the surface deformation above the grouting reinforcement area. Three lines and eight columns of monitoring points were arranged at the surface projection of the grouting reinforcement area, as shown in Figure 6. L is the projection line of the tunnel face on the ground surface, and D is the middle line in the direction of tunnel excavation. J-1 to J-4 are inspection holes 1 to 4, and the longitudinal and transverse spacing of the monitoring points was 3 m. In total, 24 monitoring points and 4 inspection holes were set. In addition, as stated in Section 5.3, the monitoring points were arranged in the monitoring area, but the longitudinal and transverse spacing of the monitoring points was set to 1 m.

![Figure 6. Plane layout of surface monitoring points](image)

**Figure 6.** Plane layout of surface monitoring points

4.2. Monitoring scheme

The total station was used to measure the height of the monitoring points. A point outside the grouting scope was taken as the reference point. The heights of the monitoring and reference points were measured before and after the grouting reinforcement. The surface uplift amount caused by grouting and the accumulated surface uplift amount after grouting can be obtained by comparing the height data of the monitoring and reference points.

5. Analysis of field test results

5.1. Temporal variation characteristics of surface uplift

The grouting points at the left and right of the monitoring area were symmetrically arranged to compare the effect of the film bag grouting technology with that of the ordinary grouting method. Film bag grouting and ordinary grouting were performed at points 2-4 and 2-5, respectively. C-S slurry was used, and the grouting pressure, grouting amount, and other variables were controlled at the same time. The surface uplift value of each monitoring point was monitored every 15 minutes, and grouting was stopped at 60 minutes. The grouting started at 0. The uplift values of six points at the left side of the monitoring area (1-1, 2-1, 3-1, 1-3, 2-3, 3-3) and six points at the right side of the monitoring area (1-6, 2-6, 3-6) were monitored.
2-6, 3-6, 1-8, 2-8, 3-8) were selected for a time-dependent test of the surface uplift, and the results are shown in Figure 7.

Four sets of grouting schemes were designed to analyze the influence of the different grouting material types, grouting volume, and grouting technology on the surface uplift deformation, as shown in Table 1.

Table 1. Grouting plan

| Grouting material type | Grouting volume | Grouting technology     |
|------------------------|-----------------|-------------------------|
| Plan 1                 | C-S slurry      | 1 m³                    | Film bag grouting        |
| Plan 2                 | C-S slurry      | 1 m³                    | Ordinary grouting        |
| Plan 3                 | C-S slurry      | 1.5 m³                  | Film bag grouting        |
| Plan 4                 | Cement slurry   | 1 m³                    | Ordinary grouting        |

The curves indicate that the uplift value of each monitoring point is proportional to time with the progress of the grouting process, regardless of whether the film bag grouting process is used or not. The growth rate of the surface uplift has an accelerating trend because, in the initial stage of grouting, the injected slurry will first compact the rock stratum, which will mainly cause horizontal compaction. After the rock stratum is compacted to a large extent, the slurry will cause a greater vertical surface uplift. When the grouting is stopped, the surface uplift value will stabilize. With the use of the film bag grouting process, the maximum uplift value is reduced from 12.6 to 10.3 mm, which reflects a decrease of 22.3%. Furthermore, the average decrease of the six sets of data corresponding to each point is 24.2%, confirming that the use of the film bag grouting process effectively controls surface uplift. In the test, the interaction of these two grouting methods is not significant. The effect of grouting point 2-4, which was at the right of the monitoring area, should be less than that of grouting point 2-5, which was at the left of the monitoring area. Therefore, the actual effect of the film bag grouting technology on controlling the surface uplift should be slightly stronger than that indicated by the test results.

5.2. Spatial variation characteristics of surface uplift

The surface uplift data of each monitoring point were recorded after grouting for 60 minutes, as stated in Section 5.1. The uplift values of nine points at the left side of the monitoring area (1-1, 2-1, 3-1, 1-2, 2-2, 3-2, 1-3, 2-3, 3-3) and nine points at the right side of the monitoring area (1-6, 2-6, 3-6, 1-7, 2-7, 3-7, 1-8, 2-8, 3-8) were selected for the spatial change characteristic test of the surface uplift values, and the results are shown in Figure 8.
Figure 8. Changes in surface uplift value with position

The left (right) side of the y-axis is the surface uplift value caused by the film bag (ordinary) grouting process. The response of the surface uplift to the grouting position has a diffusion effect. That is, the farther away from the grouting point, the smaller the surface uplift value. In the same vein, the farther away from the grouting point, the smaller the surface uplift value. In the same column, the surface uplift in the middle is larger than that on both sides because the distance between the middle line and the grouting point is smaller than the distance between the other lines and the grouting point. The surface uplift values of the first and third lines are similar, but the third line is slightly higher than the first line. The movement of groundwater may have led to the uneven diffusion of the slurry.

A comparison of the left and right sides of the y-axis indicates that film bag grouting can effectively reduce the surface uplift under the same grouting amount, grouting pressure, and grouting time. With the use of film bag grouting, after grouting for 30 minutes and 60 minutes, the average uplift value of the surface decreases from 2.82 to 2.32 cm and from 7.14 to 5.84 cm, which reflect decreases of 21.6% and 22.3%, respectively.

A comparison of Figures 8(a) and 8(b) shows that the connection of the uplift value in Figure 8(a) is approximately linear, whereas that in Figure 8(b) is an upward convex curve. The main reason is that the slurry will diffuse along the direction of less resistance. After 30 minutes of grouting, the slurry spreads to all parts of the monitoring area, and the diffusion is relatively uniform. Over time, the injected slurry increases, and the cleaved slurry vein will accumulate more near the grouting point, resulting in a faster increase in the uplift value near the grouting point.

5.3. Analysis of influencing factors of maximum surface uplift value

Four sections of grouting cycle with similar geological conditions were selected for the field tests on the law of surface uplift caused by grouting. Grouting was performed according to the width direction of the monitoring area; thus, a section of the grouting cycle was regarded as 6 m. According to the drilling layout, which is shown in Section 3.2, 5 lines and 15 columns of grouting holes were arranged in the monitoring area. The horizontal and longitudinal intervals of the grouting holes were 1.5 m. Then, the grouting schemes in Table 1 were implemented in accordance with the different research objectives. During the test, the order of reinforcement was controlled strictly; reinforcement could only start in the second column after the first column was completely reinforced. The monitoring points were set 1 m apart to better explore the change in the surface uplift value in the monitoring area caused by the different grouting plans. Therefore, the total number of monitoring points in the x-axis direction within the monitoring area was 22. The left boundary of the monitoring area was taken as the x-axis, and the lower boundary of the monitoring area was taken as the y-axis. The variation in the maximum uplift value of plans 1 to 4 with the grouting process is shown in Figure 9.
(1) Influence of grouting method
According to an analysis of the curves in plans 1 and 2, the maximum surface uplift values under the film bag grouting technology and ordinary grouting process are 2.8 cm and 3.7 cm, respectively. Therefore, the film bag grouting method can significantly reduce the surface uplift on the strongly weathered stratum. Under the same grouting amount and grouting material, the maximum uplift value under the film bag grouting technology decreases by 32.1%.

(2) Influence of grouting volume
An analysis of the curves in plans 1 and 3 indicates that the maximum surface uplift values are 6.2 cm and 2.8 cm when the single-hole and single-section grouting volumes are 1.5 m³ and 1 m³, respectively. When the grouting technology and the grouting material are consistent, the maximum surface uplift value increases by 121% with a 50% increase in the grouting volume. With the progress of the grouting, the growth rate of the surface maximum uplift value is gradually accelerated; the holes along the first line result in the slowest growth in the surface uplift value; the holes along the third, fourth, and fifth lines increase in turn.

(3) Influence of grouting material
According to an analysis of the curves in plans 2 and 4, the maximum surface uplift values under the cement slurry and C-S slurry are 1.2 cm and 3.7 cm, respectively. Under the same grouting conditions, the surface uplift value of the C-S slurry is 3.08 times that of the cement slurry.
The reasons for the above phenomena are analyzed as follows. The adoption of film bag grouting can prevent the diffusion of slurry in shallow strata during the deep grouting process, effectively prevent the upward flow of slurry, and ensure that the slurry only enters the deep stratum, thereby reducing the surface uplift value of the grouting reinforcement area.
The split grouting vein produced by grouting will first compress the surrounding strata laterally and cannot cause a significant deformation of the surface. When the horizontal compaction deformation of the stratum reaches the limit, the deformation caused by the slurry entering the formation will cause the overall uplift of the surface. The grouting area corresponding to the holes of the third, fourth, and fifth lines is the repeated grouting area. Hence, repeated grouting will significantly increase the maximum uplift value of the surface, and the additional grouting amount will be converted into the surface uplift value.
The gel time of cement slurry is relatively long, from 2 to 4 hours, while the gel time of C-S slurry ranges from 10 seconds to several minutes. In the process of grouting, the gelation resistance of slurry increases rapidly, leading to a small diffusion range of the C-S slurry and a large thickness of the slurry pulse. Therefore, the corresponding surface uplift value of C-S slurry is relatively large. At the same time, the supporting and compaction effects of C-S slurry are both strong, which ensures the effect of stratum reinforcement. C-S slurry is used in the outer ring of the grouting reinforcement area.
whereas cement slurry is used in the inner ring. This process limits the surface uplift in the area and ensures the reinforcement effect.

6. Analysis of grouting effect
In this project, surface uplift was effectively controlled by restricting the single-hole and single-section grouting volume to 1.2 m$^3$, using film bag grouting, using a combination of cement slurry and C-S slurry, strengthening the surface monitoring, and other measures. The maximum surface uplift value was 1.8 to 2.5 cm.

Before the grouting reinforcement of the test area, the average permeability coefficient of inspection holes 1 to 4 was $2.65 \times 10^{-5}$ cm/s, as determined via the water injection test. After the grouting reinforcement, the permeability coefficients of the four inspection holes became less than $10^{-6}$ cm/s, and the average permeability coefficient was $3.52 \times 10^{-7}$ cm/s. These findings indicate that the fractures in the stratum were well filled, and the grouting reinforcement achieved good results.

7. Conclusion
In this paper, based on the grouting reinforcement project for a subway tunnel, a field test of the surface uplift law caused by grouting was conducted to verify the reliability of the film bag grouting technology treatment project, and the following valuable conclusions were obtained.

1. With the progress of grouting, whether the film bag grouting process is used or not, the uplift value of each monitoring point is directly proportional to time, and the growth rate tends to accelerate. After the grouting is stopped, the surface uplift value tends to stabilize.

2. The spatial distribution of surface uplift is generally symmetrical, and the response to the grouting position has a diffusion effect; the farther away from the grouting point, the smaller the surface uplift value.

3. Film bag grouting can reduce the surface uplift values of strongly weathered strata. Given the same grouting amount and grouting material, the maximum uplift value in this work decreased by 32%.

4. Under the same grouting technology and grouting materials, the grouting amount increased by 50%, and the maximum uplift value of the surface increased by 121%. The surface uplift value of the C-S slurry was 3.08 times that of the cement slurry with the same grouting amount.

References
[1] Nikakhtar L, Zare S, Abad H M, et al. Numerical Modelling of Backfill Grouting Approaches in EPB Tunneling[J]. Journal of Mining and Environment, 2020, 11(1): 301-314.
[2] Li SC, Zhang WJ, Zhang QS, et al. Research on advantage-fracture grouting mechanism and controlled grouting method in water-rich fault zone[J]. Rock and Soil Mechanics. 2014, 35(3): 745-751.
[3] Wu Y, Wang K, Zhang L, et al., Sand-layer collapse treatment: An engineering example from Qingdao Metro subway tunnel. Journal of Cleaner Production, 2018, 197: 19-24.
[4] Li HL, Zhang CR, Lu K. Nonlinear analysis of response of buried pipelines induced by tunneling[J]. Rock and Soil Mechanics. 2018, 39(S1): 289-296.
[5] Zhang ZG, Shi MZ, Zhang CP, et al. Research on deformation of adjacent underground pipelines caused by excavation of quasi-rectangular shields[J/OL]. Chinese Journal of Rock Mechanics and Engineering.
[6] Gollegger J. Numerical and analytical studies of the compensation grouting[D]. Austria: Graz University of Technology, 2001.
[7] Tang ZW, Zhao CG, Zhang DL. Design of displacement grouting and prediction of the effect for construction of underground structures[J]. China Civil Engineering Journal. 2007, 40(08): 79-84.
[8] Tang ZW, Zhao CG. Mechanisms of ground heave by grouting and analytical solutions & numerical modeling[J]. Rock and Soil Mechanics. 2008, 29(06): 1512-1516.
[9] Zhang M, Wang XH, Wang Y. Mechanism of grout bulb expansion and its effect on ground uplifting[J]. Journal of Central South University of Technology. 2011, 18(6): 874-880.

[10] Zhang SJ, Liu RT, Li SC, et al. Study on ground surface heave affected by grouting in sandy soil layer[J]. Chinese Journal of Underground Space and Engineering. 2018, 14(04): 1097-1104.

[11] Tazio Strozzi, Reynald Delaloye, Damien Poffet, Jürgen Hansmann, Simon Loew. Surface subsidence and uplift above a headrace tunnel in metamorphic basement rocks of the Swiss Alps as detected by satellite SAR interferometry, Remote Sensing of Environment, Volume 115, Issue 6, 2011, Pages 1353-1360, ISSN 0034-4257.

[12] Zhao YH. Forward Horizontal Grouting Technology of Subway Station Ends[J]. Advanced Materials Research, 2014: 364-367.

[13] Cao L, Jiang MY, Gu CH, et al. Research on Key Technology and Engineering Application of Dam Membrane Bag Control Grouting [J]. Hunan Water Conservancy and Hydropower, 2019(6):27-29.