Advance Grouting Technology for a Large Surge Tunnel

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Abstract: The large water inrush during excavation construction is a prominent problem in tunnels because of their fractured surrounding rock conditions and complex lithology, which seriously affects the tunnel construction progress and safety. Advanced grouting ideas of combining plugging and draining, mainly involving draining and supplementing water plugging, have been put forward according to different geological conditions. In this study, we used three different advanced grouting techniques to dispose of the water inrush from the palm face, block the large water inrush points in time, control the water inrush from the palm face, and successfully dispose of the large water inrush from the tunnel. Through a comparative analysis, we found a more effective advance grouting technology under different geological conditions, which can be applied for future use by other researchers.

1. Introduction
The grouting technology is an indispensable key link in the underground geotechnical engineering construction because it plays an important role in filling and reinforcing the stratum, waterproofing, and plugging and is significant in underground space development.

The water plugging grouting technology dates back to 1802 when Charles Bering, a French engineer, mixed lime and clay with water and pressed it into rock fissures. After the British invented “Portland cement” in 1824, the cement grouting method has been widely used as an important engineering measure[1-6]. In 1884, British engineers introduced the grouting method into tunnel excavation engineering. Accordingly, the grouting theory also came into being with the development of the grouting method[4].

The development of the engineering grouting technology in China is relatively late. In the early 1950s, China initially mastered the grouting treatment technology in rock foundation with good geological conditions. With the expansion of human activities, some special projects needed grouting materials for rapid solidification. Take for example the case of single-liquid grouting, which can easily cause pipe plugging in the grouting pipe. To solve this pipe plugging problem, the two-liquid grouting technology was developed. Cement–water glass double-liquid grouting emerged in 1967[7]. In 1987, a super-early strong secondary grouting mortar without shrinkage was developed by the China Building Materials Research Institute on the basis of expanding agent research. The mortar obtained great promotion and application[8].

Tunnel projects with different geological and water inrush conditions are often included in the construction process of water conservancy projects. Most especially in tunnel construction with unfavorable geological section, large water inflow, rich water layer, and high groundwater level, significant safety hazards and construction difficulties restrict the construction progress and economic investment.

2. Engineering overview
The Xiaolangdi Yellow River Diversion Project in Shanxi Province is a large-scale water diversion project from the Xiaolangdi Water Control Project on the main stream of the Yellow River to the Sushui River Basin in Shanxi Province. The project mainly solves concerns on living, agricultural irrigation, and industrial water use in Yuncheng City and its surrounding counties, thereby providing great social effect and significance. The scope of the #1 diversion tunnel of the construction I bid is from S0 + 000 to S5 + 000 (length: 5000 m). The #0 construction adit is close to the Xiaolangdi reservoir area. The problem of a large water inflow is prominent in the excavation process, and the surrounding rock condition is poor. The proportions of class IV and V surrounding rocks reach 98.3%. The design maximum water inflow of the control section is 12,000 m³/d, while the measured maximum water inflow is 100,000 m³/d. Water gushing not only increases the construction difficulty and safety risk, but is also the most critical factor restricting the construction progress.

3. Geological conditions
The project area, which is located at the edge of the provincial boundary, is a region with complex hydrogeological and tectonic conditions. The large fractures in the longitudinal and transverse areas of the surface valleys cut across the tunnel axis and connect with the reservoir area, extending long and cutting deep with a strong destructive effect. An unknown structural overlapping exists, and the stratum is upside down and chaotic. The reservoir area has a high-pressure water level, and the difference between the designed and uncovered enclosure types is large; thus, the geological conditions are extremely poor, and construction is extremely difficult. The tunnel bottom elevation is below el226.00, which is 40–50 m lower than the reservoir water level all year round. A regional F1 fault can be found in the east of the tunnel section. An extension greater than 1.5 km, a staggered distance > 200 m, a broken zone width of approximately 30–50 m, and an impact zone > 100 m can also be found from the southern reservoir area and the northern Banjian River. The groundwater in the construction area is mainly recharged by the reservoir area, followed by the atmosphere and the precipitation supply. The uncovered strata are Ordovician carbonate rocks (limestone and mudstone). The fissured karst is extremely developmental, brittle, and easily cracked and eroded. Groundwater activities below the water level are frequent. Karst fissures are characterized by crosstalk, cavities, small- and medium-sized caves with developed yellow, soft, and weakly soluble marl, large thickness, and long extension. The regional large-scale fault structure, its multi-stage activity superposition, and the instability of its own physical and chemical properties leading to the stability of the surrounding rock in this part are extremely poor.

The S0 + 690.00–S0 + 709.00 section is Ordovician Middle (O₂) characterized by a gray–yellow mudstone intercalated with marl. Meanwhile, the S0 + 709.00 to S0 + 720.00 section is a muddy dolomitic limestone sandwiched between marl and limestone with a broken periphyton structure and an extremely developed small-sized structural fissure. A large gush of water (approximately 400 m³/h) is observed from the 0 + 705.2–0 + 720.0 palm surface and hole section. The surrounding rocks are extremely unstable and belong to category V. S0 + 705.20 has two groups of shear fissures: 1) L1 toward 20°NW inclined 70° and 2) L2 toward 80°NW inclined 60° in the palm surface and two walls. The structural surface is flat with a ferrous oxide color. The broken mass is approximately 3–5 cm. The S0 + 717.60 palm surface and both walls develop a group of shear tensor fissures (i.e., L3, which is inclined to 360°W with 80° angle and is filled with mud and sand). The water gush is controlled by shear fissure and gushes out from the fissure surface (stratigraphic yield: 120° < 40°; local variations: large).
Figure 1. #1 diversion tunnel: S0 + 690.00~S0 + 720.00 section of the tunnel geologic cataloging display figure

Table 1. Statistical table of joints and fissures

| Number | Occurrence | Number of pieces | Type | Extensio n length (m) | Seam width (mm) | Surface features | Fillers and others |
|--------|------------|------------------|------|-----------------------|-----------------|-----------------|-------------------|
| L1     | 20° NW     | 70°              | 10   | Tensile               | >4              | 2               | Straight and rough | Argillaceous sand |
| L2     | 80° NW     | 60°              | 8    | Tensile               | >5              | 3               | Straight and rough | Argillaceous sand |
| L3     | 360° W     | 80°              | 4    | Tensile               | >3              | 1~3             | Straight and rough | Argillaceous sand |

4. Advance grouting ideas
In the water inrush treatment of a diversion tunnel, large inrush points are blocked; the water inrush from the palm face is controlled; the construction progress and safety are guaranteed; and the drainage cost of the tunnel is reduced. However, the water inrush of the tunnel cannot be plugged by conventional water plugging grouting because of the complex geological conditions of the tunnel, well-developed karst fissures, long extension, and good connectivity. The current water plugging effect and the reduced consolidation grouting consumption during the later tunnel lining are being considered due to the development of the fissure seepage. The comprehensive comparison and analysis of efficiencies have solved the difficulty of grouting construction, shortened the construction time of tunnel grouting, and accelerated the excavation speed of tunnel circulation.

A large amount of water gushes from the palm surface; hence, advance palm surface detection must be conducted before grouting to ensure the construction safety. When a down-the-hole drill is used to add horizontal water detection holes in the water-rich concentrated section of the face, one to three horizontal water detection holes, which can be adjusted and determined according to the actual water inflow, are arranged in the middle of the face. The horizontal water detection hole laid in the water-rich section can be used as the grouting hole when unloading the pressure hole and performing advance plugging grouting. The water detection hole is 15~20 m deep. The hole diameter is Φ76 mm.
Drilling and grouting are immediately stopped if the drill falls out during the drilling process. The hole is reopened after completion, and sweep hole drilling is performed. Different grouting methods should be adopted for special geological conditions and large water inflow. In the #1 diversion tunnel section S0 + 609.00–S0 + 710.00, three types of advance grouting techniques were performed at three sites (i.e., S0 +693 m, S0 + 701 m, and S0 +705 m pile numbers of the palm face) depending on the palm surface excavation during the excavation construction. As regards the choice of materials, cement–water glass double-liquid slurry was used for the advance grouting of the diversion tunnel because of its low price, short setting time, fast speed, high stone strength, safety, and non-toxicity\(^9\)\(^{-12}\).

5. Cement–water glass slurry ratio and setting time
The ratios of the cement-based slurry were 0.8:1 and 0.5:1. The water glass dilution concentration was 39.5 Bé. The double-liquid volume ratios (C/S) were 1:1, 1:0.75, 1:0.5, 1:0.25, and 1:0.1. Table 2 presents in detail the setting time (indoor test) of cement and the cement–water glass double-liquid slurry ratio.

| Serial number | water/cement ratio | Initial setting time (min) | Final condensation time (min) |
|---------------|--------------------|----------------------------|-------------------------------|
| 1             | 0.5:1              | 465                        | 597                           |
| 2             | 0.8:1              | 523                        | 609                           |

Table 2. Cement-based slurry coagulation schedule

| Water/cement ratio | Condensation time | Slurry: water-to-glass volume ratio |
|-------------------|-------------------|------------------------------------|
|                   | Initial setting time (s) | 1:0.25  | 1:0.5  | 1:0.75 | 1:1 |
| 0.8:1             | Initial setting time (s) | 56      | 91     | 163    | 236 |
|                   | Final condensation time (s) | 123     | 162    | 242    | 322 |
| 0.5:1             | Initial setting time (s) | 51      | 67     | 101    | 193 |
|                   | Final condensation time (s) | 101 | 124    | 174    | 275 |

Table 3. Coagulation schedule for the cement–water–glass double-liquid slurry ratios

Figure 2. Gelation times for different cement slurry-to-water glass volume ratios

6. Advance grouting

6.1. Shallow hole grouting on the palm surface + double-liquid grouting on the whole section
6.1.1. Introduction
Pile S0 + 693 m of the #1 diversion tunnel was exposed in the excavation process. Furthermore, two groups of shear cracks were developed in the palm surface and two walls. The gushing water was subjected to shear fracture control, surging from the fracture facing level (visual flow $Q > 300$ m$^3$/h). First, the shallow hole grouting of the palm surface seepage was adopted. Next, a YQ70 submerged hole driller was used to construct the advance water exploration hole. Grouting on the palm surface seepage was then performed. After completing the grouting for the performance of a normal tunnel excavation, we decided whether or not to grout the system depending on the water gushing in the water exploration hole.

6.1.2. Shallow hole grouting on the palm surface
The shallow hole grouting on the palm surface mainly adopted the method of drilling and grouting for the concentrated gushing water part of the palm surface. Figure 3 presents the grouting arrangement. The operation steps are as follows:

(1) First, grouting is performed in the gun and anchor holes that are currently gushing water on the palm surface in the order of I and II holes. The hole closure is then adopted. A grouting pressure of 0.5 MPa and cementitious slurry ratios of 0.8:1 and 0.5:1 were used to perform grouting of the whole hole section.

(2) After grouting and blocking the existing gush hole, grouting holes of $\Phi 108$ mm and $L = 6$ m are arranged at the palm face to grout the palm face again (i.e., also divided into I and II sequence holes) after completing the palm surface grouting to form a rock plug closed slurry.

(3) If no water gushing occurs in the drilling process, drill to the end and inject grout into the whole hole once. Stop if water is found in the drilling process. Subsequently, drill a hole and take a section of the forward injection until the design section length position is reached.

(4) The layer-by-layer water release and decompression and the layer-by-layer grouting method can also be used in the case of the large water pressure and quantity. For the lower pipe grouting, the middle-pipe water is released, while for the middle-pipe grouting, the upper-pipe water is released to lift the water layer by layer (i.e., water drainage is at the top of the vault above the regulations). Outside of the water stop curtain ring, the injection sequence is bottom–up and inside–out.

(5) When drilling an advanced water exploration hole, the probe hole will be used for grouting if the surge water is large by taking the drilling method while grouting. The system grouting will then be completed. The tunnel excavation is done after the surge becomes small or does not exhibit any surge.
6.1.3. System grouting

System grouting aims to systematically drill and grout the palm surface according to the specified distance between the grouting holes. Figure 4 depicts the grouting arrangement. The process description is presented below:

1. Lay-out Φ70 advance grouting holes at 2 m intervals at the edge of the excavation at the palm surface. Use a YQ70 down-the-hole drill or a rock electric drill for drilling a depth of 20–30 m. The drilling depth can be adjusted according to the results of the material exploration and the actual drilling conditions. If possible, try to increase the drilling depth to reduce the number of cycles. Arrange the grouting holes horizontally along the tunnel axis direction. Facilitate drilling construction.

2. The grouting process must be consistent with the abovementioned shallow hole grouting process. In cases where the end standard is still not reached despite using 0.5:1 cement slurry grouting and consuming 2 T lime, water glass is taken in during the grouting process. The double-liquid slurry is mixed at the orifice using two injection pumps. Furthermore, the slurry ratio is adjusted and controlled by controlling the flow of the slurry during grouting. The double-liquid volume ratios (C/S) are 1:1, 1:0.75, 1:0.5, and 1:0.25. The slurry is changed step by step according to the ash consumption in each stage (i.e., not more than 2 T).

3. As regards the cementitious slurry infusion end standard, if the slurry-absorbing amount is not more than 1.0 L/min, continue the infusion under the maximum infusion pressure (infusion time: 10 min). For the cement–water–glass double-liquid grouting end standard, when the injection quantity is less than 1.0 L/min, the process can be finished under the maximum injection pressure. Avoid clogged lines.

4. When grouting is finished, randomly set up Φ108 advanced holes around and in the center of the palm surface with 2 m distance and 20 m–Φ108 depth. The decrease or disappearance of the gushing water means that advance grouting has reached the predetermined effect.

6.1.4. Grouting effect

Centralized grouting is performed to grout holes with large water gushing in the palm surface. The actual grouting parameters are as follows: hole depth (L) = 4.5–6.4 m; grouting pressure (P) = 0.5 MPa; and grouting suction (Q) = 26804.854 L to 43578.08 L without water glass.
When the shallow hole grouting was completed, we still found some cracks on the palm surface seeping water. Hence, we systematically performed grouting of the seeping part. Considering the actual situation at the site, we drilled holes with a submerged drill at the seepage part and took the grouting method while drilling. We then immediately conducted borehole grouting when water gushing occurred during drilling to speed up the cement paste setting. The slurry was mixed with water glass and re-drilled. Grouting was performed after sealing. The grouting parameters are as follows: hole depth (L) = 6.3–17.3 m; grouting pressure (P) = 0.5 MPa; grouting suction (Q) = 35062.51–39060.60 L; and water glass blending amount: 0–1930.43 Kg. No water seepage was seen on the palm surface after grouting. A large gush of water, however, appeared after four excavation cycles. Figure 5 illustrates the site photos before and after grouting.
6.2. Shallow hole grouting on the palm surface + double-liquid grouting on the whole section

6.2.1. Introduction
In the excavation process of the #1 diversion tunnel, we found that two groups of shear cracks existed on the tunnel face and in the two walls of the S0 + 701 m pile. The gushing water gushed out from the cracks toward the plane, and the visual flow (Q) was equal to 300 m³/h. When the palmtop adopted the subsurface drilling for super detection holes, a large water inflow ahead of the water hole was found, indicating that a karst cave or a large crack existed in front of the palmtop. Meanwhile, the grouting cement consumption was large in the palm face of the S0 + 693 m pile. The cement consumption was large; thus, we adjusted the grouting scheme using 0.5:1 pure cement slurry to open the grouting. Water glass was then added according to different ratios to accelerate the slurry setting. During the pre-grouting of the S0 + 701 m palm face with reference to the S0 + 693 m grouting method, the water pressure increased because of the water gushing. The maximum grouting pressure was increased to 1.0 MPa, and 0.5:1 pure cement slurry was used directly at the beginning of grouting. Double-liquid slurry irrigation (with water glass) was used in the absence of a significant change in the suction volume and pressure after pouring 2 t cement.

6.2.2. Grouting effect
When grouting, we first used a 0.5:1 pure cement slurry to grout the concentrated gushing hole of the palm surface in sequence. After filling in 2–3 t cement, no significant change in the slurry absorption and pressure was observed. Water glass was mixed into the slurry. Subsequently, grouting was performed step by step according to the volume ratios of 1:1, 1:0.75, 1:0.5, and 1:0.25. No water seepage was observed on the palm surface, even after adding water glass to complete the grouting hole blocking. The grouting parameters are as follows: hole depth (L) = 2.8–22.7 m; grouting pressure (P) = 0.5–1.0 MPa; grouting slurry absorption (Q) = 1918.96–8758.4 L; and blending amount of water glass: 288.96–1586.82 kg.
No seepage was seen on the palm surface after grouting was completed, and two cycles were excavated. Figure 6 depicts the site photos before and after grouting.
6.3. Shallow hole grouting on palm surface + full-section mortar grouting + mortar advance grouting

6.3.1. Introduction
After excavation, we found a crack in the palm face of pile S0 + 705 m with a large amount of water seepage. The following measures were taken for the S0 + 705 m pile combined with the grouting situation in the two times previously mentioned and the effect after irrigation:
(1) First, we referred to the grouting method (cement–water–glass double-liquid grouting) of the S0 + 701 pile to perform shallow hole grouting on the palm face of pile number S0 +7 05 m.
(2) Large cracks and cavities are filled using a mortar to reduce the cement consumption. Advanced grouting (pure cement slurry or double slurry grouting) is then performed.

6.3.2. Mortar grouting
The construction steps for mortar grouting are described below:
1. drilling → installation of the orifice pipe → mortar grouting → completion of the grouting closed hole → second advance grouting → surge water reduction, grouting completed → tunnel excavation.
Considering the existence of a number of small seepage cracks on the surface of pile number S0 + 705 m, we performed manual tapping to enlarge the crack before grouting and conducted caulking. A sealing treatment was also performed with a hemp thread to better seal the cracks and prevent the occurrence of large slurry and leakage in the grouting process.

The mortar was grouted with the GS50E grouting pump. The cement was PO 42.5 cement. The largest grain of sand was less than 5 mm. A seepage in the water extraction tunnel was observed. Furthermore, the sodium silicate concentration was 39.5 Bé, and the injection method was a whole hole primary press-in.

The mortar ratio was 0.5:1:0.3 to 0.5:1:1 (mass ratio of water:cement:sand). The cement slurry was mixed in a high-speed pulping machine. The mixed slurry was then conveyed to the GS50E grouting pump. Sand was added in the GS50E grouting pump and then directly pumped into the GS50E grouting hole. The mixing quantity of sand changed from small to large during grouting. The first mix contained a small amount of sand (i.e., 0.3 proportion of the mixing quantity) in the cement slurry. If the injection amount of the mortar does not change after 15–20 min of grouting, the sand content shall be increased by stages according to the proportion of 0.1. The sand content shall not block the pipeline.

If the water inflow in the grouting hole is large, and the pressure is high, or if the sand blending in a large proportion for grouting is not enough to block the pipe, 10–50% (volume ratio) sodium silicate can be added into the mortar as accelerator.

Considering the fluidity of the gushing water in the cracks and caves, the mortar was connected with an external water source. Accordingly, 5–20% (mass ratio of mortar) of hemp wire was added to the mortar to increase its sealing effect on the cracks and cavities. Hemp yarn is manufactured into the finished products by manual gunny-bag cutting. The mixing amount changes from small to large when hemp yarn is added. It shall be adjusted according to the grouting situation on site, and the grouting pipeline shall not be blocked.

The mortar grouting pressure was 0.5–2 MPa, with a maximum of 2 MPa. We closed the grout for 12 h after grouting, then used the YQ70 down-the-hole drill to perform advance drilling and determine the effect of grouting and seepage ahead (i.e., whether there is a large gush of water and small cracks) to ensure the diffusion radius and the grouting effect of the slurry. Cement slurry or double slurry grouting is preferred for plugging. If large karst caves and fissures are encountered or if the cement slurry (double-liquid slurry) grouting does not achieve the sealing effect, the abovementioned solution is then again taken. The process was repeated until the water seepage in the probe hole became smaller so as not to affect the excavation. Grouting was then finished, and the tunnel was excavated.
6.3.3. Grouting effect

6.3.3.1 Shallow hole grouting on the palm surface
The cracks and the solution cavity of the palm surface were obvious after excavation, and the grouting leakage during grouting was serious. Considering these, we performed the shallow hole water glass double-liquid grouting on the palm surface to close the cracks and the solution cavity of the cave, such that the palm surface is closed.

The parameters are as follows: hole depth $L=2.3 \sim 5.0$ m, grouting pressure $P=0.5 \sim 2.0$ MPa, grouting suction $Q=136.64 L \sim 1948.6 L$, the blending amount of water glass is $0 \sim 179.31$ Kg.

In order to prevent grouting in large area during the shallow hole grouting of the tunnel face, the small water seepage parts are firstly drilled and grouted, and then the parts with large water seepage are drilled and grouted in sequence.

Because of the large water seepage hole water pressure and water amount is larger, when first around the big water seepage hole drilling grouting pressure relief hole, pressure relief hole is $20^\circ$ Angle of inclined crack, and then install $\Phi 100$ PE pipe will pour water, will be sprayed concrete cover cracks, finally respectively for grouting in turn. During grouting, the pressure relief hole is first filled successively, and the large seepage hole is finally filled.

(2) Mortar grouting
After grouting the shallow holes in the palm face, we performed advance grouting according to the two previously mentioned grouting methods, taking the same method of grouting while drilling. The fissures and the cavities during the drilling process were large. In addition, using pure cement slurry and water glass double-liquid slurry could not achieve the sealing effect; hence, grouting was performed using a grouting mortar.

The actual advance grouting parameters are as follows: the depth of the first section hole was 3.3–8.7 m; the grouting pressure was 0.28–1.61 MPa; the depth of the second section hole was 10.3–11.5 m;
and the grouting pressure was 0.24–1.53 MPa. The sand admixture amount was 725.41–4638.6 kg, while the water glass reference amount was 86.4–1870.01 kg.

In the process of advance grouting drilling on the palm face, holes #37 and #42 encountered karst caves in the second stage of the grouting drilling. The drill pipe fell off, and the cavity depth was approximately 0.6 m. Therefore, in this grouting process, we directly poured mortar and added hemp wire and water glass in the slurry. The karst caves were then backfilled and sealed.

We performed the advance drilling detection after completing the advance grouting on the palm surface. The water content in the hole was small when the drilling depth was 15 m, proving that this test grouting achieved an expected result. Figure 8 depicts the site photos before and after grouting.

Figure 8. S0 + 705 m comparison of the site photos before and after grouting

7. Comparison of the grouting effects
7.1. Construction period comparison

According to the site statistics, the S0 +693 m, S0 +701 m, and S0 +705 m pile numbers of the diversion tunnel were grouted in advance of the surge. Table 4 shows a comparison of the construction periods.

| Place | Starting and ending dates | Actual time spent (d) | Length of excavation after filling (m) | Extended meter time (d) | Grouting method |
|-------|---------------------------|-----------------------|----------------------------------------|------------------------|----------------|
| S0 + 693 m grouting | 3.2~3.10 | 9 | 8.2 | 1.1 | Shallow hole grouting on palm surface + double-liquid grouting on whole section |
| S0 + 701 m grouting | 3.19~.21 | 3 | 4.2 | 0.71 | Shallow hole grouting of palm surface + double-liquid grouting of whole section (controlled suction) |
| S0 + 705 m grouting | 3.26~4.18 | 14 | 19.6 | 0.71 | Grouting of shallow holes of palm surface + mortar grouting of whole section + mortar advance grouting (less 10 d equipment purchase time) |

Table 4 illustrates that the lead grouting time of S0 +705 m, S0 +701 m, and S0 +693 m of each extension was 0.71 and 1.1 days. In the crack section, the grouting in the shallow hole of the palm surface + double-liquid grouting in the full section (controlling the amount of slurry absorption) was beneficial to the construction schedule (S0 +701 m). Meanwhile, in the sections with fissure and karst cavity, the method of palm face shallow hole grouting + full-section mortar grouting + mortar advance grouting (S0 +705 m) exhibited advantages in terms of the construction period (i.e., savings in the construction period) and was found beneficial to the excavation progress of the diversion tunnel.

7.2. Comparison of material consumption

According to the site statistics, Table 5 presents a material consumption comparison of the water gushing advance grouting at S0 +693 m, S0 +701 m and S0 +705 m in the diversion tunnel.

| Serial number | Item | S0 + 693 m | mS0 + 701 m | mS0 + 705 m | Note |
|---------------|------|------------|-------------|-------------|------|
| 1 | Ruler cycle length (m) | 8.2 | 4.2 | 19.6 | |
| 2 | Number of grouted holes (pc) | 5 | 8 | 41 | |
| 3 | Total depth of hole (m) | 41 | 54.2 | 192.7 | |
| 4 | Total depth of grouting hole Φ50 (m) | 10.9 | 20.5 | 83.8 | |
| 5 | Total depth of the borehole in advance exploration: Φ70 (m) | 33.7 | 108.9 | |
| 6 | Total cement volume (t) | 222.075 | 63.687 | 209.847 | |
| 7 | Total water glass volume (t) | 2.127 | 6.224 | 8.878 | |
| 8 | Total fine sand volume (t) | 0 | 0 | 81.718 | |
| 9 | Cement consumption (t/m) for linear meter feed (t/m) | 27.1 | 15.2 | 10.7 | |
| 10 | Water glass consumption (t/m) in linear meter feed 0.3 (t/m) | 1.5 | 0.3 | 0.5 | |
The comparison of the material consumption presented in Table 5 leads to the following conclusions:

1. The grouting method of the face shallow hole grouting + full-section mortar grouting + mortar advance grouting (S0 + 705 m) consumes less cement per linear meter.

2. The grouting method of the face shallow hole grouting + full face double-liquid grouting (S0 + 693 m) consumes less water glass for the linear meter footage.

7.3. **Investment comparison**

An investment comparison based on the S0 + 693 m, S0 + 701 m, and S0 + 705 m pile numbers of the diversion tunnel was made in terms of the construction period, compensation for work delay, and material consumption (Table 6).
Table 6. Comparison table of investments in advance grouting

| Serial number | Item                              | S0 + 693 grouting | mS0 + 701 grouting | mS0 + 705 grouting | mNote |
|---------------|-----------------------------------|-------------------|--------------------|--------------------|-------|
| 1             | Ruler cycle length (m)            | 8.2               | 4.2                | 17.7               |       |
| 2             | Grouting costs                    |                   |                    |                    |       |
| 3             | Grouting costs                    |                   |                    |                    |       |
| 4             | Grouting costs                    |                   |                    |                    |       |
| 5             | Overfill costs                    |                   |                    |                    |       |
| 6             | Overfill costs                    |                   |                    |                    |       |
| 7             | Overfill costs                    |                   |                    |                    |       |
| 8             | Overfill costs                    |                   |                    |                    |       |
| 9             | Compensation                      |                   |                    |                    |       |
| 10            | Compensation                      |                   |                    |                    |       |
| 11            | Total cost (Yuan)                 |                   |                    |                    |       |
| 12            | Per meter cost (Yuan/m)           |                   |                    |                    |       |

Table 6 shows that the grouting method of the face shallow hole grouting + full face mortar grouting + mortar advance grouting (S0 + 705 m) consumes the least cost for the linear meter footage.

8. Conclusions

This study put forward the advanced grouting idea of combining plugging and draining mainly with draining and supplementing with water plugging during the advanced grouting process of a diversion tunnel to block large water inrush points in time, control water inrush at the face of the palm, ensure construction progress and safety, and reduce the tunnel drainage cost. The comparison of the construction period, material input, and investment showed no karst cavity in the zone with developed fissures. Therefore, the method of palm face shallow hole grouting + full-section double-liquid grouting (controlling grouting volume (S0 + 701 m)) is advantageous for progress and the economy. The combination of the palm face shallow hole grouting + full-section grouting + mortar advanced grouting (S0 + 705 m) was used in the zone with developed fissures and caves. Consequently, this combination can more effectively close the inrush water and has advantages in terms of schedule and economy.

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