Research Article

Study on Stability of Tunnel Surrounding Rock and Precipitation Disaster Mitigation in Flowing Sand Body

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Received 5 September 2021; Accepted 2 November 2021; Published 14 December 2021

Flowing sand is a special surrounding rock encountered by tunnel construction. Due to the looseness and low viscosity of the flowing sand, after excavation, the sand body is easy to flow along the open surface. In addition, the water seepage also causes tunnel instability. Considering the characteristics of water seepage, how to improve the stability of flowing sand bodies and prevent the instability of surrounding rocks has become a difficult problem. In this paper, a parametric experiment on the surrounding rock taken from the project site was carried out, and then, a numerical simulation of the flowing sand body was conducted to study the precipitation construction method and stability of the flowing sand body. Other than that, the tunnel face vacuum dewatering, vertical vacuum dewatering at the top of the tunnel, and the vacuum dewatering technology of the gravity well in poor geological section were systematically analyzed in our research. A radial vacuum enclosed precipitation process for the face of the tunnel was proposed, which effectively solved the problem concerning continuous seepage of water in the front. Through numerical simulation and field experiments, the basis for determining the precipitation parameters of the tunnel face was obtained, while aiming at the top position of the tunnel, a vertical vacuum negative pressure precipitation method of intercepting the top seepage water and the water supply behind the top of the tunnel was proposed. For the bottom of the tunnel, setting gravity wells on the side walls for the purpose of preventing seepage at the bottom was put forward. The application of these methods in the project ensured the safety of construction and improved the construction schedule. After the completion of the dewatering construction, the method of inserting plywood into the small pipe was adopted to avoid the collapse of the dry sand. Then, to solve the problem of borehole collapse in flowing sand bodies, pipe feeding was introduced, thus further enhancing the precipitation effect. Furthermore, in view of the problem that the dewatering hole in the flowing sand body is easy to collapse, resulting in the failure of 60% of the dewatering hole and the sand body is extracted from the dewatering pipe, causing the risk of the cavity at the top of the tunnel, a method of pipe following is presented to avoid the damage of geotextile caused by directly inserting the dewatering pipe and further improve the dewatering effect. All the above processes together form an omnidirectional three-dimensional negative pressure precipitation method that considers the special sand body flow and water seepage of unfavorable geology and that has been proved to enhance the stability of surrounding rock in practice.

1. Introduction

With the development of society and economy, the tunnel construction process is gradually accelerating. Quicksand formation is a type of formation sometimes encountered in tunnel engineering. It is generally characterized by poor diagenesis, and its engineering properties are closer to compacted silt fine sand. During the construction of the tunnel, the support is prone to crack in dry sand, and the sand will flow out from the cracks, resulting in a cavity at the top of the tunnel, thus further causing engineering accidents. When the water content is large, the mechanical properties of the quicksand layer deteriorate rapidly under the action of water. To be specific, the surrounding rock is deformed and collapsed, and the quicksand is severe, while the stability is extremely poor. In this condition, the construction is
extremely difficult, and the risk is extremely high [1–3]. Especially, when the water-rich quicksand stratum has worse stability, the safety of tunnel construction is threatened. Therefore, it is necessary to carry out precipitation construction in the stratum with rich water and quicksand.

Regarding the precipitation construction technology of water-rich quicksand formations, there are few domestic and foreign construction cases, and corresponding research materials are also scarce. However, some scholars have conducted some research, mainly focusing on the research of advanced grouting and reinforcement [4, 5], advanced precipitation, and excavation methods. Wu et al. conducted research on Xiamen Xiang’ an Subsea Tunnel [6]. In order to ensure a smooth passage through the water-rich sand layer, underground diaphragm walls and drain relief wells were used on the surface to control groundwater, and advanced pregrouting was taken to consolidate sand in the tunnel, while as for the construction plan of layer combination, the CRD method of excavation is adopted. Wang et al. aimed to reduce the risk of water inrush and mud outburst in the Bieyancao tunnel on the Yiwan railway and adopted full-face curtain grouting to reinforce the surrounding rock [7]. Besides, radial reinforcement and grouting were implemented to reinforce the ground. After the construction, the full-face pregrouting reinforcement measures were applied to guarantee the construction safety [8]. Moreover, Deng introduced the differential equation of seepage movement in the phreatic aquifer, which laid the foundation for the theory of groundwater steady flow [9]. Beyond that, Deift et al. proposed the differential equation of unsteady flow motion in the phreatic aquifer [10], while Mroueh and Shahrour [11] used the three-dimensional finite element method to study the influence of the ground loss caused by tunnel excavation on the existing foundation.

Analytical methods, finite difference methods, boundary element methods, and finite element methods are main precipitation calculation methods. In general, the finite element method not only maintains the advantages of the original variational method but also has the flexibility of the difference method, which makes up for the shortcomings of the classical variational method. Considering that, it is currently the most effective method for numerical calculations [12–15]. From the study on well-point precipitation in 1950, Gong et al. [16] put forward the viewpoint of precipitation “funnel.” Shang [17] observed the change of the vacuum degree in the soft foundation reinforcement project with the vacuum-heap loading method and then found that the vacuum degree decreased with the increase of depth. In addition, Huang [18] studied the stress state, constructed a mathematical model of foundation stability under vacuum conditions, and finally proposed the attenuation formula of vacuum degree under vacuuming, while Liang [19] researched the water-rich sections of Beijing subway tunnels and obtained the control methods of vertical jet grouting piles and horizontal jet grouting piles in the tunnel, which provided a safe construction environment for tunnel excavation. Besides, Wu et al. [20] analyzed and summarized the construction of tunnels in the water-rich sand layer in Hangzhou and concluded that the liquefaction of the water-rich sandy silt layer was solved by the full-section pregrouting, combined with the auxiliary measures such as the advanced pipe shed and precipitation problems with piping. Through the application analysis and research on the construction method of the rich water section belonging to Shenzhen subway tunnel, it is concluded that the water-stop curtain, the dewatering well, the surface chemical grouting, the deep hole grouting in the cave, and the advanced small pipe grouting in the cave are the main factors [21]. Here, it should be noted that auxiliary construction methods can improve the stability of surrounding rock and ensure construction safety and quality. Li [22] obtained a small pipe dense grouting, advanced drainage in the tunnel, and enhanced initial support strength via the application research on the construction technology of Shenzhen cross-street tunnel through the water-rich sand layer to ensure the smooth passage of the tunnel. Furthermore, Peng et al. [23] analyzed the groundwater treatment in the water-rich sandy silt section of Hangzhou Jiefang Road tunnel and found that the light well point in the tunnel is an effective and economical way of precipitation. Apart from that, compared with grouting and blocking water, its cost is reduced to a great extent.

Scholars have gained rich results when concerning researching precipitation technology in the formation of water-rich quicksand. Studies have shown that water and temperature have a certain impact on the physical and mechanical properties of rocks [24–29]. In engineering excavation and construction, mining method and stratum buried depth also have an impact on rock mechanical properties. For example, in coal mining, mining rate and coal seam occurrence depth are important factors affecting the physical and mechanical properties and mechanical response of coal and rock [30, 31]. In addition, under complex geological environment, freezing thawing and cyclic loading have a significant impact on rock fracture [32, 33]. It can be seen that for the engineering of excavating rock and soil or underground resource reservoir, the stability and safety of surrounding rock are affected by a variety of environmental and complex human factors. Then, for tunnel engineering, complex conditions will cause instability risk of surrounding rock and then form hidden dangers of geological disasters. A water-rich sand stratum is a kind of extremely unstable geological area. When considering its stability and safe excavation, how to reduce precipitation and reduce disasters have a very important impact on the safe implementation of the project and the stable operation of the tunnel. However, there are few reports about the precipitation problem in the large-deformation section in water-rich and soft rock. Due to the special stratum status of the project, using traditional methods, the effect is not ideal, and the construction progress and construction quality are difficult to be effectively solved. Therefore, the vacuum negative pressure precipitation method is optimized and improved, followed by good results having been achieved. In this case, a certain coal-transport railway tunnel is taken as the engineering background to analyze and discuss the precipitation problem in the water-rich soft rock section with large deformation in this paper.

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2. Sample Preparation and the Parameter Test Experiment

2.1. Sample Preparation. The sampling site is a special railway tunnel for coal transportation in southwestern China, which traverses the soft rock of the Tertiary fine sandstone formation and is featured with loose rock quality and extremely bad diagenesis. Besides, it belongs to the extremely soft rock with extremely poor stability and is easy to soften in contact with water. When the groundwater is developed or the water content is high, the surrounding rock softening is obvious. In addition, the sandstone is mostly silt-like, and water gushing occurs in the base, while the water is immersed into silt, and the arches and side walls collapse, and blocks are serious. In this case, sand samples were collected at different locations in this tunnel.

2.2. The Quicksand Parameter Test Experiment. During the tunnel construction process, the sand body is very easy to slide, which brings great risks to the construction. In order to better guide the construction, corresponding experiments on the physical and chemical properties of sand are conducted.

2.2.1. Density and Moisture Content Determination. During the construction process, due to the phenomenon of sand gushing and sand boiling in some areas, great risks appeared in the construction. Thus, in order to better guide the construction, tests were conducted on four different water gushing sections, mainly on the density and moisture content of quicksand, as shown in Figure 1.

The results are obtained through experiments, as shown in Table 1. Through the mastery of these data, theoretical data is provided for the optimization of the construction process, and at the same time, a basis is presented for the selection of construction methods.

2.2.2. Particle Size Analysis. The particle size of dry sand was tested, as shown in Table 2.

The composition of the sand particle size is not much different, and the particle size is relatively fine, with more than 90% less than 0.5 mm, which is a poor gradation. Besides, the cementation is not good and it is easy to collapse. At the same time, the tunnel is medium-coarse sand, but the mud content is small and about 5% on average. Moreover, the mud content of sand bodies in domestic and foreign tunnels was investigated, and most of them were around 20%, which is one of the reasons why the tunnel construction in this study is extremely difficult.

2.2.3. Surrounding Rock Reinforcement Measures. In order to study the stability of the dry sand tunnel, a compressibility experiment was carried out on the dry sand here to determine the corresponding reinforcement measures, so as to provide the necessary parameters for the effective maintenance design of the surrounding rock. Apart from that, the experimental results show that the dry sand possesses a higher compression rate, and the compression rate corresponds directly to the water content. Therefore, the sand can easily collapse without taking measures.

2.3. Reinforcement Measures. In this study, due to the low mud content of the sand body in the project (as shown in Figure 2(a)), many problems occurred in the construction. Considering that, a series of measures have been taken in reinforcement, and curtain grouting has been adopted for the tunnel face. At the same time, horizontal jet grouting piles were used to reinforce the periphery of the tunnel face, and the side walls of the lower steps and the bottom of the pavement were excavated and supported with jet grouting piles to strengthen the side walls. At this time, the strength of the tunnel consolidation construction process has reached the highest level and cannot be further enhanced, but the effect is still not apparent. In this case, it can be seen that the pure reinforcement measures still have large defects for this project.

In order to improve the surrounding rock and increase the stability of the sand body, curtain grouting reinforcement, horizontal jet grouting pile reinforcement, and oblique jet grouting pile reinforcement are adopted. In the curtain grouting reinforcement, the grouting parameters are changed on site to adjust the setting time of the grout, but the final effect is still not ideal, as shown in Figure 2(b). After the overall grouting, it becomes ring-shaped, layered, and vein-shaped, and its self-stabilization ability is poor. Due to the high pressure of the surrounding rock water body, the place where the grouting is not tight will be the easiest point for water to flow out, which will eventually lead to instability of the tunnel face and affect the progress of the project. Besides, in the construction of horizontal jet grouting piles along the periphery, it is effective in some parts, but the whole is not very ideal. To be specific, insufficient occlusion is common, and it is difficult to operate at the angle of construction and to ensure the quality of jet grouting piles. Apart from that, the grouting consolidation strength itself is insufficient. Affected by water and sand intrush, the water pressure is large, which makes it easy to break through the water inrush at the poor local effect and then enlarges the overall effect of grouting, as shown in Figure 2(c). Furthermore, in the construction concerning of the side wall of the lower step, the bottom of the paving and the supporting construction with the inclined side wall jet grouting piles, the side wall jet grouting piles are well occluded, as displayed in Figure 2(d). However, the pile-forming distance in each cycle is limited,
generally up to about 6 meters, and during the actual excavation process, only 2 to 3 meters can be dug, and then supplementary reinforcement construction of horizontal jet grouting piles is required.

3. Theoretical Analysis of Precipitation in Shifting Sand Formation

3.1. Precipitation Numerical Simulation Calculation. FLAC 3D numerical simulation software is commonly employed in the research of tunnels, mining, and rock and soil instability analysis [34–40]. For the water-rich sand layer encountered during the construction process, FLAC 3D finite difference software was used to analyze the sand layer precipitation. Besides, a single downpipe is simulated to dewater the sand layer under negative pressure conditions (-0.05 MPa, -0.06 MPa, -0.07 MPa, and -0.08 MPa). Thus, the influence radius of different negative pressure drops can be obtained, which can provide a theoretical basis for the arrangement of dewatering holes in engineering construction, whereas the numerical simulation takes the water-rich sand layer as the research object simplifies the calculation model and assumes that the sand layer is uniformly distributed. The physical and mechanical parameters of the sand layer are shown in Table 3.

The size of the model is 5 m × 2 m × 5 m, and the precipitation hole is set at a position of 2 m from the bottom. Other than that, the precipitation hole adopts a cylindrical grid,

| No. | D10 (mm) | D30 (mm) | D50 (mm) | D60 (mm) | Dav (mm) | Nonuniformity coefficient (Cu) | Curvature coefficient (Cc) |
|-----|----------|----------|----------|----------|----------|-------------------------------|---------------------------|
| 1#  | 0.095    | 0.15     | 0.19     | 0.22     | 0.241    | 2.32                          | 1.08                      |
| 2#  | 0.120    | 0.18     | 0.24     | 0.27     | 0.274    | 2.25                          | 1.00                      |
| 3#  | 0.086    | 0.14     | 0.22     | 0.27     | 0.263    | 3.14                          | 0.84                      |
| 4#  | 0.098    | 0.16     | 0.19     | 0.22     | 0.219    | 2.24                          | 1.19                      |

Table 1: Test results of physical properties of quicksand.

| Bulk density (kg/m$^3$) | Apparent density (kg/m$^3$) | Water content before precipitation (%) | Water content after precipitation (%) |
|-------------------------|-----------------------------|----------------------------------------|--------------------------------------|
| 1546.3                  | 2565.5                      | 19.2                                   | 6.4                                  |

Figure 2: Construction effect of grouting reinforcement.
and its periphery is surrounded by a radial grid around the cylindrical body, while the remaining sand layers are all rectangular grids. The model is divided into 58149 nodes and 53440 units, and the geometric model is presented in Figure 3.

In the model, displacement boundary conditions are selected to define the model, when five surfaces, namely, the front, rear, left and right sides, and the bottom are subjected to displacement constraints. Besides, the upper surface is a free boundary, and the initial stress field is considered in accordance with the self-weight stress field. Furthermore, a water level is set on the upper boundary of the model, and the software automatically generates pore pressure based on the water level and the porosity of the soil. Apart from that, we set the leakage boundary condition on the outer boundary of the precipitation hole and add negative pressures of -0.05 MPa, -0.06 MPa, -0.07 MPa, and -0.08 MPa to the outer boundary of the precipitation hole and then calculate. After that, during the calculation process, we observe and record the distribution of sand pore pressure, as shown in Figure 4, while the influence radius of negative pressure precipitation is determined by the distribution of sand pore pressure, and the calculation results are seen in Table 4.

The negative pressure precipitation has a greater impact on the pore pressure of the upper part of the precipitation hole. Then, a closed elliptical isobaric area with upper and lower sides will be established near the precipitation hole. In this area, the precipitation hole has the greatest impact on the sand body. Leaving this area, the influence radius of negative pressure precipitation gradually decreases, while the isobar formed by precipitation basically coincides with the precipitation funnel curve. According to the calculation results, the influence radius of different negative pressure precipitations is obtained, as displayed in Table 4:

As the precipitation pressure continues to increase, the precipitation radius increases. In the actual construction process, the size of the precipitation pressure should be determined according to the onsite hydrogeological conditions. For precipitation in areas with poor stratum stability, the precipitation pressure should not be too high and should be determined in conjunction with onsite protective measures. From Figure 5, in the numerical model, the precipitation displacement is acquired.

During the precipitation process, the sand will flow with the extraction of water, resulting in an increase in the sand within the radius of the precipitation hole, while there will be sand erosion in a certain area above the precipitation hole. Besides, during the construction process, the support measures in this area should be strengthened. From Figures 5(b)–5(d), it can be seen that there is a triangular strain concentration area within 1 m of the influence radius just above the precipitation hole, and the sand in this area accepts the lost sand from above. Compared with other areas, the soil will deform to a great extent, and the density of sand particles will be relatively increased. Moreover, affected by the negative pressure of precipitation, the stress is relatively concentrated within the radius of precipitation, and the stress outside the radius of precipitation is basically and evenly distributed, as presented in Figure 5(c). Therefore, in the actual project, the support measures for the soil above the dewatering hole should be enhanced. In addition to that, monitoring equipment should be installed within 2 m above the dewatering hole to monitor the deformation of the soil in real time in order to respond to the danger in time.

3.2. Theoretical Calculation. The process of precipitation completion is also that of reducing the water content of the semicylinder to the water content of the sand body when it can be excavated. Therefore, the following formula can be derived:

\[
Q_2 - Q_1 = \frac{1}{2}\pi r^2(q_1 - q_2).
\]

Among them, \(Q_1\) represents the normal water inflow \((m^3)\) within the precipitation range of a single downpipe; \(Q_2\) refers to the pumping capacity of a single downpipe \((m^3)\); and \(q_1\) denotes the moisture content (%) of the quicksand without pumping water, while \(q_2\) indicates the water content (%) after pumping. By further derivation, the
calculation formula of the precipitation radius can be obtained:

\[ r = \sqrt{\frac{2(Q_2 - Q_1)}{\pi(q_1 - q_2)}} \]  

According to the measurement results of field practice, the difference between the absolute value \( Q_2 \) and \( Q_1 \) of the pumping water of a single downpipe is calculated, as shown in Table 5.

Through the monitoring data, the precipitation radius under different pressures of the specific water inflow is calculated here, and the calculation result of the formula is brought into it, as shown in Table 6.

By comparing the results obtained from the theoretical computer field measurement, it is shown that the precipitation radius calculated by the numerical simulation is very close to that calculated by the theoretical calculation, and there are only a few errors. Besides, the reasons for these errors are related to the simplification of the model. Therefore, the calculation result can be used as a reference for the layout of downwater pipes in actual construction.

4. Onsite Vacuum Negative Pressure Precipitation Technology

Through the above experiments and theoretical analysis, the theoretical values of precipitation water pressure and precipitation radius are obtained and are applied in the field to formulate reasonable precipitation parameters. At the same time, during the application process, it was found that there was still water leakage at the top and bottom after the construction was completed, which brought certain difficulties to the construction. Therefore, the measures for omnidirectional precipitation of the tunnel face, the top of the tunnel and the bottom of the tunnel were optimized and designed.

4.1. Vacuum Negative Pressure Precipitation Technology for the Face. Vacuum negative pressure precipitation in the cave sucks the air in the well point pipe, horizontal pipe, and water storage tank through a vacuum pump to form a certain degree of vacuum (i.e., negative pressure). The groundwater outside the pipeline system is pressed into the well point pipe under the action of the pressure difference and then to the storage tank through the horizontal pipe. Besides, it is pumped away. As a result, the water level drops, the void ratio decreases, the soil is consolidated, and the operation reaches a dry and wet state. Furthermore, in order
to achieve a better effect of vacuum negative pressure precipitation in this section, the length of the precipitation pipe here is 9 m, and that of the precipitation pipe in the actual precipitation range is 7 m. The vacuum precipitation process of the entire tunnel face is displayed in Figure 6:

The precipitation pressure of this project is generally -0.06 MPa, while the precipitation radius is 1 m, and the mutual influence coefficient is 0.8, so that the most suitable distance between the precipitation pipes is 0.8 m at this time. Besides, the layout of the downpipe at the tunnel face is shown in Figure 7.

Each of the downfall pipes is 9 m, and they are formed by welding 1.5 m long steel pipes in sections. Besides, the pipe body is drilled with 8 mm holes with the 10 cm spacing in a plum blossom pattern. Apart from that, no precipitation drilling is provided for the pipe end of 2 m and the pipe head of 0.5 m. After each section of the pipe is drilled, two layers of geotextile are used to wrap it, and a layer of the 100-mesh filter screen is wrapped around it. After winding, every 20 cm interval is used to tie tightly. Other than that, the 32 mm diameter precipitation steel pipe uses 25 steel pipes as the joints of each section and is welded and connected. Furthermore, each downfall pipe is equipped with a special structure pipe head of 10 cm, and the bottom end of the pipe head adopts a steel welded crosshead with a diameter of 8 mm and is sealed at the bottom. The schematic diagram of the downwater pipe layout is shown in Figure 8.

When the vacuum negative pressure was employed for precipitation at the beginning, PVC pipes were used. At the same time, after drilling the holes, we retreat the drill and directly stuff the processed and wrapped precipitation pipes into the holes. Besides, the filter screen layer wrapped around the downfall pipe has a large friction with the sand body, which can easily damage the filter screen layer. As a result, the extracted water contains a large amount of sediment, causing blockage of the pipe and even the upper sand body to empty with the precipitation, forming a cavity and resulting in a large area of landslides. When the PVC pipe is used for precipitation, the construction will have a great impact on the precipitation pipe, and it is very likely to cause damage to the precipitation pipe. Besides, during the construction, the rear water will continue to penetrate into the face of the tunnel, and it is difficult to guarantee the tunneling length. Clear water flows out after the pipe is down, as shown in Figure 9(a).

The process has been improved as follows. After the drilling is completed, do not retract the drill and insert the
wrapped downpipe through the middle of the hollow drill rod. Then, we slowly withdraw the pipe and leave the downpipe in the borehole to ensure the integrity of the downpipe and improve the quality of the precipitation. Apart from that, we pull out the cork of the branch pipe section connected with the main pipe, connect the branch pipe with
the well point pipe, tie it firmly with 10# lead wire, and wrap it tightly with a sealing tape. After that, we check the connection of each pipe. Furthermore, through the above operation process, the precipitation effect is obvious, the safety of the construction is ensured, the construction progress is accelerated, and the benefit is improved. As for the effect, it is given in Figure 9(b).

4.2. Vertical Vacuum Negative Pressure Dewatering Technology on Tunnel Top. In order to speed up the construction and precipitation progress, in addition to precipitation at the tunnel face, vertical precipitation at the top of the tunnel was also coordinated, as shown in Figure 10. Besides, the precipitation process is the same as that of the tunnel face. The length of the precipitation pipe is 9 m and the row spacing is 6 m, while the precipitation effect is obvious. Apart from that, the construction process is almost the same as the horizontal vacuum precipitation process, and only the differences are explained. Furthermore, we arrange the parameters as required for the precipitation section, use red paint positioning marks for the drilling points and spacing according to the design, and prepare in advance for the hole positions that affect the drilling.

By adopting vacuum negative pressure precipitation technology on the top of the tunnel, the emergence of water strands at the top of the tunnel is effectively avoided, thereby controlling the phenomenon of voiding at the top due to the flow of pressurized water along the gap and taking away the sand at the top. In addition to that, the rear water penetrates to the face of the tunnel, indirectly speeding up the precipitation progress and ensuring the safety of construction.

4.3. Vacuum Negative Pressure Dewatering Technology of the Gravity Dewatering Well in the Cave. Vacuum negative pressure precipitation ensures that there is no running water phenomenon in the upper and middle guide construction faces. In order to prevent water from gushing out during invert construction and avoid sand boiling, in this research, a dewatering technique for dewatering wells in the cave is proposed, when the diameter of the drilled hole is 290 mm, while XY-2B drilling rig is adopted, and the protective barrel should be 0.30 m above the ground next to the hole to prevent surface sewage from infiltrating into the well. Besides, the shaft wall pipes are all bridge steel pipes, and their diameter is 108 mm (outer diameter). Apart from that, the water filter pipe is wrapped with a layer of geotextile and a layer of 100 mesh nylon gauze. In addition, the diameter of the water filter pipe is the same as that of the well wall pipe, whereas the sedimentation tube exists at the bottom of the filter tube, when the diameter is the same as that of the filter tube; the length is 0.50 m, and the bottom of the sedimentation tube is sealed. Furthermore, the area that is 4.00 m below the bottom of the diving well is filled with gravel as a filter layer. In order to prevent the infiltration of ground sewage and ensure the effect, high-quality clay must be used to fill the ground surface and compacted above the surrounding filling surface of the gravel material.

After the completion of the well construction, the deep well pump should be run in time, while drainage pipes,
cables, etc. should be laid, and the pumping and drainage system should be installed, followed by the pumping test being able to start. Besides, these devices shall be marked on site. Moreover, during well washing and dewatering operation, pipes shall be used to drain water into the sump, and the water shall be discharged into the preset drainage ditches outside the site through the drainage pipes preset outside the site that should be cleaned regularly to ensure the smooth flow of the drainage system. The effect is shown in Figure 11.

In the reinforcement measures, in order to control the sand boiling phenomenon, the oblique rotary jet grouting pile is adopted to form the partition wall. Since the sand layer is a whole, it cannot prevent water from penetrating from the bottom of the partition wall to the bottom plate. Therefore, through the gravity dewatering wells, it is possible to achieve no water gushing during the invert excavation of the tunnel in the water-rich quicksand formation and to ensure the dryness of the construction surface. In addition, this technology can well control the groundwater level line to be lower than the lowest point of invert construction and overcome the difficulty of invert construction in rich water and quicksand formations.

5. Tunnel Excavation Technology after Precipitation Is Completed

After the completion of the tunnel precipitation, the sand layer is almost dry. However, dry sand is a kind of soil with special properties, with different water content, and its mechanical indexes are quite different. Moreover, the mechanical behavior of the surrounding rock varies with the size of the tunnel span and section. Because of its small cohesive force, an empty surface is formed when the tunnel is excavated, and it is prone to collapse under the action of gravity due to the disturbance of the excavation. Moreover, its deformation is abrupt, discontinuous, and irreversible, and tunnel construction is very risky. Therefore, deformation control and collapse prevention must be put in the first place in tunnel construction in dry sand formations.

5.1. Tunnel Excavation Technology. The dry sand tunnel is excavated with the CD method or three-step arc reserved core soil, while both the upper part and the lower part are excavated by pneumatic shovels and pneumatic picks. Besides, dump trucks tracklessly transport the ballast out. Since the tunnel in this study is a single-track tunnel with a small cross-section, the natural collapse angle of dry sand is generally 45°. Therefore, the three-step arc-shaped reserved core soil construction method is selected.

The advanced support will use advanced small conduits for prereinforcement, which will cause less disturbance to the surrounding rock during the excavation process. Due to the small particle size of dry sand, it must be encrypted when carrying out advanced support. Therefore, the reinforcement measures of the encrypted small conduits have been taken, as shown in Figure 12(a). Apart from that, the length of the leading small pipe is 3.0 m, the circumferential spacing is 0.15 cm, the excavation is carried out every 1.5 m, and the overlap length is 1.5 m. In construction, holes are arranged on the steel frame web at intervals along the 158° range of the vault to ensure that the extrapolation angle of the small catheter is 5° ~10°. In addition, the first shotcrete is used to seal the face, and then, the small pipe is drilled and installed. Besides, the dry sand layer advanced small pipe construction technology mainly includes two processes of hole layout and drilling and pipe installation. Moreover, to guarantee that the dry sand does not collapse, a wooden
insert plate is installed between the steel arch and the small pipe so as to prevent the dry sand from slipping. After drilling the bolt hole with the YT-28 air gun, the small pipe is driven in from the middle of the section steel frame, and the exposed end is supported on the steel frame behind the excavation surface, which forms a prestress system with the steel frame, whereas, after the construction of the small pipe is completed, the steel arch is erected on the face of the tunnel, and the flexible plywood of 250 × 500 × 5 mm is made at the same time, as shown in Figure 12(b).

The installation of plywood has played a great role in preventing the collapse of dry sand, avoiding large-scale landslide accidents caused by the sliding of dry sand from the middle of the small pipe, ensuring the stability of the surrounding rock, and solving the collapse problem fundamentally.

The following points should be paid attention to when adopting this construction technology. During the excavation process, a special person is responsible for following up and commanding, and the operation must be carried out in strict accordance with the requirements. Besides, the upper guide is designed to change the original double-row small catheter into a single-row small catheter, with one in every 15 cm. After excavation, it must be closed and formed into a ring in time, and the lock-foot anchor pipe must be installed in time, whereas, after overexcavation and small-area landslides are treated, it should be ensured that the backfilling behind the steel frame is compact, and grouting holes should be reserved for large landslides. In addition, the bottom of the invert tunnel is supported and sealed well in time. Apart from that, we follow up the invert in time as required to ensure that the step distance of the invert and the second liner is always kept within a safe step distance, and as close as possible to the tunnel face.

5.2. Analysis on Monitoring Measurement Data Results. One vault sinking point and two clearance horizontal convergence measurement lines are arranged on each measurement section of the tunnel. Besides, measure until the lining structure is closed and the sinking basically stops. Furthermore, the measurement section layout is shown in Figure 13, while the convergence of the tunnel in the vertical and horizontal directions is displayed in Figure 14.

From the horizontal convergence data, it can be seen that the maximum displacement is 45.06 mm. Besides, the curve is smooth, and the data slightly fluctuates. Apart from that, it is judged that the surrounding rock is stable. Furthermore, the total displacement of the vault subsidence is 49 mm, and the temporal curve regression analysis shows that the data tends to be stable, and the surrounding rock is judged to be stable.

6. Conclusion

Aiming at the construction of quicksand tunnels, in this paper, laboratory parameter measurement experiments and numerical calculations are performed, when combined with field experiments, to study the precipitation technology, construction methods, and stability of quicksand surrounding rocks for tunnels in quicksand formations. The main conclusions are as follows:

(1) For tunnel construction in the quicksand stratum, the disadvantages of reinforcement measures under such geology are analyzed, and a comprehensive three-dimensional negative pressure dewatering construction method is proposed. For the phenomenon of the sand influx on the tunnel face and sand boiling on the bottom, the tunnel face is put forward, whereas, for the water replenishment behind the top of the tunnel, a construction method of intercepting the water replenishment by the vertical vacuum dewatering on the top of the tunnel is introduced. Besides, for the phenomenon of sand boiling
on the bottom plate, a method of setting gravity dewatering wells on the side walls is presented to ensure the safety of construction and improve the construction progress, and it is obviously reflected in the construction progress. Furthermore, before this method is adopted, the excavation is 15 m in 8 months, and after this method is used, the average excavation is 25 m per month.

(2) Since the borehole in the quicksand formation is easy to collapse, the method of feeding the dewatering pipe from the drill pipe avoids the damage of the geotextile caused by the direct insertion of the dewatering pipe, enhances the precipitation effect, reduces the construction risk, and realizes the rapid construction.

(3) When the precipitation is completed, considering that the natural collapse angle of dry sand is generally 45°, it is more reasonable to use the three-step arc-shaped reserved core soil construction method. At the same time, the plywood is inserted into the back of the small duct during the construction, which eliminates the risk of the tunnel construction caused by the collapse of the dry sand radically and ensures the safety of the construction.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

**References**

[1] M. Q. Zhang, Z. J. He, G. Z. Xiao, and R. Chengmin, "Research on the tunnel engineering characteristics and construction technology of the tertiary water rich sand," *Journal of Railway Engineering Society*, vol. 2016, no. 9, pp. 76–81, 2016.

[2] F. Cao, "Special research on water-stability characteristics of tertiary system sandstone in Lanzhou area during tunnel construction," *Journal of Railway Engineering Society*, vol. 12, no. 31, pp. 21–25, 2012.

[3] B. G. Zhen, "Characteristics analysis of the tertiary sandstone in Lanzhou-Chongqing tunnel Taoshuping tunnel," *Railway Engineering*, vol. 5, pp. 55–57, 2013.

[4] M. Eriksson, H. Stille, and J. Andersson, "Numerical calculations for prediction of grout spread with account for filtration and varying aperture," *Tunnelling and Underground Space Technology*, vol. 15, no. 4, pp. 353–364, 2000.

[5] E. C. Almer, *Grouting for pile foundation improvement*, [Ph.D. Thesis], Delft University, Delft, Netherlands, 2001.

[6] S. J. Wu, H. Q. Tang, W. X. Meng, X. L. He, and Y. G. Li, "Construction technology of Xiamen Xiang’an subsea tunnel crossing water-rich sand layer," *Chinese Journal of Rock Mechanics and Engineering*, vol. 26, no. 2, pp. 3386–3821, 2007.

[7] S. G. Wang, M. Q. Zhang, H. J. Huang, W. Y. Chen, and H. L. Yin, "Construction technology of F1 high pressure and water-rich fault in Biyancao tunnel on Yiwan railway," *Journal of Railway Engineering Society*, vol. 9, no. 120, pp. 66–70, 2008.

[8] J. Hai, "Construction method of the rich water surrounding rock section of Xiangshan tunnel," *Shanxi Architecture*, vol. 35, no. 3, pp. 316–317, 2009.

[9] X. F. Deng, *A study on rock deformation control of a tunnel underpassing flyover bridges in rich water and shifting sand strata*, Southwest Jiaotong University, Chengdu, 2009.

[10] P. Deif, C. Tomei, and E. Trubowitz, “Inverse scattering and the Boussinesq equation,” *Pure and Applied Mathematics*, vol. 35, no. 5, pp. 567–628, 1982.

[11] H. Mroueh and I. Shahrouj, “Three-dimensional finite element analysis of the interaction between tunneling and pile foundations,” *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 26, no. 3, pp. 217–230, 2002.

[12] G. L. Li and F. Wang, *Study on the main technical measures of the Tertiary argillaceous weakly cemented water-rich fine sandstone tunnel*, Journal of Chongqing Jiaotong University, 2015.

[13] S. C. Li, G. R. Shi, and J. Wu, "The pre-reinforcement construction technology of Taoshuping tunnel with water-rich undiagenetic silt fine sand," *Modern Tunnel Technology*, vol. 48, no. 2, pp. 116–119, 2011.

[14] F. Y. Yang, "Construction technology of water-rich tertiary silt sandstone section of Chengershan tunnel," *Tunnel Construction*, vol. 42, no. 8, pp. 65–66, 2013.

[15] C. J. Xu, "The key construction technology of the H series siltstone section of Humaling tunnel," *National Defense Traffic Engineering and Technology*, vol. 6, pp. 55–58, 2011.

[16] X. N. Gong, *Examples of Foundation Pit Engineering* 5, vol. 6, China Construction Industry Press, Beijing, 2014.

[17] S. Z. Shang, "Hoegntotger static probe performance and application," *Water Transport Engineering*, vol. 1, pp. 53–56, 1996.

[18] T. Huang, "Experimental study on the use of vacuum preloading method to deal with highway soft foundation slumping," *China Civil Engineering Journal*, vol. 6, no. 7, pp. 133–139, 2009.

[19] Y. S. Liang, "Construction technology of rotary jet grouting pile in urban subway," *Tunnel Construction*, vol. 27, no. 3, pp. 84–87, 2007.

[20] Q. L. Wu, Z. W. Liu, and W. Q. Zhang, "Super shallow buried short-distance double-hole tunnel construction in water-rich fine sandy soil layer," *Construction Technology*, vol. 33, no. 10, pp. 18–20, 2004.

[21] F. Zhang, "Water-stop construction technology for surrounding rock of water-rich sand tunnel," *Journal of Shijiazhuang Railway Institute*, vol. 18, no. 1, pp. 99–102, 2005.

[22] Y. C. Li, "Construction technology of large-span flat-top and shallow-buried tunnels in water-rich sand," *National Defense Traffic Engineering and Technology*, vol. 4, pp. 61–63, 2007.

[23] Z. H. Peng, C. T. Yan, and Q. J. Meng, "Application of well point precipitation in tunnel construction in water-rich silt sand," *Western Exploration Engineering*, vol. 12, pp. 118–120, 2004.

[24] G. Feng, X. C. Wang, Y. Kang, and Z. T. Zhang, "Effect of thermal cycling-dependent cracks on physical and mechanical properties of granite for enhanced geothermal system," *International Journal of Rock Mechanics and Mining Sciences*, vol. 134, article 104476, 2020.
G. Feng, X. C. Wang, M. Wang, and Y. Kang, “Experimental investigation of thermal cycling effect on fracture characteristics of granite in a geothermal-energy reservoir,” *Engineering Fracture Mechanics*, vol. 235, article 107180, 2020.

A. Nakao, Y. Nara, and T. Kubo, “P-wave propagation in dry rocks under controlled temperature and humidity,” *International Journal of Rock Mechanics and Mining Science*, vol. 86, pp. 157–165, 2016.

J. J. Hu, H. P. Xie, Q. Sun, C. B. Li, and G. K. Liu, “Changes in the thermodynamic properties of alkaline granite after cyclic quenching following high temperature action,” *International Journal of Mining Science and Technology*, vol. 31, no. 5, pp. 843–852, 2021.

P. H. Jin, Y. Q. Hu, J. X. Shao, G. K. Zhao, X. Z. Zhu, and C. Li, “Influence of different thermal cycling treatments on the physical, mechanical and transport properties of granite,” *Geothermics*, vol. 78, pp. 118–128, 2019.

T. Meng, R. C. Liu, X. X. Meng, D. H. Zhang, and Y. Q. Hu, “Evolution of the permeability and pore structure of transversely isotropic calcareous sediments subjected to triaxial pressure and high temperature,” *Engineering Geology*, vol. 253, pp. 27–35, 2019.

M. Z. Gao, J. Xie, Y. Gao et al., “Mechanical behavior of coal under different mining rates: a case study from laboratory experiments to field testing,” *International Journal of Mining Science and Technology*, vol. 31, no. 5, pp. 825–841, 2021.

M. Z. Gao, J. Xie, J. Guo, Y. Q. Lu, Z. Q. He, and C. Li, “Fractal evolution and connectivity characteristics of mining-induced crack networks in coal masses at different depths,” *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, vol. 7, no. 1, p. 9, 2021.

Y. Wang, B. Zhang, B. Li, and C. H. Li, “A strain-based fatigue damage model for naturally fractured marble subjected to freeze-thaw and uniaxial cyclic loads,” *International Journal of Damage Mechanics*, vol. 30, no. 10, pp. 1594–1616, 2021.

Y. Wang, Y. F. Yi, C. H. Li, and J. Q. Han, “Anisotropic fracture and energy characteristics of a Tibet marble exposed to multi-level constant-amplitude (MLCA) cyclic loads: a lab-scale testing,” *Engineering Fracture Mechanics*, vol. 244, article 107550, 2021.

S. Chuang, C. Dongxu, W. Laigui, and W. Lin, “Quantitative evaluation of the constraint effect and stability of tunnel lining support,” *Tunnelling and Underground Space Technology*, vol. 112, article 103920, 2021.

F. Yue, B. Liu, B. Zhu, X. L. Jiang, L. Chen, and K. Liao, “Shaking table test and numerical simulation on seismic performance of prefabricated corrugated steel utility tunnels on liquefiable ground,” *Soil Dynamics and Earthquake Engineering*, vol. 141, article 106527, 2021.

D. W. H. Su, P. Zhang, H. Dougherty, M. van Dyke, and R. Kimutis, “Longwall mining, shale gas production, and underground miner safety and health,” *International Journal of Mining Science and Technology*, vol. 31, no. 3, pp. 523–529, 2021.

S. Sinha and G. Walton, “Integration of three-dimensional continuum model and two-dimensional bonded block model for studying the damage process in a granite pillar at the Creighton mine, Sudbury, Canada,” *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 13, no. 2, pp. 275–288, 2021.

R. F. Wang, F. T. Zeng, and L. Li, “Stability analyses of side-exposed backfill considering mine depth and extraction of adjacent stope,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 142, article 104735, 2021.

C. B. Basnet and K. K. Panthi, “Evaluation on the minimum principal stress state and potential hydraulic jacking from the shotcrete-lined pressure tunnel: a case from Nepal,” *Rock Mechanics and Rock Engineering*, vol. 52, no. 7, pp. 2377–2399, 2019.

N. A. Do and D. Dias, “A comparison of 2D and 3D numerical simulations of tunnelling in soft soils,” *Environmental Earth Sciences*, vol. 76, no. 3, p. 102, 2017.