Study on Comprehensive Treatment Technology of High-speed Railway Passing Through Giant Karst Tunnel

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Abstract: In the mountainous areas of Southwest China, a karst landscape is well developed. There, exposed giant karst caves in the construction of high-speed railway tunnels cause great construction difficulties and safety risks for the tunnel crossing. In this paper, the study object is the project on giant karst cave of the Qianjiang–Changde railway high-mountain tunnel. After the karst cave was revealed, unmanned aerial vehicle detection, three-dimensional laser scanning, and blasting vibration monitoring were used to study the stability of the karst cave. It was found that the karst cave has a higher risk of falling rocks. On the basis of careful consideration of construction, operation safety, and economy, the “backfill cave ballast + grouting to reinforce on the upper part” scheme was determined for the treatment of the karst cave. During the process of disposal, the surface and layered settlement of backfill were monitored, in which it showed that the surface settlement control was reasonable, and the settlement mainly came from the bottom of the grouting layer, the top of non-grouting backfill, and original accumulation. To prevent the risk of falling rocks, we performed permanent safety protection of the wall and the roof for the karst cave and temporary safety protection of the mobile scaffold. Finally, the backfill treatment of the giant karst cave of high-mountain tunnel was smooth, the settlement after construction was controllable, and it met the design requirements.

1. Introduction

With the rapid advancement of economic globalization, transportation has been a key element in promoting global economic success, in which railway transportation plays a vital role. The development of railway construction technology has also paid more attention to the world [1–2]. High-speed rail tunnels can considerably shorten driving distances and improve transportation efficiency. In the mountainous areas of Southwest China, a karst landscape is well developed. Various karst caves were exposed during tunnel construction for the Qianjiang–Changde railway. These large-scale and complex karst caves significantly increase the difficulty of tunnel construction and bring great challenges to the treatment of karst caves [3].

The treatment of giant karst caves in the Panshan tunnel [4] and Zhushabao No. 2 tunnel [5] adopted the method of layered and segmented backfilling of large-volume hollow concrete. The treatment of the giant karst cave in the Longlingong tunnel [6] adopted the method of grouting reinforcement after the backfill of the hard tunnel spoil. The treatment of large semi-filled karst caves in the Xiaocunba tunnel [7] adopted the comprehensive technology of “backfill mortar stabilizing dangerous rock at the..."
arch + pile foundation cap structure across the karst cave + reinforced composite lining structure of the tunnel.” The treatment of the giant karst cave in Yujingshan tunnel [8] adopted the method of bridge crossing and backfilling the cavity at the bottom of the tunnel. The treatment of the giant karst cave in the Yangqiaoaba tunnel [9] adopted a change of route. The treatment of the giant karst cave in the Yanwan tunnel [10] adopted the method of backfilling spoil at the bottom of the cave + bridge crossing at the top of the cave and set arch protection for the tunnel structure. The treatment of the hall-like karst cave in the Naqiu tunnel [11] adopted a layered backfill spoil scheme. Huang et al. [12] assessed the effect of consolidation measures taken in stabilizing the tunnel cross-section in the vicinity of Bleßberg cave, and also its longer-term stability. Access to the most important caves in Slovenia's motorways is preserved by concrete tubes closed with metal covers at the roadside.

On the basis of the engineering practices mentioned previously, it can give better guidance in treating karst caves during constructions; however, the project in constructing a tunnel slanting through a giant karst cave, which is a rare and complicated project, applied the backfill method, as discussed in some studies. In this paper, in the construction of a high-mountain tunnel passing through a giant karst cave, we proposed 11 disposal schemes of the three treatment methods, namely, line avoidance, bridge crossing, and backfilling. After comparison and analysis of various factors, the disposal scheme of “cave ballast filling + grouting reinforcement of upper backfilling body” in the backfilling disposal method was finally adopted. During and after the implementation of the scheme, the settlement law of the backfill body under static load (construction load) was studied through settlement monitoring and numerical simulation, and the rationality of the backfill disposal scheme of cave ballast was verified. The research results will provide an effective solution for the engineering problem of a tunnel passing through a huge karst cave, which has important engineering application value and can provide reference and demonstration for similar projects.

2. Project overview and stability analysis of karst cave

2.1 Project overview of karst cave

The DIK53 + 678 giant karst cave in the high-mountain tunnel of Qianjiang–Changde railway is mainly composed of three parts, namely, the main dissolution fissure channel, the hall-like channel, and the No. 1 branch hole. The main dissolution fissure channel is accompanied by the No. 2 branch hole, as shown in Figure 1.

The main dissolution fissure channel is approximately 450 m long and 7–45 m wide. It is developed in N45°E direction toward the large mileage, and the bottom accumulation body is high in the middle and low at both ends. There are three pits along the channel. The No. 2 branch cave is developed on the south side of the channel and is in N70°E direction; the cave is approximately 5–8 m wide, 3–8 m high, and 120 m in horizontal extension.

The hall-like channel is 124 m long, 32–63 m wide, and 46–65 m high (Figure 2). The top of the cave is a natural suspended ceiling, with a large width clearance of up to 40 m.

The length of the tunnel crossing the hall-like channel and the main dissolution fissure channel at an angle of 42° is approximately 71 m. The height of the cavity above the road shoulder is 12–16 m, and the depth of the cavity below the road shoulder is 30–55 m. The development scale of the karst cave is huge; thus, treatment and protection of the karst during construction is difficult and risky.
2.2 Stability analysis of karst cave

With the reveal of the giant karst cave, considering its huge scale and the long period of investigation and treatment, a pre-treatment plan was firstly adopted; that is, the flat guide detoured to continue construction, and a construction branch channel leading to the bottom of the cave was set up. To evaluate the stability of the karst caves more comprehensively and accurately, we used some new technologies, such as unmanned aerial vehicle (UAV) detection, three-dimensional laser scanning, and blasting vibration testing, in addition to conventional detection technologies, such as drilling and geophysical exploration, to explore the filling properties and the overall deformation and development morphology of the karst caves.

Here, for UAV detection, UAV imaging technology was used to perform multi-point aerial photography on areas not seen by the investigators, in which they discovered the existence of dangerous rocks distributed on the walls and the roof of the cave. The images were useful in investigating the risk factors of the cave. On the basis of UAV detection, we clarified the distribution...
of dangerous rocks and then defined these rock into three categories, namely, wall-mounted type, suspended type, and stacked type. Moreover, we used the three-dimensional (3D) laser scanning technology that uses a 3D scanner to perform non-contact high-speed laser mapping of the cave. The overall shape of the cave can be surveyed and mapped by sub-regional and periodic station scanning method; the long-period surrounding rock deformation data can also be obtained. On the basis of the 3D laser scanning chromatographic analysis, the displacement of dangerous rock in the cave is identified; the high-risk dangerous rock is labeled at the designated point, and the displacement rate of surrounding rock was obtained for the evaluation of karst cave stability. In the blasting vibration test, a blasting vibration instrument was used to collect the influence of the blasting distance of the face on the vibration of the surrounding rock and to find the relationship between the rocks falling in the cave and the vibration rate of the surrounding rock. On the basis of the blasting vibration test of the surrounding rocks of the karst cave, the correlation between the blasting charge amount, bursting point position, and falling rock of karst cave are studied; the vibration wave velocity of the surrounding rocks is obtained for stability evaluation.

After a comprehensive investigation, the following was found. (1) The bottom of the karst cave was piled up with stones, with a thickness of 37.3–65.5 m. Among them, the accumulation body above 12–47.5 m was limestone debris, which was the cave wall and roof collapse in the later period; the accumulation body below the depth had clay soil or interlayer or lens body, and the maximum thickness was approximately 7 m. (2) There were many dangerous rocks on the sidewalls, and a large flat layer was formed at the roof of the cave. The karst caves can be divided into stable flat roof areas and unsteady sidewall areas. Among them, the top of the unsteady sidewall area was an unstable slump arch. There were many dangerous rocks and longitudinal and horizontal joint cracks on the sidewalls. The dangerous rocks were attached or suspended, that is, wall-mounted rocks and hanging rocks, with a high risk of falling, as shown in Figure 3. (3) Figure 4 shows the result of 3D laser scanning by chromatographic analysis, in which the red color indicates large displacement to the cave. It can be found that the parts of the sidewall rocks were displaced into the cave, the entrance of the tunnel and the construction branch channel were deformed obviously, the deformation range of the sidewalls was large, and the displacement of some positions was large. There are 22 dangerous rocks with a displacement of more than 30 mm on the top and sidewalls of the cave, and the maximum displacement was more than 80 mm. (4) Rock blasting vibration monitoring showed that the blasting of the tunnel had the greatest impact. When the blasting vibration speed exceeded 1 cm/s, the rocks begin to fall; when the blasting vibration speed exceeded 1.5 cm/s, the range of falling rocks expanded, and the number and size of the falling rocks increased, as shown in Figure 5.

![Figure 3. Dangerous rocks in the wall: (a) attached and (b) suspended rocks](image-url)
Figure 4. 3D laser scanning mapping and monitoring of the cave

Figure 5. Photos of the falling rocks in the karst cave

On the basis of the detection results, three evaluation indexes are proposed, namely, displacement rate of surrounding rock ($V_1$) (unit: mm/week), vibration wave rate of surrounding rock ($V_2$) (unit: cm/s), and fracture development rate of dangerous rock ($V_3$) (unit: cm/week). According to the analysis of the monitoring data combined with the change rule of karst cave's stable state, the weight value of each index was determined, and the quantitative evaluation formula of karst cave's stability was established. Finally, the stability coefficient ($T$) value of karst cave is calculated by Eq. (1). When $T < 1$, the karst cave is in steady state; when $T \geq 1$ and $T < 2$, the karst cave is in an unsteady state. When $T \geq 3$, the karst cave is in an extremely unstable state (Table 1).

$$T = 0.3V_1 + 0.4V_2 + 0.3V_3$$  \hspace{1cm} (1)

| Index | Values range | Evaluation result | Values range | Evaluation result | Values range | Evaluation result |
|-------|--------------|-------------------|--------------|-------------------|--------------|-------------------|
| $V_1$ | $V_1 < 1.0 \text{ mm/week}$ | $T < 1$ steady state | $1.0 \text{ mm/week} \leq V_1 < 3 \text{ mm/week}$ | $1 \leq T < 3$ unsteady state | $3 \text{ mm/week} \leq V_1 \leq \frac{1}{1.5} \text{ cm/s}$ | $T \geq 3$ extremely unstable state |
| $V_2$ | $V_2 < 1.0 \text{ cm/s}$ | | $1.0 \text{ cm/s} \leq V_2 < 1.5 \text{ cm/s}$ | | | $3 \text{ mm/week} \leq V_2 \leq \frac{1}{3} \text{ cm/week}$ |
| $V_3$ | $V_3 < 1.0 \text{ mm/week}$ | | $1.0 \text{ mm/week} \leq V_3 < 3 \text{ mm/week}$ | | | |

In summary, the overall stability of the giant karst caves is poor, especially the number of dangerous rocks on the sidewalls is large, the anti-disturbance of the karst cave is poor, and the risk of falling rocks is high. Thus, the treatment scheme should be reliable, and people should pay attention to protection during construction.

3. Comparison and selection of karst cave treatment schemes and safety protection in


3.1 Comparison and selection of karst cave treatment schemes

On the basis of the previous studies on treatment construction cases of similar large-scale karst cave [4–16], in this study, we proposed the three commonly used methods, namely, route avoidance, bridge crossing, and backfill treatment, and the 11 alternative schemes. The feasibility analysis of the schemes was carried out on the basis of the project overview of the karst cave and also considering the evaluation indicators, namely, safety, economy, and construction period, as shown in Table 2. Finally, the “backfill cave ballast + grouting to reinforce on the upper part” scheme was adopted.

Table 2. Analysis of karst cave treatment schemes

| Method                  | Scheme                                                                 | Feasibility Analysis                                                                                                                                                                                                 | Remarks                                                                                     |
|------------------------|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Route avoidance        | (1) The tunnel detours to the left slightly to avoid part of the cave cavity | Although schemes 1 and 2 can reduce the span length of the karst cave or avoid the karst cave, the existing projects have a low utilization rate and high cost. After the route is changed, the tunnel needs to cross the intermountain depression. The terrain conditions are complex, and there are still many engineering construction risks; scheme 3 cannot change the bottom suspended height of the tunnel, and the treatment of the bottom cave is still required. | The amount of abandoned projects is more, and the cost is more serious. After the line is changed, there are still many difficulties and risks in the construction of the projects, which are not used. |
|                        | (2) The tunnel detours to the left largely to avoid the cavity of the cave completely |                                                                                                                                                                                                                      |                                                                                                                                                        |
|                        | (3) Adjust the slope of the tunnel                                       |                                                                                                                                                                                                                      |                                                                                                                                                        |
| Bridge crossing        | (1) Continuous frame bridge                                            | All four schemes can reduce the treatment works of the bottom cavity, but they have high requirements on the bearing capacity of the bottom foundation. It needs to pass through the thick accumulation body and be supported by the bedrock at the bottom. The process is complicated, and the construction is difficult. The bridge construction is needed to set up the viaduct construction, the technology was complex, and the blasting construction of arch bridges would greatly disturb the karst caves; the bridge pier had weak anti-rockfall impact capability, which posed a serious threat to the safety of construction personnel, equipment, and operation period. | There are many difficulties and unfavorable factors in construction, and the long construction period is required, which is not used. |
|                        | (2) Three-span simply-supported beam bridge                            |                                                                                                                                                                                                                      |                                                                                                                                                        |
|                        | (3) Single-pier T-shaped rigid frame bridge                             |                                                                                                                                                                                                                      |                                                                                                                                                        |
|                        | (4) Deck spandrel-braced bridge                                         |                                                                                                                                                                                                                      |                                                                                                                                                        |
| Backfill treatment     | (1) Backfill cave ballast + grouting to reinforce on the upper part     | The four options to fill the cavity at the bottom of the tunnel can provide a more stable foundation for the tunnel and eliminate the hidden safety hazards caused by the suspension at the bottom of the tunnel; the backfill can reduce the overall space of the cave, and at the same time, it can reverse the pressure | The backfill method had a simple construction process, a short construction period, low construction cost, and strong feasibility. |
|                        | (2) Backfill graded gravel + grouting to reinforce on the below part    |                                                                                                                                                                                                                      |                                                                                                                                                        |
Alternate backfill graded crushed stone and concrete slab + grouting to reinforce on the below part

Backfill large-volume hollow concrete + grouting to reinforce on the below part

(3) Alternate backfill graded crushed stone and concrete slab + grouting to reinforce on the below part and dissolve the cave wall inward. It has a strong anti-rockfall impact capability, and the backfill platform can be used to protect the cave walls and roof during construction. The backfill thickness in the cave is too large, and the settlement problem will be the core issue that needs to be paid attention to during and after construction.

(4) Backfill large-volume hollow concrete + grouting to reinforce on the below part

As shown in Table 3, after the comparison of the four schemes, scheme 1 had greater advantages in terms of the construction period, economy, and safety than the other three schemes.

Table 3. Comparison of backfill schemes

| Category       | Scheme 1                                                                 | Scheme 2                                                                 | Scheme 3                                                                 | Scheme 4                                                                 |
|----------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Construction period | The required material is waste slag, which is convenient to obtain materials; it uses simple technology; and the shortest construction period | A large number of fillers need to be prepared; the materials are purchased in large quantities; the process is complex; the construction period is long. | The situation is the same in scheme 2. | The process is complex and tedious; the amount of masonry backfill is large; the construction period is the longest |
| Economy        | Approximately ¥69.26 million                                              | Approximately ¥117.45 million                                            | Approximately ¥128.71 million                                            | Approximately ¥101.38 million                                            |
| Safety         | The filling adopted the technology of high dumping filling, which made the workload in the tunnel less and the construction safety and easy to control. | The volume of piles at the bottom of the cave is large; the amount of mechanical construction in the cave is large; the construction risk is high. | The situation is the same in scheme 2. | The amount of construction in the cave is large; the demand for construction personnel and machinery is large; the construction risk is the highest. |

After comparison, the “backfill cave ballast + grouting to reinforce on the upper part” scheme was finally selected. This scheme was applied for the first time in the disposal of giant karst cave in the world by investigation and analysis. The use of this scheme saved approximately ¥60 million in cost compared with the graded “gravel + concrete plate backfilling” scheme. After applying this scheme, an ultra-thick backfill was formed in the cave, which was in turn the bottom accumulation body (early accumulation body + late collapse), non-grouted cave ballast, grouted cave ballast, 5% cement graded crushed stone, and roadbed, its thickness exceeded 100 m (Figure 6).

In addition, in terms of karst cave, construction safety and protection put forward the overall
protection: weeks line protection and the main protection, full framing and spray anchor net cable protection, and the spray anchor net cable protection + mobile scaffolding construction safety protection scheme, as shown in Figure 7. Compared with the overall protective full framing, it saved approximately ¥36 million of material cost and greatly reduced the construction difficulty. In the end, the total cost of the disposal of the giant karst cave saved approximately ¥96 million.

**Figure 6.** Illustration of backfilling in the cave

(a) Construction of karst cave sidewall anchor net spraying cave
Figure 7. Construction and effect of karst cave safety protection

3.2 Safety protection in construction

Because of the poor overall stability of the cave, the dangerous rocks of the roof and sidewalls were constantly spalled. To ensure the operation safety during the construction period and the stable during the operation period, we took the necessary safety protection measures, which were from two aspects. (1) Temporary safety protection during the construction, in which a movable steel scaffold was used to resist the risk of falling rocks in a short time. (2) Permanent safety protection, in which the anchor mesh spraying scheme was used to protect the walls and roof of the karst cave permanently.

3.2.1. Temporary protection scheme

The overall structure of the scaffold was triangular and mainly composed of roof trusses, purlins, steel plates, and waste tires. The assembly sequence was as follows: (1) erecting a triangular roof trellis, (2) laying the purlins above the roof trusses, (3) using double steel plates as the outer layer of the purlins, (4) using the tire made of rockfall buffer structure, and (5) using bolt connection method to connect them. The three-sided roof of the roof truss structure was formed by welding steel and steel plates, in which the weld was not less than the bearing capacity of the parent material. To enhance the structural integrity and stability, we provided a contact beam on the top of the roof truss and a vertically detachable diagonal support steel pipe in the middle of the waist, as shown in Figure 8. It was calculated that the scaffold structure could resist impact loads up to 580 kN, which was equivalent to the impact load caused by 0.7 t falling rocks of 50 m high.
3.2.2 Anchor net spray protection scheme

Anchor mesh spray scheme was used to permanently protect the roof and wall of the cave on the two sides of the centerline of the main tunnel at a distance of 20 m (corresponding to the mileage of the main tunnel DIK53 + 634–721) and above the elevation of 758 m. Φ22 mm mortar anchor + spray layer + reinforced mesh + local active protection net was adopted to protect the wall. The roof of the cave was protected by an expanded shell prestressed hollow grouting bolt + spray layer + active protection net + reinforced mesh; the support parameters are shown in Table 4. When the karst cave was backfilled to 750 m in height, the anchor net spraying support working platform was filled according to the equipment working height and the supporting range. Anchor net spraying protection is carried out on the “first cave wall, then cave top, first sides and then middle” principle.

Table 4. Permanent support parameter table

| Parameters               | Specification of roof                        | Specification of wall                        |
|-------------------------|----------------------------------------------|----------------------------------------------|
| Type of anchor          | An expanded shell prestressed hollow grouting | Φ22 mm mortar anchor                         |
|                         | bolt                                         |                                               |
| Length of anchor        | 6 m                                          | 4 m                                          |
| Spacing of anchor       | 1.5 m × 1.5 m                                | 1.5 m × 1.5 m                                |
| Specification of steel  | 200 cm × 200 cm                              | 200 cm × 200 cm                              |
| mesh                    |                                              |                                               |
| Thickness of C25 concrete spraying layer | 15 cm                                        | 15 cm                                        |

4. Study on settlement mechanism of ultra-thick backfill body

The giant karst cave was treated with the “backfill cave ballast + grouting to reinforce on the upper part” scheme. Because of the large volume of the karst cave, the bottom accumulation body and the upper backfill body constituted an ultra-thick backfill body. To effectively investigate the settlement stability and check its treatment effect, we established an online settlement monitoring system on the site, and its research results can be used to explore the law of settlement within the backfill and provide theoretical support for the engineering practice about this scheme.

4.1 Monitoring plan design

The measuring points of the online settlement monitoring system are mainly arranged at the center of
the line and near the sidewalls on both sides. The surface settlement monitoring has a setup of 18 measuring points to form three monitoring lines, which are located on the outside of the left sidewall, the centerline of the tunnel, and the outside of the right sidewall. The measuring point numbers are BU1–BU6, BM1–BM6, and BD1–BD6, and each measuring line was provided with a reference point, as shown in Figure 9. The layered settlement monitoring object was divided into two parts, namely, the newly added backfill on the upper part and the original accumulation body on the bottom, with a total of 6 measuring holes and 29 measuring points, as shown in Figure 10. Among them, FQ1–5 are shallow holes that are used to monitor backfill on the upper part. FS1 is a deep hole that is used to monitor the original accumulation body on the bottom. The distance between two measuring points in each measuring hole is 10 m, and four or five measuring points are arranged according to the hole depth, as shown in Figure 11. The delaminated monitoring was mainly arranged on the centerline of the line, with a total of three measuring points, numbered LC1–LC3 used to monitor the vacant distance between the road substrate and the backfill to avoid the impact of differential settlement on railway construction and operation.

**Figure 9.** The layout of surface monitoring points
4.2 Analysis of surface settlement

During the operation of the monitoring system, several constructions, such as grouting in the upper 20 m ballast body, roadbed, sidewalks on both sides, initial support of the tunnel, back arch, second lining construction, and backfilling of the tunnel cavity, were carried out in the cave. There was a crossover between constructions. The results of the separation layer monitoring showed that there was no change, so the separation layer monitoring was not analyzed below.
For the long-term monitoring of surface settlement, the data collection period was one time per 4 h, and the daily settlement value was taken as the average value of the day. A total of 382 days of settlement data were collected, as shown in Figure 12.

The following can be seen from the surface settlement monitoring curve of the backfill.

1. The cumulative settlement of the left monitoring line is similar to that of the middle monitoring line, the maximum value is close to 220 mm, and the settlement value of the right monitoring line is approximately 140 mm, which is less than the other two lines. The thickness of the backfill in the left and middle monitoring lines is less than that in the right, and the thickness of the original accumulation body is greater than that in the right. From the perspective of settlement development,
the left and right monitoring lines grew faster in the early stage and gradually stabilized in the middle and late stages, which was related to the construction load of the sidewalls. In contrast, the middle line increased slowly in the early stage and began to increase substantially during the construction of the tunnel. It showed that there is a great correlation between the settlement of the filling body and the location of the upper construction load.

(2) As the construction load at the corresponding location increased, the cumulative settlement of each monitoring line first increased rapidly, the growth rate gradually slows down, and the settlement gradually stabilized. It showed that there are many pores in the filling body at an early stage, and the pores under the construction load are greatly reduced. With the increase of time, the internal porosity of the filling body became smaller and smaller, and the influence of the increase of construction load on the settlement of the backfill body gradually weakened, and the settlement eventually stabilized.

(3) After the tunnel construction was completed, the construction in the tunnel was completed, and there is no additional load. The cumulative settlement increase rate of each monitoring line gradually approached zero. The cumulative settlement generated before this time accounted for more than 90% of the total settlement during the entire monitoring period. It showed that the settlement of the ultra-thick backfill is mainly affected by its gravity and the upper construction load, and the construction load can accelerate settlement so that the settlement tended to stabilize in advance.

4.3 Analysis of layered settlement
A total of 336 days of layered settlement monitoring data were collected. The settlement value of each monitoring hole and the interlayer compression value were analyzed. The difference in settlement calculation between the two monitoring points was the compression value between the monitoring points.

4.3.1. Settlement analysis of backfill
Figure 13 shows the settlement curve of the layered monitoring points of the backfill.

(1) The cumulative settlement value of the monitoring points 1 and 2 located within the range of the grouting backfill in each monitoring hole was small, and the time of tending to stability was ahead of other monitoring points. It showed that the grouting technology could control the settlement of the backfill well and can reduce the settlement value and shorten the settlement stability time.

(2) The interlayer compression of the backfill in the 0 to –7 m depth was less than 3 mm, which was composed of 5% graded crushed stone layer and 2 m thick grouting tunnel ballast layer at the top, whereas the interlayer compression of grouting ballast in the –7 to –17 m depth was less than 10 mm. It showed that the layered compaction and grouting reinforcement could control settlement. The FQ2 and FQ4 monitoring holes had a large compression value in this layer, indicating that there was a problem of insufficient grouting at the bottom part of the grouting layer. Within the range of –27 to –47 m, the compression value was large, and this depth layer was an extremely large part of it was the non-grouting backfill, and the construction adopts the throwing and filling process to fill it. During the filling period, the block rock had a large porosity and a large amount of compressive deformation.
4.3.2 Analysis of layered settlement of bottom accumulation body

It can be seen from Figure 14 that the layered compression of the accumulation body gradually decreased with the increase of depth, and the settlement of the collapse in shallow layers (−40 to −60 m depth) accounted for a large amount. The deep layer (−60 to −80 m depth) is mainly an early accumulation body, and the interlayer compression is extremely small. It showed that the deep accumulation body was very dense, and the load of the upper backfill and the construction had almost no effect on the deep accumulation.

The results of layered settlement analysis showed that the settlement of the ultra-thick backfill mainly come from the non-grouting backfill and the shallow collapse body, which were affected by the construction load, the cumulative settlement of graded crushed stone mixed with 5% cement after layered compaction, and grouting backfill was small and tended to stabilize in advance.

5. Conclusions

(1) The stability of the giant karst cave was analyzed through various detection methods, and it was found that the karst cave had the characteristics of poor overall stability, multiple dangerous rocks, and high risk of falling rocks. A total of 11 kinds of treatment schemes were proposed for the giant karst caves. On the basis of comprehensive consideration of construction, operation safety, and economy, the karst cave treatment scheme of “backfill cave ballast + grouting to reinforce on the upper part” was finally determined.
(2) The permanent safety protection of anchor net spraying on the wall and roof of the cave and the temporary safety protection of the movable scaffold were used to prevent the risk of falling rocks, which made the backfill treatment of the giant karst cave smooth.

(3) The construction load had an obvious effect on the settlement of the ultra-thick backfill. The settlement of the ultra-thick backfill mainly came from the non-grouted ballast and the shallow collapse, and the settlement of graded crushed stone mixed with 5% cement, grouted ballast, and deep accumulation body was small. The technology of compaction and grouting can effectively reduce the value of the settlement and shorten the settlement stability time.

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