Design and Construction of Tunnels in Karst Geology on Yichang-Wanzhou Railway, China

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1 Introduction

Yichang-Wanzhou Railway starts Yichang East Station and ends Wanzhou Station, with a total length of 377km, which is the most difficult railway at home and abroad until now. There are totally 159 tunnels, 339km in length, accounting for 60% of the whole railway length. Along the railway, 70% is located in Karstic geology, with the geological problems of underground stream, Karst and Karst water, talus, fracture zone, coal seam, gas, high ground stress and natural gas etc. The main difficulties for the tunnel projects are filled cavities with high water pressure, faults with high water pressure as well as structures crossing various huge Karst cavities.

2 Technique of “Energy release & pressure reducing”

During the construction of Yichang-Wanzhou railway, filled cavities with high pressure and rich water were encountered many times. While as for the filled cavities with high water pressure and large water volume, it was prone to have areas where grouting is not available, resulting in bursting of water and mud, casualties and economic loss as well as construction disruption. In this case the method of “Energy release & pressure reducing” is presented based on study and practice.

2.1 Feasibility study of “Energy release & pressure reducing”

“Energy release & pressure reducing” is a new construction method aiming at the filled cavity with high pressure and rich water, which takes accurate blasting on purpose at right time to blast cavity to release high pressure water and reduce potential energy and slurry pressure in order to eliminate the high risks in the tunnel, then it undertakes dredging and support to pass rapidly as well as building of base structure and secondary lining.

2.2 Applicable condition and time

The method of “Energy release and pressure reducing” is to be taken when filled cavity with high pressure and rich water or silt and sand layer are encountered, which should not affect the environment based on evaluation.

It is better to take the method of “Energy release and pressure reducing” in drought with no rain or less rain, since it takes time to excavate, support and treat to structure. If it is undertaken in rainy season, it may cause hidden risks in construction due to constant rain supply.

2.3 Main content

The method of “Energy release and pressure reducing” is a comprehensive technique to deal with the filled cavity with high pressure and rich water. The implementing procedures are shown in fig.1.

2.3.1 Cavity probing

The advance geological forecast was adopted in Yichang-Wanzhou railway, which took geological
sketch and TSP at first and then drilling to forecast Karst and Karst water in advance and search for cavity ahead.

**Fig. 1** Implemented procedures of “Energy release and pressure reducing”

### 2.3.2 Cavity interpretation
To release energy and reduce pressure in filled cavity with high pressure and rich water, it is necessary to determine the nature of filled material, water pressure, and water volume in cavity as well as cavity size in longitudinal direction, and analyse and identify the cavity type, size and source.

### 2.3.3 Cavity determination
It is key to determine the cavity during energy release and pressure reducing, which plays a decisive role in accurate blasting of cavity. Based on calculation simulation and analysis and practice, it is determined to take 2.5~3m rock pillar as the critical distance approaching cavity for intact limestone.

### 2.3.4 Cavity disclosure
Cavity disclosure means that when face approaches the critical boundary of filled cavity with high
pressure and rich water, the disclosure of cavity is carried out according to special accurate blasting design in order to release water and fillings accumulated in cavity and eliminate energy. This special accurate blasting design is based on concrete critical distance and size of section, and it requires the area of cross section of disclosed cavity after blasting should be no less than 2m×2m to facilitate energy releasing in cavity rapidly and completely.

2.3.5 Cavity treatment
After energy release and pressure reducing in filled cavity with high pressure and rich water, the water pressure in cavity is almost zero, so cavity treatment is safe. But three situations may occur, depending on affect of filled medium, water pressure, water volume in cavity and release time, i.e. complete releasing of water and filling medium, releasing of water but filling medium, releasing of water and partial releasing of filled medium. Therefore it should determine the scheme of construction treatment based on the state after energy release and pressure reducing. The lining structure of cavity should be reinforced and the class of pressure resistance is determined based on actual measured water pressure, combined with surface survey and geological analysis. It is necessary to take drainage by means of permanent drainage tunnel to guarantee safety after operation considering the feature of disclosed cavity. With a view of understanding of force state of cavity during construction and operation and evaluating of structure safety, it should take long-term monitoring to the structure of cavity.

2.3.6 Eight items of special safety design
To guarantee construction safety, eight items of special design are adopted in the method of “energy release and pressure reducing”, they are of hydrological monitoring, drainage system outside tunnel, monitoring & alarm system outside tunnel, drainage channel inside tunnel, separation of neighboring cavities inside tunnel, monitoring & alarm system inside and outside tunnel, condition for entering tunnel and escape route.

2.4 [Case study] “Energy release and pressure reducing” applied in “No.526 and 617 combined cavity” in Yunwushan tunnel

2.4.1 Cavity probing and interpretation
(1) Cavity scale: The affected scope of “No. 526 and 617 compound cavity” in Yunwushan tunnel was determined based on advance drilling holes and the developing pattern of cavity is shown in fig.2.
(2) Filled medium: The sand gushing from drilling hole was determined to be medium sand after being sieved. And it was difficult to obtain satisfied effect of water blocking by ordinary cement grouting in view of this. Furthermore it was also very difficult to reach this goal even if microfine cement grouting was taken, which its technical requirement is very high.
(3) Hydrological feature: It made use of the advance probe holes to release water in cavity at site, and the following conclusions were drawn by water release test: a) There was a corresponding relationship between drainage capacity of drilling hole and surface rainfall, which the water volume in drilling hole increased within one day after rainfall. Meanwhile the drainage capacity was affected by blocked drilling hole induced by filled medium in cavity. b) The data of water pressure test showed that the water pressure didn’t exceed 0.8MPa and it demonstrates there was a relationship between water pressure and rainfall on surface. C) Drainage through drilling hole has little impact on water pressure. It is difficult to reduce water pressure in short time by means of drainage through drilling hole.
(4) Environment feature: The cavity was located at the core of anticline of Baiguoba, with developed Baiguoba fault. This fault was tensioned longitudinally at first, then compressed and distorted, exhibiting reverse fault at the place where tunnel was excavated. The tunnel, with overburden of around 750m at this place, was covered with Karst depression, funnel and sinkhole on its surface. Water in filled cavity is collection of that in Karst depression, and the system of underground stream didn’t form water supply to cavity.

2.4.2 Cavity determination
It was decided to take the method of “Energy release and pressure reducing” regarding No. 526 cavity in Yunwushan tunnel. It took pneumatic and deep drilling to determine the boundary of
cavity on face when tunnel was approaching cavity. Thus the cavity ahead was divided into four areas, with the rock thickness less than 2.5m in area I, and that of 2.5 ～ 4.5m and 4.5 ～ 9m in area II and area III respectively, and that of more than 9m in area IV. (see fig.3). In this case the area I and II must be disclosed in order to blast cavity.

![Fig.2 Development pattern of “NO.526 and No.617 combined cavity”](image2)

![Fig.3 Boundary determination of No. 526 cavity”(Unit:cm)](image3)

2.4.3 Cavity disclosure and treatment

To guarantee one-pass success of blasting, the drift was excavated at the lower place with thick rock to form a free surface based on determined cavity boundary. The cavity was disclosed by blasting. All the water and filled medium in No.526 cavity were released and it was constructed under the umbrella arch by backfilling of concrete. The water pressure in No.617 cavity was reduced to zero, and the tunnel passed by under the help of dredging and backfilling.

3 Informative grouting in fault with high pressure and rich water

3.1 Survey

It was totally 10528m long for Qiyueshan tunnel on Yichang-Wanzhou railway, with the max. overburden of 670m. And it was most difficult for the construction of Deshengchang trough valley area at the central tunnel, with the shape of trough valley of strip (see fig.4) and length of 68km and width of 550m. Under the trough valley it was the developed F11 fault.

![Fig. 4 Topography of trough valley](image4)

![Fig.5 Coring on surface at F11 fault zone](image5)

3.2 Technical program demonstration

3.2.1 Primary construction of F11 fault

Advance deep drilling showed: The fault was consisted of tectonic breccia, interbed of marlit and fault gouge, and sandwich of clastic argillaceous limestone and limestone, with the rock of highly fractured, containing abundant high pressure water. The max. water flow of single advance
probing hole was 1800m³/h and the water pressure was 2.5MPa. Full face curtain grouting was taken to block water in view of F11 fault with high pressure and rich water. The statistics of technical data of site construction was listed Table 1.

<table>
<thead>
<tr>
<th>Location</th>
<th>Mileage</th>
<th>Grouting thickness /m</th>
<th>Amount of grouting hole</th>
<th>Big pipe-roof /Piece</th>
<th>Total /Piece</th>
<th>Grouting time/Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal drift</td>
<td>First cycle</td>
<td>PDK365+367~+342</td>
<td>5</td>
<td>63</td>
<td>35</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Second cycle</td>
<td>PDK365+344~+319</td>
<td>8</td>
<td>103</td>
<td>35</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td>Third cycle</td>
<td>PDK365+330~+308</td>
<td>8</td>
<td>103</td>
<td>35</td>
<td>138</td>
</tr>
<tr>
<td>Main tunnel</td>
<td>First cycle</td>
<td>DK365+355~+327.5</td>
<td>8</td>
<td>122</td>
<td>51</td>
<td>173</td>
</tr>
</tbody>
</table>

3.2.2 Technical program demonstration
The F11 fault was more than 200m long and it was difficult to guarantee the construction period by full face curtain grouting. Therefore a more reasonable technical program should be made.

3.3 Design concept of informative grouting
3.3.1 Full face curtain grouting
The full face curtain grouting has been developed in Seikan tunnel in Japan in view of fault with high pressure and rich water, with its basic concept shown in fig.6. The grouting was carried out at certain scope outside the loose area which was assumed to be induced by excavation of tunnel to form a water-resistant zone against water pressure, thus the high water pressure will not act on lining or support directly. In the design stage, it was assumed the ground was of uniform and the outer water pressure was distributed evenly. Therefore grouting consolidation should be taken in loose area. Based on the study results of Seikan tunnel, the formular of consolidation radius R in fault with high pressure and rich water was derived:
\[ R = (4\sim6)a \]
Where \( a \) is the radius of tunnel. In addition the \( R \) related to water pressure which was increased with the increasing of water pressure and volume.

3.3.2 Design concept of informative grouting
Regarding the F11 fault, the construction principles of “grouting consolidation, pressure reducing by drainage, alternating progress and construction under water” were presented. And the informative grouting was developed during the construction. The concept of design for informative grouting was shown in fig.7. In the design, it was assumed that the ground was uneven and the distribution of outside pressure was not uniform either due to uneven permeability.

![Fig. 6 Design concept of full face curtain grouting](image)

![Fig. 7 Design concept of informative grouting](image)
3.3.2.1 Uncertain stratum assumption and area partition

(1) It was assumed that the ground was uneven and uncertain.
(2) The design for basic area was carried out according to concept of grouting consolidation, with the scope of 3~5m out of tunnel contour line, i.e. 0.5~1 times of tunnel diameter. In the design, it was based on two loops of grouting holes both inside and outside, with the outside ones 3~5m away from tunnel contour line and the inside ones 1~3m away from tunnel contour line.
(3) Partition probing (6 areas in the figure) was taken at the gray (uncertain) ground around tunnel by choosing 4-6 outer grouting holes. Based on water volume and pressure in probe hole, two areas was divided outside tunnel, with one area of abundant water and another of less water. The probe hole being taken as grouting hole should be grouted strictly complying with the requirement.

3.3.2.2 Information tracking and local consolidation

(1) The grouting parameter was determined based on water volume in advance probe hole. As for the holes with large water volume, it took grouting at constant pressure following the principle of grouting against water, with the grouting pressure 2~3 times of water pressure, effectively blocking the fissures flowed by ground water. Thus the water volume and pressure in the area with abundant water were reduced after grouting.
(2) Grouting was taken according to the design for basic grouting area, with the sequence of “outer loop grouting first and then inner loop grouting, staggered hole grouting for the same loop”.
(3) Advance segmental grouting was taken strictly. There were 3 levels to control it considering the length to be grouted in segment (grouting space) in view of water yield in drilling hole and the condition of drilling.
There are also three classification based on water yield in the drilling hole, i.e. ≤10m³/h for class I, 10~30m³/h for class II and >30m³/h for class III. Furthermore there were three grades for holes, i.e. the first grade with no collapsed hole, the second grade with slight collapsed hole and the third grade with serious collapsed hole.
(4) After completing the grouting in basic area, complementary grouting was taken to the area with abundant water by drilling additional holes, with the scope to be 1~2m away from basic grouted area. Meanwhile regional water yield was checked.

3.3.2.3 Process control

The general grouting mechanism of informative grouting was to block fissure to reduce water and consolidate rock mass to improve ground. In the course of grouting, unstrained water blocking by grouting based on regional positional hole was taken at first, and water in ground was effectively controlled. Then grouting was carried out following the concept of water blocking with reasonable space, staggered grouting and regional intensification by additional holes.

3.3.2.4 Standardized evaluation of grouting effect

As for grouting in fault with high pressure and rich water, both water blocking and consolidation effect must be included in the inspection items, with the focus on process control. Regarding the check of blocking effect, it should cover water blocking rate and ground permeability after grouting. And the check to ground density and stability after grouting should be carried out concerning the consolidation effect. In view of the current evaluation methods of grouting effect, it was determined to adopt the methods of P-Q-t curve analyzing, drilling hole water yield analyzing, grouting volume analyzing, inspection hole water yield measurement and stability analyzing of inspection hole (holing test).
3.4 Design and application of informative grouting

The research and application of informative grouting was carried out in the cycling grouting at the exit of Qiyueshan tunnel at the station of DK365+318~+293. On July, 16th, 2009, it approached at the station of DK365+318 for the main tunnel excavation of Qiyueshan tunnel exit section. And the probing based on the six advance grouting holes showed that a central area of water inflow existed at the station of DK365+302~+295, with the water volume at right side to be larger than that of left side. The max. water volume in drilling hole of exploring section was 84m³/h and the actual measured water pressure was 1.2MPa.

The informative grouting was taken on July, 13th, 2009 and it was finished on July 5th, it only took 23 days.

4 Design and construction of tunnel passing huge cavity

The Karst can be classified based on its shape, size, feature and nature of filling and character of dynamic change of water inflow, and the classifications were shown in fig.9.

4.1 Treatment technology of Karst

4.1.1 Treatment program

In the course of Karst treatment, it should give the priority on safety and quality to reach the aim of safe construction, stable structure and secure operation. It was necessary to establish corresponding measures aiming at size, feature and filling of cavity and water, realizing management with standardized mode shown in table 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>Karst type</th>
<th>Countermeasure</th>
</tr>
</thead>
<tbody>
<tr>
<td>With no water</td>
<td>cavity or channel</td>
<td>Backfilling program</td>
</tr>
<tr>
<td>Fill cavity</td>
<td>&quot;Peripheral grouting consolidation + Pipe-roof&quot;</td>
<td></td>
</tr>
<tr>
<td>Large dry cavity</td>
<td>Slab span, group steel piles, pile foundation + pile cap, embankment filling and beam span</td>
<td></td>
</tr>
<tr>
<td>Karst water</td>
<td>Drainage, grouting for water blocking, weep hole, water blocking and consolidation of deposit and bypassing</td>
<td></td>
</tr>
</tbody>
</table>
4.1.2 Countermeasure against Karst water

(1) Drainage: As for water-passing cavity with small size, water drainage was taken in principles to maintain existing channel. It was not allowed to block channel at discretion to avoid water hazard.

(2) Grouting: It was difficult to guarantee the construction safety due to the geological disease of bursting of water and mud resulted by direct excavation when it was confirmed that the ground ahead was filled cavity with high pressure and rich water. And full face advance grouting was taken to block water and then large pipe-roof was constructed by principle.

(3) Weep hole: Weep hole should be made to drain water of underground stream and guarantee the safety of tunnel construction and operation when underground stream was encountered.

(4) Consolidation and water blocking of deposit: Controlled grouting was taken to consolidate when tunnel passes through deposit in underground stream at Karst area, which maintained the existing drainage system of underground stream. Then tunnel construction went ahead.

(5) Bypassing: Bypassing should be taken as much as possible in the precondition of tunnel function being not affected (such as parallel pilot and auxiliary drift etc.), when extreme demanding geological condition was encountered.

4.1.3 Design of tunnel lining structure in Karst geology

Model test and site test were taken to study the distribution law of water pressure on lining structure regarding the type of Karst encountered in Yichang-Wanzhou railway, and then the lining structure was determined combined with considering the measures of treatment.

4.2 [Case study] Karst treatment at the station of DK237+091 in Xiacunba tunnel

The cavity was disclosed at the station of DK237+091 in Xiacunba tunnel on Jan. 2, 2006. This cavity was developed at the length around 30m along the alignment. The tunnel was cut through by cavity. And the program of “arch span structure” was taken, which the solid arch structure of 1-22.5m with spandrel was adopted, see fig.10.

5 Conclusion

The tunnels in Karst geology on Yichang-Wanzhou Railway, with extreme complex geological condition and demanding construction, are the typical ones with high risks in underground works in China. Several technical problems of world class have been resolved attributed to well-organized management and technical innovation during the construction period of six years.

With the study and application of the method of “Energy release and pressure reducing”, it has successfully overcome the difficulties encountered in filled cavity with high pressure and rich water in Yesanguan tunnel, Dazhiping tunnel, Yunwushan tunnel and Maluqing tunnel, eliminating the risks in construction and operation. And the construction period was largely reduced as for the section of filled cavity with high pressure and rich water in Qiyueshan tunnel after the informative grouting has been applied. All the risks in these tunnels were reduced significantly and the progress was speeded up.

“The construction technique of tunnels in Karst and fault zones with high pressure and rich water” has been developed during the construction of Yichang-Wanzhou railway in China, providing a good reference for the similar projects in the future.