Repair works for karst water flowing into the Yuanliangshan railroad tunnel, China

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Abstract: The Yuanliangshan tunnel is a key control project, which lies between Chongqing and Huaihua. It extends 11.068km, and the greatest depth in the tunnel is 780m. When the tunnel cuts across the eastern limb of the Dongmaling anticline, construction encountered a sector that included a zone of well-connected karst rocks. In addition, the area is susceptible to large and intense rainfall. During tunnel construction there were extensive and repeated inflows of water and mud-rock particularly in the section DK361+764 to DK360+873, causing many machines and tools to be buried or damaged resulting in serious obstructions, delays and tremendously increased costs. Through initial analysis, the authors concluded that the inflowing water and mud-rock are from the main piping network of an underground karst river, which is fed by rainfall. Torrential rainfall occurs frequently in anticlinal areas during the rainy season - for example, from May to September of 2003. Section DK 361+764 to DK360+873 again experienced large, sudden and continuous inflows of water (mud, sand, gravel). In order to guarantee the safety of the tunnel construction and its operation, and in view of the nature of the karst and the associated water and debris inflow, the authors compared the choice of sluicing-hole drains, flat-guide drains, sealed-block and block-drains, and finally the first of these was adopted. Fortunately, the tunnel and lined cuttings were kept stable by draining the water-mud-gravel through sluicing drains. This indicated that it was a correct choice to adopt this scheme for renovating the east limb of the anticlinal source of the inflows.

Résumé: Le tunnel Yuanglianshang est les travaux de contrôle clef de la construction du chemin de fer de Chongqin-Huaihua. Longueur du tunnel est de 11.068km. La profondeur maximum entterrée est de 780m. Au moment de l'exécution du tunnnel à l'est de la montagne Tongmalin, on a rencontré la région du développement fort du karst de la circulation horizontale. A cette région, le karst est très développé. Il est une bonne connexité, plus plusieurs fois de pluie forte. Les sections de DK361+764, DK360+873 surgissaient l'houle avec des sables et des sols. Une partie de matériels sont submergés, enterrés et abimés. Il enpêche gravement l 'avancement de l'exécution. Il y a eu une grande perte économique. D'après l'analyse élémentaire, on estime que l'eau surgente, le renard et la source de boue, de sbale et de pierre est relatif étroitement au développement des réseaux des pipes karstiques ou l'inféroflux. Il peut accepter directement la compensation de la pluie atmosphérique. Pour assurer l'exécution et la sécurité du tunnel, selon la situation du développement du karst de cette section, la caractère de l'eau surgente et le houle et l'influence de la pluie, on a établi les quatres méthodes pour faire la comparaison et le choix : le canal d'évacuation, l'évacuation de l'advection, le bouchage, le bouchage et l'évacuation etc. Enfin, on a choisit le moyen de canal d'évacuation. Du mai au septembre 2003, la période de pluie, il y a plusieurs l'averse, les sections de DK361+764, DK360+873 surgissaient aussi beaucoup de l'eau surgente, le renard et la source de boue, de sbale et de pierre. Mais, ils sont évacués passer par le canal d'évacuation nouvellement construit. Le tunnel et la structure du revêtement sont sain et sauf. Il atteste la méthode qu'on a prise la mesure du canal d'évacuation pour traiter la catastrophe de l'eau surgente, le renard et la source de boue, de sbale et de pierre.

Keywords: Karst, caverns, limestone, railroads, stability, tunnel

GENERAL OUTLINE OF GEOLOGY AND GEOMORPHOLOGY OF THE TUNNEL

The special long tunnel of Yuanliangshan is the key control project of the planned railway, which lies between Chongqing and Huaihua. It extends 11.068 km, the entrance of which is located on the Zhangjia dam on the Xisha River east bank, at mileage DK351+ 465 and 549.16 m elevation. The exit is located at the Tanchang River's west bank of the source of Shumawang River, at mileage DK362+533 and 503.74 m elevation. The mileage of the highest point of the tunnel is DK355+820 at 560.52 m elevation. The greatest depth in the tunnel is nearly 780 m, with corresponding mileage DK353+035 and 552.16 m elevation. The tunnel lies in the contiguous area of fold mountain of east Sichuan, west Hubei and the Guizhou Plateau, located in the hinterland of Wuling Mountain, and crosses the Maoba-Yuanliangshan area that divides the water system of the Wu River from the Yuan River. The tunnel is of medium or low depth and cutting river valleys; terrain conditions are quite difficult. Its overall height is 500~800m. The geomorphological features are obviously controlled by tectonics and lithology. In addition, the geological structure is extremely complicated with anticlinal folds forming beautiful hills and synclinal folds the path of the Guizhou River in the fold area of Sichuan, Hunan and Hubei. The fold belt trends about northeast 35° in Yanshan and then about northeast 18° in Xishan. The south of the folded belt is NNE-trending.

The main geological structure of the running tunnel includes the Maoba syncline and the Tongmaling anticline and its associated or secondary faults; among which DK357+665~DK362+533 is Tongmaling anticline section consting of the sedimentary rocks of Cambrian age (∈) and Ordovician (O) carbonate rock. The lithology is mainly classified as limestone, dolomitic limestone, lime dolostone, dolostone intercalated with thin-bedded marl, shale and marly limestone. The axial portion of the Tongmaling anticline cuts across the Qingshan, Genshan and Yudipo. It is 60 km in length and in plan is shaped a bit like 'S'. The axial has 3 high points which can be divided into 3 sections of south, middle, and north respectively. The anticline section cut across is a portion of the north section of the Tongmaling anticline, and the south is entered from Laoguashan. The high point of the tunnel is located slightly north of Yudipo, appearing short axial anticline. And it is gradually plunging along the axis towards south and north directions and finally towards Dazhuyuan in the north and then out of the zone. While inside, the length of the tunnel is 11.7 km and axes is orientated N20~30°E. The two limbs tend to dip more gently in the east (40~50°) and more steeply in the west (50~80°). The axial plane is inclined to the east. The section between part of Laoguashan in the south of short axis anticline and Dadongshan axial zone are cut by faults. The stratum with the longest history appearing from the core of anticline is Middle Cambrian Gaotai Formation (∈2g). The sequence of the two limbs are Middle Cambrian Gaotai Formation (∈2g), Pingjing Formation (∈2p), Upper Maotian Formation (∈3m), Genjiadian Formation (∈3g) and stratum mainly consisting of Ordovician (O) carbonate rock (Figure1). The anticline section develops and distributes three longitudinal compression faults along the stratum strike of F1, F2, F01. Affected by multi period evolution, the core of the anticline is orientated as a compound anticline of shape 'M' and bedding fracture and cross fracture are intensely developed. The axial zone of the anticline forms a mountain (extending in the NNE direction), two limbs surrounds like a valley and the karst landform is completely developed. It has the characteristics of plateau, i.e. third-order plateau with elevations of 1100~1150 m, 950~1050 m and 700~800 m. The plateau at 1100~1150 m has eluvium of tens of centimetres in thickness and archaic depression of imperfect modality. The east limb is located in a line of Xujia~Yangjiagai, with the geomorphology of a miniature trough, depression, peak-cluster, or gentle slope and so on. The gentle slope zone also has residual clay of tens of centimetres thickness. The western limb lies in Santan village, with the geomorphology of a gentle slope, miniature trough, depression and so on. The plateau with an elevation of 700~800 m has large-scale geomorphology of dissolution troughs and peak-clusters in both the east and west sides. In the trough, the paternoster depression develops, the long axis direction of which is in accordance with that of the anticline axial zone. Thus, the existence of the anticline section will benefit for the mature of karst and karst water. During construction, the east limb of the Tongmaling anticline in Yuanliangshan tunnel on the exit section of DK361+764,DK360+873 has suffered extensive and repeated water and mud-rock ingress.

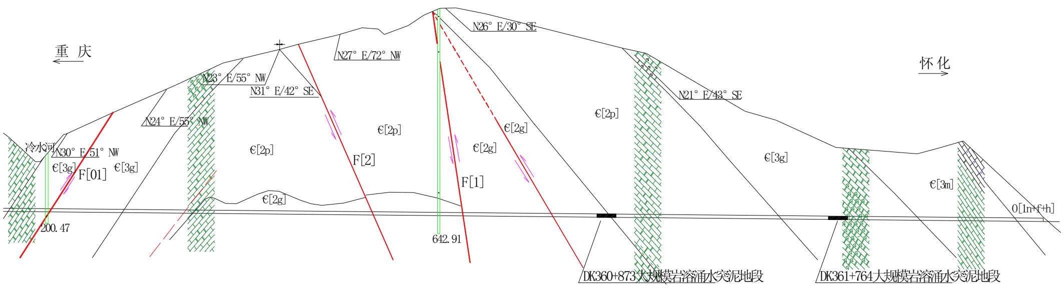

Figure 1. Section sketch map of Tongmaling Anticline Section in Yuanliangshan Tunnel (proportion 1:10000)

CHARACTERISTICS OF RECHARGE, RUNOFF AND OUTFLOW OF KARST WATER IN TONGMALING ANTICLINE

The east and west limbs of the anticline are limited by non-soluble rock of Silurian age and their surrounding is cut by the surface water system. The drainage base of karst water in Tongmaling is definded as the elevation of the soluble rock and non-soluble rock contiguous area which is cut across by surface water. In addition, the surface watershed is almost consistent with the underground watershed and precipitation is the only supply source for surface water and groundwater. A line from Jianzishan (elevation-1185.5m) ~ Yuanliangshan (1202m) ~ LanBanDeng (1156m) ~ DaTongshan (also named DaDongshan, 1151.7m) ~ Tea Garden (1030.4m) in a nearly N-S direction, along the trend of anticline axis, is the watershed of the east and west limbs of the anticline. The line from Laoshan (level-1218.3m) ~ Jianshanzi (1185.5m), in almost an E-W direction, is the watershed of the west limb of the anticline. Karst water in the west limb, located in the south of the watershed, drains longitudinally mainly along terrain to the south in the form of spring or spring groups, partly in landscape orientation. While most of the watershed karst water in the west limb of the anticline in the Juetai Dam ~ DaDongshan section, located in the north of the watershed, drains by cross frature to the valley of the Lengshui River (also named the Hou River) in the form of spring or spring groups, which can be used as the part of the drainage base of karst water in the section. The karst waters in the section and that from the west limb of northern DaDongshan, drain longitudinally mainly along terrain in the north direction to cut breadthwise across the Lenghe River valley anticline in the form of an underground river or karst spring group. It was investigated that the lowest elevation of any underground river or spring group (such as the Yaxueko underground river), appearing in the west limb of this river valley, is about 520 m.

The elevation of the interchange between the Lengshui River and the ZhuPa River is about 467 m and the lowest karst spring appearing in the area of river valley that runs across the north limb of the anticline is about 474 m. So, it is considered that the karst water in the east and west limbs of the north anticline section, hardly develop below 450 m. Most groundwater, located in the west limb of the anticline in Juetai Dam ~ DaDongshan, drains mainly in landscape orientaton to the Lengshui River. The elevation of the river is 660 m, which can be used as the lowest elevation for karst water development. While on the line from Baomuping to Jiazhou in the south of Lanbandeng, groundwater drains mainly to the XiangMa River. The elevation of the river in Jiazhou is 385 m, which can be used as the lowest elevation for karst water development in the east limb of the anticline of the section.

Above all, there is not an integrated karst water system in the anticline. Precipitation is the only supply source for karst water. Besides forming surface runoff, most of the precipitation drains underground and then forms karst groundwater runoff and finally drains to the surface water system. The characteristics of recharge, runoff and outflow are: recharge dispersely by section, relatively integrated runoff along longitudinal crack-in-layer and transverse cracks, and relatively integrated drainage in the form of spring and underground river according to each section and subsystem.

HAZARDS OF WATER AND MUD-ROCK INGRESSING IN THE WEST OF THE ANTICLINE SECTION OF CONSTRUCTION TUNNEL AND ITS ANALYSIS

Hazards of water and mud-rock ingress during the construction

When the tunnel exit cuts across the east limb of the Dongmaling anticline to the core of karst water of vertical endless loop belt —→ season changed belt —→ horizontal endless loop belt—→sluggish stream belt in depth, the construction encounters an intense developed belt of karst in the east limb (i.e. a ‘pipelinea network developed belt of the underground river or karst spring group), in addition to too much intense rainfall. There was extensive water (sand and stones) ingress and again at DK361+764, DK360+873, which caused lots of machines and tools to be buried or damaged and the tunneling met with serious delay and obstruction, with considerable financial loss.

Analysis of water and mud-rock pouring up

Each point of water ingress at DK361+764, DK360+873, especially at DK361+764, has relatively obvious characteristics. During the construction the water ingress appears as: spraying water, turbid water, with plenty of mud and sand and also the initial water flow is extremely high, the duration time of flood peak is short, the water ingress decreases sharply and tends to be stable and so on.

After sealed-block at DK361+764, water and mud-rock ingress appears to have the characteristic of transferring elsewhere. The karst ‘pipeline’ bedding collapsed along the right wall of the top of the cave at DK361+764 and was blocked completely on 11 February 2002. Then groundwater was blocked up in the karst pipeline and consequently water levels and hydraulic pressures increased. Finally, groundwater broke through the relatively weak rockmass on the left side of the advance at DK361+764.(here originally a corrosion crack, Figure 2). Thus, it successively caused two extensive water ingresses on 22 February 2002 and 3 March 2002, the process of which carried a lot of mud, sand and stones. Afterwards, the channel was blocked by these stones, mud and sand, so that only a little water came out of the fracture. Due to the reduction of counter pressure the upper part of the floor and the weaker rockmass on the base of left wall was broken by the underground water, the water bursting out around this area. Primary analysis indicated that the three spots of karst water channel, such as the right side of the karst ‘pipeline’ at DK361+764, the spot of water pouring up at the top of the left wall and the base of left wall, should be closely connected to be the same water system (Figure 3).

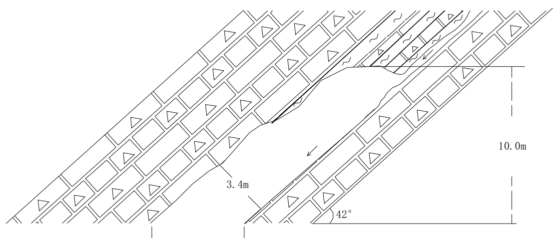

Figure 2. Karst development on the right wall of Yuanliangshan tunnel

Analysis indicated that the phenomenon of water ingress at DK361+764, from the initial intermittent, with airflow before climax, to many spots transferring after blockage, and finally ejecting many rocks from the water exit, shows the karst water is completely developed, that many branch-shape drainage networks exist and that the tunnel exposed the main ‘pipeline’ of natural karst indirectly.

Each time, when extensive water inflowed from each point at DK361+764, DK360+873 etc, the water carried a lot of mud, sand and stones (35%). One source of the sediment was the filling and sediment from the original karst cave, underground river and karst 'pipeline'. For example, at DK361+764 ~ +758 section, two big corrosion bedding fractures are developed. One of them is a fracture close to the exit terminal (i.e. near the top of the cave), about 0.11 m in width, filled with grey and yellow silt and carrying some dolomite and limestone fragments. The other is close to the entrance terminal (i.e. near the bottom of the cave), about 0.4 m in fracture width, filled with yellow silt and carrying limestone and dolomite fragments. Because of extensive mud ingress time after time, the fillings were washed out and the rock collapsed to form a kind of bedding-collapsed cave with dimensions of 5.4 m × 3.4 m × 10.0 m (height) (Figure 2).

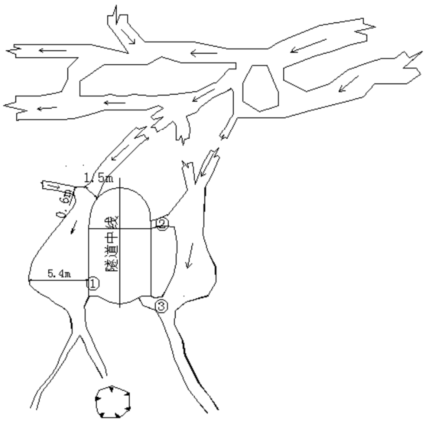

Figure 3. Karst connection in DK361+764

The other sediment source is the loose rockmass body of solution cavities. During the process of forming the Tongmaling anticline, some tectonic movement took place and the rock body was injected with some horizontal veins. In addition, under the effects of efflorescence and corrosion, the rock is fragmented and the wall rock of the solution cavity is loosened, which can be carried during the process of forceful circulation and alternation of the groundwater.

Each point of water ingress at DK361+764,DK360+873 section, if there is a long period without rainfall, the amount of water ingress will be small and stable. When it is raining, especially after extensive rainstorms lasting from several minutes to several hours, the capacity increased sharply and with lots of mud, sand or stones. When the storms last for several hours or several tens of hours, capacity will decrease sharply and trend to stability. For example, after one to two hours of heavy rainfall on 6 July 2002, an extensive water and mud-rock ingress occurred, with an almost instantaneous maximum of up to 27.5 m^3/s and plenty of stone fragments with mud were piled up. It has been indicated that these points are closely connected with the underground river or the krast spring group of the main 'pipeline' networks and can directly receive the recharge from precipitation. Due to the influence by multi-periodic structural evolvement, although the anticline is not a junction structure; the fractures have developed intensely in all directions and have a good condition for recharge, runoff and outflow. There are three situations which are the primary recharge source for groundwater: especially the following two: one is in the karst doline and depression belt with an elevation of about 950~1050 m; the other is in area of huge karst trough of Paomu~Taoziping with an elevation of about 700~800m. The precipitation can be rapidly absorbed and filtered and the coefficient of infiltration reaches 0.6~0.8. Bedding plane fracture, corrosion fractures and accomplished karst 'pipeline' are good tunnel for filtering.

ALTERNATIVE REPAIRING PROJECTS COMPARISON

In order to guarantee the safety of the tunnel building and its operation, and in view of the development of the karst and features of the water and mud-rock ingress and the degree of rainfall on the east limb of the anticline, we compared the choices of a sluicing-hole drain, a flat-guide drain, sealed-block and block-drain for the remediation of the karst water inflowing in the east limb of the anticline.

Sluicing-hole drain

A sluicing-hole should be on the left 25 m of the line, with 1732 m in length, a profile gradient of 19% and a sectional dimension of 3.5m×3.65m. Below the hole is a concrete sluicing-sink, with 1.2 m of sluicing height. The end of the sluicing-hole is set and controlled in accordance with corresponding plane at DK360+800. To draw the water in the sluicing-hole then drainage, a lateral diversion hole (or catchment drill) is respectively set up at DK361+764, DK360+873 and other points with high water output.

Flat-guide drain project

A flat-guide drain at PDK360+800~PDK362+574 section extends 1774 m in length, with 1.2 m width. Below the flat-guide drain is a concrete sluicing-sink, with 1.2 m in height. Its sluicing bottom is 1.99 m lower than the groove cover of the positive-hole. To draw the water into the flat-guide drain, a lateral diversion hole (diversion sink or catchment drill) is set up at DK361+764 and other points with high water output .

Sealed-block project

Concrete, delivered by high voltage pump, is used to seal-block all the karst capacities and ‘pipelines’ at DK361+764, DK360+873~+950. Hydraulic pressure resistant lining is adopted to positive-hole at DK361+764, DK360+873~+950 sections and corresponding flat-guide drain at PDK361+660~+820 and PDK360+820~+980 section, the intensity of flat-guide drain is slightly lower than the positive-holes.

Block-drain project

Block-drain is defined as blocked karst ‘pipeline’ by mud, sand and stone fragments to make clean water flow out in the right quantity. In short, it is a means to drain water and reserve mud, sand and stone fragments.

Projects comparison

The sluicing-hole drain and flat-guide drain projects can avoid the water and mud-rock extensively pouring up in the scope of tunnel cave and their direct effects on the tunnel and its lining cutting structure. However, disadvantages exist. Arbitrarily draining the groundwater and its mud, sand and stone fragments, will influence the local environment in the short term. It has the potential problem to make solution cavities enlarge and cause solution cavity and ground collapse. With respect to flat-guide drains, due to the limitation of longitudinal slope, the drains fill up easily and there is a lot of work to clean the silt out. The application of flat-guide drains will influence the current construction of the tunnel discharge capacity. There are also problems in relation to fire rescue access during the operation and reservation of double lines and it is still necessary to break a sluicing pipeline when building the dual lines.

The sealed-block approach is adopted to make groundwater find a new way out, so as to be in balance again. If we can get the expected effect, there will be fewer problems in the phase of railway operation. However, there are lots of unexpected factors when carrying out this alternative. If anticipated impact is reached, it will lessen a lot of trouble during the railroad operation. First of all, due to the influence of the high-pressure karst water, lining cutting structure is at risk. Secondly, in order to find a new exit, groundwater may outflow at the weakest position in the cave, while it is difficult to ensure the range of reinforcing lining cutting structure and injection.

The block-drain approach will neither cause lots of erosion of mud, sand and stones nor form the high hydraulic pressure, and neither threaten the tunnel lining cutting structure nor influence the environment. It is the most reasonable approach in theory. However, under the current technology and equipment conditions, it is difficult to realize. The sealed-block approach involves a large amount of work and the effect is influenced by the rock structure which is difficult to predict. Besides, after sealed-block, lining cutting will endure more hydrostatic pressure and both the constructed lining cutting built and flat-guide should be reinforced. The block-drain approach is difficult in construction, big in engineering quantities, large in investment and that is reason we adopted the drain project.

We compared the choices time and again and finally adopted the sluicing-hole drain approach. The advantages and disadvantages of each repair method are listed in Table 1.

Table 1. Correlation of the different remediation approaches

<table>
<tr><th>Plan</th><th>Environmental effect</th><th>Drainage capacity</th><th>Constructive difficulty</th><th>Operative maintenance</th><th>Structure safety</th><th>Investment</th></tr>
<tr><td>drainage plan for drainage hole</td><td rowspan="2">Having a certain degree of effect on surface zoology environment. The mud with higher sand amounts flows into the Taichang River, having an effect on the water quality during a short time.</td><td>Satisfying flux and cut-and-fill requirements</td><td>Easy</td><td>Small amount of desilting</td><td>Safe</td><td>Larger</td></tr>
<tr><td>Paralleling drainage plan</td><td>Not satisfying the flux requirement, it is easy to fill up when rock dissolving with sands.</td><td>Easier</td><td>Large amount of desilting. Having a certain of effect on paralleling firefighting function</td><td>Safe</td><td>Smaller (large investment when building complex line)</td></tr>
<tr><td>Ponding plan</td><td>No effect</td><td></td><td>Having a certain degree of difficulty</td><td>No maintenance</td><td>Having risk</td><td>Large</td></tr>
<tr><td>Plan combining ponding and drainage</td><td>No effect</td><td></td><td>Difficult</td><td>No maintenance</td><td>Safe</td><td>Large</td></tr>
</table>

CONCLUSIONS

When cutting across the east limb of the Dongmaling anticline, the tunnel construction encountered a sector that developed an ‘endless loop tape’ of water ingress, in addition to prolonged rainfall. There were extensive and repeated water and mud-rock ingress periods on the section DK361+764, DK360+873, which caused a lot of machine and tool burial or damage, and the tunnelling met with serious delay and obstruction. We had to sustain tremendous financial loss. In order to guarantee the safety of the tunnel construction and its operation, and in view of the development of karst and features of the water and mud-rock ingress and the effect of the rainfall in the east limb of the anticline, we compared the choice of the sluicing-hole drain, flat-guide drain, sealed-block and block-drain for the remediation. Finally, we adopted the first one; from October 2002 to April 2003, the project of sluicing-hole drain was constructed. In the rainy season from May to September 2003, the Tongmaling anticline section in the Yuanliangshan tunnel encountered heavy rainfall and many sections, such as DK 361+764, DK360+873 suffered extensive water (mud, sand, stones) inflowing suddenly and continuously. Fortunately, the tunnel and lining cuttings are safe and sound by draining the water-mud-stones through sluicing holes. That indicates it is a correct choice to adopt the sluice hole drain approach to remediate the hazards of karst water inflowing from the east limb of the anticline.

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