Model Test Study on In-service Karst Highway Tunnel

Rao Jun-ying[1], Fu He-lin[1], Liu Yun-si[1], Yin Quan[1], Zhang Hai-ming[2]

1. School of Civil Engineering, Central South University, Changsha, Hunan 410004, China

2. College of Civil Engineering and Mechanics, Xiangtan University, Xiangtan, Hunan 411105, China

ABSTRACT

This article, based on the Baishan Tunnel, optimized the selection for the similar materials of karst caves filler, surrounding rock and lining, carried out a study on similar model test to in-service karst highway tunnel with the geometric similarity ratio of 1/40. Then, the distribution law and trend of surrounding rock pressure were revealed. Subsequently, the mechanical behaviors of the surrounding rock were discussed after endowing some treatment to these caves. The results show that: ①the Ⅴ surrounding rock from Baishan Tunnel can be properly simulated by the mixture of barite powder, plaster powder and cement with the proportion of 1:12:2; ②applying the lower elastic modulus material, compared to surrounding rock, to fill those karst caves, which will lead to greater compression deformation under the same load; ③when these caves were laid nearby the spandrel, haunch and springing, karst caves will cause unsymmetrical pressure to tunnel lining. Although, those caves have been filled, which should be attached great importance during the tunnel service.

KEYWORDS: in-service tunnel; highway tunnel; karst cave; similar model test

FOREWORD

For the sustainable development of highway and railway construction, a number of tunnels are inevitable in the encirclement of karst caves or water-eroded grooves. Although karst area will be treated during tunnels constructing, the unorganized groundwater will take tunnel surrounding medium away, it will also lead to stress redistribution and cause tunnel disease or potential safety hazard to tunnel structures. Thus, scholars have carried out a series of studies on tunnels in karst area, such as follows: Li took a research on geological disaster forecast and warning and water inrush mechanism in karst tunnels[1]. Wang confirmed to accept the advanced prediction to construction procedure and the costs to construction organization[2]. Zhang put forward the hydraulic energy technology for concealed karst caverns with high pressure and deposit in tunnel construction[3]. Michael[4] and Rudolf Lied[5] revealed the mechanism of karst cavern separately. Laurent discussed the mechanical mechanism of anisotropic karst aquifer with numerical simulation[6]. All aforementioned studies have attempted to solve the adverse effects for karst tunnels construction in the manner of practical technology, numerical simulation or theoretical analysis.

However, hardly research relates to the mechanical behaviors of in-service karst tunnels, and no research involves in-service karst tunnels in the way of model test. Therefore, the study on in-service karst tunnel with similar model test is carried out, and this method is used for finding the influence of surrounding rock and lining by treated karst caverns for in-service tunnels.

ENGINEERING SITUATION

As the reference of [7], the left Baishan Tunnel is 1713.0m (K5+231~K6+944), and the right is 1821.3m (K5+250~K6+937), it's about 50m in average burial depth and 87.1m in maximum. The Ⅴ rock is nearly 1/3 to the whole surrounding rock. In Ⅴ rock area, the thickness of initial lining is 26cm, the secondary lining is 60cm, and 15cm for reserved deformation between them.

In this model test, the size of lining and mechanical parameters of surrounding rock relies on the Ⅴ rock area of Baishan Tunnel. The geometric similarity ratio is 1/40. So, the selected optimal cross section of lining is shown in Figure 1. Then, the similarity coefficients of geometrical size(L), volume-weight (γ), elastic modulus (E), Poisson ratio (μ), stress (σ), strain (ε), internal friction angle (φ), load (F), time (t), displacement (u) and mass (m) for similar materials can be obtained.

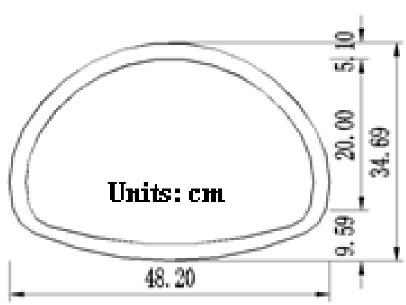


Figure 1: Optimal cross section of lining

SIMILAR RATIO AND SIMILAR MATERIALS

SELECTING

Similar Ratio Selecting

As the load applied to tunnel, the variant pressure of surrounding rock and altered stress and strain is the main effect. Meanwhile, the material strength and elastic modulus play a major role in that condition. So, the selected similarity criteria are shown as:

$$\begin{cases} \frac{\alpha_\gamma \alpha_L}{\alpha_E} = \frac{\alpha_\gamma \alpha_L}{\alpha_\sigma} = 1 \\ \alpha_\upsilon = 1 \end{cases} \tag{1}$$

In Eq. (1), α_γ, α_L, α_E, α_σ and α_υ are as shown in Reference [7]. Therefore, Eq. (1), combined with the similarity theorem, could deduce the similar ratio to physical parameters, which are shown in Table 1.

Table 1: Similar ratio of the parameters

Parameters	Symbols	Similarity criteria	Similar ratio (Model/Protomodel)	Remarks
L	α_L	α_L =1/40	1/40	Selecting
γ	α_γ	α_γ=1.85/24	1/1.3	Preparation/ Field test
σ	α_σ	$\alpha_\sigma = \alpha_L \alpha_\gamma$	1/52	
E	α_E	$\alpha_E = \alpha_L \alpha_\gamma$	1/52	
F	α_F	$\alpha_F = \alpha_L^3 \alpha_\gamma$	1/83200	Point load
ε	α_ε	-	1.00	
μ	α_ν	-	1.00	
φ	α_ϕ	-	1.00	
t	α_t	$\alpha_t = \sqrt{\alpha_L}$	1/6.325	
u	α_u	$\alpha_u = \alpha_L$	1/40	
m	α_m	$\alpha_m = \alpha_\gamma \alpha_L^3$	1/83200	

Similar Materials Selecting

In order to simulate the mechanical and deformation behaviors for surrounding rock, lining and treated karst caves, there are three kinds of similar materials should be selected in this model test.

(1) The similar materials for lining

For the best simulation, using the mixture of water and gypsum with the ratio of 1.3:1 to simulate the secondary lining(as shown in Figure 2 and Figure 3), applying the Φ0.46@5mm wire mesh (as shown in Figure 4) to simulate the φ8@200mm mesh reinforcement. The elastic modulus of lining similar material is E_s=0.511GPa, the other parameters of lining and its similar material are shown in Table 2.

Figure 2: Stirring for lining mixture **Figure 3:** Test blocks of lining similar material

Figure 4: Wire mesh with Φ0.46@5mm **Figure 5:** Testing elastic modulus for test blocks

Figure 6: Test blocks from surrounding rock

SIMULATION MATERIALS

Table 2: Material parameters of lining and its similar material

Materials	γ kN·m^{-3}	σ_c (MPa)	E_s (GPa)	μ
Lining in protomodel	26.0	25.8	26.7	0.17
Lining in model	19.3	0.485	0.511	0.18
Similarity ratio	0.7423	0.0189	0.0191	1.0588

It can be noted from Table 2 and Eq.(1) that the similar degree of σ_c and E_s are 101.8% and 103.1%, which possess well similarity.

(2) The similar materials for Ⅴ surrounding rock[7]

For simulating the Ⅴ surrounding rock, arrange the medium coarse sand to act as aggregate, put the barite powder, gypsum powder and cement to mix for cementing material, in which coarse to cementing material is 3:1 and the water to that mixture is 1:8 in weight. Four different groups of similar materials in all are designed, and six test blocks for each similar material. One group of them is shown in Figure 6. After a series of experiments (as shown in Figure 5), the mean values of their major physical and mechanical parameters are arrived, as shown in Table 3.

Table 3: Material parameters of surrounding rock simulation materials

Materials	A:B:C (by weight)	γ (kN·m^{-3})	f_t (MPa)	f_c (MPa)	E_r (GPa)	μ	C (kPa)	φ (°)
Ⅴ rock	-	24.50	4.60	59.60	51.30	0.19	30.30	16.7
Surrounding rock simulation materials	1:11:3	21.07	0.116	1.333	1.312	0.17	0.54	16.5
	1:12:2	20.84	0.096	1.277	1.174	0.18	0.66	16.9
	1:13:1	19.99	0.083	1.120	1.059	0.18	0.71	17.1
	1:14:1	19.51	0.074	0.987	0.912	0.19	0.80	17.6
Selected ratio	1:12:2	1.18	47.92	46.67	43.70	1.06	45.91	0.99

Notes: A—barite powder, B—gypsum powder, C—cement.

In order to select the most suitable similar material for the Ⅴ surrounding rock. Then, the similar degree of this four groups of similar materials are deduced from Table 3 and Eq.(1), as shown in Table 4.

Table 4: The result of similar degree for similar materials

Ratio	$\alpha_\sigma / \alpha_\gamma \alpha_L$ (×100%)	$\alpha_E / \alpha_\gamma \alpha_L$ (×100%)
1:11:3	96.1	84.1
1:12:2	99.3	92.9
1:13:1	108.6	98.8
1:14:1	120.2	112.0

Obviously, compared the data in Table 4, the compound with the ratio of 1:12:2 holds the highest similar degree in this four groups, which is the selected similar material for the Ⅴ rock.

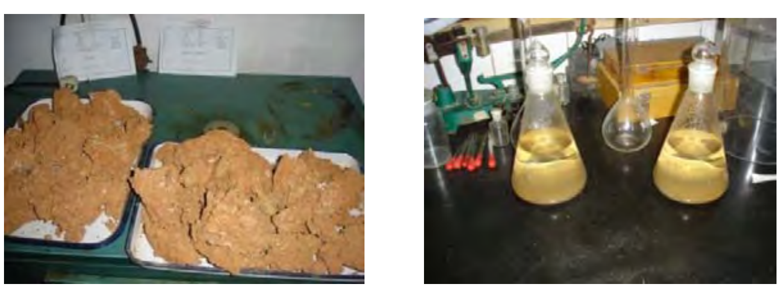
(3) The similar materials for treated karst cave

During the Baishan tunnel construction, for improving the load bearing capacity of karst areas, the silt in karst caves is cleared first, then they are filled with M7.5 mortar flagstone. Because the red clay holds almost the same possion ratio with mortar flagstone, they can match the similarity criteria of $\alpha_\upsilon = 1$, it is feasible to simulate mortar flagstone with the red clay in this test. The samples of the red clay and the test for their parameters are shown in Figure 7 and the results are shown in Table 5.

Table 5: Parameters of karsts filler and simulation material

Materials	γ (kN·m^{-3})	E_f(MPa)	μ
M7.5 mortar flagstone	25.6	5.65×10^3	0.35
Red clay	17.6	7.800	0.35
Similar ratio	0.688	0.0014	1.00

The karst caves are laid at the five feature points of the tunnel lining, they are the vault, left spandrel, left haunch, left springing and soffit. The distance between caves and the tunnel secondary lining contour line is 5cm, the diameter of these caves is 15cm (as shown in Figure 10 and Figure 11).



（a） Red clay samples （b） Parameters testing

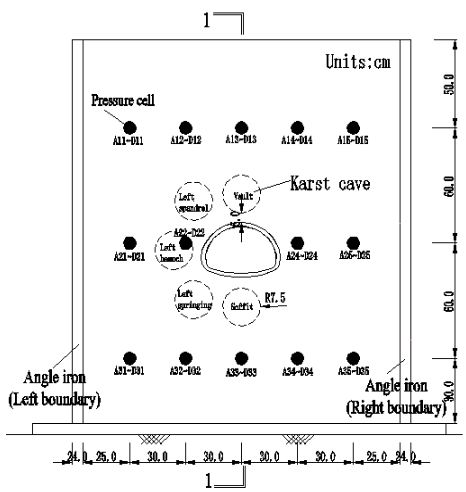
Figure 7: Parameters testing of red clay samples

MODEL TEST CUBE AND TEST INSTRUMENT SET

The model test cube and loading procedure just as shown in the reference of [7]. With the designed ratio, pouring and punning the rock simulation material layer-by-layer. The pressure is collected by earth pressure cells, the layout of these cells and karst caves are shown in Figure 10 and Figure 11.

Figure 8: Burying of earth pressure cells and treated caves

Figure 9: Model test cube



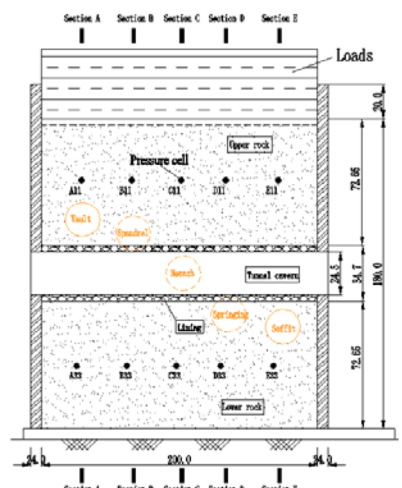
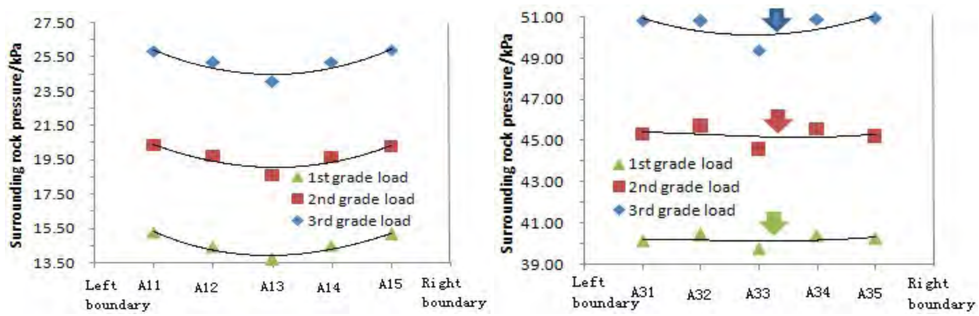


Figure 10: Layout of earth pressure cells and karst caves

Figure 11: Sectional drawing of 1-1

DISCUSSION OF THE TEST RESULTS

There are 3 load grades in this test. After an hour of each load grade, a group of pressure is collected. The surrounding rock pressure of all measure points in the burial depth of 50cm and 170cm is shown in Figure 12 to Figure 16.



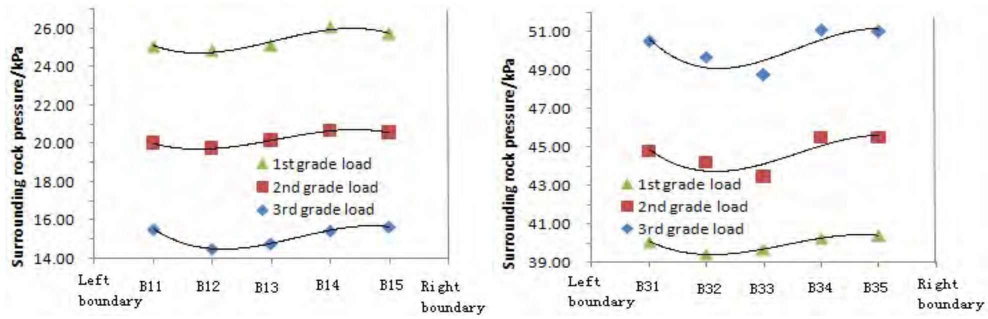
(a)Burial depth of 50cm (b)Burial depth of 170cm

Figure 12: Surrounding rock pressure of measuring points on section A

In this test, the layout of karst cave in section A (as shown in Figure 11, so as section B, C, D and E) is right above the vault. The pressure in section A has a distinct trend that it decreases gradually from left and right boundary to the tunnel center line, and this trend is clearer and clearer as getting closer to the karst cave.The shap of this trend-line presents concave type, approach to the symmetric “U” style (as shown in Figure 12). The primary explanation is that the elastic modulus of karst cave filler is weaker than surrounding rock, when they are subjected to the same load, the filler will produce greater deformation than the surrounding rock, which leads to smaller pressure in this sphere of influence. Additionally, at the same depth, the farther for earth pressure cell from karst cave, the smaller effect suffered, and the measured value of earth pressure is greater. Conversely, the value is smaller. As the whole loading end, the minimum pressure of burial depth of 50cm, 170cm respectively decreased by 7.25%, 3.06% to the maximum value.

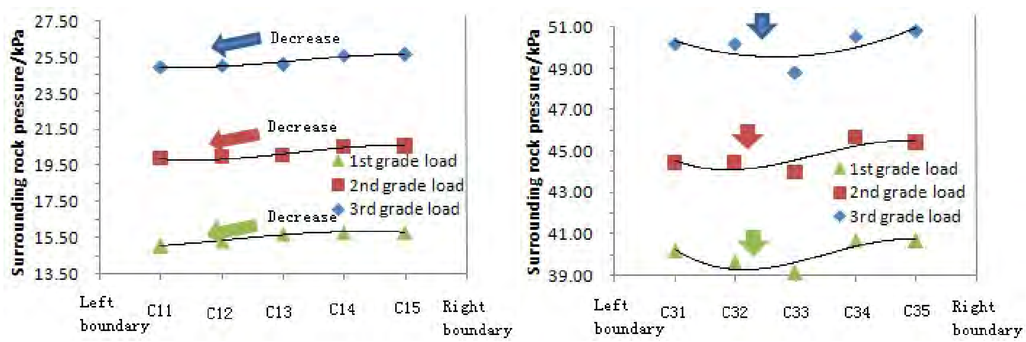
In section B, the karst cave is laid above the left spandrel. With the same burial depth and load, the rock pressure of the right tunnel center line is a slightly greater than that of the left under the effect of lower elastic modulus filler. The rock pressure decreases by degrees from right boundary toward left boundary. The trend-line presents as check mark (“√”) type and the minimum pressure appears around the left spandrel, which happens in different burial depth too, as shown in Figure 13.

In section C, the karst cave is laid left of the left haunch. The pressure, in 50cm depth, also decreases by degrees from right boundary to left, while the minimum value attends at the right above the left haunch. So, the trend-line approaches to the style of “／”, and the gradient of this trend-line is about 0.18, as shown in Figure 14(a). Meanwhile, in 170cm depth, it keeps the same variation tendency as the depth of 50cm, the minimum value comes around the right of the left haunch, and the trend-line of rock pressure is similar to that of section B, as shown in Figure 14(b).



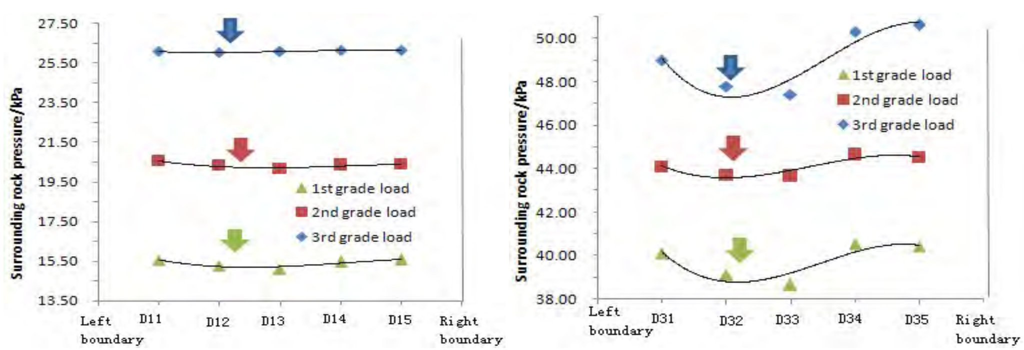
(a)Burial depth of 50cm (b)Burial depth of 170cm

Figure 13: Surrounding rock pressure of measuring points on section B



(a)Burial depth of 50cm (b)Burial depth of 170cm

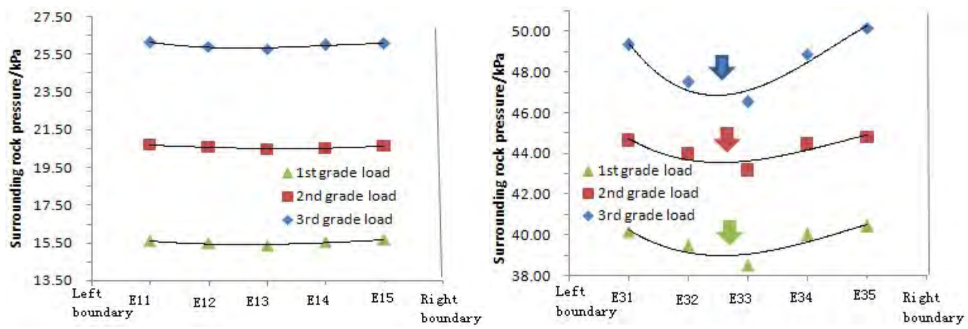
Figure 14: Surrounding rock pressure of measuring points on section C



(a)Burial depth of 50cm (b)Burial depth of 170cm

Figure 15: Surrounding rock pressure of measuring points on section D

In section D, the karst cave is arranged around the left springing. It reveals that the pressure decreases from right boundary to left slightly in 50cm depth, the trend-line approximates to "—" type, as shown in Figure 15(a). In this section, as to the depth of 170cm, the law of development for rock pressure is every similar to that of section B, but the rangeability is much sharper, and the minimum is 6.3% less than the maximum.



(a)Burial depth of 50cm (b)Burial depth of 170cm

Figure 16: Surrounding rock pressure of measuring points on section E

In section E, the karst cave is placed under the soffit, which helps the surrounding rock at 50cm depth to keep farther away the karst cave than the other conditions. So, the rock in 50cm epth is less affected by karst cave, which leads the rock pressure almost the same at this depth. The development trend of rock pressure, in 170cm depth, is similar to that of section A in 50cm depth. However, with the load increasing, the surrounding rock pressure decrease gradually, and the minimum pressure appears nearby the left side of soffit.

The rock pressure in 110cm depth is shown in Table 6. The measure points of A23~E23 lie in the tunnel cavern, and no earth pressure cells are set (as shown in Figure 10), so no data are collected. According to the data in Table 6, they demonstrate akin to that in the burial depth of 50cm and 170cm.

Table 6: Pressure of measuring points in depth 110cm on section A~E (kPa)

Measure points	A21~E21	A22~E22	A23~E23	A24~E24	A25~E25	Remarks
Rock pressure of section A	27.66	26.87	-	27.10	27.59	1st grade load
	33.24	32.72	-	32.65	33.27	2nd grade load
	37.86	36.18	-	36.19	37.92	3rd grade load
Rock pressure of section B	26.99	25.97	-	26.01	27.05	1st grade load
	32.42	31.15	-	32.05	32.72	2nd grade load
	37.64	36.50	-	36.90	37.68	3rd grade load
Rock pressure of section C	26.75	25.50	-	27.70	27.64	1st grade load
	32.00	30.47	-	32.65	32.40	2nd grade load
	36.50	35.20	-	36.35	37.80	3rd grade load
Rock pressure of section D	27.00	25.33	-	27.00	27.20	1st grade load
	32.40	30.35	-	32.52	32.36	2nd grade load
	37.60	36.31	-	37.77	37.90	3rd grade load

Rock pressure of section E	27.72	26.24	-	26.50	27.95	1st grade load
	32.95	31.60	-	31.64	33.16	2nd grade load
	38.60	37.15	-	37.30	38.63	3rd grade load

CONCLUSIONS AND PROSPECTS

By the model test study on in-service karst highway tunnel, we can obtain the following conclusions:

(1) Give the confirmation again that the proportion of 1:12:2 to the mixture of barite powder, plaster powder and cement can simulate the Ⅴ surrounding rock;

(2)The treated karst caves still have some influence to the surrounding rock pressure. In this test, the elastic modulus of the filler is weaker than that of surrounding rock, which leads greater compressive deformation to the rock and differential settlement to the ground.

(3)As the treated karst caves laid nearby the vault, spandrel, haunch, springing or soffit, which will cause different impact on the surrounding rock pressure distribution. By these influence, the surrounding rock pressure trend-line s approximately show as: " U ", " √ ", " / " and " — " styles. Moreover, their minimum values are all found nearby the treated karst caves.

(4)Although at the same section, the treated karst caves hold different degree of influence to surrounding rock pressure. As far as the same burial depth concerned, the closer to karst cave, the more rock pressure is released, and the pressure maintains in a lower level.

(5)As the treated karst caves are placed to the vault or soffit, the rock pressure distributes in a symmetric way around the tunnel center line, which can also transfer symmetric load to lining. While they are arranged to the spandrel, haunch or springing, the unsymmetrical pressure occurs, which is much more harmful to tunnel lining.

However, when karst cave filler's elastic modulus is equal to or greater than that of the surrounding rock, which needs to take a further research. In addition, the fluid-solid coupled interaction and the interaction between seepage flow and corrosion rock masses to the rock mechanical behavior or tunnel lining disease should be launched a deep study in future.

ACKNOWLEDGEMENT

This paper is sponsored by Chinese Fund of natural Science (50878213), and Guangdong Provincial Highway Administration bureau Science Project (201114), here thank them.

REFERENCES

[1] Li Shu-cai, Xue Yi-guo, Zhang Qing-song, Key technology study on comprehensive prediction and early-warning of geological hazards during tunnel construction in high-risk karst

areas [J]. Journal of the China Rock Mechanics and Engineering, July 2008, 27(7): 1297-1307. (in Chinese)

[2] Wang Meng-shu. Hydro geological and geological forecast of tunnel construction in the karst district[J]. Railroad Survey, 2004, (1)：7-10. (in Chinese)

[3] Zhang Xu-dong. Study on deeply buried tunneling water burst mechanism and treatment technique[D]. Chongqing: Chongqing University，2010. (in Chinese)

[4] Michael zhiqiang yang, Efic c.drum. Stability evaluation for the sitting of municipal landfills in karst, Engineering geology, 65 (2002):185-195.

[5] Rudolf Liedl, Martin Sauter, Dirk H3uckinghaus, et al. Simulation to the development of karst aquifers using a coupled continuum pipe flow model, Water Resources Research, 2003 (3).

[6] Laurent EI Senloht, Mahmoud Bouzelboudjen, Laszlo Kiraly, et al. Numerical versus statistical modeling of natural response of a karst hrdrogeological system[J], Journal of hydrology, 202(1997), 244-262.

[7] Rao Jun-ying, Liu Yun-si, Yin Quan. Stability study of surrounding rock with model test and numerical simulation for highway tunnel in multi-cavern area[J], Electronic journal of geotechnical engineering, Vol.17(2012), Bund.X, 3561-3573.

E-mail address of author for correspondence is: rao-ale@163.com