International Journal of Civil Engineering and Environmental Science. Volume 3, Issue 1, (2013) 23-31
http://www.cayley-nielson.com/ijcees/

Structural Analysis on Shallow Railway Tunnel

Mao Li
College of Environmental Science and Engineering, Nankai University, P.R. China
E-mail: maoli@nankai.edu.cn

Abstract

Based on the CRD method in the construction of Liangcun tunnel, the deformation and stress of tunnel and supporting structure were monitored. According to two different kinds of tunnel excavation sequence, the displacement and internal force of tunnel structure were analyzed and compared by numerical analysis. The deformation monitoring results show that the influence of each department excavation on the measuring result in descending order is respectively ①, ②, ③ and ④. The crown settlement affected by the excavation of department ② is larger than that of department ③. The stress monitoring results show that the surrounding rock pressure of inside tunnel is larger than that of outside tunnel and the surrounding rock pressure of inside tunnel became larger after the excavation of other departments. The axial force of the steel brace is mainly compressive stress and the axial force at hence is maximum. The numerical analysis results show that both the deformation of surrounding rock and the force of tunnel structure induced by excavation sequence one, of which the first department of excavation is the outside tunnel, is smaller, and the safety factor is also higher. The monitoring and calculation results show that the reasonable construction for shallow tunnel should be the outside tunnel's excavation and initial lining first, and then the insider tunnel.

Keywords: Shallow tunnel; center cross diagram (CRD) method; field monitoring; numerical simulation; safety factor; reasonable procedure.

1. Introduction

Along with the development of railway and highway construction in the mountain area of western China, an increasing number of shallow tunnels built in poor surrounding rock and bearing unsymmetrical pressure were encountered, which have brought significant technical problems to their construction. A lot of theoretical researches and engineering practices on this problem have been carried out. LI Hong-bo, LI Hui, QIU Chang-lin studied the deformation rules of surrounding rock, and analyzed the rock deformation mechanism based on in-situ measured data including surface subsidence, crown settlement, horizontal convergence. ZHOU Ji-ming, JI Mao-wei, LI Yong-suo analyzed the variation of surrounding rock pressure, steel brace force, axial force of anchor bolt and internal force of lining through site measurements, and studied the internal force of supporting structure of shallow tunnels built in poor surrounding rock sustained unsymmetrical pressure. GUO Chun studied the structural internal force induced by the excavation of each section in CRD method.

It is difficult and high-risk in the construction of shallow tunnel sustained unsymmetrical pressure, especially when using CRD method, in which the procedure conversion is complex and the construction period of initial support is long. It is a problem needed to be solved immediately that to reveal the deformation mechanism of surrounding rock, analyze the mechanical response of supporting structure, and optimize the construction procedure through in-situ monitoring. However, relative research is still not

ISSN 2333-5416 /
December, 2013

enough. In this paper, according to the CRD construction procedure used in Liangcun tunnel, combined with in-situ monitoring of deformation and stress, the surrounding rock deformation and internal force of supporting structure were analyzed, and the reasonable construction procedure of bias shallow tunnel was studied using finite element method.

2. Engineering situation and measuring point arrangement

2.1. Engineering situation

Liangcun tunnel in Ganzhou-Shaoguang railway is a two-lane railway tunnel, whose stake number is DK177+360 to DK177+740. Its total length is 380m and maximum depth is 37m. The strata of this tunnel are Quaternary Holocene disability, slope silty clay and coarse-grained soils, the underlying soil is Upper Cretaceous siltstone and sandstone, Carboniferous limestone under the EC. Adverse geological structure is two vertical faults through the tunnel and the width of fault fracture zone is about 30m. Surrounding rock weathers strongly and has lots of joints and fractures. A part of muddy siltstone and sandstone disintegrates rapidly after the excavation. Surrounding rock is mostly class VI, while small amounts of them is class V. Geological conditions and hydrogeological conditions are unfavorable for the construction. The surface elevation fluctuates greatly, and the tunnel structure sustains obviously unsymmetrical pressure.

The support structure of shallow tunnel is composite lining, and the construction was carried out by CRD method after pre-supporting. The excavation length per cycle does not exceed 0.6m. The excavation procedure is shown in Fig. 1, the first excavation area is ①, then area ③, final excavation area are ② and ④.

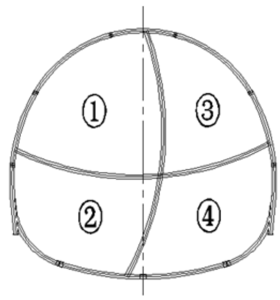
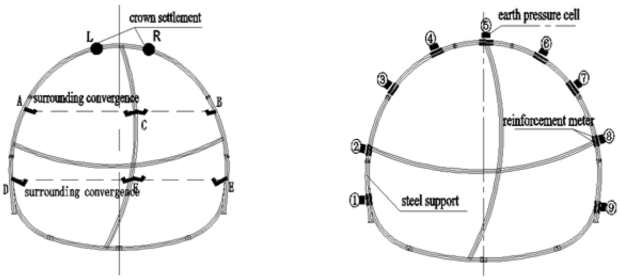


Fig. 1 Excavation sequence of Liangcun tunnel

2.2 Measuring point arrangement

In the process of Liangcun tunnel construction, deformation and stress monitoring were carried out. Displacement and deformation monitoring includes crown settlement and surrounding convergence measurements. Stress monitoring includes the pressure monitoring between surrounding rock and lining and steel bracing force measurement. Each measuring point’s arrangement was shown in Fig.2.

DK177+385 and DK177+405 measurement section were selected as typical deformation monitoring sections to analyze. The arrangement of measuring points is shown in Fig. 2(a). To obtain the amplitude and distribution of pressure between surrounding rock and initial lining, and the internal forces of steel support, 9 TYJ-20 vibrating string type earth pressure cells and 18 GJJ-11 embedded vibrating string type reinforcement meters were buried in vault, hence and side walls in DK177+385 section. The measuring points of earth pressure cells and reinforcement meters are arranged at the same position, as shown in Fig.2 (b).



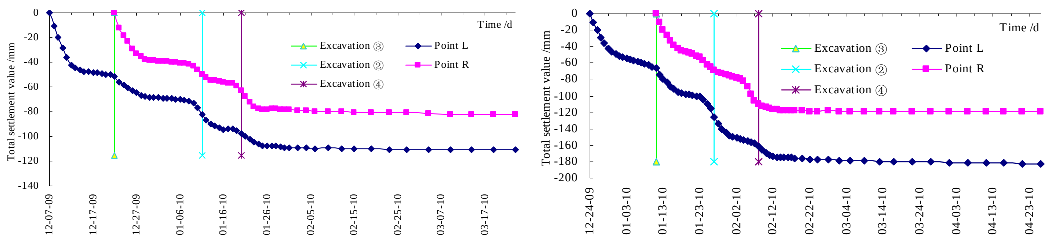
(a) crown settlement and surrounding convergence (b) surrounding rock pressure and steel bracing force

Fig. 2 Measuring points arrangement

3. Monitoring results analysis

3.1 Crown settlement

Crown settlement can reflect the degree of surrounding rock being disturbed and the load exerted on the initial support. The crown settlement versus time curves is shown in Fig. 3.



(a) DK177+385 section (b) DK177+405 section

Fig. 3 Crown settlement versus time curves

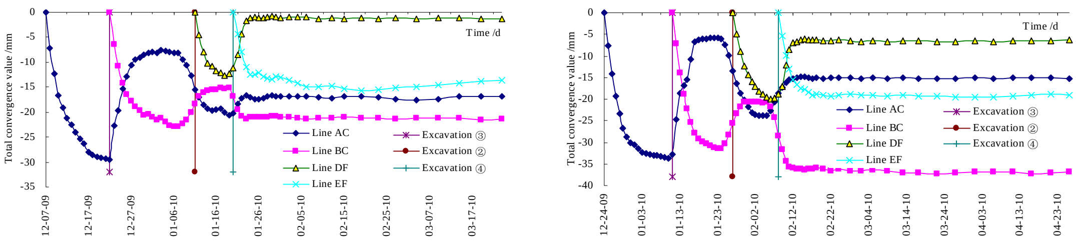
Combined with the construction situation, two crown settlement figures are rendered as step-down curves, with four significant stages, and the inflection points appears at the time of each area's excavation in the monitoring section. The height of each stage reflects the impact of the excavation of each area on the crown settlement. The higher the stage is, the greater the degree of influence is. Relative results are calculated and shown in Table 1. It can be seen that the impact of each area excavation on the crown settlement in decreasing order is ①, ②, ③ and ④. So the influence of area ③ is smaller than area ②, which means the impact of unsymmetrical loading is relatively small, and the current construction process is reasonable.

Table 1 Impact of each department excavation on crown settlement

	Point L				Point R			
	DK177+385		DK177+405		DK177+385		DK177+405	
	Settlement	Percentage	Settlement	Percentage	Settlement	Percentage	Settlement	Percentage
Area ①	-48.15	43.35%	-60.72	33.27%	-	-	-	-
Area ③	-20.88	18.80%	-39.33	21.55%	-40.87	49.82%	-51.08	42.74%
Area ②	-24.81	22.34%	-51.94	28.46%	-16.13	19.66%	-28.22	23.62%
Area ④	-17.22	15.51%	-30.53	16.73%	-25.03	30.51%	-40.20	33.64%

3.2 Surrounding convergence

Surrounding convergence is the relative displacement value between two fixed points in the opposite direction of the tunnel; it mainly refers to deformation measurement of the horizontal distance between two points on the tunnel walls. The surrounding convergence versus time curve is shown in Fig. 4.



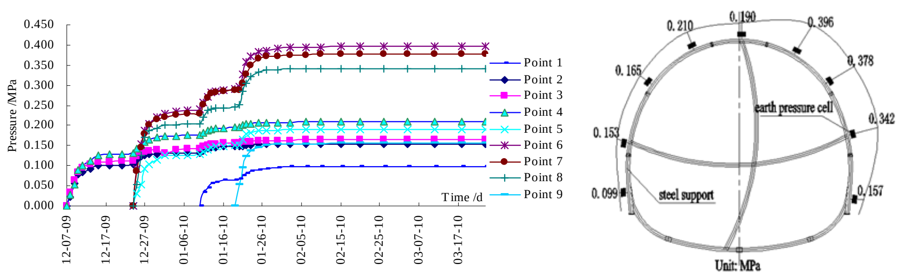
(a) DK177+385 section (b) DK177+405 section

Fig. 4 Surrounding convergence versus time curves

Just like crown settlement, the surrounding convergence of AC can also be divided into four stages. As can be seen from the figure, with the excavation of area ③, the horizontal convergence of department ① increases while the corresponding parts of department ③ decreases, two measuring points show opposite horizontal movement trends. The reason is, a. After the excavation of area ①, earth pressure behind the vertical support releases and steel support starts to rebound; b. There is a certain bias phenomenon at this section of tunnel, so the surrounding rock on the left side tends to move under soil pressure.

3.3 Pressure measurement between surrounding rock and initial lining

The measurement results of pressure between surrounding rock and initial lining are shown in Fig.5(a). It can be seen that the pressure between surrounding rock and sprayed concrete increase gradually after the completion of initial support, and then gradually tend to be stable. When the excavation of tunnel is completed, the pressure distribution is plotted is shown in Fig. 5(b). Fig. 5(b) shows that the pressure at the tunnel vault is smaller than that at the hence, and the pressure of initial lining in the inside tunnel is larger than that in the outside tunnel. This means the security of inside tunnel is lower than that of outside tunnel. It is important to employed reasonable excavation procedure to balance the pressure on supporting structure.

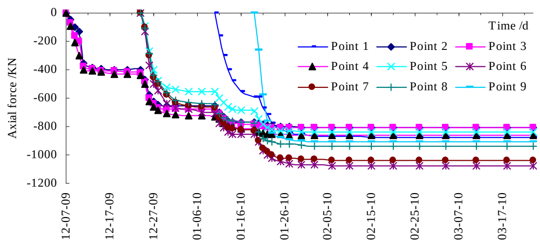


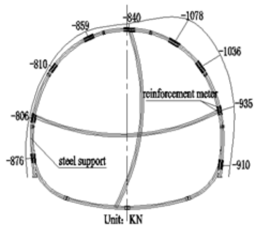
(a) Surrounding rock pressure versus time curves (b) Surrounding rock pressure distribution

Fig. 5. Surrounding rock pressure and its time-history curves at DK177+385 section

3.4 Steel bracing force measurement.

The strain of steel bracing can be calculated from the natural frequency of reinforcement meter. According to principle of mutual deformation and plane section assumption, the strain of concrete can be obtained, and so does the stress of concrete. Axial force of section, i.e. the sum of the force of concrete and steel are then calculated and shown in Fig. 6(a). It can be seen from Fig. 6(a) that the axial forces gradually increases after the completion of initial support and tend to be stabile as the temporary inverted arch being completed. But with the excavation of other areas, there is again an obvious increasing trend. Based on the calculation results, the axial force distribution along the section is plotted in Fig. 6(b). As can be seen from, the axial forces of steel bracing in the inside tunnel is larger than that in the outside tunnel. The axial force is mainly compressive, and the axial force at hence is larger than that at other positions, so the probability of buckling in the inside is higher.





(a) Axial force of steel support versus time curves (b) Axial force of steel support distribution

Fig.6 Axial force of steel support and its time-history curves at DK177+385 section

3.5 Analysis of monitoring results

Deformation monitoring results indicate that the deformation of each department during its own excavation is gradually stabilized, but there is a sudden change of the deformation when the excavation of other departments, it indicates that the mutual influence of each department excavation can not be neglected and the influence of each department excavation on the measuring point in descending order is respectively department ①, ②, ③ and ④. The reasons for this phenomenon is not only affected by the construction method, but also the impact of bias under the construction process of shallow tunnels compared with the general tunnel constructed by CRD method.

Stress monitoring result also indicates that the pressure of initial lining in the inside tunnel is larger compared with the outside tunnel and the axial forces in the inside tunnel is larger than the outside tunnel, the impact of bias under the construction process of shallow tunnels is large compared with the general tunnel constructed by CRD method. So it should select a reasonable construction process in order to obtain a more favorable stress distribution forms and reduce the impact of bias under construction.

Compared the differences of deformation and the impact of bias, the outside tunnel's excavation and initial lining should be first, and then the inside tunnel's excavation from the security considerations. It is necessary to improve the safety of the tunnel structure by reducing the further disturbance of small security department of the tunnel.

4 Numerical analysis of reasonable construction procedure

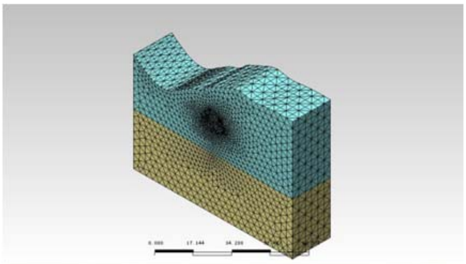
4.1 Calculation model

A three-dimensional numerical simulation of the tunnel sustained unsymmetrical pressure and constructed by the CRD method was established by MIDAS/GTS. Then two different construction sequences are calculated and compared. Supporting structure and strata in the FEM model are in accordance with the construction drawings and geological investigation report. The stratigraphic architecture method is used to calculate the numerical model. A more reasonable distribution of the load exerted on the initial support can be obtained by setting rational load releasing coefficients. The load releasing coefficients are respectively set to 0.50, 0.25 and 0.25.

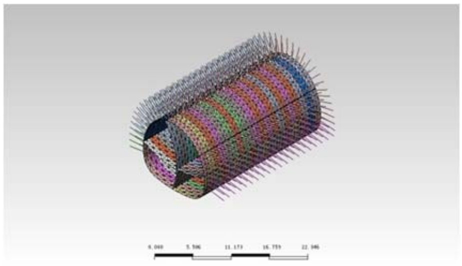
The calculation region of this FEM model is shown in Fig. 7(a). the left and right boundary are 50m away from the center of the tunnel, the upper boundary is straight up to the surface, and the bottom boundary is 50m below the tunnel. The left and right side are restrained at x direction, the bottom is restrained at x, y and z direction, while the surface is free. The FEM model of the tunnel and its supporting structure is shown in Figure 7. The surrounding rock in this model is Mohr-coloumb model, while sprayed concrete and anchors are simulated using elastic model. The material parameters are shown in Table 2.

Table 2. Material parameters of FEM model

Material category	Rock parameters	Shotcrete parameter	Anchor Parameters
Modulus (tonf/m^3)	950	2.3×10^6	2×10^7
Poisson's ratio	0.3	0.2	0.3
Bulk density (tonf/m^3)	2.5	—	—
Cohesion	1.8	—	—
Friction angle	46	—	—
Gravity density (tonf/m^3)	—	2.2	7.85



(a) Coupling Mesh of tunnel



(b) Initial and temporary support structure

Fig.7 FEM model of the tunnel and its supporting structure

Two different excavation processes are simulated by this numerical model: process one, the left side is excavated firstly, the whole sequence is ①②③④; process two, the right side is excavated firstly, the whole sequence is ③④①②. Through the simulation of two different excavation processes, the rock deformation, stress distribution, and the range of the plastic zone are obtained. Then which process is more reasonable can be decided.

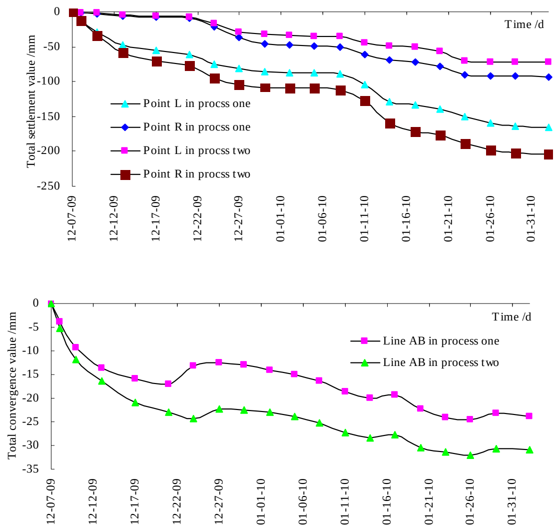
4.2 Displacement analysis

Crown settlement and surrounding convergence versus time curves of two different excavation processes calculated from the FEM model are shown in Fig. 8.

The calculation results of crown settlement show that, at measuring point L, the crown settlement of process one is 164.89mm while process two is 71.85mm; at measuring point R, the crown settlement of process one is 93.63mm, while process two is 204.73mm. The crown settlement shows that process one induces smaller surrounding rock deformation.

From Fig.8 (b), it can be seen that the surrounding convergence of process one is 23.98mm, while process two is 30.96mm. In both two processes, the left side wall shows a trend of expansion, while the right sidewall shows a trend of convergence. It indicates that the tunnel structure is biased seriously and the tunnel tends to move to the left.

Displacement results shows that process one will induce smaller deformation of supporting structure and surrounding rock. So it can be concluded that process one is more reasonable than process two.

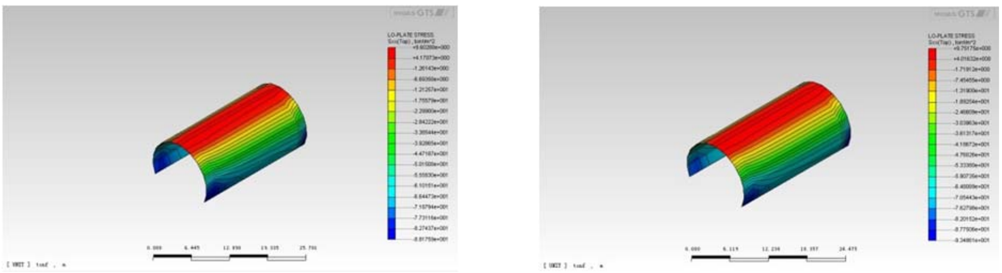


(a) Crown settlement (b) Surrounding convergence

Fig. 8 Time-history curves of displacement

4.3 Stress analysis

The stress contours of sprayed concrete in two different processes are shown in Fig. 9. The surrounding rock pressure at the hence of tunnel versus time curves are shown in Fig. 10.



(a) process one (b) process two

Fig.9 Stress contour of sprayed concrete in two processes

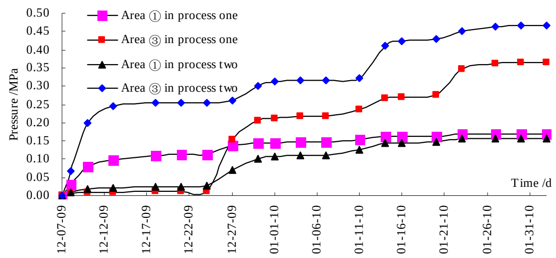


Fig.10 Surrounding rock pressure versus time curves

It can be seen from Figure 9 that the surrounding rock pressure of tunnel on the left is larger than that on the right side. The pressure at vault is relatively smaller, and the pressure at hence and arch foot is relatively larger. The pressure of process two is larger than that of process one. The plastic zones in process two appear at the inside hence, its maximum depth is 7.5m. The plastic zones in process one appear at the left crown foot of inside tunnel, its maximum depth is 8.5m.

The difference of maximum stress at the left hence in two processes is 0.014MPa, and the right hence is 0.101MPa. So process one is more reasonable than process two. With the cover layer thickness increases, the difference of pressure becomes smaller, and the deviation is smaller.

4.4 Tunnel safety evaluation

In this paper, the security of mid-partition is mainly evaluated by its safety factor which is calculated from Equation (1).

$$KNe = 0.5R_a b h_0^{2} + R_g A_g'(h_0 - a')$$

(1)

Where K is safety factor, b represents the width of section, h0 is the effective height of section, a´is the nearest distance from the center of gravity of Ag´to the edge of section, Ra represents the ultimate compressive strength of concrete, Rg is the tensile or compressive strength of reinforcement.

The security of secondary lining is reflected by the safety factor of its control section. Its value is the internal force calculated from numerical analysis divide the ultimate bearing capacity of supporting structure. The safety factor of mid-partition and secondary lining in two processes is shown in Table 3.

Table 3 Safety factor of two processes

	Process one	Process two
Safety factor of mid-partition	3.76	3.83
Safety factor of secondary lining	0.9	1.8

It can be seen from Table 3 that the safety factor of mid-partition and secondary lining of process one are both lower, especially the safety factor of secondary lining, which is only a half of process two. So it can be concluded that process one is superior to process two. Especially when the bias phenomenon is more obvious, the difference in safety will be greater.

5. Conclusions

Deformation monitoring results indicate that the influence of each department excavation on the measuring results in descending order is respectively department ①, ②, ③ and ④. The crown settlement of department ① affected by the excavation of department ② is larger than that of department ③. Compared the difference of deformation induced by excavation of each department, the outside tunnel should be excavated first to reduce the impact of bias and increase security.

The rock pressure test results indicate the pressure on initial lining in the inside tunnel is larger compared with the outside tunnel, the security of initial lining in the inside tunnel is low. Steel brace force monitoring results show that steel support axial force is mainly compressive stress, the axial force in the hence is maximum, and the axial forces in the inside tunnel is larger than the outside tunnel. So the reasonable construction process should be the outside tunnel’s excavation first, and then the inside tunnel.

The calculation results indicate that there are large differences between the deformation and stress of two different processes. Both the deformation of surrounding rock and the force of tunnel structure induced by excavation sequence one, of which the first department of excavation is the outside tunnel, is smaller, and the safety factor is also higher. So the excavating the outside tunnel firstly is relatively reasonable.

References

[1] LI Hong-bo, DAI Yong-hao, Song Ji-hong, et al. Construction monitoring for Xiakou soft rock tunnel under high geostress and its supporting measures. Rock and Soil Mechanics, 2011(Z2): 496-501.

[2] Li Hui, Chui Pengfei, Yang Xiaohong, et al. Monitoring on Tunnel through the Goaf and Analysis of Its Results. Chinese Journal of Underground Space and Engineering, 2011, 7(4): 753-758.

[3] QIU Chang-lin, LIU Bin, HE Lin-sheng, et al. Model test and in-situ monitoring of double-arch tunnel with integrated middle wall.Rock and Soil Mechanics, 2012, 33(9): 2625-2631.

[4] ZHOU Ji-min, HE Chuan, FANG Yong, et al. Mechanical property testing and back analysis of load models of metro shield tunnel lining in loess strata. Rock and Soil Mechanics, 2011, 32(1): 165-171.

[5] JI Mao-wei, WU Shun-chuan, GAO Yong-tao, et al. Construction monitoring and numerical simulation of multi-arch tunnel. Rock and Soil Mechanics, 2011, 32(12): 3787-3795.

[6] LI Yong-suo, ZHANG Ke-neng, et al. Monitoring of lining structure of tunnels built by using pipe-roof pre-construction method. Chinese Journal of Geotechnical Engineering, 2012 (8): 1541-1547.

[7] GUO Chun, YU Shang-yu, WANG Ming-nian. The influence of excavation by sections with CRD method on the structural internal force and safety factor in undersea tunnel construction. Hydrogeology and Engineering Geology, 2009, 36(1).