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Numerical Analysis of Advanced Displacement in Construction Progress of Tunnel Excavation with Weak Surrounding Rock

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Abstract: Analysis of advanced displacement in construction progress of tunnel excavation with weak surrounding rock is carried out by numerical method and comparison of model test result. In allusion to the problems of regional landslides and extruded large-deformation seriously impacting the stability of rock mass in construction process of large-section tunnel with weak surrounding rock, the elastic-plastic numerical simulation relying on Liangshui tunnel of Lan-Yu railroad is conducted on mechanical behaviors and deformation steric effect of tunnel construction and the calculation results are compared with the modeling data. The research results show that: the steric effect of excavation face is the dominant factor in the incidence of working face and the stress of surrounding rocks gradually releases from excavation face; the range of 0.5~1 times the cave diameter around rock mass in front of working face is the disturbance range and the key area of stabilization and reinforcement for wake surrounding rock. According to the analysis and construction practice, the supporting structure of large-section tunnel with weak surrounding rock should be established as soon as possible to control the displacement change of surrounding rock in the range of load-bearing ring, reduce disturbance and improve the self-bearing capability of surrounding rock. Because of the distinct excavation steric effect of weak surrounding rock, the secondary lining structure must be established in time to bear the later pressure and restrict the large displacement of surrounding rock. The research results can provide reliable basis for engineering stability control of analogous tunnels.

Keywords: Advanced displacement, elastic-plastic, large section tunnel with weak numerical simulation, steric effect, surrounding rock

INTRODUCTION

Since the strategy of west development was implemented by government, the transport system of western areas has entered a fast developing period. More and more large-section tunnels crossing weak and broken surrounding rock strata are constructed with complex mechanical effect of construction process and the rapid constructions are faced with many engineering problems such as regional landslides and extruded large-deformation seriously restricting construction periods and levels. The excavation of tunnel is the dynamic change with time and space. With the propulsion of working face, the tunnel surrounding rock is disturbed continually, where the stress and deformation will develop with time and space, especially to tunnel with weak surrounding rock having more significant steric effect (Wei-Shen and Jian, 2004). Therefore, it is important to decrease the disturbance of weak surrounding rock caused by tunnel construction and make it in a relatively stable state. In order to closely simulate the mechanical state in different construction processes, not only the complex characteristic of rock mass media and various construction operation modes including partial excavation sequences, supporting structural forms and timings are considered, but also the steric constrained effect in the propulsion process of working face during tunnel excavation should be taken into account, all of which have great influence on the stability of tunnel surrounding rock and could guide design and construction.

The existing researches show that: the changing regularity of advanced displacement in front of working face during tunnel excavation, which is usually determined by 3-D numerical analysis and empirical equation with the specific description of advanced displacement curves, can be used to forecast the development trend of surrounding rock deformation with the propulsion of working face and calculate the total surrounding rock deformation (Schubert *et al.*, 2002; Sun, 1996; Sulem *et al.*, 1987; Schubert and Steindorfer, 1998; Carranza-Torres and Fairhurst, 2000; Yang *et al.*, 2011). The changing conditions of radial displacement at certain point of tunnel surrounding rock in front of working face can be indicated by the advanced displacement curves shown in Fig. 1.

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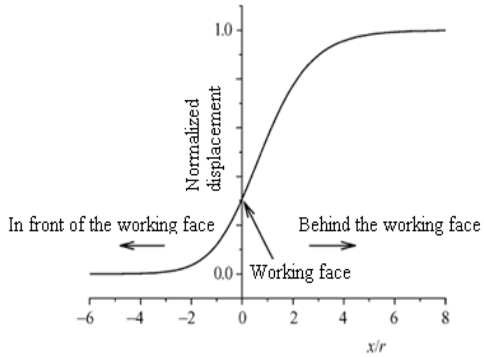


Fig. 1: The advanced displacement curves

The advanced displacement curves indicate the changing conditions of radial displacement at certain point of tunnel surrounding rock in front of working face showed in Fig. 1, in which the X axis is the distance between a fixed section and working face (the relative distance *x/r* is often adopted) and the Y axis is the ratio (normalized displacement) of the surrounding rock deformation at *x* point with a certain distance from excavation face $u_r\ (x)$ and the surrounding rock deformation at the same point with infinite distance from excavation face $u_{r\infty}$ (the section outside the influence range of steric effect of working face) (Schubert and Steindorfer, 1998; Carranza-Torres and Fairhurst, 2000).

At present, this form of curve can be reflected by many empirical equations, for example, a fitting equation with one specific on-site measurement data was offered by Hoek to reflect the relationship of the advanced displacement at a certain section in front of tunnel working face and the distance between this section and working face (Evert, 2002):

$$\frac{u_r(x)}{u_{r\infty}(x)} = \left(1 + e^{\left(-\frac{x}{1.1r}\right)}\right)^{-1.7} \tag{1}$$

The above equation is feasible only when the geologic conditions of other tunnels are close to the geologic conditions of this tunnel without universal application; the finite element method was adopted to calculate the advanced displacement curves under elastic strata and put forward the following exponential experience equation (Nguyen and Guo, 1996):

$$\frac{u_r(x)}{u_{r\infty}(x)} = 0.29 + 0.71 \times \left(1 + e^{\left(-1.5\frac{x}{r}\right)}\right)^{0.7} \tag{2}$$

The research done by Panet and Guenot (1982) proved that the advanced displacement curves of tunnel surrounding rock could not be fitted by logarithm function or index function commendably, while the better fitting results could be obtained by the following power function:

$$\frac{u_r(x)}{u_{r\infty}(x)} = 0.265 + 0.735 \times \left[1 - \left(\frac{1}{1 + x/0.84r_p}\right)^2\right] \tag{3}$$

In which, r_p is the radius of plastic area when the fixed section had enough distance far form the working face. Although Eq. (3) has representativeness and practical value in the analysis of advanced displacement curves in front of working face, the radius of tunnel plastic area is affected by the grid size of numerical model with inconvenient determination. All the above equations have considerable constraints, so the essential 3-D numerical simulation and analysis are still needed to determine the regularity of advanced displacement more accurately. Now, the ideal elastic-plastic finite element numerical simulation for the surrounding rock deformation of Liangshui tunnel is carried out to study the deformation regularity of displacement characteristics during the construction process of tunnel with weak surrounding rock by bench method and analyze the steric effect of excavation face to provide the corresponding academic reference for the design, construction and monitoring of large-section tunnel with weak surrounding rock in future.

OBJECT OF SIMULATION AND ESTABLISHMENT OF MODEL

Engineering background: The Liangshui tunnel of Lan-Yu railroad is located at the mountains on the left bank of Pai-lung River, Wudu District of Gansu Province, the terrain of which is relatively steep with relative elevation of 400 m and the tunnel length and maximum buried depth are 4922.35 and 346 m respectively. The tunnel portal mileage is DK357+082 and the tunnel exit mileage is DK362+084. The tunnel portal is located at the side of 212 National Road near the funeral home of Wudu District and the tunnel exit is located at the slope on the right bank of North Valley River, Wudu District. The strata traversed by tunnel trunk are phyllite splint rock of Upper-Middle Silurian, carbonaceous phyllite splint rock and limestone, etc. The carbonaceous phyllite splint rock is the major stratum giving priority to carbonaceous phyllite with main color of dark-gray and grayish-black, where the carbonaceous and lepidoblastic textures with schistose structure and soft stone of Classes IV~V are contained. The rock mass has drape development affected by above-mentioned structure and is extremely fractured with poor integrality. The technical difficult problem faced by projects of tunnel with weak surrounding rock is the large deformation control, the countermeasures premise of which is to clear out the large-deformation mechanism and the steric effect during construction

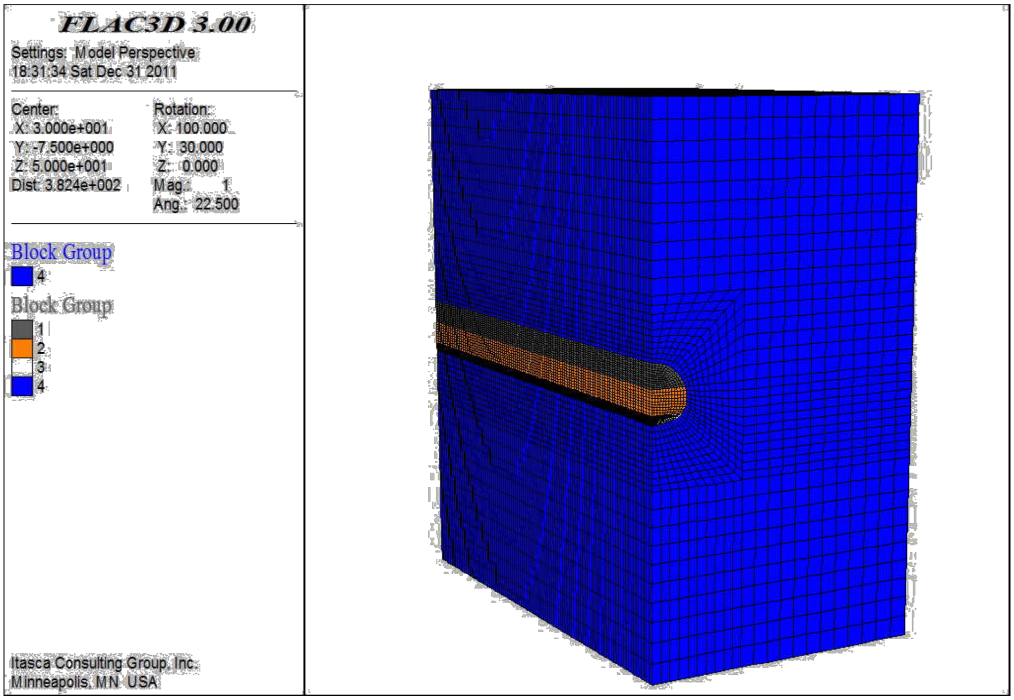


Fig. 2: 3-D numerical simulation model of Liangshui tunnel

process of weak surrounding rock (Chun-De *et al*., 2008). Therefore, the study for the regularities of surrounding rock deformation and load release during construction process of large-section tunnel has important scientific significance and engineering value.

Establishment of mechanics model: The ideal elastic-plastic constitutive model is adopted in the numerical simulation with Mohr-Coulomb yield criterion. The virtual support releasing method based on theory of geostress releasing method and the Null model of $FLAC^{3D}$ are used to incarnate the tunnel excavation process. According to the specific engineering practice, the up-and-down bench method is used to simulate all load steps in the whole process of self-gravity→tunnel up-bench excavation (Proc. 1)→tunnel up-bench supporting (Proc. 2)→tunnel down-bench excavation (Proc. 3)→tunnel down-bench supporting (Proc. 4).The hexahedron element is adopted to define the rock mass structure and corresponding entity elements are also adopted to define C25 concrete lining structure and bolting structure with elastic constitutive model (Gen-De, 1995; Li *et al*., 2008). The meshing is dense near tunnel and sparse far from tunnel, i.e. the gird radially spreads from dense and small to sparse and big starting from the center in order to meet the accuracy requirement of model calculation. The modeling and meshing are processed by ANSYS and the ANSYS-$FLAC^{3D}$ software is adopted for the former processing data conversion. For the symmetry of model, the calculation can be carried out towards the half model founded along vertical symmetric plane. The geological basis of simulation is DK357+260～DK358+000 with average buried depth of 200 m; the sizes of model are that: the horizontal and axial distances of model are 120 m and 100 m and the upper and lower boundaries respectively are 60 m from tunnel center. The displacement constraint conditions of model are that: the X axis constraint is applied to the left and right boundary lines; the Y axis constraint is applied to the bottom boundary and the top boundary is free boundary. The following assumptions should be satisfied in simulation: the loess rock mass is isotropic elastic-plastic material; the soil horizons are continuous media; the surrounding rock only considers the initial self-gravity stress field ignoring tectonic stress. The meshing of computational model is shown in Fig. 2 with 125800 units and 134734 nodes.

The type of primary supporting adopted in this study is the support combining sprayed concrete with bolt. The excavation heights of up-bench and down-bench are both 5.375 m with circulation footage of 2 m and the supporting is applied one circulation footage behind excavation. Five working conditions of surrounding rock grades; the specific mechanical parameters of surrounding rock and supporting material are shown in Table 1:

RESULTS AND ANALYSIS OF NUMERICAL SIMULATION

Displacement characteristics analysis of fixed section: The curves of radial displacements of tunnel vault and hance during excavation process by bench

Table 1: Mechanical parameters of surrounding rock and supporting material

Material		Internal frictional angle (°)	Cohesion (MPa)	Elastic modulus (GPa)	Poisson's ratio
Parameters of surrounding rock	Cond. 1	21	0.15	1.5	0.42
	Cond. 2	24	0.22	2	0.4
	Cond. 3	27	0.3	2.5	0.38
	Cond. 4	30	0.37	3	0.36
	Cond. 5	33	0.45	3.5	0.34
C25 sprayed concrete		-----	-----	23	0.2
Bolt		-----	-----	210	0.30

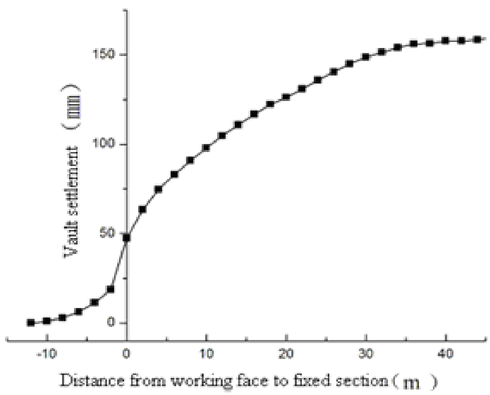


Fig. 3: The curve of vault settlement under Cond. 3

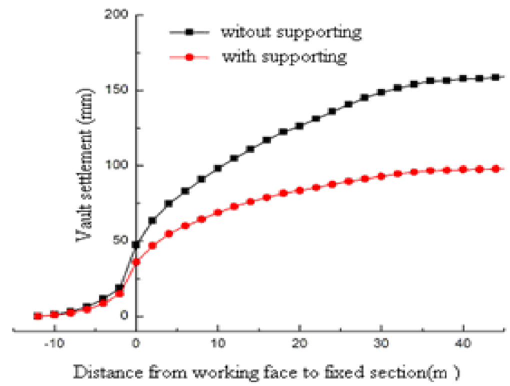


Fig. 5: Curve of vault settlement with and without supporting

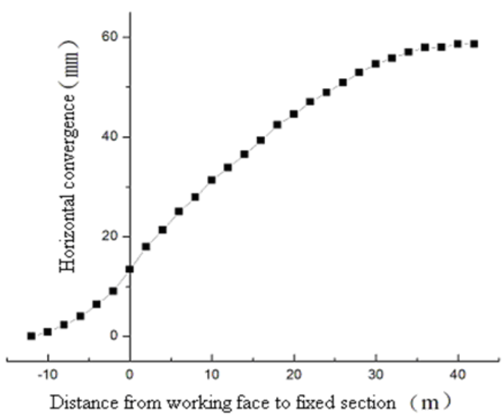


Fig. 4: The curve of horizontal convergence under Cond. 3

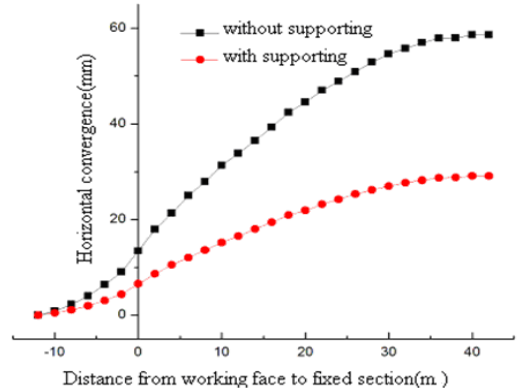


Fig. 6: Curve of horizontal convergence with and without supporting

method under typical Cond. 3 without supporting condition are shown in Fig. 3-4. It can be seen from the figures that the surrounding rock stress around excavation face is released gradually for the steric effect of excavation face; accordingly, the surrounding rock displacement is also released gradually. Because of the tunnel excavation, the surrounding rock within a certain distance range in front of excavation face is disturbed causing the radial advanced displacement of cave wall. The evolutive regularity of advanced displacement is that: when the distance between working face and fixed section enters into a certain range, the deformation is produced in the rock mass of fixed section; although the rate of deformation presents periodical feature with the propulsion of working face, the holistic deformation value maintains growth all the time. When the working face passes through the fixed section for a certain distance, the steric effect of excavation face almost disappears and the rate of deformation descends gradually; when the fixed section is beyond the steric effect range of working face, the surrounding rock deformation of section stops. It also can be seen from the figures that the influence ranges of working face on tunnel ahead are not the same at different parts; the influence distances at vault and hance are 10 m (about one times the cave diameter) and 15 m (about 1.5 times the cave diameter) respectively.

Displacement analysis with or without supporting condition: The curves of radial displacements of tunnel vault and hance during excavation process by bench method under Cond. 1 with or without supporting condition are shown in Fig. 5-6. It can be seen from

Fig. 5 that the advanced displacement is produced at the vault of fixed section when the distance from working face to fixed section is about one times the cave diameter and the vault settlement gradually becomes stable when the working face is beyond 3 times the cave diameter from fixed section, i.e., the fixed section is not affected by the continuative excavation. The final values of vault settlements with and without supporting condition are 103.87 and 166.88 mm respectively showing that the application of supporting can effectively reduce the vault settlement of fixed section and shorten the stable time of settlement after tunnel excavation. The value of advanced displacement with supporting condition is 35.89 mm taking up 33.65% of the total displacement after stability and that case without supporting condition is 47.33 mm taking up 28.31% of the total displacement after stability. It is thus clear that the percentage of advanced displacement with supporting condition is obviously higher than that case without supporting condition.

It can be seen from Fig. 6 that although the changing trend of horizontal convergence at tunnel hance is basically consistent with that of vault settlement under same excavation condition, the changing values of displacement are relatively small. The advanced displacement is produced at the hance of fixed section when the distance from working face to fixed section is about 1.5 times the cave diameter and the horizontal convergence gradually becomes stable when the working face is beyond 3 times the cave diameter from fixed section, i.e., the fixed section is not affected by the continuative excavation. The final values of horizontal convergence with and without supporting condition are 28.64 and 57.23 mm respectively. The value of advanced displacement with supporting condition is 8.8 mm taking up 32.14% of the total displacement after stability and that case without supporting condition is 14.55 mm taking up 24.69% of the total displacement after stability.

Displacement analysis under different conditions of surrounding rock: The curves of vault settlement during excavation process by bench method under different working conditions with supporting are shown in Fig. 7. It can be seen from the figure that the changing trends of vault settlements under different working conditions are basically the same and the order from big to small of vault settlements is that: Cond. 1>Cond. 2>Cond. 3>Cond. 4>Cond. 5; the final values of vault settlements with supporting respectively are 323.04, 190.31, 114.50, 66.62 and 54.81 mm and the corresponding percentages of initial advanced displacements respectively are 25.70, 25.47, 25.65, 25.54 and 25.82%, respectively. The changing trends of horizontal convergences under different working conditions are basically consistent with those of vault settlements under same excavation condition. In the case with supporting, the weaker surrounding rock

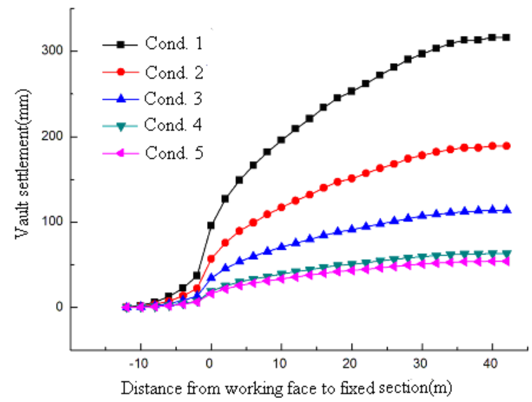


Fig. 7: Vault settlements under different conditions with support

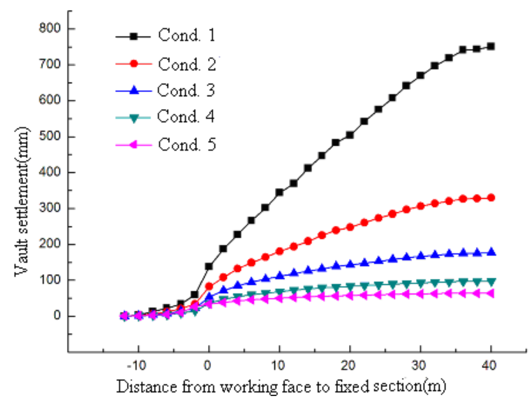


Fig. 8: Vault settlements under different conditions without support

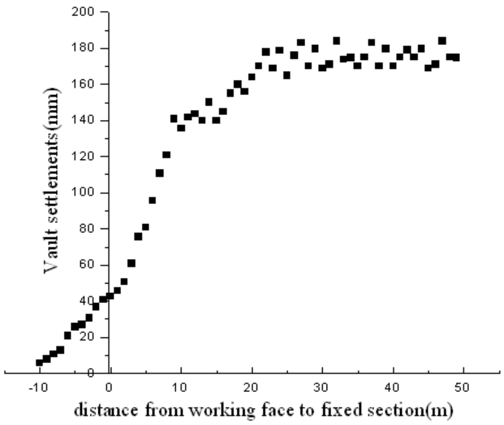
grade is, the larger surrounding rock displacement caused by tunnel excavation is, but the percentages of advanced displacements are basically the same.

The curves of vault settlement during excavation process by bench method under different working conditions without supporting are shown in Fig. 8. It can be seen from the figure that the changing trends of vault settlements under different working conditions are basically in line with those of Fig. 7 and the order from big to small of vault settlements is that: Cond. 1>Cond. 2>Cond. 3>Cond. 4>Cond. 5; the final values of vault settlements without supporting respectively are 750.25, 329.99, 177.05, 97.48 and 68.01 mm and the corresponding percentages of initial advanced displacements respectively are 18.2, 24.4, 29.6, 35.5 and 43.1%, respectively. The changing trends of horizontal convergence under different working conditions are basically consistent with those of vault settlements under same excavation condition. In the case without supporting, the weaker surrounding rock grade is, the larger surrounding rock displacement caused by tunnel excavation is, the smaller percentage of advanced displacement turns. The values of displacements under different working and supporting conditions are shown in Table 2.

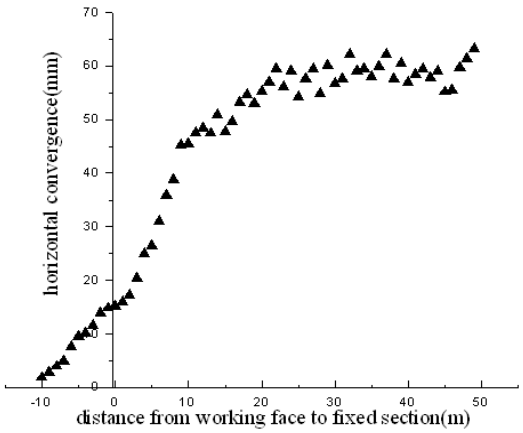
Table 2: Variation of displacements under different working and supporting conditions

	Condition	Cond. 1	Cond. 2	Cond. 3	Cond. 4	Cond. 5
No	Advanced displacement (mm)	137.91	82.75	53.01	35.88	29.21
supporting	Total displacement (mm)	750.25	329.99	177.05	97.48	68.01
	Percentage (%)	18.2	24.4	29.6	35.5	43.1
Supporting	Advanced displacement (mm)	323.04	190.3	114.50	66.62	54.81
	Total displacement (mm)	80.6	47.33	28.52	16.55	13.44
	Percentage (%)	25.70	25.47	25.65	25.54	25.82

Fig. 9: Large model test bench



(a)



(b)

Fig. 10: Advanced displacement in model text

MODEL TEST AND COMPARISON

The Large model test bench (Qiang-Yong *et al*., 2007; Shu-Cai *et al*., 2011) of the National Railway Ministry was used to do the related model test (Fig. 9), in which the surrounding rock parameters were based on Cond. 3 and the similarity ratio was defined as 1:35 according to the bench size. Simultaneously, related similar material was researched to fill the bench according to surrounding rock conditions and similarity ratio. The result of the displacement changing with the working face's movement shown in Fig. 10

The comparison of numerical results with model test results in the same typical section is carried out to verify the reliability of numerical simulation. The values of measuring results are generally greater than those of numerical results with basically consistent trend and regularity. The reason is that the continuity analysis method is adopted in the numerical simulation, but the similar material of actual model not ideal continuous media; some tiny cracks would be produced inside the model when the applied load in tunnel excavation process is too far and the discontinuous deformations caused by cracks take up part of the measurement.

CONCLUSION

Base on Liangshui tunnel of Lan-Yu railroad in Gansu province, elastic-plastic numerical simulation on mechanical behaviors of tunnel construction and steric effect of deformation is carried out to obtain four conclusions as follows:

- The working face has steric constrained effect on the nearby surrounding rock in excavation, where surrounding rock stress gradually releases with the increase of distance away from the working face, so does the deformation and influence range comes to 1.5 times the cave diameter in front of tunnel face and 3 times in the rear.
- With the same excavation conditions, values of vault settlement are always greater than those of horizontal convergence, whose changing trends are similar with the propulsion of working face; the displacement with supporting condition is less than that case without supporting showing the importance of supporting in tunnel construction with weak surrounding rock.

- In partial excavation with supporting, the disturbed range is 1.5~1 times the cave diameter in front of the working face, which is the important area and least boundary of weak and broken surrounding rock needed to be reinforced. Therefore, the supporting structure should be established as soon as possible to control the displacement change of surrounding rock in the range of load-bearing ring, reduce disturbance and improve the self-bearing capability of surrounding rock; the secondary lining structure must be established in time to bear the later pressure and restrict the large displacement of surrounding rock.
- In the case with supporting, the weaker surrounding rock grade is, the larger surrounding rock displacement caused by tunnel excavation is, but the percentages of advanced displacement are basically the same. However, in the case without supporting, with the lower of surrounding rock grade, surrounding rock displacement caused by tunnel excavation tunnel larger and the percentage of advanced displacement turns smalI

Due to the complexity of rock mechanical research object, there are errors in the establish of mechanical models, the process of mathematics and mechanical method and the selection and test of rock mechanical parameters, all of which can cause the inaccuracy of quantitative numerical results. However the importance of analysis and calculation method should not be negative and it is foreseeable that quantitative analysis is the developing trend of rock mechanics and the scientific support of experience judgment. The above-mentioned numerical simulation for advanced displacement of tunnel with weak and broken surrounding rock is carried out to reveal the adjusting process of displacement at main parts in tunnel, provide basis for the further study on stability of Liangshui tunnel with relevant supporting measures.

REFERENCES

Carranza-Torres, C. and C. Fairhurst, 2000. Application of the convergence confinement method of tunnel design to rock masses that satisfy the Hoek-Brown failure criterion. J. Tunnelling Underground Space Technol., 15: 187-213.

Chun-De, M., L. Xi-Bing and H. Bing-Nan, F. Chen, X. Ji-Cheng and L. Di-Yuan, 2008. Settlement behavior of coal mine waste in different surrounding rock conditions. J. Cent. South Univ. Technol., 15: 350-355.

Evert, H., 2002. Practical Rock Engineering Technology. Feng-Shou, T.L. *et al*. (Eds.), the Yellow River Water Conservancy Press, Zhengzhou, (In Chinese).

Gen-De, Z., 1995. Soil Constitutive Model and its Engineering Application. Science Press, Beijing, (In Chinese).

Li, W., *et al.*, 2008. ANSYS Example Analysis of Tunnel and Underground Engineering. China Water Power Press, Beijing, (In Chinese).

Nguyen, M.D. and C. Guo, 1996. Recents progress in convergence confinement method. Proceeding of EUROCK'96, In: Barla, G. (Ed.), Prediction and Performance in Rock Mechanics and Rock Engineering. Rotterdam, Balkema, pp: 855-860.

Panet, M. and A. Guenot, 1982. Analysis of convergence behind the face of a tunnel. Proceeding of 3rd International Symposium, Tunnelling, In: Jones, M.J. (Ed.), London, IMM, pp: 197-204.

Qiang-Yong, Z., L. Shu-Cai and Y. Chun-An and G. Xiaohong, 2007. Development and application of new type combination 3D geomechanical model test rack apparatus. Chinese J. Rock Mech. Eng., 26(1): 143-148.

Schubert, W. and A. Steindorfer, 1998. Advanced monitoring data evaluation and display for tunnels. Proceeding of Tunnels and Metropolises, In: Negro Jr, A. and A. Ferreira and A. Rotterdam (Eds.), Balkema, pp: 1205-1208.

Schubert, W., A. Steindorfer and E.A. Button, 2002. Displacement monitoring in tunnels-an overview. J. Felsbau, 20: 7-15.

Shu-Cai, L., L. Qin, L. Li-Ping, Z. Yong, W. Hanpeng *et al*., 2011. Development of large-scale geomechanical model test system for tunnel construction and its application. Chinese J. Rock Mech. Eng., 30: 1368-1374.

Sulem, J., M. Panet and A. Guenot, 1987. Closure analysis in deep tunnels. Int. J. Rock. Mech. Min. Sci. Geomech. Abstr., 24: 145-154.

Sun, J., 1996. Underground Engineering Design Theory and Practice. Shanghai Science and Technology Press, Shanghai.

Wei-Shen, Z. and Z. Jian, 2004. Stability Analysis and Modeling of Underground Excavations in Fractured Rocks. Elsevier, Amsterdam.

Yang, M., Q. Sun, L. Wei-Chao and K. Ma, 2011. Three-dimensional finite element analysis on effects of tunnel construction on nearby pile foundation. J. Cent. South Univ. Technol., 18: 909-916.