Research Article

Numerical Simulation of Mining-Induced Damage in Adjacent Tunnels Based on FLAC^{3D}

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The Bayueshan (BYS) tunnels are adjacent tunnels which comprise key engineering structures important for Yurong highway from Chongqing to Sichuan, China. The tunnels were established crossing over the old goafs of a coal mine. The tunnels have been damaged three times between 2014 and 2016. To evaluate the reasons for the damage, fast Lagrangian analysis of continua in three dimensions (FLAC^{3D}) was used to simulate the underground coal-mine excavation yearly from 2012 to 2015. The simulation results show that the subsidence of the ground surface increased annually. The maximum subsidence of the left tunnel was 505 mm and that of the right tunnel was 512 mm. The excavation led to increase in the tunnels' stress concentration. The simulations further show that uneven horizontal displacement and subsidence were the major factors in inducing tunnel construction defects. Poor geological conditions, water, and vehicle dynamic loads were also important factors that induced damage. Several engineering suggestions for ways to maintain the tunnels are given in this paper, and the research provides a reference for safety evaluation for tunnels crossing over an old goaf.

1. Introduction

Underground mining can change rock's original stress condition, and the rock mass will move to achieve a new balance [1, 2]. Mining-induced subsidence will cause deformation of the construction above a goaf or destruction [3–5]. In China, with rapid economic development in recent decades, numerous highways and railways have been established in which tunnels must pass through a coal-mining area or over old goafs [6–8]. There are mainly three major methods used to predict coal-mine subsidence of tunnels. The first is based on the model of stochastic medium theory [9, 10], the second on the theory of the elastic-plastic medium theory [11, 12], and the third and most used is numerical simulation [13–15]. The stochastic medium method is a semiempirical influence function, and it can be used to obtain reliable subsidence results with the parameters of field observation [1], but it lacks a reasonable

explanation of deformation mechanisms. The elastic-plastic medium theory is often based on a hypothesis and simplified model, but it cannot reflect the actual geological and mining conditions, and its results are often significantly different from actual ones [16, 17]. Numerical simulation is currently the method that is used mostly in tunnel damage analysis [18–20]. Anasys, FLAC^{3D}, UDEC, and 3DEC are mostly used numerical simulation software [13, 21, 22]. Chongqing Bayueshan (BYS) tunnel is an important length of highway engineering from Chongqing to Sichuan, China. The BYS tunnel was established over a coal mine, and some parts extend through the mine's old goaf. The coal mine is still in production, and the underground mining and old goaf have caused the tunnels to crack, beginning in 2014. To evaluate the deformation influence on the tunnels and provide more information on tunnel maintenance, a fast Lagrangian analysis of continua in three-dimension (FLAC^{3D}) model was devised to simulate the tunnel deformation and damage.

FIGURE 1: Geological profile of left tunnel (reproduced from [10]).

FIGURE 2: Boundary conditions of the model.

FIGURE 3: Geometry of the model: (a) three-dimensional simulation model; (b) tunnel geometry; (c) relative position of coal seams and tunnel.

TABLE 1: Laboratory rock-mass properties.

Rock	ρ (kg/m ³)	K (GPa)	G (GPa)	C (MPa)	σ (MPa)	φ (°)
Coal	1,420	6.1	1.9	2.11	2.6	29.5
Mudstone	2,437	15.6	8.9	2.2	1.8	38
Sandstone	2,690	10.7	6.15	1.55	1.38	41
Sprayed concrete	2,300	14.0	10.2	2.0	1.5	50

ρ : density; K : bulk modulus; G : shear modulus; C : cohesion; σ : tensile strength; φ : internal friction angle.

The research results are used as a basis for BYS tunnel maintenance design engineers.

2. Geological Conditions

According to the bore hole, the research area strata are mainly constituted by the Quaternary Xujiache Formation of

the Triassic upper system and the Triassic Jialingjiang Formation. Xujiache Formation is the main coal-bearing stratum, as shown in Figure 1. Lithologies of the rock are gray black shale, sandy shale, brown yellow mud stone, and gray post. There are six lithological segments, the thicknesses of which are in the range of approximately 400 ~ 600 m. This formation is parallel nonconformity with underlying strata.

FIGURE 4: Subsidence contour of coal mine (units: mm): (a) 2012; (b) 2013; (c) 2014; (d) 2015.

The investigated area contains three segments: the second, third, and fourth segments.

The second segment is a light gray, thin to medium thick layer, constituted by coarse feldspar quartz sandstone. Its thickness is 160 m ~ 200 m.

The third segment is gray black, thin to medium thick layer, a mud stone and silt stone interbed, partly with carbon mud stone and thin coal seam. The coal seam is 0.15 m ~ 0.35 m. It is the main coal seam in this area. The layer thickness is approximately 40 m ~ 70 m. This segment belongs to soft rock. The rock has poor interlayer bonding and good joint development, and the rock mass has integrity.

The fourth segment is a light gray, thin to medium thick layer with coarse feldspar quartz sandstone and partly boulder clay. This segment thickness is 50 ~ 70 m. This segment belongs to hard rock with simple interlayer bonding and good joint development, and the rock mass has integrity.

3. Simulation Model

3.1. Introduction of $FLAC^{3D}$ and Mohr–Coulomb Criterion. $FLAC^{3D}$ is a finite-difference program developed by Itasca Co. The software can simulate different materials with mechanical behavior of failure and plastic flow. It is good at simulating problems of failure and instability, especially numerical stability with large displacements, including collapse [23]. $FLAC^{3D}$ uses the explicit solution method to

solve the nonlinear problem quickly with small memory overhead. It provides 12 material constitutive models: a null model, three elastic models, and eight plasticity models. The Mohr–Coulomb strength criterion is a nonlinear constitutive model often used in rock and soil engineering numerical simulation [15, 19] and is expressed by the following equation:

$$f_s = \sigma_1 - \sigma_3 \frac{1 + \sin \varphi}{1 - \sin \varphi} + 2c \sqrt{\frac{1 + \sin \varphi}{1 - \sin \varphi}}, \quad (1)$$

where σ_1 and σ_3 are the maximum and minimum principal stress, respectively, and c and φ are the cohesion and internal friction angle, respectively. When $f_s > 0$, the material will fail by shearing. Under a normal stress state, the rock can fail by tensile strength. In the work described in this paper, the Mohr–Coulomb model was used for the rock and the null model for the excavation area.

3.2. Boundary Condition and Model Geometry. According to the geological conditions of two coal mines, the model was built with 1 : 1 geometric scale. The rock was simplified into layered rock mass with single thickness. The simulation models are free displacement only with a boundary displacement constraint. As shown in Figure 2, the Z displacement of the model bottom, the X displacement of the left and right sides, and the Y displacement of both the front

FIGURE 5: Subsidence of tunnel slice: (a) Left 2012; (b) Left 2013; (c) Left 2014; (d) Left 2015; (e) Right 2012; (f) Right 2013; (g) Right 2014; (h) Right 2015.

FIGURE 6: Continued.

FIGURE 6: Maximum principal stress contours of tunnels (unit: MPa): (a) 2012; (b) 2013; (c) 2014; (d) 2015.

TABLE 2: Maximums deformation values of tunnels.

Item	Tunnel	2012		2013		2014		2015	
		Value	Position	Value	Position	Value	Position	Value	Position
σ_1 (MPa)	Left	14.02	124	13.87	125	13.13	113	13.6	114
	Right	16.96	101	17.07	100	19.18	100	19.61	101
σ_{xx} (MPa)	Left	9.05	133	9.02	133	10.21	133	10.35	133
	Right	11.45	100	12.07	101	13.09	100	13.22	100
σ_{yy} (MPa)	Left	6.57	130	6.72	130	6.72	131	6.84	131
	Right	11.2	100	11.74	101	12.74	100	12.91	100
σ_{zz} (MPa)	Left	6.25	124	8.20	-7	8.20	-9	8.43	-7
	Right	6.96	100	6.38	-24	8.07	-20	7.00	-21
U_x (mm)	Left	83	294	102	330	149	335	161	335
	Right	84	252	102	365	156	368	152	368
U_y (mm)	Left	-55	123	-67	122	-96	123	-99	122
	Right	-48	182	-56	182	-75	180	-75	174
W (mm)	Left	-328	193	-372	193	-493	193	-505	193
	Right	-332	180	-375	181	-498	181	-512	181

FIGURE 7: Continued.

FIGURE 7: SXX contours of tunnels (unit: MPa): (a) 2012; (b) 2013; (c) 2014; (d) 2015.

and back sides are fixed. To obtain the subsidence, the top of the model is set to free. The load applied to the studied model is only under gravity. No tectonic stress is considered in this research.

Tunnel crack is a plane strain problem, and, to reduce the boundary effect, the geometry is decided by the deformation edge, which should be large enough for investigating area mining subsidence. The model geometry used in this paper is shown in Figure 3(a). Coal and rock layers in the model were generated with a wedge mesh. The twin-tunnels model is shown in Figure 3(b). The tunnels were generated with a radial cylinder and cylindrical shell. The wedge, radial cylinder, and cylindrical shell were all built in mesh elements in the $FLAC^{3D}$ software. The built model has 106,586 zones and 414,359 grid points. The excavation area used the null model.

3.3. Rock Properties. The actual rock properties were not available to the authors, so several average values [24–26] were used in the model, as shown in Table 1. The parameters in the table are laboratory test-piece values, but naturally rock is a large rock mass and has numerous joints and cracks. The results of a significant amount of research show

that strength of rock mass is approximately $1/10 \sim 1/30$ of that of the test pieces [9, 27, 28]. In the present paper, the bulk and shear moduli applied to the model were both $1/15$ of the laboratory values.

4. Results

4.1. Subsidence Characteristics of Mining. To obtain the damage mechanism, four simulation steps were designed according to the yearly excavation engineering conducted after the tunnel was completed. The subsidence of the surface is shown in Figure 4, illustrating that upon excavation, both the surface-subsidence value and size of the influence area are increased yearly. The maximum surface-subsidence values were 290 mm (2012), 335 mm (2013), 457 mm (2014), and 471 mm (2015).

Figure 5 shows the subsidence contour of the tunnel profile. With tunnel underground excavations of K_7 , K_9 , and K_{10} , the tunnels' subsidence values and influence area sizes all increased yearly. The subsidence of the sectional elevation contours is shown in Figure 5. The slice contour shows the change process of the rock after coal-mine excavation. As shown in the figure, the maximum subsidences are directly over the top of the

FIGURE 8: Continued.

FIGURE 8: SY Y contours of tunnels (unit: MPa): (a) 2012; (b) 2013; (c) 2014; (d) 2015.

working panel and decrease from the coal roof to the surface. The subsidences of the tunnel increased yearly, and there were not uniformly distributed. The uneven settlement often causes stress concentration and structural failure.

4.2. Stress Fields of Tunnels. The maximum principal stresses of the tunnels are shown in Figure 6. The stress concentrations are located at the roof of the both tunnels, and the influence areas are LK35 ~ LK35 + 160 and RK35 + 13 ~ RK35 + 156. The maximums of the maximum principal stresses are shown in Table 2. The XX stresses (stresses along the tunnel) are shown in Figure 7. The XX-stress concentrations are located at LK34 + 994 ~ LK35 + 153 for the left tunnel and at RK34 + 987 ~ RK35 + 123 for the right tunnel. The YY stresses (stresses perpendicular to tunnel) are shown in Figure 8. The YY-stress concentrations are located at LK35 + 53 ~ LK35 + 154 for the left tunnel and at RK35 + 31 ~ RK35 + 134 for the right tunnel. The ZZ stresses (stresses along the direction of plumb) are shown in Figure 9. The ZZ-stress concentrations are located at LK35 + 212 ~ LK35 + 333 for the left tunnel and at RK35 + 189 ~ RK35 + 370 for the right tunnel. As shown in

the stress-contour figures, both the roof and floor of the tunnel were bearing stress concentration. Both tunnels have a stress-concentrated area and exhibit structural stress imbalance.

4.3. Displacement Characteristics of Tunnels. The X displacements (displacements along the tunnel direction) are shown in Figure 10. The X displacement increased yearly, and the mostly uneven X-direction horizontal movements were located at LK35 + 84 ~ LK35 + 107 and RK35 + 71 ~ RK35 + 127. The Y displacements (displacements perpendicular to the tunnel direction) are shown in Figure 11. The much larger uneven influence areas of the Y displacements were located at LK35 + 39 ~ LK35 + 154 and RK35 + 29 ~ RK35 + 137. The Z displacements (subsidiences) are shown in Figure 12. The maximum subsidence of the left tunnel is 505 mm at LK35 + 193 and that of the right tunnel is 512 mm at RK35 + 181. The subsidence increased yearly, and the areas of subsidence that exceeded 450 mm were LK35 + 157 ~ LK35 + 250 and RK35 + 154 ~ RK35 + 259.

FIGURE 9: Continued.

FIGURE 9: SZZ contour of tunnels (unit: MPa): (a) 2012; (b) 2013; (c) 2014; (d) 2015.

4.4. Statistics of Maximum Values and Locations. The maximum deformation values of principal stress, XX stress, YY stress, ZZ stress, and their displacements are shown in Table 2.

5. Tunnel Damage Analysis

The first crack in the tunnel occurred on September 4, 2014, at LK35 + 162 ~ LK35 + 171 after a heavy rain. The concrete surface was cracked (the crack was 1 cm wide and 4 m high) from the road surface to the arch, as shown in Figure 13.

On November 15, 2014, the right tunnel was cracked at RK35 + 268 (the crack was 3 cm wide and 6 m high), as shown in Figure 14(a). On July 7, 2016, the tunnel was cracked after a heavy rain at LK35 + 220; the lining of the wall was cracked, and the fracture penetration is shown in Figure 14(b).

The numerical simulation results show that the maximum subsidence was laid up on the downhill side. The numerical simulation surface deformation law and subsidence value, range, and size basically conform to the conventional mining subsidence law. The subsidence, stress, and

strain can be used as a reliable simulation results in the tunnel damage analysis.

Construction of the tunnel in which the cracked areas are located was completed on April 26, 2011. After being in service for approximately three years, the tunnel deformation and cracking mainly resulted from supplementary loading. Several noteworthy characteristics are as follows.

First, the tunnel damage mainly occurred after a heavy rain or after the rainy season. The research area was mainly formed by a fractured rigid rock mass. In fact, some fissures are connected with the goaf or old goaf. Underground mining is the major factor for the tunnel cracking, and the rain is an important cause of it.

Second, the cracked area did not locate above the goaf directly but located outside the goaf boundary.

Third, the tunnel support structure is also influenced the stability of the tunnel. Some cracks occurred near the support change area.

Fourth, all of the cracks occurred at the tunnel movement joint position. The joints moved together, or there was relative movement between joints which caused the lining to crack.

FIGURE 10: Continued.

FIGURE 10: X-displacement contours of tunnels (unit: mm): (a) 2012; (b) 2013; (c) 2014; (d) 2015.

6. Discussion

The BYS tunnel cracks have damaged some structure of the tunnel, and the dropping cement has led a mining car to drop out. As the above simulation results and analysis show, the reason for the tunnels' defects was mainly caused by the underground excavation of the ChangRong coal mine. It led to the tunnel subsidence and uneven horizontal movement. The rock movement caused the tunnel and the road at K35 + 335 ~ K35 + 500 to move, as well the tunnel lining to break or deformation seams to join together. In addition, the tunnel was always damaged after a new panel excavation. A delay of 3 ~ 5 months resulted, which was the time required for rebalancing the rock.

The tunnel was established in a coal-mine area and crosses over the mine's old goaf, with the support type mostly IV or V. Poor supporting geological conditions comprise another reason for the tunnel damage.

Third, damage occurred three times during the rainy season or after a heavy rain, showing that the rain changed the original balance of the rock and induced the tunnel cracking. Rain can reduce tunnel strength. In addition, after

the rainy season, the rock will shrink owing to water loss, which also induces tunnel deformation. Water is a factor that induces tunnel damage.

Since the tunnels are also a highway road, vehicle dynamic loads have a long-term influence on the structure. Since the tunnel crosses over a goaf, vehicle dynamic load can change the mechanical equilibrium of the broken rock mass. This, in turn, will cause tunnel deformation and additional stress. Vehicle dynamic load also induces tunnel damage.

To prevent deformation and harm from reoccurring, the coal mine has been closed. More protective measures, such as reinforcing the goaf, are needed.

The numerical simulation results were used to analyse the crack caused by coal mine. It shows that the main reason to cause the tunnel crack is the long-term, small production excavation. The coal mine was forced to stop production after the tunnel cracked. And the tunnel was maintained. And all the goaf was reinforced with the grouting filling method. The simulation results provide a technical reference for the implementation of those measures.

FIGURE 11: Continued.

FIGURE 11: Y-displacement contours of tunnels (unit: mm): (a) 2012; (b) 2013; (c) 2014; (d) 2015.

FIGURE 12: Continued.

FIGURE 12: Z-displacement contours of tunnels (unit: mm): (a) 2012; (b) 2013; (c) 2014; (d) 2015.

FIGURE 13: Crack of LK35 + 168 (September 4, 2014) (source from [10]).

FIGURE 14: Images of tunnel cracks (source from [10]): (a) RK35 + 268; (b) LK35 + 220.

7. Conclusions

The following conclusions are drawn from the results of the present study:

- (1) To study the law of tunnel damage caused by mine excavation, a $FLAC^{3D}$ model was built based on the geological and topographic information. The surface and tunnel movement were consistent with the general mine subsidence law of surface and rock-mass deformation.
- (2) The tunnel stresses σ_1 , σ_3 , σ_{XX} , σ_{YY} , and σ_{ZZ} were analysed, and results show that the stress-concentration area coincides with the damage position of the tunnel. Rock movement-induced subsidiary stress concentration is the major reason for the tunnel damage.
- (3) Old goaf deformation, poor geological conditions, water, and vehicle dynamic load also influenced the tunnel deformation and compromised its deformation resistance. Therefore, additional measures are needed to prevent the reoccurrence of traffic hazards.

Data Availability

The data used to support this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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