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Research Article

Study of Tunnel Damage Caused by Underground Mining Deformation: Calculation, Analysis, and Reinforcement

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Bayueshan tunnel (BYS) is an important construction crossing over coal mine goaf. The underground mining subsidence has led the tunnel cracked seriously in three years after it was built. In order to evaluate the coal mine influence and future stability of the tunnels, probability integral method (PIM) was used to calculate the tunnel deformation. PIM is an experience function method based on random medium theory which is used widely in China. With the parameters analyzed, the tunnels' subsidence was calculated. The results show that it can interpret the tunnel damage well, and the maximum normal strain positions fit the damaged tunnel positions well. It proved that PIM can be used to evaluate the tunnel's radial deformation caused by underground coal excavation. In order to maintain tunnels to keep a long-term stability, the future deformation was calculated in case the coal excavation continues. It shows that the tunnel would be cracked again if the excavation continued. Other reasons such as the old goaf deformation and water and vehicle dynamic load are also important reasons for the tunnels' deformation. In order to keep traffic safety, it needs to reinforce the cracked foundation under the tunnel. Then, grouting injection was proposed to reduce the old goaf deformation under the tunnels. If the fracture zone under the tunnels disturbed by the dynamic traffic load, the old goaf will face a risk of sudden collapse. So, to ensure the grouting effect, the grouting depth should be deeper than the sum of traffic load influence depth and height of coal mine caved fissure zone. The grouting scope should keep all the crack rock area under the tunnel from being disturbed by the dynamic traffic load. This design can reduce the sudden collapse risk of the goaf and reduces the vehicles' load disturbance on the cracked rock. The researched technology provides an engineering guidance to tunnel subsidence calculation, stability evaluation, and maintenance in complex geological and engineering situations.

1. Introduction

Underground coal mining plays an important role in China's economic development. China's coal production is about 3.6 billion tonnes per year. Underground mining subsidence could cause damage to houses, land, and other constructions. The lands damaged by underground coal mine in China are more than 1.50 million hectares [1] and increases by 70 thousand hectares every year. For the wide area of goaf and subsidence, a lot of roads have changed their alignment or faced the problem of old goaf deformation. For the safety evaluation, numerical simulation is often used to get the stress and normal strain [2, 3], and probability integral method is used to calculate the residual deformation of old goaf [4, 5]. According to different positions between road tunnel and goaf, Tong classified three typical conditions: the tunnels below mine level, the tunnels intersecting with the coal seam, and the tunnels above mine level and gave protection measures for those conditions [6]. Simulation can be used to assess the tunnel convergence in caved zones [7, 8]. Fang et al. have simulated the tunnel deformation under the caved zone. The scale model experiments show that the tunnel settlement has a relation with the distance of caved zone to the tunnel and dip angle of caved zones [9, 10]; the conclusions have guiding significance to tunnel design under caved areas. Numerical simulation such as FLAC (Fast Lagrangian Analysis of Continua), UDEC (Universal Distinct Element Code), and FEM (Finite Element Method) method also have been used widely to calculate or assess the tunnel deformation in mined area [7, 8, 11, 12]. Most of those research studies were just interested in the deformation of the tunnel cross section caused by the old goaf. But BYS tunnel cracks were mainly caused by the coal mining after the construction was completed. The tunnel was damaged by the underground coal mine; tunnels were cracked mainly by the differential movement along or perpendicular to the tunnels. Tunnel lining and surrounding rock are secondary reasons. PIM is an appropriate method to calculate the tunnel deformation caused by rock redistribution after underground coal mining.

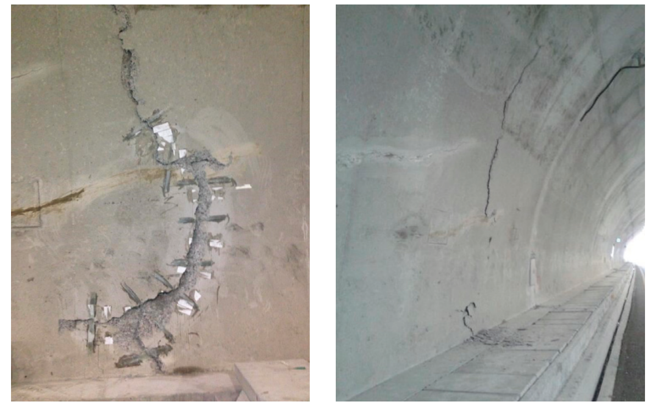
Grouting is a widely used method on reinforcement in tunnel engineering [13, 14]. Grouting in caved zone can be used to reinforce the goaf and reduce the goaf deformation. It can increase the strength of surrounding rock effectively [15, 16]. A suitable grouting scheme should keep balance between effect and grouting cost [16, 17]. So grouting depth and scope were designed based on dynamic traffic influence and height of coal excavation cracked zone.

Highway tunnels over the goaf are a complicated problem that has a relationship with geological, goaf condition, water, and tunnel supporting method. Tunnel deformation of coal mine subsidence is a complex problem that has no unified solution. Chongqing BYS tunnel is located in western China. Two tunnels were damaged by both old goaf and underground coal mining. Tunnel deformation was calculated first, and a fix measurement is proposed in order to maintain the tunnel. The research gives a reliable way of tunnel deformation evaluation and old goaf reinforcement.

2. Geological

2.1. Engineering Introduction. The BYS tunnel is an important construction in the highway from Chongqing to Chengdu. The tunnels are double-separate-hole highway tunnels which have 18.8 ~ 44.6 m separation. The tunnel construction is 16.25 m wide and 8.20 m high. The left hole is 3270 m long starting from LK32 + 065 (elevation is 342.11 m) to LK35 + 335 (elevation is 304.57 m). The right hole is 3302 m long from RK32 + 066.15 (elevation is 342.12 m) to RK35 + 368.15 (elevation is 303.92 m). The investigated area of the tunnels was built from December 31 2010 to April 23 2011.

CR and XS are two collieries in the investigated area. Both collieries had mining activities under the tunnel from 2012 to 2015. The tunnels were damaged by the underground mine deformation from 2014. The first crack was LK35 + 168 on September 4 2014. The crack was 1 cm wide and 4 m in height from the tunnel foot, as shown in Figure 1. Then RK35 + 268 tunnel lining structure cracked on November 15 2014 (Figure 2(b)); the crack was 3 cm wide and 6 m in height from the foot. The crack extended to the top of the tunnel on June 9 2015(Figure 2(b)). ZK35 + 220 cracked on July 7 2016 (Figure 3). In order to ensure the traffic safety and keep the stability of the tunnels, a major repair is necessary. This paper calculated and predicted the mining subsidence and tunnel deformation which can be used as guidance for tunnel maintenance.



(a) (b)

Figure 1: Crack of LK35 + 168 (September 4 2014).

2.2. Coal Mine under the BYS Tunnel. There are two collieries in the investigated area: CR and XS. CR coal mine is 3.375 Km long from south to north, and 0.55 Km long from east to west. It has two adits and two air shafts; production is 9 tonnes per year. Mine method is inclined wall type blasting mining method, wooden support, and all caving roof management. The coal dip angle is 47° on average. CR mined K_5, K_7, K_9, and K_{10} coal seams.

The K_5 coal seam is located on the floor of Triassic system, upper series of third member of XJ formation (T_3XJ^3), 40 m above the second member (T_3XJ^2), and 45 m lower than the K_7 coal seam. Thickness of this layer is 0.22~0.26 m, average 0.24 m. Under the K_5 floor are mudstones and sandy mudstones.

The K_7 coal seam is located on the Triassic system, middle series, third member of XJ formation (T_3XJ^3), 34 m lower than the K_7 coal seam. Thickness of this layer is 0.20~0.25 m, average 0.23 m. Under the floor are mudstones and sandy mudstones.

The K_9 coal seam is located on the Triassic system, upper series of third member of XJ formation (T_3XJ^3), 8~9 m lower than the K_{10} coal seam. Thickness of this layer is 0.31~0.35 m, average 0.33 m. Under the floor are mudstones and sandy mudstones.

The K_{10} coal seam is located on the Triassic system, upper series of third member of XJ formation (T_3XJ^3), 28 m lower than the fourth member of XJ formation (T_3XJ^4) coal seam. Thickness of this layer is 0.44 ~ 0.50 m, average 0.48 m. Under the floor are mudstones and sandy mudstones.

The XS coal mine covers an area of 1.6078 Km^2. The coal mine has one adit. It is mined by the strike long wall method and all caving roof management method. The XS coal mine mined the K_{11} and K_{12} coal seam and production was 9 tonnes per year.

(a) (b)

Figure 2: Crack of RK35 + 268. (a) First cracked (November 15 2014). (b) Cracked after mended (June 9 2015).

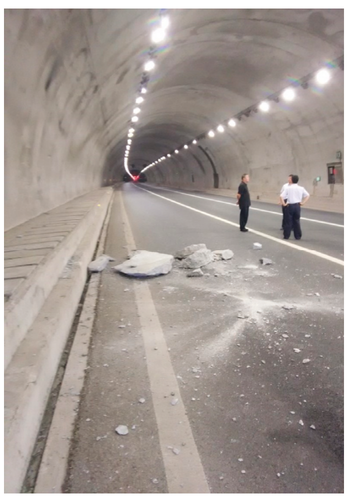


Figure 3: Crack of LK35 + 220 (July 4 2014).

The K_{11} coal seam is located on the fifth member of XJ formation (T_3XJ^{5-1}), 5∼7 m lower than K_{12} coal seam. Thickness is 0.34∼0.55 m, average 0.47 m. This coal seam is stability occurrence.

The K_{12} coal seam is located on the fifth member of XJ formation (T_3XJ^{5-1}) and mine thickness is 0.40∼0.51 m, average 0.49 m.

The geological section of the tunnel is shown in Figures 4 and 5. And the mine plan and its mine times are shown in Figures 6–11.

As shown in the figures, the coal mine did not stop excavation during and after the construction of the tunnel, so the damage has great relation with mining activities after the tunnel construction complete. So, the deformation was calculated and compared with damage positions.

3. Tunnel Deformation Calculation

3.1. Probability Integral Method. There are various methods of mine subsidence calculation. The most used in China is a profile function based on statistic medium algorithm [18]. The method was introduced to China by Baochen Liu and Guohua Liao in 1960s [19, 20] and was developed into a more reliable and easy used model named PIM. This method has just eight parameters based on geological data, and reliable surface deformation can be obtained.

In order to calculate the surface deformation caused by coal mining, the rock was simplified as statistic medium and formed with small statistic movement elements. As shown in Figure 12, after the small element in the first layer was excavated, there are same chances for the two elements in the second layer to fill it. So as shown in the figure, the surface subsidence is similar to the Gaussian bell function when one element was excavated in the first layer.

The PIM is based on this statistical theory and can obtain the subsidence with geometry integral of all excavation space.

This model is easily accepted by engineers and technical personnel and selected as a government recommended method for mine subsidence prediction and damage estimation [21].

The PIM calculates deformation of underground mining by equations (2)–(6) [20].

$$W_e(x) = \frac{1}{r} e^{-\pi (x^2/r^2)}, \tag{1}$$

$$\begin{aligned} W(x,y) &= \sum_{j=1}^{n} \iint_{D_j} W_0 W_e(x,y)\, ds\, dt \\ &= \sum_{j=1}^{n} \iint_{D_j} \frac{W_0}{r_j^2} e^{-\pi (x-s)^2+(y-t)^2/r_j^2}\, ds\, dt, \end{aligned} \tag{2}$$

$$\begin{aligned} i(x,y,\varphi) &= \frac{\partial W(x,y)}{\partial x}\cos\varphi + \frac{\partial W(x,y)}{\partial y}\sin\varphi \\ &= \sum_{j=1}^{n} \iint_{D_j} \frac{-2\pi W_0}{r_j^4} \Big\{ [(x-s)\cos\varphi \\ &\quad + (y-t)\sin\varphi] e^{-\pi\left(\left((x-s)^2+(y-t)^2\right)/r_j^2\right)} \Big\}\, ds\, dt, \end{aligned} \tag{3}$$

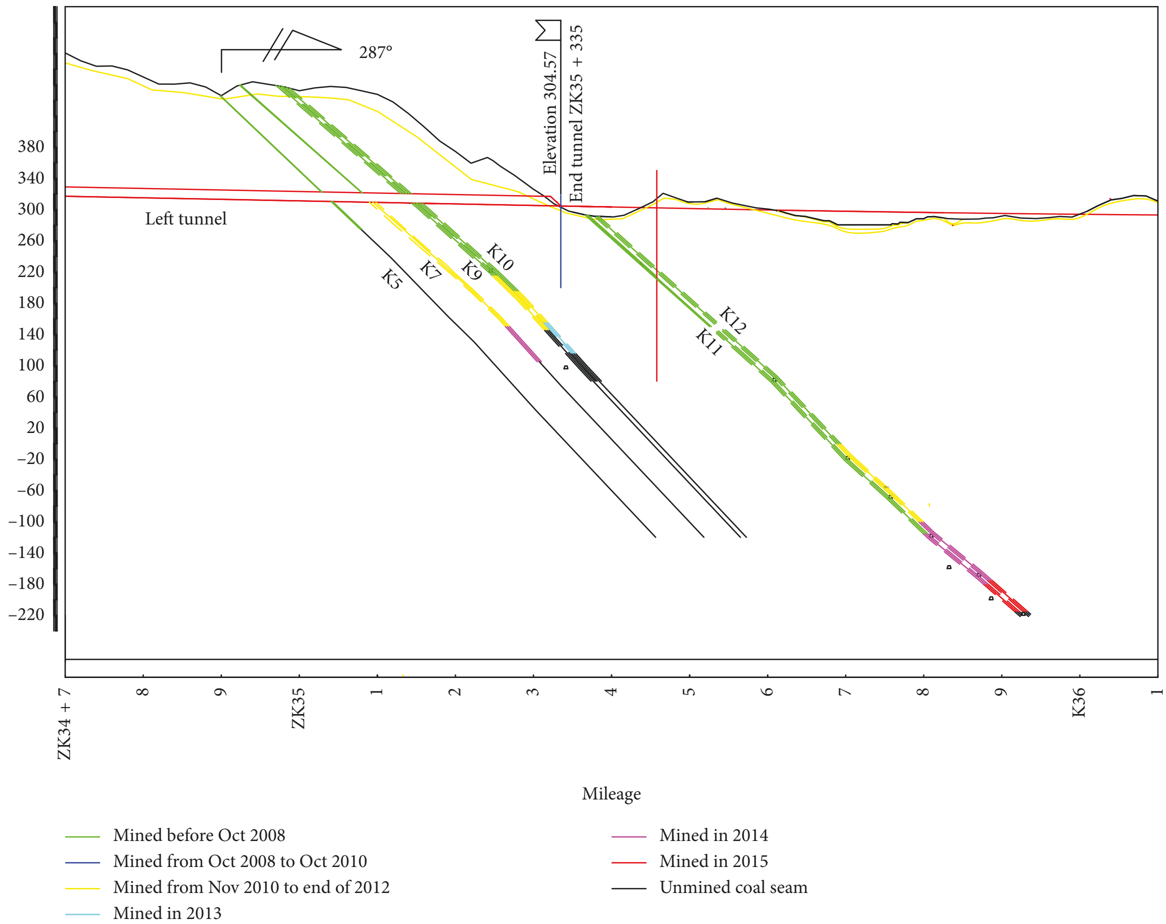


Figure 4: Section of left tunnel.

$$K(x,y,\varphi) = \frac{\partial i(x,y,\varphi)}{\partial x}\cos\varphi + \frac{\partial i(x,y,\varphi)}{\partial y}\sin\varphi = \sum_{j=1}^{n}\iint_{D_j}\left[\frac{-2\pi W_0}{r_j^4}\left\{1-\frac{2\pi}{r_j^2}\left[(x-s)\cos\varphi + (y-t)\sin\varphi\right]^2\right\}e^{-\pi\left(\left((x-s)^2+(y-t)^2\right)/r_j^2\right)}\right]ds\,dt, \quad (4)$$

$$U(x,y,\varphi) = \sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi b W_0}{r_j^3}\left\{\left[(x-s)\cos\varphi + (y-t)\sin\varphi\right]e^{-\pi\left(\left((x-s)^2+(y-t)^2\right)/r_j^2\right)}\right\}ds\,dt, \quad (5)$$

$$\varepsilon(x,y,\varphi) = \sum_{j=1}^{n}\iint_{D_j}\left[\frac{-2\pi b W_0}{r_j^3}\left\{1-\frac{2\pi}{r_j^2}\left[(x-s)\cos\varphi + (y-t)\sin\varphi\right]^2\right\}e^{-\pi\left(\left((x-s)^2+(y-t)^2\right)/r_j^2\right)}\right]ds\,dt, \quad (6)$$

where (x, y) are coordinates of the surface point, φ is direction angle of surface movement; W_0 is the maximum ground subsidence, given by $W_0 = mq\cos\alpha$; $W_e(x, y)$ is the subsidence of a small unit mining; r is the major influence radius given by $r = H/\tan\beta$; H is mining depth; q is the subsidence factor; b is the displacement factor; m is the mining thickness; $\tan\beta$ is tangent of major influence angle; D is the calculation of mining area that deviation of inflection point (S) removed from actual mining area; n is the total number of mining panels; and α is the dip angle of the coal seam [19].

For inclined coal seam, as shown in Figure 13 [20], the inflection point of subsidence curve is not located directly above the boundary of the goaf but moved to the dip side point O; the angle between OC and horizontal line is another probability integration parameter θ_0 called propagation angle of extraction. S is the parameter of the point of subsidence inflection [22]. It is a distance of roof overhanging in the goaf boundary. The subsidence inflection is shifting because of the roof overhanging.

Therefore, parameters of the PIM are q, b, $\tan\beta$, θ_0, and S; S is different in dip direction (S_1), rise direction (S_2), and strikes (S_3) and (S_4). Those eight parameters are all required in a mining subsidence calculation. The parameters are often obtained from back analysis of field survey results of subsidence in the nearby area.

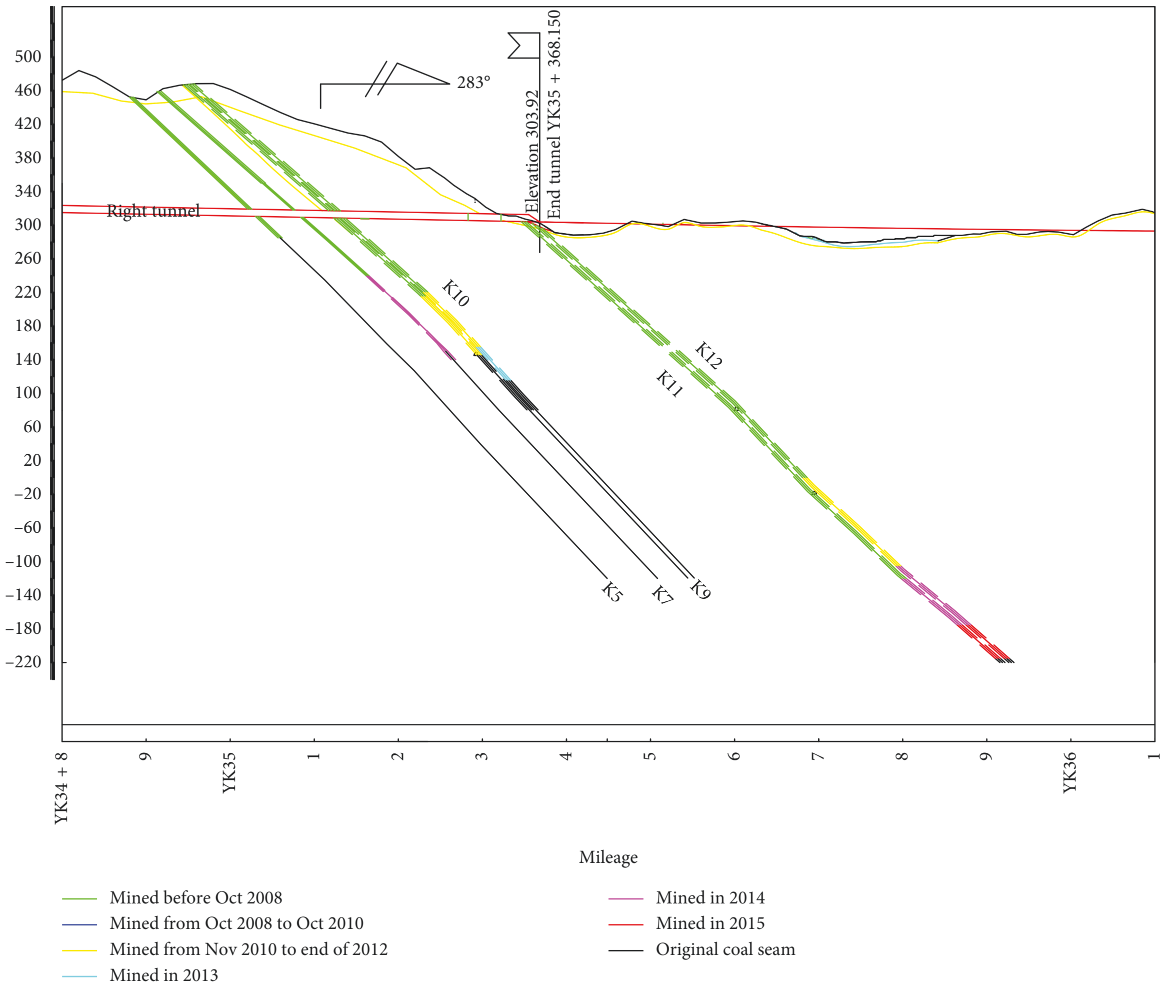


Figure 5: Section of right tunnel.

And the results of subsidence, tilt, curvature, horizontal displacement, normal strain are marked as W, i, K, U, and ε.

The PIM method is a semiempirical physical model. The parameters can be obtained from site survey data. In China, there are a lot of coal mines that have parameters that are closely linked with their own geological and mining conditions. Then, reliable mine subsidence and deformation can be obtained from parameters based on field measurement.

3.2. Parameters Used in BYS Tunnel Deformation Calculation. The XS and CR coal mines are located between Sichuan and Chongqing in western China. The coal seam dip angle is nearly 45°. A lot of research work in nearby area of Sichuan has been done. According to geological and mining method, the XS and CR are steep seam, medium overlaying hard rock coal mines. According to reference [21], the conditions are similar to those of Nantong Coal Mine of Sichuan area. The observed parameters can be found in [21, 23, 24], as shown in Table 1.

There are also empirical equations that can be referenced. According to the rock classification table in reference [21], the investigated area is medium hard rock overlaying, and the parameters of medium rock are $q = 0.55{\sim}0.85$, $\tan\beta = 1.92{\sim}2.4$, and $S = (0.08{\sim}0.3)H$.

θ_0 is a parameter to locate the subsidence position for dip coal seams. The CR and XS coal mines are both dip angle coal seams, so the θ_0 can be obtained from the following experience equation:

$$\theta_0 = 90^\circ - 0.68\alpha, \quad \alpha \leq 45^\circ. \tag{7}$$

3.3. Influence of Old Goaf. The mining history of the investigated area extends long before the tunnel was built. The tunnel crossed over old goaf. According to related research, nearly 99.8% of mine subsidence occurred within 2 ~ 3 years of coal excavation [25–28]. And some observations show that the residue subsidence of old goaf is often smaller than 5%~10% maximum subsidence [29].

BYS tunnel is located at a mine colliery with long history but the tunnel was only built in October 2010. In order to calculate the subsidence caused by underground mining, the problem was simplified to three stages.

First, ignore the subsidence influence of old goaf excavated before October 2008 which was 2 years before the tunnel was built.

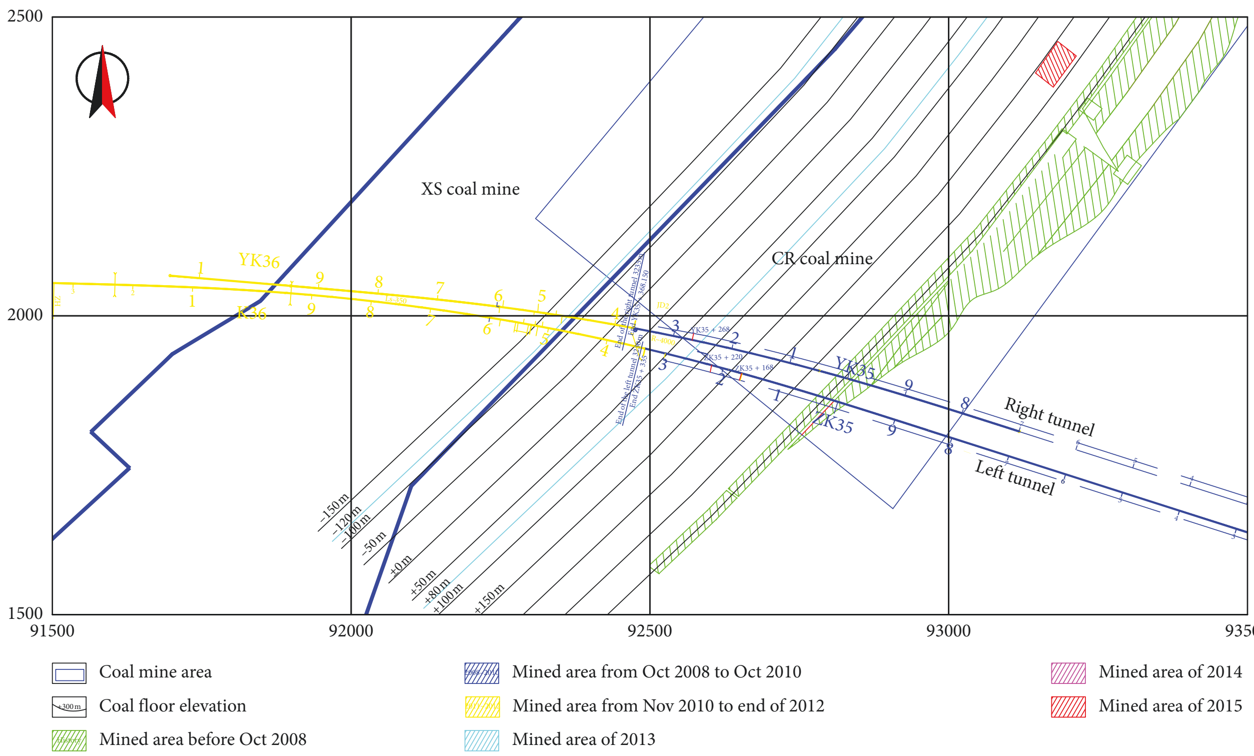


Figure 6: Coal mined area of K_5 seam.

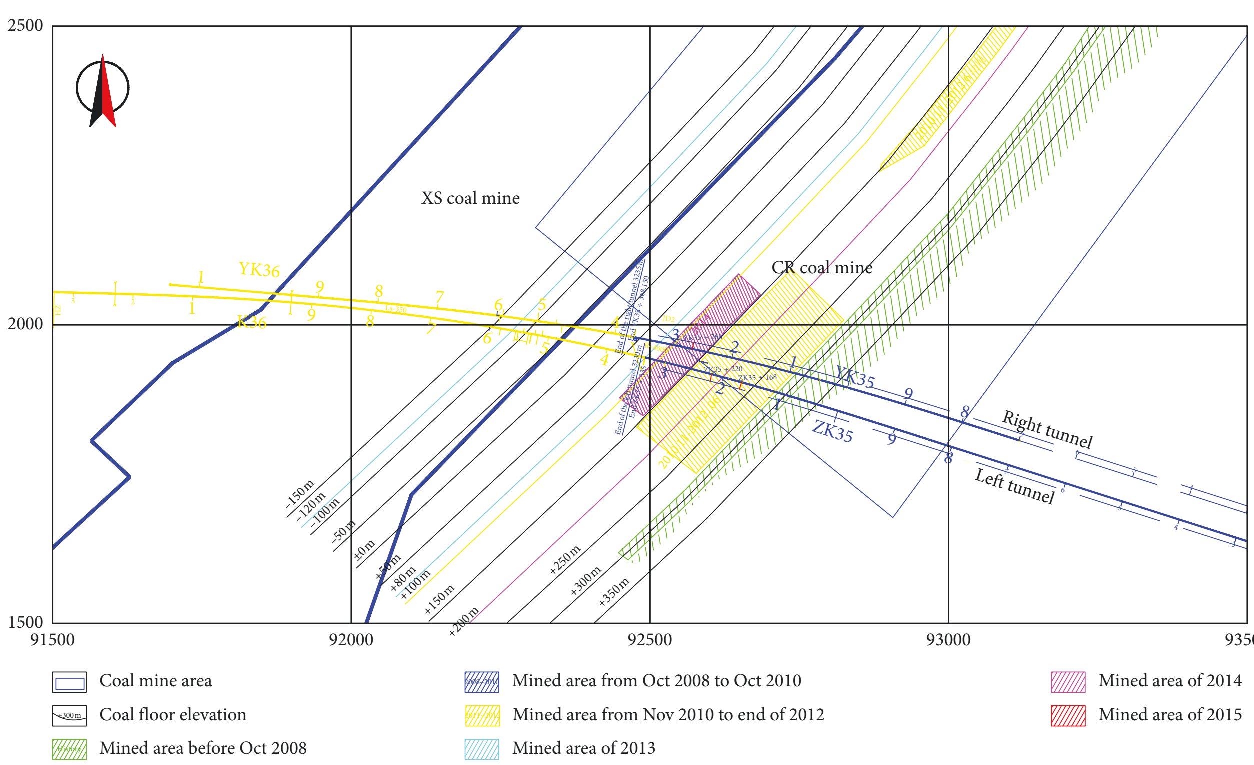


Figure 7: Coal mined area of K_7 seam.

Second, the influence between November 2008 and October 2010 seems as residues' subsidence; use 10% of the initial mining subsidence factor.

In the third stage, deformation caused by mining after the tunnel construction is completed (October 2010) should use the initial subsidence factor.

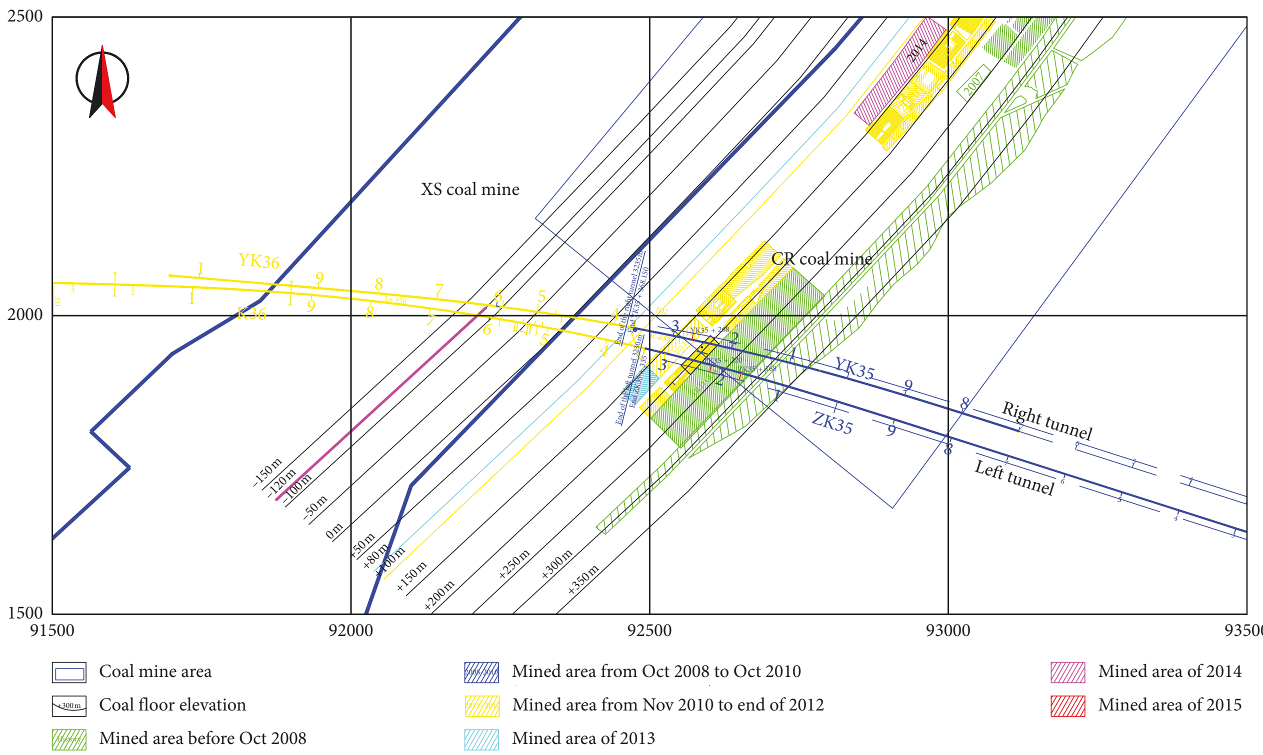


FIGURE 8: Coal mined area of K_9 seam.

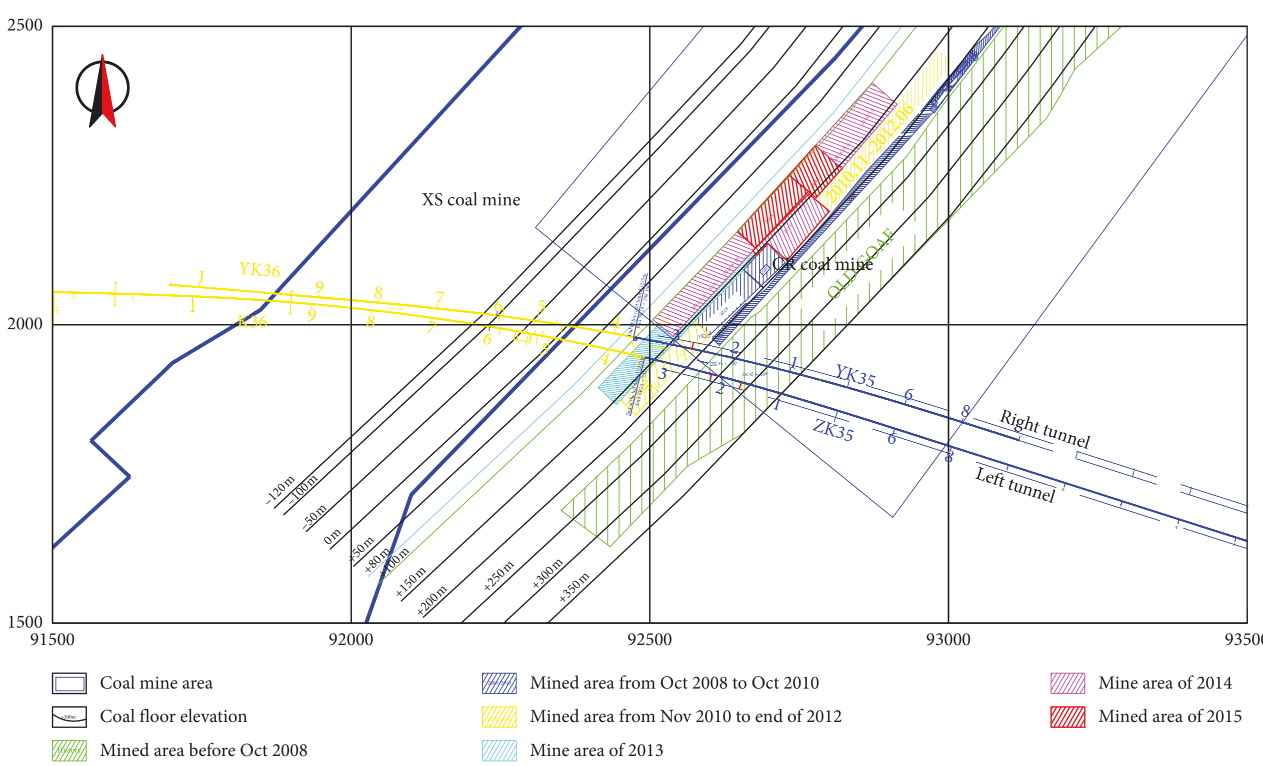


FIGURE 9: Coal mined area of K_{10} seam.

3.4. Influence of Multi-Seam. There are four coal seams in the investigated area. The influence of repeated mining should also be considered. The factor K is a parameter to evaluate repeated mining influence on the subsidence. For a repeat mining, the factor can be obtained from the following equation [20, 21, 30]:

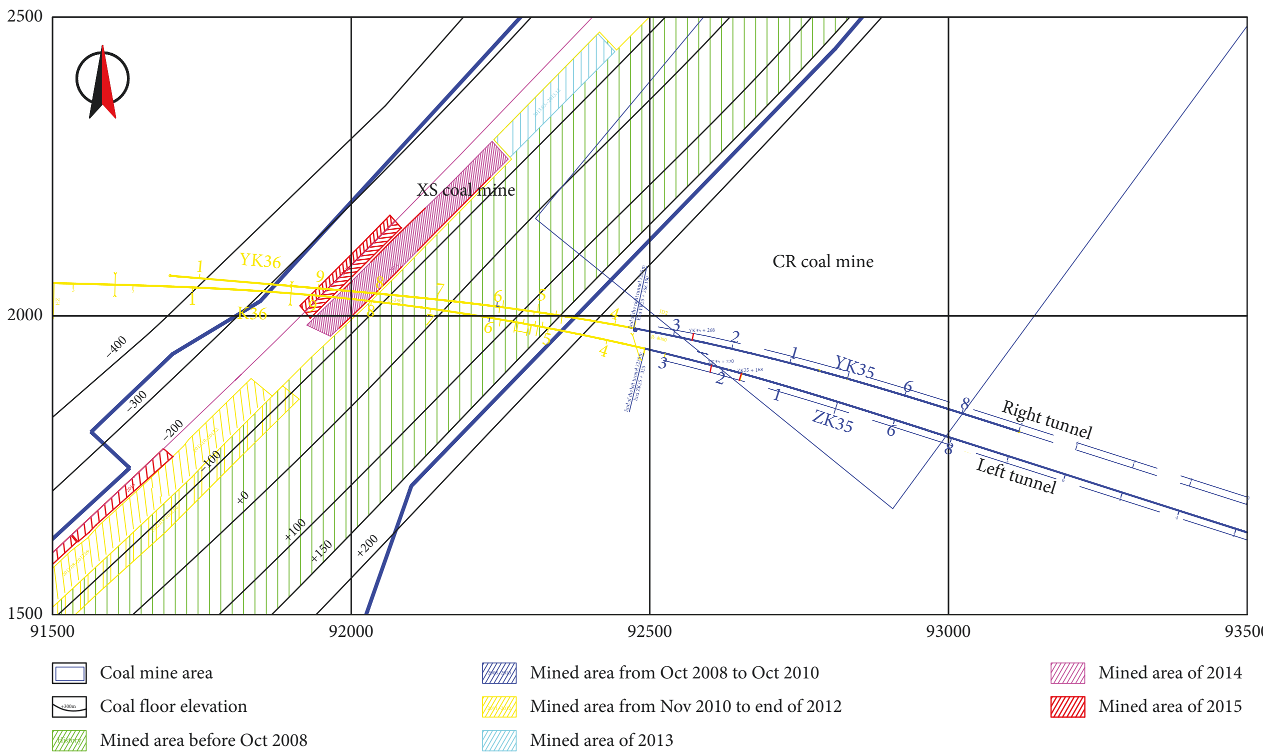


Figure 10: Coal mined area of K_{11} seam.

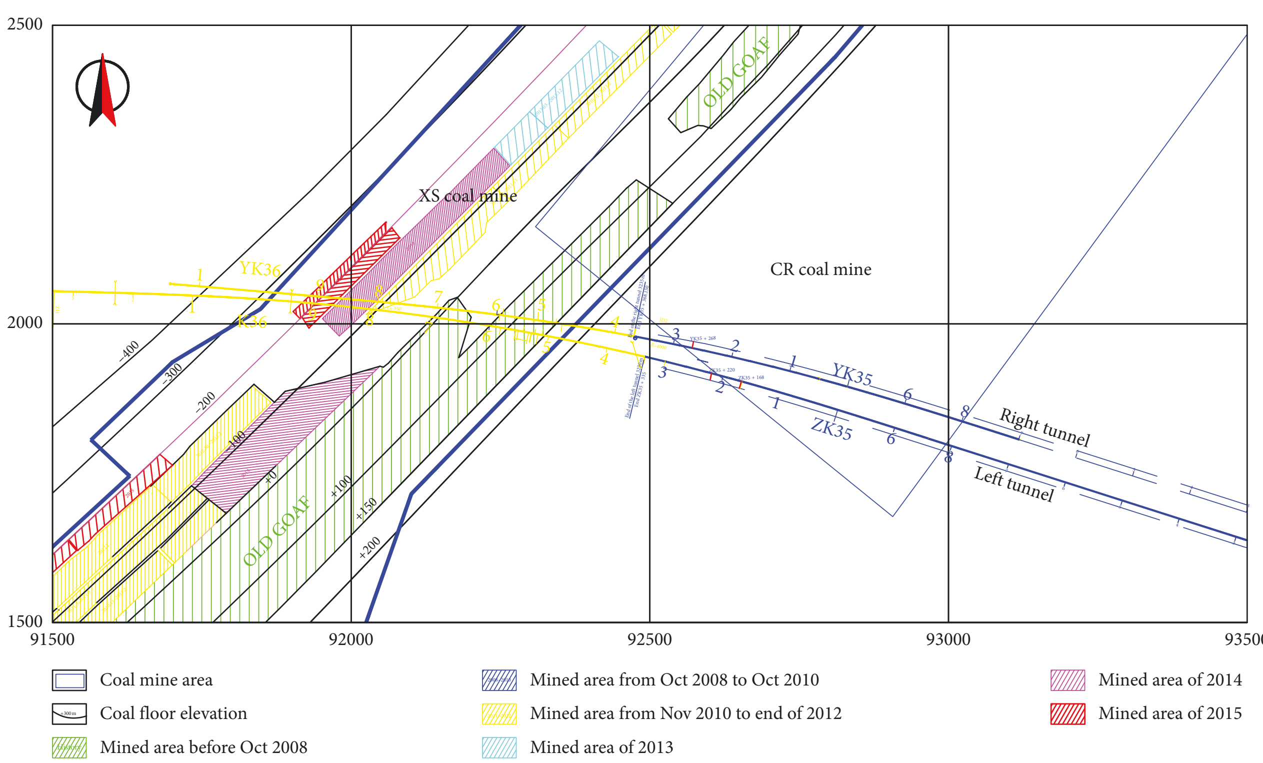


Figure 11: Coal mined area of K_{12} seam.

$$q_r = (1 + K)q, \tag{8}$$

where the repeat mining factor q_r always depends on the porosity of the failure rock; for this area $K = 0.1$ [31].

As shown in Figures 4 and 5, the K_5 coal seam has not been mined after October 2008. The mining of K_7 seam has influenced K_9 and K_{10} and will disturbed by K_5, so the K_7 coal seam is a repeat mining influence subsidence. K_9 and

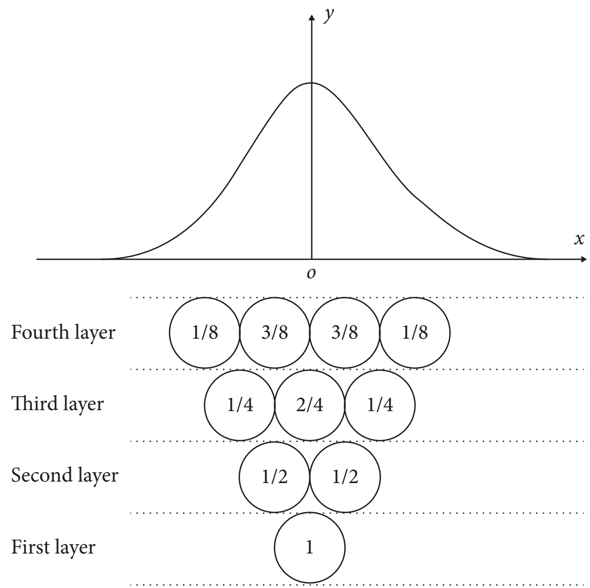


Figure 12: Theory of statistic model.

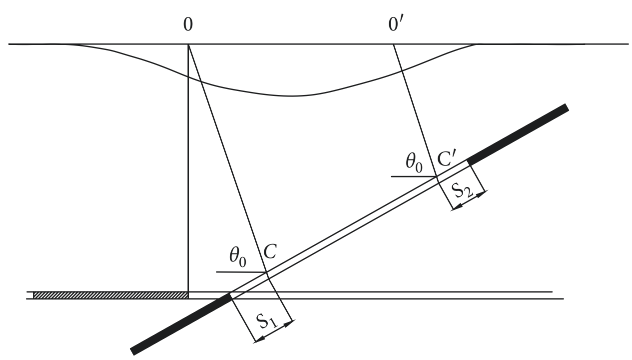


Figure 13: Diagrammatic sketch for PIM parameters of inclined coal seam (© reproduced from Li et al. [22] under the Creative Commons Attribution License (CC BY-NC-ND 4.0)).

Table 1: PIM parameters of Nantong Coal Mine.

Station	M (m)	q	b	$\tan\beta$	θ_0 (°)	S_1 (m)	S_2 (m)	S_3 (m)	S_4 (m)
2309	2.5	0.6	0.11	1.4				−0.18H	−0.31H
4106	3.0	0.6	0.17	1.5	73	+0.05H	−0.02H		
4305	3.0	0.6	0.23	1.3	80	−0.11H	+0.05H		
0362_Up	1.2	0.6		1.15	78	−0.16H	−0.19H		
0362_Down	2.5	0.6		1.45	78	−0.16H	−0.19H		

K_{10} were mined at almost the same time and do not influence the other coal seams, so use the initial subsidence factor. K_{11} and K_{12} are very close and were mined at the same time, so the factor of K_{11} and K_{12} also uses the initial subsidence factor.

3.5. Parameters Used. As in the analysis above, the PIM parameters selected are shown in Table 2.

3.6. Results. Using the method and parameters above, the tunnel deformation was calculated, as shown in Figures 14 and 15.

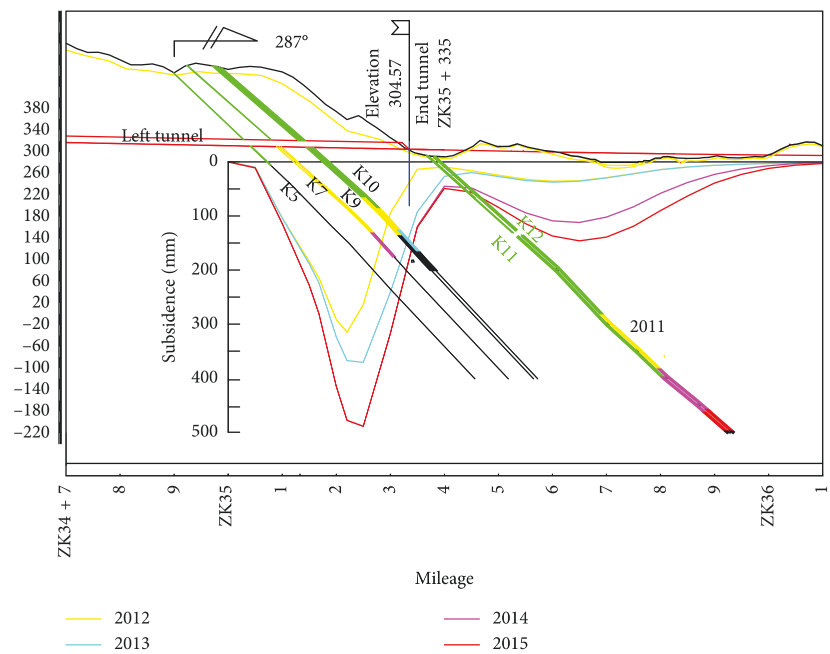
The results show the following:

(1) The Normal strain along the tunnel of ZK35 + 168 caused by 2013 coal mine was 2.06 mm/m and 2.61 mm/m by 2014 coal mine which is the biggest tensile strain of the investigated left tunnel. The tunnel lining was cracked in September 4 2014 after a torrential rain. The crack was 4 m high and 1 cm wide. The tunnel was damaged by the horizontal dilation.

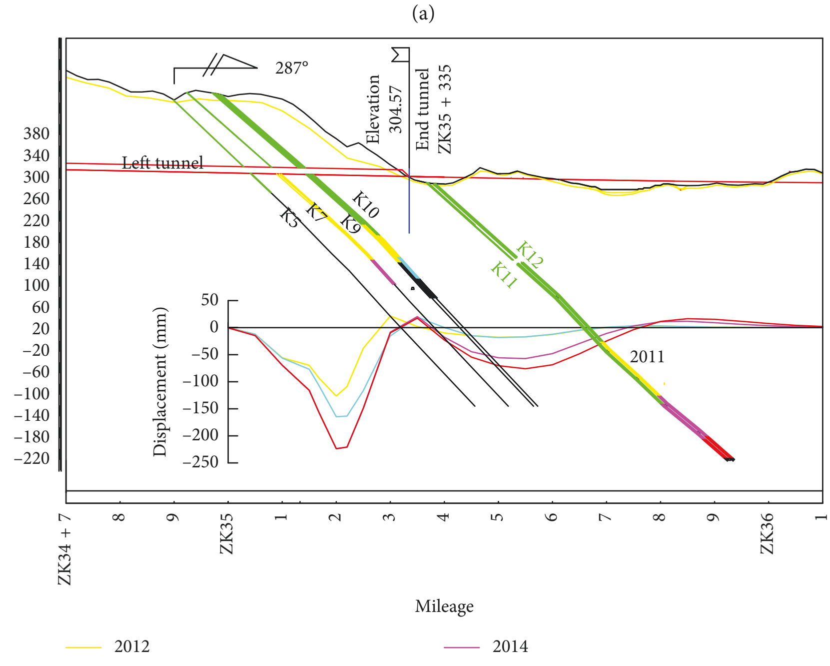
(2) The normal strain of YK35 + 268 was −1.12 mm/m with 2013 coal mine and −2.58 mm/m caused by 2014 coal mine which means the strain was compression

Table 2: PIM parameters used in calculation.

Excavation time	Coal seam	q	b	$\tan\beta$	θ_0	S_1	S_2	S_3	S_4
October 2008–October 2010	All	0.07	0.23	1.40	73°	0.05H	0.05H	0.05H	0.05H
After October 2010	$K_5, K_9, K_{10}, K_{11}, K_{12}$	0.7	0.23	1.40	73°	0.05H	0.05H	0.05H	0.05H
After October 2010	K_7	0.77	0.23	1.40	73°	0.05H	0.05H	0.05H	0.05H

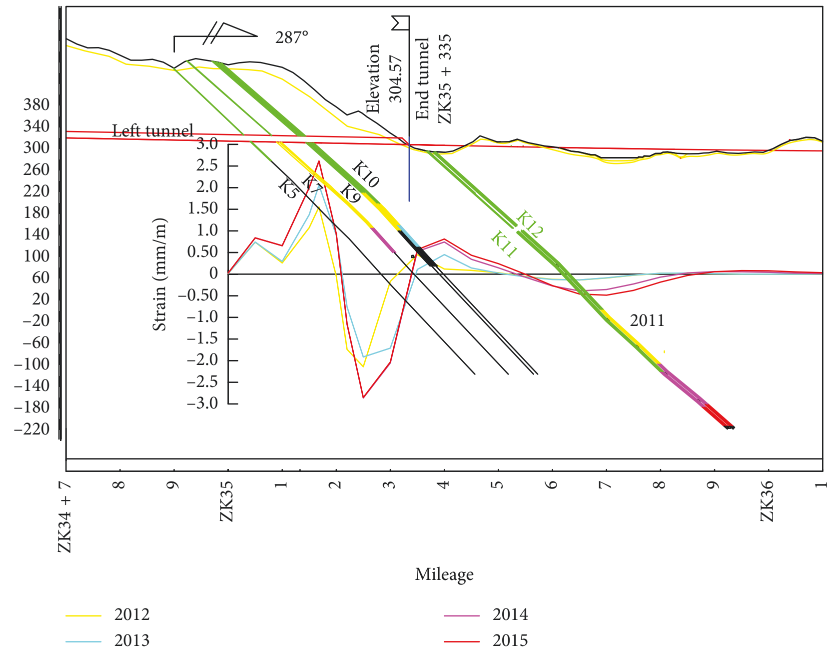


(a)



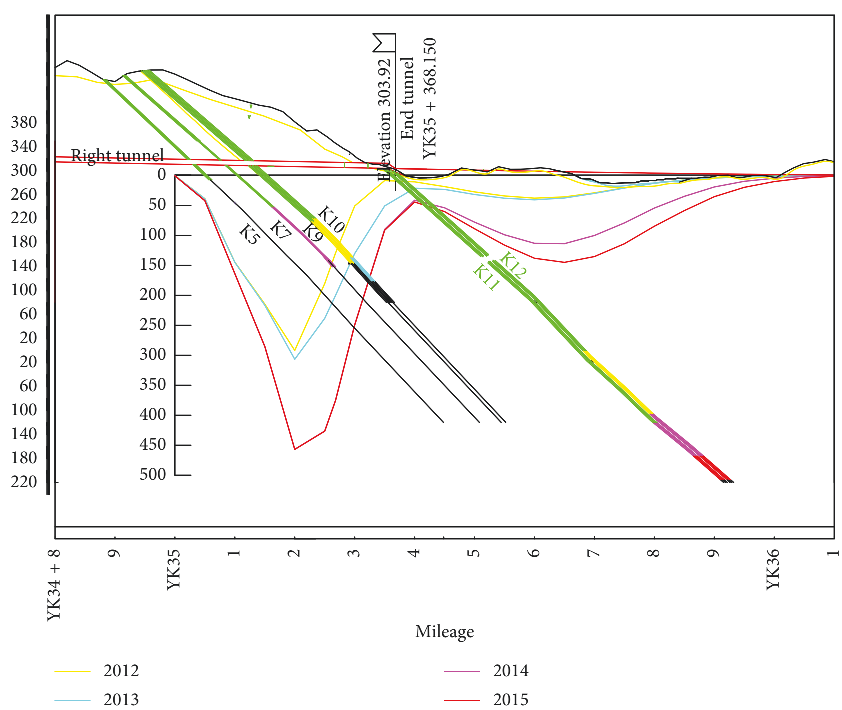
(b)

Figure 14: Continued.



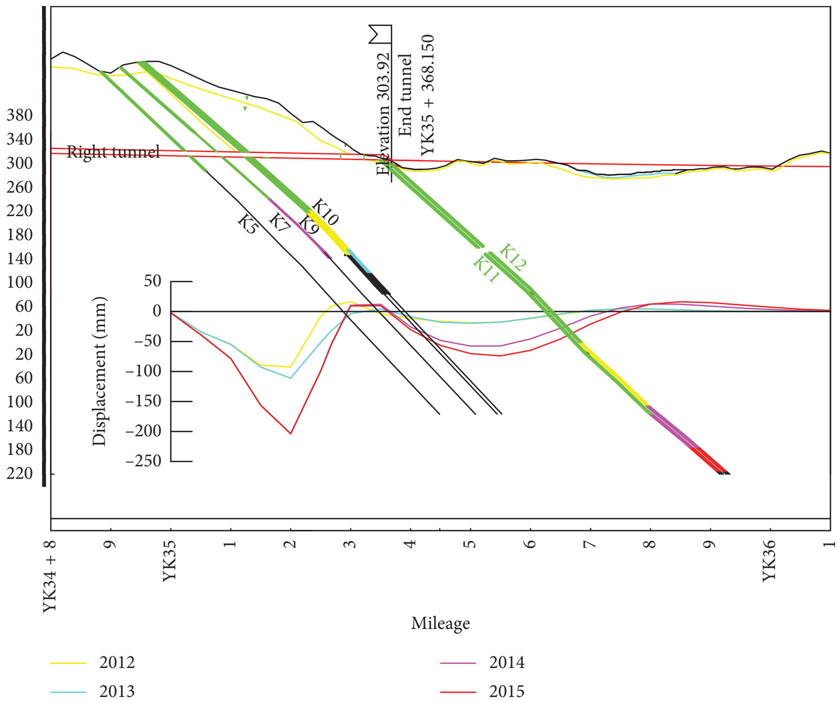
(c)

FIGURE 14: The left tunnel deformation. (a) Subsidence. (b) Displacement. (c) Horizontal strain along the tunnel.



(a)

FIGURE 15: Continued.



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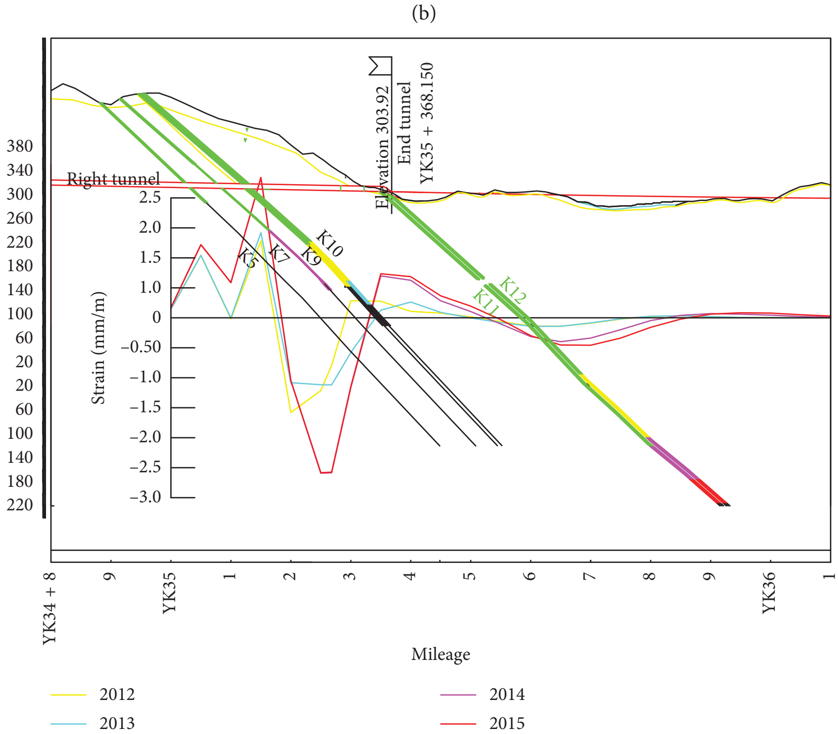


(c)

Figure 15: The right tunnel deformation. (a) Subsidence. (b) Displacement. (c) Normal strain along the tunnel.

deformation. The movement made the tunnel deformation joints join together and caused the tunnel concrete to collapse. In fact, the tunnel collapse on the second lining was 6 m high and 3 cm wide.

(3) The results show that the road of ZK35 + 350 to ZK35 + 500 was stretching, and it increased every year. With this correspondence, the crevice of the road area was ZK35 + 450 to ZK35 + 490.

(4) At ends of the both tunnels, the deformations were compression. And the damage of floor heave problem was obvious; the maximum heave value was 15 cm. And it caused the vehicles to skip up and down.

(5) In summary, the calculated tunnel deformation mainly happened between ZK35 + 100 to ZK35 + 300 of left tunnel and YK35 + 150 to YK35 + 300 of right tunnel. And the calculated results coincide with the damage and deformation phenomenon of the tunnel. It is a good proof for the calculated result.

3.7. Tunnel Deformation Prediction in Case of All Coal Resource Excavated. In order to evaluate the deformation influence of future mining, it is proposed that all coal resources of both collieries be excavated. The results are shown in Figure 16.

As shown in Figure 16, the subsidence, horizontal displacement, and normal strain along the tunnel will increase with the resource excavated for the future. The normal strain in this area has two forms.

The stretching areas are ZK35 + 000 to ZK35 + 200, YK35 + 000 to YK35 + 190, and YK35 + 340 to exit of right tunnel. For the stretching area, the tunnel lining will be fractured and the cement will be cracked. The road of the stretching area also will be damaged with some crevices.

The compression area is ZK35 + 200 to exit of left tunnel and YK35 + 190 to YK35 + 340. The damage forms of compression are deformation joints joined together, the lining, and the road lifted up.

4. Multiple Reasons Influence the Tunnel Stability

With the analysis, the underground mining is the major reason to cause the tunnel to be damaged and cracked. But there are other reasons like old goaf, underground water, and dynamic load of vehicles which also have important influence on the safety of the road and tunnel.

4.1. Old Goaf Influence. The overlaying rock of the goaf can be divided into three zones according its crack characteristics: the all caved zone, the fissure zone, and the sagging zone, as shown in Figure 17.

The caved zone: after the coal was excavated, the roof will break, crack, and cave into the goaf. The caved rock with different size will heap up in the goaf. Those rocks break up with a lot of gaps and compressible space. The borehole core shows that the rock of old goaf is very shattered. It shows that there are a lot of rock spaces in the old goaf. Those spaces will be the original source of surface deformation. With the disturbance of water and dynamic load of the vehicles, the old goaf will be compressed and the rock deformation scope will enlarge to the tunnel.

The fissure zone: the fissure zone is located up the caved zone. The rock is bent, deformed, and cracked but can keep in bedded structure. There are a lot of fissures both along and perpendicular to the bed plane. The cracked fissures are smaller in the up seam than in the down seam.

The sagging zone is located up the fissure zone and up to the surface. The sagging zone's deformation characteristic is subsidence and bending. The rock has fewer fissures. But there is also abscission between different rock seams.

The caved zone and the fissure zone can be described together as the caved fissure zone which contains space for the future rock redisplacement and deformation.

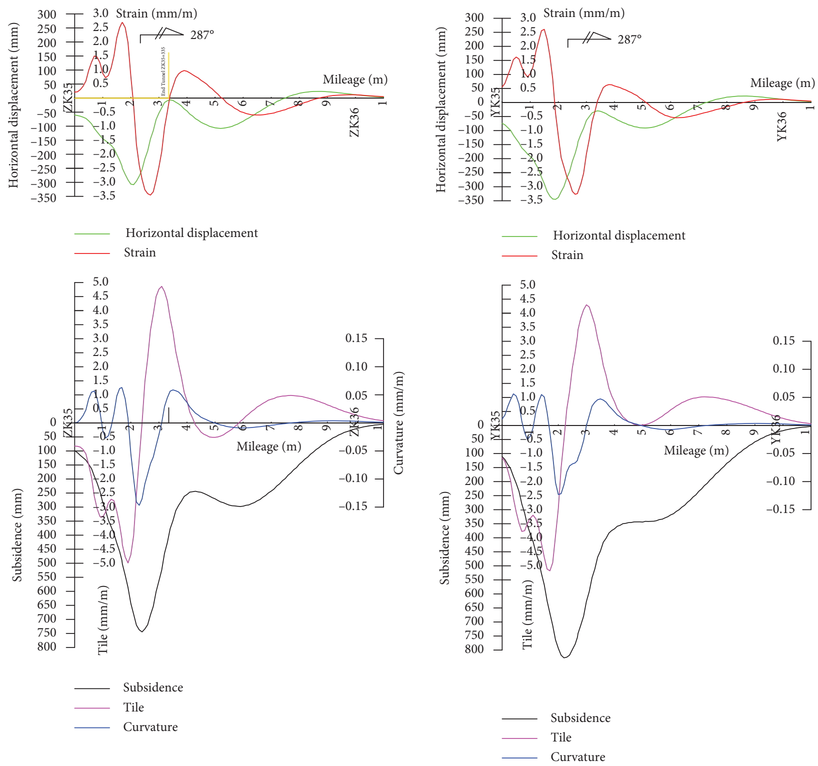
4.2. Water. The BYS tunnel damage happened in the raining season or after a torrential rain. Although the original deformation comes from the underground mining, the water activity is also an important induction factor. The water can weaken the rock strength and damage the weak interpolated layer. The water also causes additional stress on the tunnel lining.

4.3. Vehicle Dynamic Load. The vehicles have dynamic load when run on the road and can make shock waves. There is a lot of research and surveys showing that the traffic load has a limited depth of influence and tapers out at a certain depth [32–35]. For the tunnel that crosses over the $K_5K_7K_9, L_{10}$'s old goaf, the long-term dynamic traffic load can change and redistribute the cracked rock. So, the vehicle activity load is another risk for tunnel damage and sudden collapse. To keep tunnel stability, the old goaf should be reinforced and the reinforced scope should be deeper than the vehicle load.

5. Grouting Injection Measure to Reinforce the Goaf

The underground mining, water, and dynamic load can cause tunnel damage or a sudden collapse of the road. Both damages occurred on the tunnels and roads have great risk influence on the traffic safety. With the evaluation of tunnel deformation, safety, and economy, the government decided to close the two collieries and repair the tunnel in September 2016 [36]. There is little research on ways to deal with the highway crossing over the old goaf. For the small mine depth, the goaf can be rammed with great power strength; for the deep old goaf, grouting injection filling is the best way. At the same time, the surrounding rock can be reinforced by grouted materials [37]. The BYS tunnel crosses over the goaf with a small mine height and a dipping coal seam. There is little space for construction engineering in the tunnel. So, grouting to reinforce the rock under the tunnel is the best way. There are two reasons which should be considered for the grout depth and scope: height of caved and fissure zone in old goaf and the dynamic load of the traffic. The grout reinforcement should keep the caved fissure zone from being disturbed by the dynamic load.

5.1. Height of the Caved Fissure Zone. The grout reinforcement should be overlaying all the cracked rock directly under the tunnel, so the height of the caved fissure zone is very important. There are two experience equations for caved zone height, as shown below [21, 38]:



(a) (b)

Figure 16: Tunnel deformation in condition of all coal resource excavated. (a) Left tunnel. (b) Right tunnel.

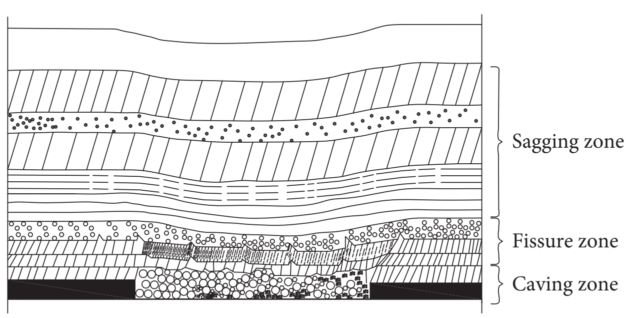


Figure 17: Three zones of overlaying rock deformation.

$$H_c = \frac{M}{(K_c - 1) * \cos\alpha}, \quad (9)$$

$$H_c = \frac{100\sum M}{4.7\sum M + 19} \pm 2.2, \quad (10)$$

where H_c is the height of caved zone of old goaf (m); M is the mine height (m); α is the angle of the coal seam (°); and K_c is the direct roof rock volume expansion coefficient, where K_c has a relationship with the rock uniaxial compression strength [39], $K_c = 1 + 0.05\sqrt{\sigma_1}$, where σ_1 is the roof uniaxial compression strength (MPa). The uniaxial compression strength of sand rock for coal seam roof is 41 MPa, then, $K_c = 1.32$. There are also two empirical formulas for fissure zone height, as shown below [20]:

$$H_f = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6, \quad (11)$$

$$H_f = 20\sqrt{\sum M} + 10, \quad (12)$$

where H_f is the fissure zone height (m). With those four equations, the caved zone height and fissure zone height can be obtained as shown in Table 3.

5.2. Dynamic Traffic Load Influence on Depth. A lot of measured research studies show that the dynamic traffic load has influence on the road and must be considered in highway design [32, 34, 40]. Liu et al. have given a load of different sized cars, as shown in Table 4 [33].

Table 3: The caved and fissure zone height.

Coal seam	M (m)	H_c equation (9) (m)	H_c equation (10) (m)	H_f equation (11) (m)	H_f equation (12) (m)	Maximum (m)
K_5	0.24	1.06	3.39	11.62	19.80	23.19
K_7	0.23	1.02	3.35	11.40	19.59	22.94
K_9	0.33	1.46	3.81	13.59	21.49	25.29
K_{10}	0.48	2.12	4.46	16.59	23.86	28.31

The dynamic load can cause the road above the goaf to suddenly collapse. Then, the reinforcement should cover all the dynamic load influence area of broken rock surrounding the tunnel. Liu et al. [33] and Tang et al.'s [35] research studies indicate that the depth of the influence reduced fast and will taper out in certain depth. The stress of vehicle dynamic load can reduce more than 90% in 8 ~ 10 m depth and lose in 10 ~ 20 m. So, in order to reduce the long-term dynamic influence, the grouting depth should be more than 20 m.

Considering the rock stability, safety, and economical cost, the drill depth was designed to be 30 m. In order to keep safety, the reinforced scope starts from 30 m prior K_5 and ends until 30 m after K_{10} coal seam's caved fissure zone. The vertical section, cross section, and ichnography plan of grouting drill are shown in Figure 18.

Table 4: Vertical stress of roadbed of 5 different size vehicle loads.

Size	Micro	Small	Middle	Bigger	Super
Load (t)	1.25	5.0	10.0	25.0	50.0
Dynamic stress (KPa)	1.2	3.0	4.9	9.7	15.8

6. Discussion

Construction on the old goaf is a difficult and high-risk problem. It is an interdisciplinary subject which involves civil engineering, underground coal mine, rock mechanical, etc. The tunnel crossing over the old goaf is even more difficult than simple construction, for it has several characteristics.

(1) The tunnels or highways are high safety requirement objects. The subsidence of coal mine or old goaf can change the curve and also cause sudden collapse of the road surface and will put the traffic at high risk.

(2) The tunnels or highways are linear objects. Those are sensitive to normal strain deformation especially tensile strain. The road construction can be cracked by the subsidiary stress of underground mining.

(3) Tunnels often are transport hubs but difficult to maintain. They should be constructed in a narrow construction space and with high cost.

(4) There is no reliable theory or model to interpret the cooperative motion mechanism between tunnel, rock, and old goaf. It is difficult to predict the tunnel deformation accurately.

This paper provides a method to calculate the tunnel deformation using experience mine subsidence method and an ordinary engineering method to calculate the grouting scope and depth according to old goaf cracked zone and dynamic load influence of the road. It can be used on an engineering-decision basis to deal with such problems, but there are more questions for further research. These questions deal with the following issues:

(1) The tunnel antideformation ability needs to be enhanced. If the tunnels are obliged to cross over the old goaf area, to construct an antideformation tunnel is the first choice. The deformation calculation protection is a complex problem that has a relationship with tunnel lining, surrounding rock, caved zone, and environment elements.

(2) The long term deformation law of old goaf needs more research. The old goaf deformation has an important relationship with the geological condition, coal mining method, geometry, underground water, etc. It is a difficult problem in tunnel engineering.

(3) Health evaluation of tunnel deformation needs more research. The traffic safety and construction health evaluation should consider the tunnel strength, deformation, surrounding rock, changes in old goaf, and even weather conditions. It is a challenging problem.

(4) The old goaf handling method also needs more research. At present, the most used method is grouting injection to fill the goaf or to reinforce the cracked rock. But the effect depends on the grouting method, area, quantity, geological conditions, coal mining method, etc. How to deal with the old goaf needs a breakthrough in thinking. The question is a dynamic system of vehicle, tunnel and its support, surrounding rock, and goaf condition.

In order to keep the BYS tunnel safe, the government decided to close the collieries and grouting to reinforce the tunnel and its surrounding rock. The project changed the mechanical property of the surrounding rock and improved the safety conditions of the tunnel.

7. Conclusion

(1) The probability integral method was used to evaluate the deformation of the tunnel underground mining. The calculated result shows that the damaged positions are closely related to maximum normal strain of the tunnel. Underground mining deformation induced the tunnel damage chiefly. The probability integral method is a reliable choice to calculate the underground mining tunnel deformation.

(2) Tunnels cross over the goaf as in the BYS case. The interrelationship between surrounding rock

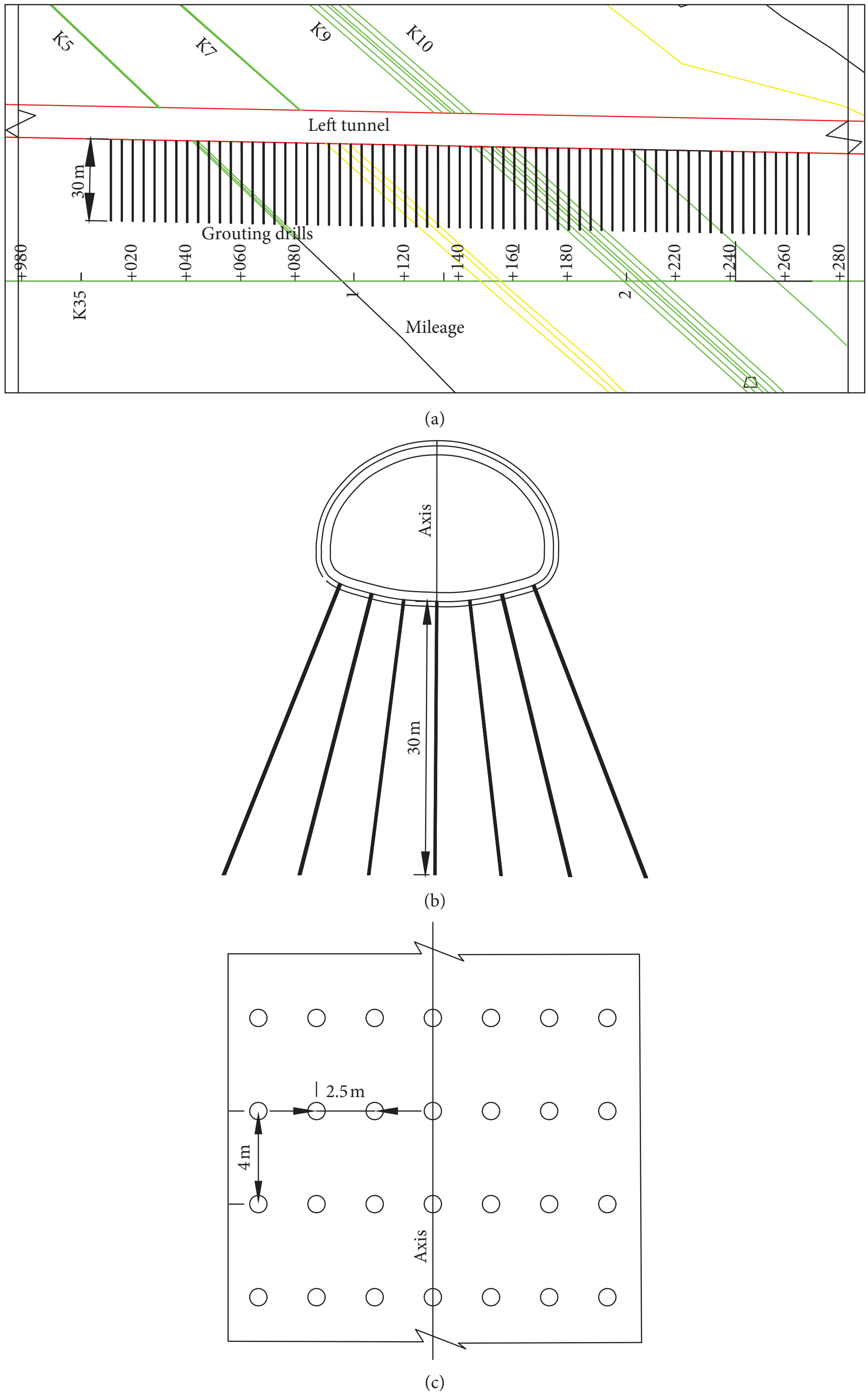


FIGURE 18: The grouting drill design drawing. (a) Vertical section. (b) Cross section. (c) Ichnography.

redistribution and long-term dynamic vehicle load has a high risk of sudden collapse. In order to reinforce the tunnel, the height of the caved fissure zone and the influence depth of the dynamic traffic load should be considered together.

(3) Closing the collieries and grouting to reinforce the goaf and overlaying rock are two main measures to be taken. One measurement can stop the new increasing deformation from excavation. And the grouting injection can reinforce surrounding rock of the tunnel and reduce the long-term deformation from old goaf. It can improve the safety condition of the tunnel, but the dynamic and complex system of tunnels, surrounding rock, goaf and vehicle load, etc., needs more research in the future.

Data Availability

Raw data were generated at China University of Mining and Technology (Beijing). Derived data supporting the findings of this study are available from the corresponding author on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Peixian Li and Lili Yan calculated and analyzed the tunnel deformation. Peixian Li and Dehua Yao calculated and designed grouting. Peixian Li and Dehua Yao worked on the tunnel damage analysis. Peixian Li completed the writing of the paper. All authors reviewed the manuscript.

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