WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2026.157477

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXII ISSUE 1 2026

 pp. 331 – 345

Research paper

Influence of Alkali injection treatment on the deformation of tunnel surrounding rock rich in H_2S

Xiaoqing Suo[1], Zhi Wang[2], Xuefu Zhang[3], Dan Qiao[4], Yuanfu Zhou[5]

Abstract: Alkali injection treatment is a key method for stabilizing surrounding rock containing H_2S. To examine the deformation of surrounding rock with and without coal seams under different excavation methods and Alkali injection treatments, the finite difference method for single-hole Alkali injection, double-side-wall excavation, and three-bench excavation is simulated. The results indicate that, under the same excavation method, compared with no Alkali injection, the displacement of the vault increases by 23.37% to 24.33% for a 3% Alkali concentration and by 34.55% to 42.70% for a 5% concentration. The horizontal convergence of side walls increases by 18.20% to 25.53% for a 3% Alkali treatment and by 46.20% to 61.08% for a 5% Alkali treatment. When two coal seams tilt through the working face, the deformation of the lower layer is more significant than that of the upper. The greatest deformation occurs at the intersection of the lower layer and the excavation line. Under different Alkali injections, compared with the three-bench excavation method, the vault settlement of the double-side-wall excavation method decreases by 7.65% to 11.37% and the horizontal convergence of sidewalls decreases by 22.80% to 72.27%. When the surrounding rock contains coal seams and is treated with Alkali injection, it is recommended to use the double-sided excavation method.

Keywords: Alkali injection, hydrogen sulfide tunnel, surrounding rock deformation, three-bench excavation, double-side-wall excavation

[1]PhD., School of Civil Engineering, Chongqing Jiaotong University, Chongqing, 400074, China, e-mail: xiaoqing@163.com, ORCID: 0009-0002-2413-4671
[2]PhD., Beijing ZhongjiaoQiaoyu Technology Co., Ltd., Beijing, 100102, China, e-mail: w2023_423@163.com, ORCID: 0009-0004-8494-390X
[3]Prof., 1) School of Civil Engineering, Chongqing Jiaotong University, Chongqing, 400074, China; 2) Institute of Future Civil Engineering Science and Technology, Chongqing Jiaotong University, Chongqing, 400074, China, e-mail: zhangxuefu400074@126.com, ORCID: 0000-0002-9387-7527
[4]Associate Prof., School of Transportation and Municipal Engineering, Chongqing Jianzhu College, Chongqing, 400072, China, e-mail: vh24435662qiaog@126.com, ORCID: 0009-0008-8477-4551
[5]Prof., 1) School of Civil Engineering, Chongqing Jiaotong University, Chongqing, 400074, China; 2) Institute of Future Civil Engineering Science and Technology, Chongqing Jiaotong University, Chongqing, 400074, China, e-mail: mail5, ORCID: 0000-0002-0326-2351

1. Introduction

As highway and railway tunnel construction rapidly expands in China, harmful gases such as methane, hydrogen sulfide and radon often leak during tunnel excavation. These toxic gases are unpredictable and pose a serious threat to health, even cause sudden combustion or explosions, seriously disrupting tunnel construction progress and threatening worker safety. Hydrogen sulfide overflow incidents have occurred in tunnels such as the Zagros [1], Micangshan [2] and Hongdoushan [3]. On-site workers have experienced varying degrees of hydrogen sulfide poisoning [4] or fatalities [5], resulting in serious delays in construction. Effective treatment measures include strengthening ventilation, Alkali dilution [6], alkali injection to neutralize sulfur [7], adsorption with activated carbon [8, 9], and treatments involving hydrogen peroxide [10] or iron chlorides/oxides [11]. Alkali injection is one of the most effective methods for neutralizing hydrogen sulfide gas. However, the alkaline solution alters the pore structure and mineral composition of the rock surface, leading to the formation of secondary precipitates and affecting the microstructure of surrounding rock [12]. The mechanical properties of surrounding rock change after Alkali injection, affecting its deformation.

Most researches on Alkali injection mainly focus on sulfur fixation mechanisms, optimization of lye concentration and mix ratios, injection pressure and hole layout [13]. The effect of Alkali injection on tunnel deformation and stability is limited. Taking a tunnel in southwestern China as an example, the diffusion range and parameters of single-hole Alkali injection are analyzed using the FLAC3D numerical simulation software. The displacement of key monitoring points such as vault settlement and horizontal convergence under different Alkali injection treatments is analyzed. In addition, the changes in the displacement of key monitoring points under different working conditions, including the surrounding rock with and without coal seams, as well as the three-step method and the double-sidewall heading construction method are compared. The results can provide a foundation for the prevention and control of hydrogen sulfide in similar tunnel construction.

2. Materials and methods

2.1. Project overview

The selected tunnel in southwestern China has a left tunnel of 5265 m and a right tunnel of 5275 m, as well as a maximum burial depth of 531 m. The tunnel passes through challenging geological conditions, including fault fracture zones, karst strata and karst water, coal seams, and goaf areas. The surrounding rock contains toxic gases such as hydrogen sulfide, methane, carbon dioxide, and carbon monoxide. The gas concentration reaches as high as 7%. There are two different coal seams on the working face (as shown in Fig. 1), which slope from left to right. The main support consists of airtight fiber shotcrete, reinforced mesh, and an I-beam steel frame. The airtight fiber shotcrete is grade C25, with a thickness of 30 cm. The reinforced mesh has a longitudinal and lateral spacingof 20 cm, as well as a bar diameter of 8 cm. The I-beam steel frame consists of 22b H-beams, with a spacing of 50 cm. The secondary lining is made of C40 grade corrosion-resistant and airtight reinforced concrete with a thickness of 60 cm.

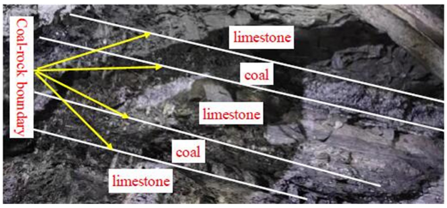


Fig. 1. Coal seam at the working face

2.2. Parameters of Alkali injection holes

Based on the tunnel design, the radius of the alkali injection hole is 5 cm and the injection pressure is 1.5 MPa. The alkali injection into each hole takes 30 minutes. Geological survey data shows that the permeability coefficient of the surrounding rock is 2×10^{-9} m/s, and the porosity is 1.64%. First, numerical simulation is used to analyze the diffusion range of alkali solution around a single injection hole assuming symmetry and neglecting gravity. Then a 1/4-circle model with a radius of 3 m is established based on Darcy's law of seepage, and a single Alkali injection hole (a radius of 5 cm) is placed at the center of the circle (Fig. 2). The influence of chemical reaction between the Alkali solution and H_2S, as well as Alkali concentration on the diffusion is neglected. The results shown in Fig. 3 indicate that the pore pressure decreases as the distance from the Alkali injection hole increases. At a distance of 1.8 m from the hole, the pore pressure is zero. Therefore, the diffusion range of the Alkali solution around the injection hole is 1.8 m. Based on grouting experience, the spacing between Alkali injection holes is set to 1.5 times of the influence. The spacing between the Alkali injection holes is 2.7 m, and a total of 25 Alkali injection holes are arranged on the working face (Fig. 4).

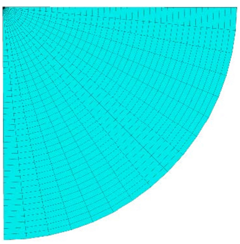


Fig. 2. Model of a single Alkali injection

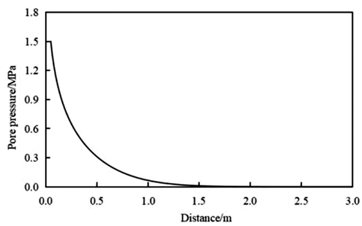


Fig. 3. Variation in pore pressure along the radial direction of the Alkali injection hole

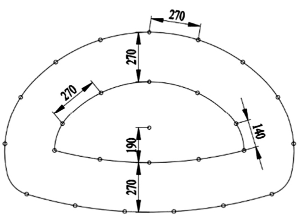
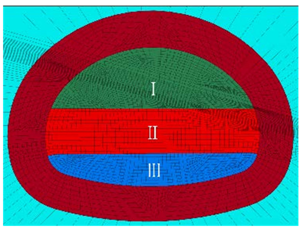


Fig. 4. Arrangement of Alkali injection holes on the working face (units: cm)

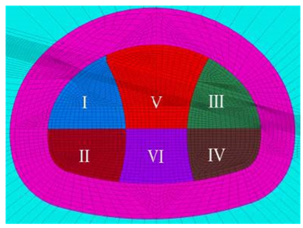
2.3. Numerical model and working conditions

(1) Numerical model

To minimize boundary effects, the upper and lower boundaries of the numerical model are set at a distance of 40 m from the tunnel excavation contour, while the left and right boundaries are set at 60 m. The upper boundary is free, and other boundaries are constrained by normal displacement. Based on the numerical simulation results of single-hole Alkali injection, a radial influence area of 2.7 m is established (Fig. 3). The mechanical properties of the surrounding rock in this influence area differ from those in other areas. The three-bench excavation method and the double-side-wall heading excavation method are simulated, and their excavation steps are shown in Fig. 5. There are seven displacement monitoring points, as shown in Fig. 6. Point A is located at the tunnel vault; points B, C, E, and F are positioned at the intersection of the coal seam and the tunnel excavation contour. Points D and G are placed on the left and right tunnel walls, respectively, to monitor the horizontal convergence.



(a)



(b)

Fig. 5. Sequence of two excavation methods: (a) Three-bench excavation method; (b) Double-side-wall heading method

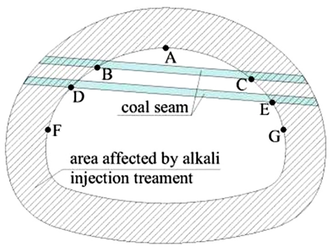


Fig. 6. Layout of displacement monitoring points

(2) Calculation parameters

Assuming the surrounding rock follows the Mohr–Coulomb constitutive model, the first supporting structure is modeled as an elastic material. The equivalent method is used to explain the role of the reinforced mesh and the I-beam steel frame in the first supporting structure system [14]. We investigate the effect of 3% and 5% sodium carbonate solutions on limestone and coal for 24 h. The laboratory tests show that after Alkali injection, the mechanical properties of limestone and coal seams are decreased by 33.75% and 53.96%, respectively. The calculation parameters for the surrounding rock and first supporting structure are shown in Table 1.

Table 1. Calculation parameters

Classification of surrounding rock	**Unit weight (kg/m^3)**	**Elastic modulus (GPa)**	**Poisson ratio**	**Cohesion (MPa)**	**Friction angle (°)**
Limestone	2300	5	0.3	0.6	35
Limestone (3% concentration of Alkali injection treatment)	2300	3.31	0.35	0.4	23.19
Limestone (5% concentration of Alkali injection treatment)	2300	2.32	0.4	0.28	16.21
Coal	1700	1.2	0.35	0.1	25
Coal (3% concentration of Alkali injection treatment)	1700	0.8	0.4	0.07	16.56
Coal (5% concentration of Alkali injection treatment)	1700	0.56	0.45	0.05	11.58
First supporting structure	2500	25.57	0.2		

(3) Working conditions

12 working conditions are examined, as shown in Table 2. The working conditions include the three-bench excavation and double-side-wall heading excavation methods, with surrounding rock either containing coal seams or not. The study also takes into account the surrounding rocks without Alkali injection treatment, as well as those treated with 3% and 5% sodium carbonate solutions for Alkali injection.

Table 2. Working conditions

Number	**Excavation methods**	**Alkali injection conditions**	**Coal seam**
1	Three-bench excavation method	Without	Without
2		3% concentration	
3		5% concentration	
4		Without	With
5		3% concentration	
6		5% concentration	
7	Double-side-wall heading method	Without	Without
8		3% concentration	
9		5% concentration	
10		Without	With
11		3% concentration	
12		5% concentration	

3. Numerical model calculation results and analysis

3.1. Deformation evolution around the tunnel under the three-bench excavation method

(1) Deformation of monitoring points during each excavation step under different Alkali injection conditions when there is no coal seam in the surrounding rock

When there is no coal seam in the surrounding rock, the deformation of monitoring points A, D and G after each excavation step under different alkali injection conditions is shown in Fig. 7. The vault settlement is the largest under Alkali injection conditions. Fig. 8 shows the displacement increments with and without Alkali injection after each step using the three-bench excavation method when there is no coal seam in the surrounding rock. During the upper excavation process, the vault displacement increases by 30.57% and 47.51% under conditions 2 and 3, respectively. After the middle and lower excavations, the vault displacement increases by 23.79% and 23.37%, respectively under a concentration of 3% Alkali solution, and by 37.37% and 36.81%, respectively under a concentration of 5% Alkali solution. The horizontal displacement of the left and right walls increases by 14.29–17.41% and 18.97–22.45%, respectively under a concentration of 3% Alkali solution, and by 44.40–232.97% and 47.96–237.76%, respectively under a concentration of 5% Alkali solution. The horizontal displacement of the left and right walls exceeds that of the vault, as the mechanical properties decrease more significantly under a concentration of 5% Alkali solution compared to a concentration of 3% alkaline solution. In this case, the horizontal displacement is significantly influenced by the tunnel height.

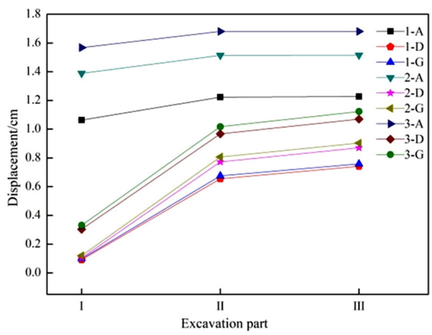


Fig. 7. Displacement in a three-bench excavation without a coal seam

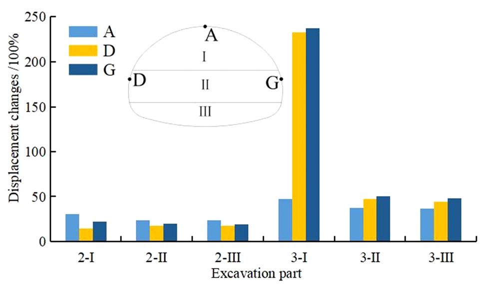


Fig. 8. Increment in displacement of surrounding rock in a three-bench excavation without a coal seam (compared to no Alkali injection)

(2) Deformation of monitoring points during each excavation step under different alkali injections when there are coal seams in the surrounding rock

When there are coal seams on the working face of the surrounding rock, the displacement of points A to G after each excavation step under different Alkali injections is shown in Fig. 9. After the upper excavation without Alkali injection treatment, the displacement of the four monitoring points (B, C, E, and F) near the coal seam is greater than that of the vault settlement and horizontal convergence of sidewalls. The largest displacement occurs at point F, where the second coal seam layer intersects the right tunnel excavation contour. The displacement values of the other monitoring points in descending order are points C, E, B, A, and G (see Fig. 9a). When there are two coal seams in the surrounding rock, the displacement of the lower seam is greater than that of the upper. Most displacement of the surrounding rock is released after the upper excavation. Figs. 9(b) and 9(c) show that compared with no treatment, the displacement around the tunnel is greater that after Alkali injection treatment. The displacement of each monitoring point after Alkali injection with a concentration of 5% is significantly greater than that with a concentration of 3%. Therefore, the deformation of the surrounding rock increases as the concentration of sodium carbonate solution increases.

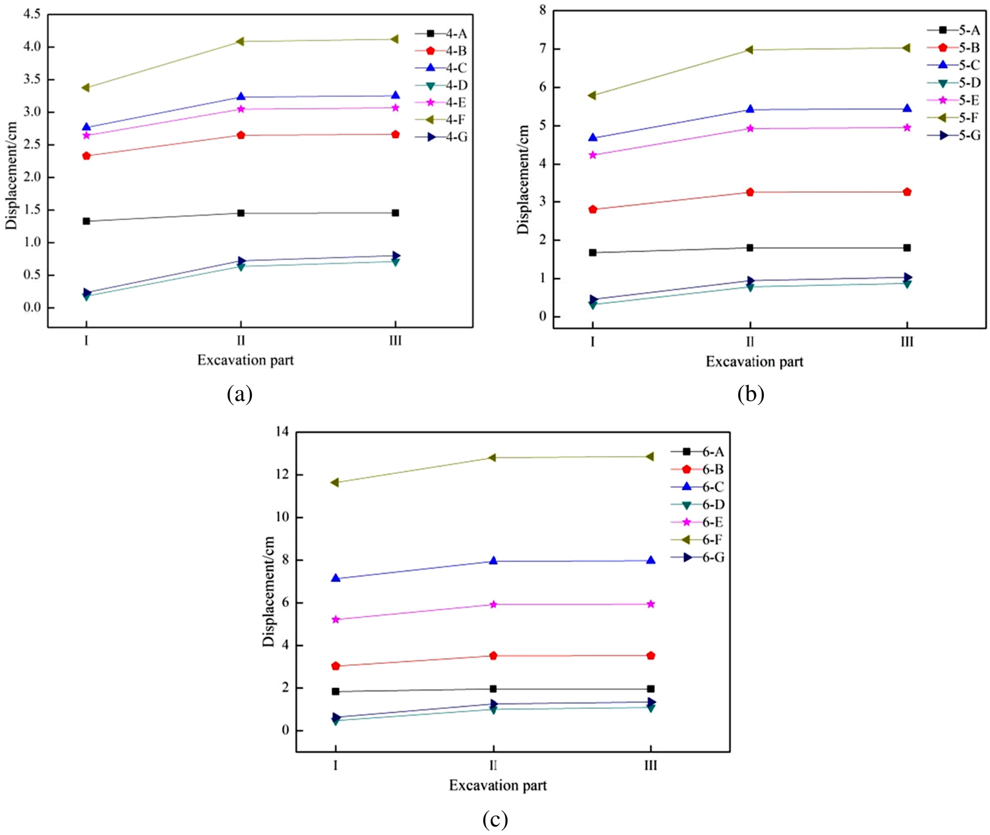


Fig. 9. Displacement during three-bench excavation of coal seam: (a) Without Alkali injection; (b) Alkali injection treatment with 3% concentration; (c) Alkali injection treatment with 5% concentration

Fig. 10 shows the increase in the displacement of the surrounding rock containing coal seams after each excavation step using the three-step method, compared to that without Alkali injection. After 3% alkali injection, the displacement increases by 19.98% to 25.88%, and after injecting 5% alkali, it increases by 30.06% to 38.12%.Points A and B show the least displacements caused by alkali injection. With a 3% alkali solution, the displacement of the left and right walls increases the most, reaching 80% and 93.25%, respectively. After the middle and lower bench excavations, the displacement of the left wall and vault increases by about 23%, and that of the right wall by about 30%. When treating the surrounding rock with a 5% alkaline solution, the maximum displacement increase occurs at point F. After each excavation step, the displacement of point A increases by 211.91% to 244.64%.

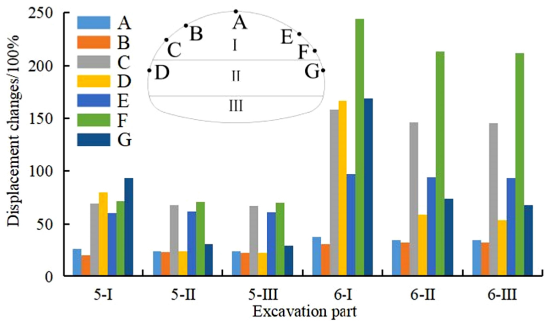


Fig. 10. Changes in displacement of surrounding rock in a three-bench excavation with a coal seam (compared with no Alkali injection)

The results show that Alkali injection treatment has the greatest impact on the displacement of the vault in the surrounding rock without coal seams [15]. The displacement of the vault increases by 30.57% with a 3% Alkali concentration, and by 47.51% with a 5% Alkali concentration. When there are coal seams in the surrounding rock, Alkali injection has the greatest effect on the displacement of coal seams. The maximum displacement increases by 71.43% with a 3% Alkali concentration, and by 244.64% with a 5% Alkali concentration.

3.2. Deformation evolution around the tunnel under the double-side-wall excavation method

(1) Deformation of monitoring points without coal seam in the surrounding rock

When there is no coal seam in the surrounding rock, the double-side-wall excavation method is used. The vault settlement varies significantly under different Alkali injection conditions, as shown in Fig. 11. After the full excavation of the working face, the vault settlement is 1.09 cm without alkali injection, 1.35 cm with a 3% alkali solution, and 1.55 cm with a 5% alkali solution. The vault settlement caused by the excavation of the upper parts is larger than that the lower. The maximum vault settlement of no Alkali injection, 3% Alkali solution, and 5% Alkali solution is 0.53 cm, 0.43 cm, and 0.85 cm, respectively. These settlements occur after the excavation of the middle upper bench, right upper bench, and left upper bench, respectively. During the construction, the displacement of points D and G remains below 1.0 cm, smaller than the vault settlement. When the Alkali injection is used, the deformation is the smallest. When the surrounding rock is treated with Alkali injection, the deformation increases as the concentration of Alkali solution increases.

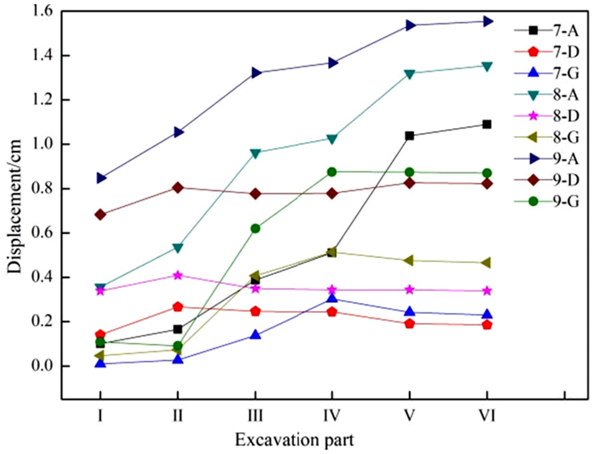
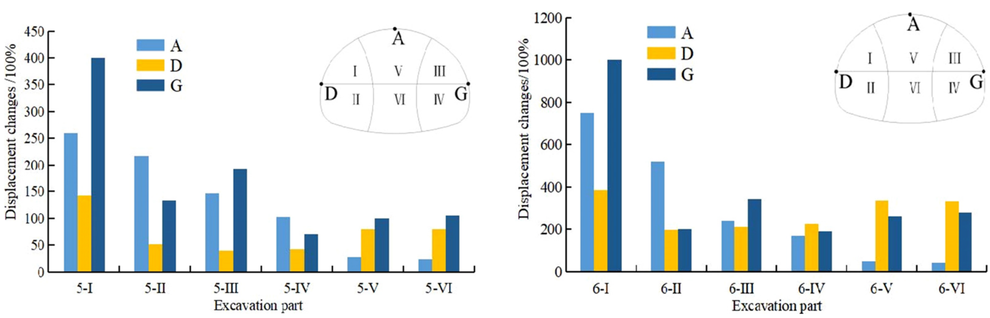


Fig. 11. Changes in displacement of surrounding rock without coal seam in different cross-sections during bilateral excavation

Fig. 12 shows the increase of displacement after each step using the double-side wall excavation method when there is no coal seam in the surrounding rock. The increase of displacement at each monitoring point decreases with each excavation step under different Alkali injections. Under alkaline injection conditions, the vault settlement after Part I excavation increases by 260% at a 3% concentration, and 750% at a 5% concentration. After each subsequent construction step, the vault settlement gradually decreases, and the vault settlement gradually decreases. Due to different excavation sequence of each wall, the displacements of monitoring points on the left and right walls are also different. The displacement of point D gradually decreases after Part II excavation and increases after Part IV excavation. The displacement of point G increases significantly after Part II excavation. As the concentration of Alkali solution increases, the reduction in mechanical parameters becomes more pronounced, leading to a decreased stiffness of the surrounding rock and a significant increase in vault settlement.

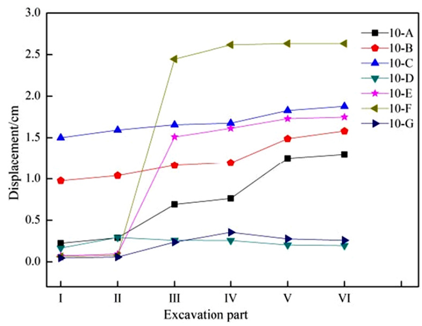


(a) (b)

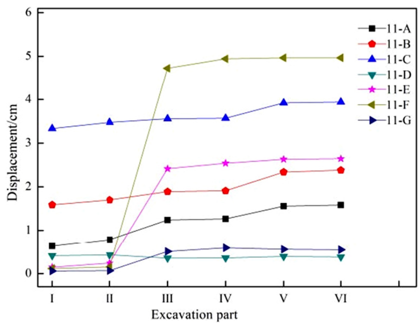
Fig. 12. Changes in displacement of surrounding rock without coal seam during double-side excavation (compared to no Alkali injection treatment): (a) 3% Alkali concentration; (b) 5% Alkali concentration

(2) Deformation of the surrounding rock with coal seam after each excavation step under different Alkali injection conditions

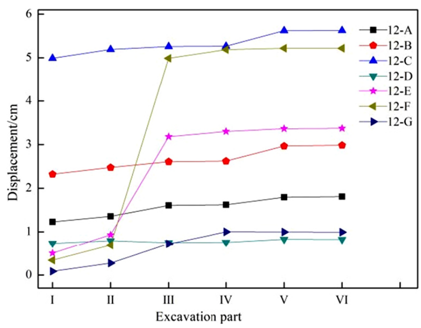
Fig. 13 shows the displacement of points A-G after each excavation step under different Alkali injections when there are coal seams in the surrounding rock. When the double-side-wall method is used to excavate the surrounding rock without Alkali injection (Fig. 13a), the displacement of points B, C, E, and F, which are related to the coal seam, is greater than that of other points. Under Alkali injection conditions, the displacement of points E and F increases significantly more than that of other points after Part III excavation. The displacement ranks in decreasing order as F, C, E, B, A, G and D. When two layers of coal seam intersect the working face, the displacement of the lower coal seam is larger than that of the upper. Figs. 13(b) and 13(c) show the variation in the displacement of the surrounding rock after each excavation step, treated with the concentrations of 3% and 5% Alkali injections, respectively. After treating with a concentration of 5% Alkali injection, the displacement of all points is greater than that 3% Alkali injection, except for point F. After part V excavation, the maximum displacement of point F with 3% and 5% Alkali injection treatments is 4.97 cm and 5.22 cm, respectively. When using the double-sided excavation method, increasing the Alkali concentration has little effect on the deformation of the surrounding rock.



(a)



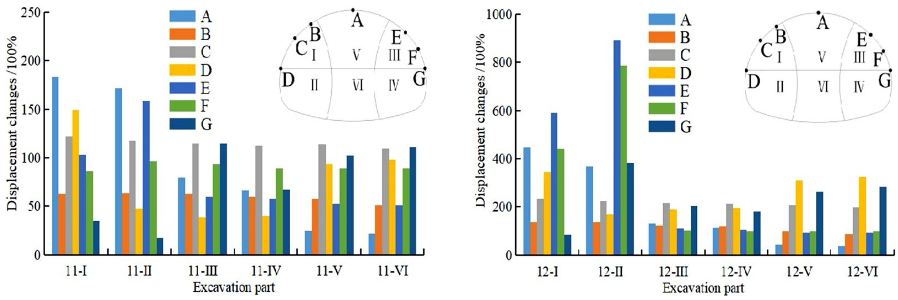
(b)



(c)

Fig. 13. Displacement of surrounding rock with coal seam during double-side-wall excavation: (a) Without Alkali injection treatment; (b) Alkali injection treatment with a 3% concentration; (c) Alkali injection treatment with a 5% concentration

Compared with no Alkali injection, Fig. 14 shows the displacement increment of the surrounding rock containing coal seams after each excavation step using the double-side-wall excavation method. After a concentration of 3% Alkali treatment, the vault settlement increment decreases gradually from 183.41% to 21.92%, and after 5% Alkali treatment, it decreases from 450.22% to 39.08%. For all Alkali injection treatments, the displacement of sidewalls first decreases and then increases. After a concentration of 3% Alkali injection treatment, the displacement increments of points B, C, and F are similar in all stages, ranging from 62.64% to 50.60%, 122.20% to 109.74%, and 96.15% to 88.64%, respectively. The displacement increment of point E varies significantly between the stages, ranging from 158.51% to 51.03%. Different excavation methods can result in varying displacement increments at certain points. After a concentration of 5% Alkali injection treatment, the displacement at all points increases significantly in each stage. The displacement increments of points B, C, E, and F are 138.21% to 88.80%, 232.47% to 199.57%, 343.37% to 169.73%, and 785.90% to 98.17%, respectively. When there are coal seams in the surrounding rock, the displacement increment at all points after double-side-wall excavation is greater than that after three-bench excavation, following Alkali injection treatment. However, using the double-side-wall excavation method, the absolute displacements of each point are smaller than those the three-bench excavation method.

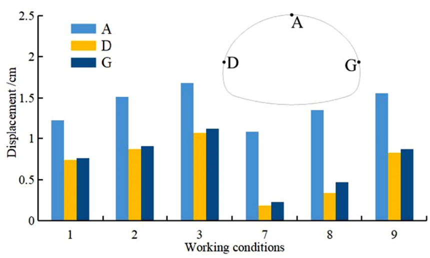


(a) (b)

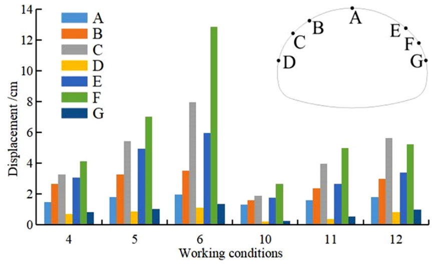
Fig. 14. Changes in displacement of surrounding rock with coal seam during double-side-wall excavation (compared with no Alkali injection treatment)

3.3. Vault settlement and horizontal convergence after all section excavation

Fig. 15 shows the displacement of the surrounding rock with coal seams under different Alkali injections and excavation methods after excavation of all sections. Regardless of whether the surrounding rock contains coal seams, the displacement of points A, D, and G using the three-bench excavation method is greater than that the double-side-wall excavation method at each excavation step. The displacement of all points increases as the concentration of Alkali injection solution increases, with point G having the largest displacement. The displacement of points D and G is smaller than that of other points. When the surrounding rock contains two layers of coal seams, the displacement of the lower coal seam is larger than that of the upper.



(a)

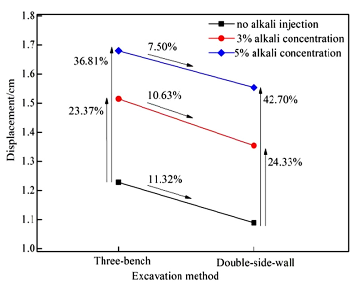


(b)

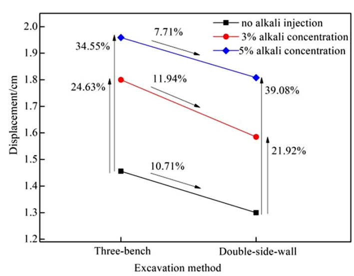
Fig. 15. Displacement of each point under different working conditions: (a) Without coal seam; (b) With coal seam

(1) Vault settlement

Fig. 16 shows the comparison of the maximum vault settlement under different excavation methods and Alkali injection treatments. When there is no coal seam in the surrounding rock, compared with the three-bench excavation method, the displacement reduction of the double-side-wall excavation method under the three Alkali injections is 7.50% to 11.32%. When the surrounding rock contains two layers of coal seams, the displacement reduction of the double-side-wall excavation method under the three Alkali injections is 7.71% to 11.94% compared to the three-bench excavation method. Under the same excavation method, when the Alkali concentration is 3% and there is no coal seam in the surrounding rock, the displacement increment is 23.37% to 24.33%; on the contrary, it is 21.92% to 24.63%. Under the same excavation method, when the Alkali concentration is 5% and there is no coal seam in the surrounding rock, the displacement increment is 36.81% to 42.70%; on the contrary, it is 34.55% to 39.08%. Compared with no Alkali injection treatment, the vault settlement with a concentration of 3% Alkali is smaller than that with a concentration of 5% Alkali. Under the same Alkali concentration, as the Alkali concentration increases, the increment in the vault settlement using the three-bench excavation method is smaller than that the double-side-wall excavation method. Under the same Alkali injection treatments, regardless of whether the surrounding rock contains coal seams, there is no significant difference in the reduction of vault settlement between the double-side-wall and three-bench excavation methods.



(a)



(b)

Fig. 16. Comparison of vault settlement under different working conditions: (a) Without coal seam; (b) With coal seam

(2) Horizontal convergence of side walls

Fig. 17 shows the comparison of the horizontal convergence under different excavation methods and Alkali injection treatments. The double-side-wall excavation method can effectively reduce the horizontal convergence in the surrounding rock without coal seams, with a reduction of 72.27%, 54.60%, and 22.80% for no Alkali injection, 3% Alkali injection, and 5% Alkali injection, respectively. For the surrounding rock with coal seams, the reduction is 70.12%, 51.08%, and 25.63%, respectively. When using the three-bench excavation method and treating the surrounding rock with 3% Alkali injection, the displacement increases by 18.20% to 25.53% compared to no Alkali injection. Similarly, the displacement increases by 46.20% to 61.08% after 5% Alkali injection compared to no Alkali injection. The horizontal convergence of sidewalls in surrounding rock with coal seams is larger than that without coal seams when treated with Alkali injection. When using 3% and 5% Alkali injection and the three-bench excavation method, the horizontal convergence increases by 7.33% and 14.18%, respectively. When using 3% and 5% Alkali injection and the double-side-wall excavation method, the horizontal convergence increases by 12.01% and 6.06%, respectively.

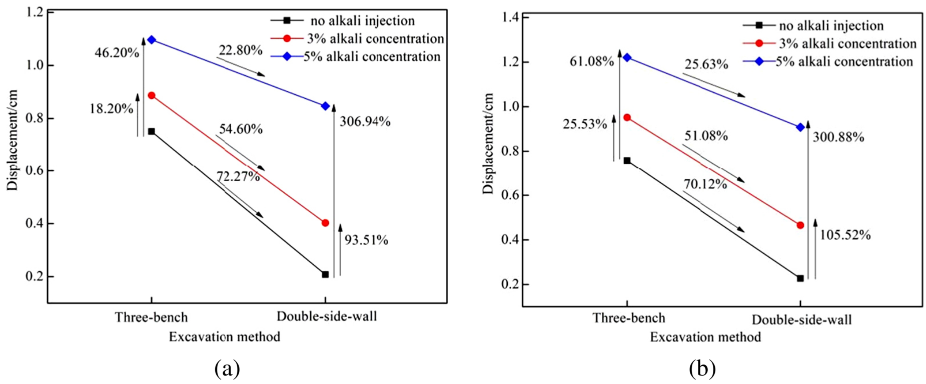


Fig. 17. Comparison of horizontal convergence of sidewalls under different working conditions: (a) Without coal seam; (b) With coal seam

4. Conclusions

This study uses numerical simulation to analyze the vault settlement and horizontal convergence of sidewalls under different conditions, including single-hole Alkali injection, different Alkali concentrations, double-side-wall excavation, and three-bench excavation methods, in the surrounding rock with and without coal seams. Main conclusions are drawn as follows:

1. The numerical simulations of single-hole Alkali injection show that the pore pressure decreases as the distance from the injection hole increases. The example tunnel has an effective diffusion range of 1.8 m, an injection hole diameter of 10 cm and a pore pressure of 1.5 MPa. The hole layout of Alkali injection is designed to be 1.5 times the diffusion range;

2. The injection of sodium carbonate solution has a negative impact on the stability of the tunnel surrounding rock, leading to increased deformation. Compared with no Alkali injection, when the surrounding rock is treated with a 3% Alkali concentration, the displacement of vault increases by 23.37–24.33%, and the horizontal convergence of sidewalls increases by 18.20–25.53%. With a 5% Alkali concentration, the displacement of vault increases by 34.55–42.70%, and the horizontal convergence increases by 46.20–61.08%;
3. When the coal seam tilts through the tunnel sidewalls, the displacement of the vault is only slightly affected. However, due to the coal seams, the horizontal convergence of sidewalls increases. The displacement increase in the side walls is similar for the three-bench and double-side-wall excavation methods. It is worth noting that when there are two coal seams, the deformation of the lower coal seam is significantly greater than that of the upper;
4. Regardless of the presence of coal seams, under all alkaline injection conditions, compared with the three step method, the deformation of the surrounding rock is smaller in the double-sided excavation method. When using the double-sided wall method, the displacement of the vault decreases by 7.65% to 11.37%, and the horizontal convergence of sidewalls decreases by 22.80% to 72.27%. Therefore, when the surrounding rock contains coal seams and Alkali injection treatment is adopted, it is recommended to use the double-side-wall excavation method.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant numbers 51604057); the Youth Science and Technology Innovation Program of Sinopec Qingdao Research Institute of Safety Engineering (Grant number YQ-59); Natural Science Foundation of Chongqing (CSTB2022NSCQ-MSX1515).

References

[1] G.J. Khave, “TBM Tunnelling in Hydrogen Sulfide Gas Bearing Ground and its Solutions”, *Geotechnical and Geological Engineering*, vol. 31, no. 5, pp. 1621–1638, 2013, doi: 10.1007/s10706-013-9669-8.

[2] Z.H. Huang, Y.X. Han, X.W. Chen, X.H. Zhou, and L.J. Wang, “Prevention and Control of Toxic and Harmful Gases (Methane Gas, Hydrogen Sulfide) in the Micangshan Extra-long Tunnel”, *Modern Tunnelling Technology*, vol. 55, no. S2, pp. 876–881, 2018.

[3] Z.Y. Chen, P.D. Su, L. Huang, H.D. Chen, and Y.B. Du, “Study on Monitoring and Prevention Technique for Harmful Gas in No.1 Inclined Shaft of Hongdoushan Tunnel”, *Modern Tunnelling Technology*, vol. 57, no. 04, pp. 178–184, 2020.

[4] Q. Deng, J. Yin, X. Wu, T. Zhang, H. Wang, and M. Liu, “Research Advances of Prevention and Control of Hydrogen Sulfide in Coal Mines”, *The Scientific World Journal*, vol. 2019, art. no. 8719260, 2019, doi: 10.1155/2019/8719260.

[5] N. Maie, S. Anzai, K. Tokai, W. Kakino, H. Taruya, and H. Ninomiya, “Using oxygen/ozone nanobubbles for in situ oxidation of dissolved hydrogen sulfide at a residential tunnel-construction site”, *Journal of Environmental Management*, vol. 302, Part B, art. no. 114068, 2022, doi: 10.1016/j.jenvman.2021.114068.

[6] D. Wang, “Exploring on Prevention and Control Technologies of Hydrogen Sulphide Gas in Construction of Tianping Tunnel”, *Railway Engineering*, no. 10, pp. 67–71, 2016.

[7] B. Tan, et al., "Status of research on hydrogen sulfide gas in Chinese mines", *Environmental Science and Pollution Research*, vol. 27, no. 3, pp. 2502–2521, 2020, doi: 10.1007/s11356-019-07058-x.

[8] O.A. Habeeb, O.A. Olalere, R. Kanthasamy, and B.V. Ayodele, "Hydrogen sulfide removal from downstream wastewater using calcium-coated wood sawdust-based activated carbon", *Arabian Journal for Science and Engineering*, vol. 45, no. 2, pp. 501–518, 2020, doi: 10.1007/s13369-019-04207-9.

[9] M.S. Reza, et al., "Preparation of activated carbon from biomass and its' applications in water and gas purification, a review", *Arab Journal of Basic and Applied Sciences*, vol. 27, no. 1, pp. 208–238, 2020, doi: 10.1080/25765299.2020.1766799.

[10] A. El Brahmi and S. Abderafi, "Hydrogen sulfide removal from wastewater using hydrogen peroxide in situ treatment: case study of Moroccan urban sewers", *Materials Today: Proceedings*, vol. 45, part 8, pp. 7424–7427, 2021, doi: 10.1016/j.matpr.2021.01.641.

[11] S. Regenspurg, J. Iannotta, E. Feldbusch, F.J. Zimmermann, and F. Eichinger, "Hydrogen sulfide removal from geothermal fluids by Fe(III)-based additives", *Geothermal Energy*, vol. 8, no. 1, art. no. 21, 2020, doi: 10.1186/s40517-020-00174-9.

[12] Y. Cheng, et al., "Microstructural changes in limestone after treatment with Na2CO3 solution: Implications for eliminating H_2S in tunnels", *Arabian Journal of Chemistry*, vol. 15, no. 12, art. no. 104320, 2022, doi: 10.1016/j.arabjc.2022.104320.

[13] X.Y. Wang, X.Z. Mu, and K. Li, "Coal seam Alkali injecting technology for hydrogen sulfide control", *Coal Engineering*, vol. 54, no. 8, pp. 67–71, 2022.

[14] Y.F. Zhou, Z. Wang, X.Q. Suo, X.F. Zhang, and Y.P. Ding, "Study on high water pressure on tunnel supporting structure based on fluid-solid coupling", *Journal of Highway and Transportation Research and Development*, vol. 38, no. 10, pp. 92–99, 2021.

[15] R. Mohamed, et al., "Nucleation and growth rate determination on alkali-activated slag under various sodium hydroxide molarity", *Archives of Civil Engineering*, vol. 70, no. 3, pp. 473–485, 2024, doi: 10.24425/ace.2024.150996.

Received: 2024-07-09, Revised: 2024-12-02