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STUDY ON STRESS CHARACTERISTICS OF HIGH-POROSITY COAL GANGUE SUBGRADE DURING FILLING PROCESS

Bing Hui
Shandong Transportation Research Institute, Jinan, China

Yingxin Hui
Ningxia Communications Construction Group Co., Ltd., Ningxia, China
e-mail: huiyx@seu.edu.cn

Xu Zhang, Wenjun Zhang
Shandong Transportation Research Institute, Jinan, China

Sheng Yan, Guangyu Men
Ningxia Communications Construction Group Co., Ltd., Ningxia, China

By analyzing geological conditions of a coal gangue filling roadbed, stress characteristics and settlement changes during the filling process of the coal gangue roadbed are simulated. The following conclusions are drawn: (1) As height of the coal gangue filling increases, the stress and settlement of each part will also increase. (2) During the filling process, the vertical stress acts as the first principal stress, and the stress and strain at the centerline of the roadbed are 10 times that of the roadbed. (3) The final stable value of uneven settlement of the coal gangue roadbed is 18.85 mm. (4) The monitoring results indicate that the settlement of the coal gangue roadbed is stable, and the settlement amount is small ensuring safety of the roadbed.

Keywords: coal gangue subgrade, subgrade stability, numerical analysis, stress characteristics

1. Introduction

As a subsidiary industrial waste in the process of coal mining, coal gangue belongs to historical materials. Due to the influence of various factors such as high ground stress, high temperature and humidity and crustal movement in underground engineering, it has its particularity, complexity and anisotropy. Spontaneous combustion, physical, chemical and biological changes occur in coal gangue stored in the natural air resulting in changes in particle characteristics of coal gangue. Especially for a coal gangue subgrade roller compaction under an external load, coal gangue subgrade particles exhibit significant changes, reflected in the porosity attenuation (Li and Wang, 2019). Finally, causing reconstruction of the coal gangue particle composition.

Li *et al.* (2020a) tested basic properties of coal gangue such as particle size distribution, loss on ignition, strength changes under water softening and compression performance. Based on this, a technology of using coal gangue as a railway roadbed filler was proposed. Through on-site tests, it has been shown that the coal gangue roadbed has excellent performance. Chen *et al.* (2020b) conducted a series of pressure plate tests on coal gangue fillers in the roadbed and analyzed variation patterns of model parameters. The research has shown that the compacted roadbed coal gangue filler has a double pore group structure, and its soil water characteristic curve (SWCC) exhibits a double step phenomenon. Fan *et al.* (2022) analyzed the dynamic evolution process, grading evolution law, and corresponding micromechanical properties of coal gangue particles during the crushing process under stress. The research has shown that the interaction between lateral confinement and unidirectional compression of granular materials is mainly compression. Zhang *et al.* (2020) studied the effects of the substitution rate (r (SCGA)) and particle size distribution of coarse SCGA on mechanical properties of concrete. The results showed that coarse SCGA had a significant impact on the mechanical properties of concrete. When the SCGA substitution rate was 100%, the compressive strength, splitting tensile strength, and elastic modulus decreased by 19.4%, 36.1%, and 32.2%, respectively. Based on this, a prediction method for coarse SCGA concrete was proposed. Chen *et al.* (2020a) systematically studied the feasibility of using mineral waste as a roadbed filler. The optimal compaction parameters for waste residue were determined. The effects of different factors on the particle size distribution and mechanical properties of slag were evaluated and construction parameters of slag recommended. Chang *et al.* (2019) validated the use of solid waste such as sludge as raw materials for production of ecological cement, bricks, ceramic materials and lightweight aggregates through sintering processes. In addition, suggestions for future research were also proposed to strengthen high value-added application of sewage sludge. Zhang and Ling (2020) reviewed the effects of four main activation methods, namely thermal activation, mechanical activation, microwave activation and composite activation with a focus on discussing their interaction mechanisms with coal gangue. This provides valuable ideas and guidance for better understanding of the pricing of coal gangue, especially for its reuse in cement-based building materials. Li *et al.* (2020b) developed a new type of green concrete using large volume fly ash and coal gangue aggregates. The research results indicated that the fly ash coal gangue mixture had the advantages of acid resistance, waste recycling and lower carbon emissions, making it more effective than previous foundation improvement methods. Li *et al.* (2020c) simulated compression deformation of four different particle sizes of coal gangue filling materials using PFC3D. The compression deformation law, particle cluster distribution and changes in the shape of coal gangue blocks of coal gangue filling materials were analyzed. Based on the force chain distribution, the microscopic mechanism of compression deformation of coal gangue filling materials was studied. Li and Wang (2019) conducted a comprehensive literature review on the utilization of coal gangue in building material production, energy production, soil improvement and other high value-added applications. The research results have opened up a new door for further application of coal gangue, hoping to inspire future related research and guide decision-making. Long *et al.* (2019) studied mechanical properties and durability of a new type of cement-soil mixture reinforced by locally discarded coal gangue aggregates. The results indicated that the addition of coal gangue significantly improved strength, stiffness and corrosion resistance of the cement-soil mixture. Chen *et al.* (2019) systematically analyzed mechanical properties and microscopic mechanisms of red mud treated loess with a small amount of cement additive (RMCL). The results showed that the content of red mud C-R had a significant impact on the unconfined compressive strength (UCS) of RMCL. An appropriate amount of red mud waste can effectively improve mechanical properties of loess roadbed fillers. Ashfaq *et al.* (2020b) conducted a carbon footprint analysis of coal gangue to evaluate its CO_2 emissions when used as an embankment material. The study confirmed the fact that the utilization of coal gangue could significantly reduce generation of carbon footprint, thereby having a positive impact on the environment. Ashfaq *et al.* (2020b) showed through leaching research that there were trace elements in coal gangue, However, it was found that their concentration levels were far below the allowable limits.

Based on characterization studies, it can be inferred that coal gangue is a potential substitute for existing traditional geotechnical materials such as soil and other recycled materials. Leistner *et al.* (2017) studied the use of an artificial binary model particle system with magnetite as the target mineral and quartz as the gangue mineral to minimize problems related to ultrafine gangue particles. The results showed that hen gangue particles were small, ultrafine magnetite could also be recovered like fine magnetite. Ashfaq *et al.* (2022) conducted a comprehensive assessment on physical, chemical, mineralogy, geotechnical engineering and environmental (trace metal mobilization and life cycle assessment) characteristics of coal gangue to assess its potential in promoting sustainable development.

The above studies have carried out a lot of analysis on the mechanical properties of mixtures of coal gangue and different materials, put forward the experimental methods of various properties of coal gangue and introduced the application of coal gangue to subgrade engineering. However, there are few studies on the high-porosity coal gangue subgrade. Based on the above investigations, the corresponding studies are carried out.

2. Engineering overview

The section of Beijing-Shanghai Expressway from Laiwu to Linyi (Rusujie) (hereinafter referred to as "Beijing-Shanghai Expressway") is located in Shandong Province. The starting point of the main line of the project is located in the southeast of Malonggu Village, Fengcheng Street Office, Laiwu City. It ends at the Rusujie of Beijing-Shanghai Expressway and connects to the Jiangsu section of Beijing-Shanghai Expressway. The main line is 232.191 km long. The main line of the project is based on the technical standards of a two-way eight-lane highway. The design speed from the starting point to Bianjiaquan section (K477+442.25-K508+000) is 100 km/h, and the design speed from Bianjiaquan to the end section (K508+000-K710+000) is 120 km/h. The integral subgrade is widened to 42 m, and width of the new single separated subgrade is 20.75 m. The field coal gangue yard has been fully spontaneously combusted in the air for nearly 30 years, and the porosity of coal gangue particles is 51.4% (Fig. 1).

Fig. 1. Coal gangue yard

According to the geotechnical engineering investigation report, the engineering geological conditions in this region are mainly divided into plain fill, silty clay and gravel soil. The stratigraphic distribution is shown in Table 1, and the groundwater level is within the range of 20 m underground.

Table 1. Stratigraphic distribution

Soil type	Average thickness [m]	Minimum thickness [m]	Maximum thickness [m]	Groundwater level [m]
Plain fill	0.4	0.2	0.6	–
Silty clay	2.0	1.0	3.0	–
Stone	13.0	11	17.5	–

3. Construction of the elastic-plastic model of s porous media coal gangue subgrade

The coal gangue subgrade has characteristics of high porosity and particle break-age. The remodeling will occur under the effect of subgrade rolling, resulting in the evolution of the coal gangue subgrade into porous media as shown by the physical and mechanical model in Fig. 2.

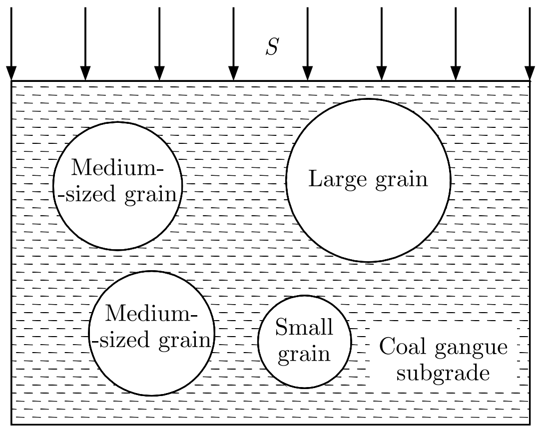

Fig. 2. Loading diagram of s porous medium of the coal gangue subgrade

3.1. Mathematical model

The coal gangue subgrade has characteristics of material heterogeneity and porous distribution. The coal gangue subgrade and foundation soil are both regarded as elastic-plastic materials, and Drucker-Prager (Jiang, 2021) ideal elastic-plastic constitutive model is adopted for the constitutive relation.

The following assumptions are used in the finite element analysis of the coal gangue subgrade:

- Each material is homogeneous, continuous and isotropic, an ideal elastic-plastic body, and the constitutive relation of soil satisfies the D-P yield criterion;
- The consolidation deformation and compression deformation of the foundation under the action of its own weight have been completed, and the embankment deformation is caused by the self-weight of the filler, without considering the influence of traffic load and climate factors on it;
- The coal gangue subgrade and foundation are unsaturated soil, without considering the consolidation of the embankment filler and foundation soil, and the influence of pore water pressure and embankment gravity load is applied once.

According to the effective stress principle of classical soil mechanics

$$\sigma = (1 - n)\sigma^e + n\mu \tag{3.1}$$

where n is porosity, μ is pore water pressure, σ^e is effective stress and σ is total stress. The coal gangue subgrade is in a dry state, $\mu = 0$, therefore

$$\sigma = (1 - n)\sigma^e \tag{3.2}$$

The composite D-P criterion with the strength limit is the failure criterion of the model.

According to the D-P failure criterion $f(\tau, \sigma) = 0$. From point A to point B on the graph, the failure envelope $f^s = 0$ is defined by the shear failure criterion

$$f^s = \tau + q_\emptyset \sigma - k_\emptyset \tag{3.3}$$

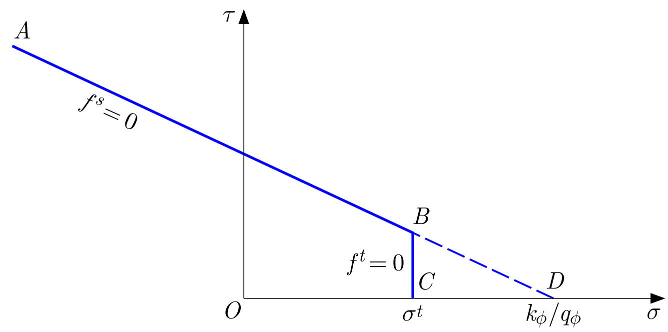

Fig. 3. Failure criterion of the D-P model

From point B to point C, by tensile failure criterion $f^t = 0$

$$f^t = \sigma - \sigma^t \tag{3.4}$$

In the formula, $q_\emptyset$ is the friction force of the D-P model, $k_\emptyset$ is the cohesive force, σ^t is the tensile strength. For the material $q_\emptyset$ is not equal to zero, the ultimate tensile strength is

$$\sigma^t_{max} = \frac{k_\emptyset}{q_\emptyset} \tag{3.5}$$

The potential function $\sigma(\tau,\sigma) = \text{const}$, consisting of g^s and g^t, is used to describe shear and tensile plastic flow, respectively. The function g^s generally corresponds to an unrelated law in the form of

$$g^s = \tau + q_\varphi \sigma \tag{3.6}$$

When the flow rule is applicable, q_φ is a constant, which is numerically equal to $q_\emptyset$. The function g^t corresponds to a relevant flow rule given below

$$g^t = \sigma \tag{3.7}$$

when the D-P failure criterion follows shear failure characteristics. First of all, considering the shear failure, from Eq. (3.4) the partial differentials are

$$\frac{\partial g^s}{\partial \tau} = 1 \qquad \frac{\partial g^s}{\partial \sigma} = q_\varphi \tag{3.8}$$

Using $f = f^s$, Eq. (3.1), we get

$$\tau^N = \tau^I - \lambda^s G \qquad \sigma^N = \sigma^I - \lambda^s K q_\varphi \qquad \lambda^s = \frac{f^s(\tau^I,\sigma^I)}{G + K q_\emptyset q_\varphi} \tag{3.9}$$

The stress tensor component can be expressed as a generalized stress by the transformation equation. In form, Eq. (3.7) can be written as

$$\tau^N = \mu \tau^I \tag{3.10}$$

where μ is the known proportional factor $\tau^N = \mu\tau^I$, where

$$\mu = 1 - \lambda^s \frac{G}{\tau^I} \tag{3.11}$$

Using the tensor component S_{ij} to represent τ, we get

$$S^N_{ij} = \mu S^I_{ij} \tag{3.12}$$

Eliminating μ from the last two expressions, we get

$$S_{ij}^N = S_{ij}^I \frac{\tau^N}{\tau^I} \tag{3.13}$$

Finally, using this definition, new stress components can be calculated by Eq. (3.8), and

$$\sigma_{ij}^N = S_{ij}^N + \sigma^N \delta_{ij} \tag{3.14}$$

Equation (3.12) is modified as follows

$$(1-n)\sigma_{ij}^N = S_{ij}^N + (1-n)\sigma'^N \delta_{ij} \tag{3.15}$$

The boundary conditions: all directions of the foundation bottom are completely constrained, and the foundation is horizontally constrained along the cross direction of the road foundation.

3.2. Calculation model

In order to eliminate the boundary effect and stress influence range, the calculation size of the model is 100 m × 10 m × 50 m, in which the subgrade calculation area size is 60 m × 10 m × 22 m, the subgrade slope is 1:0.75, and the geometric model is shown in Fig. 4.

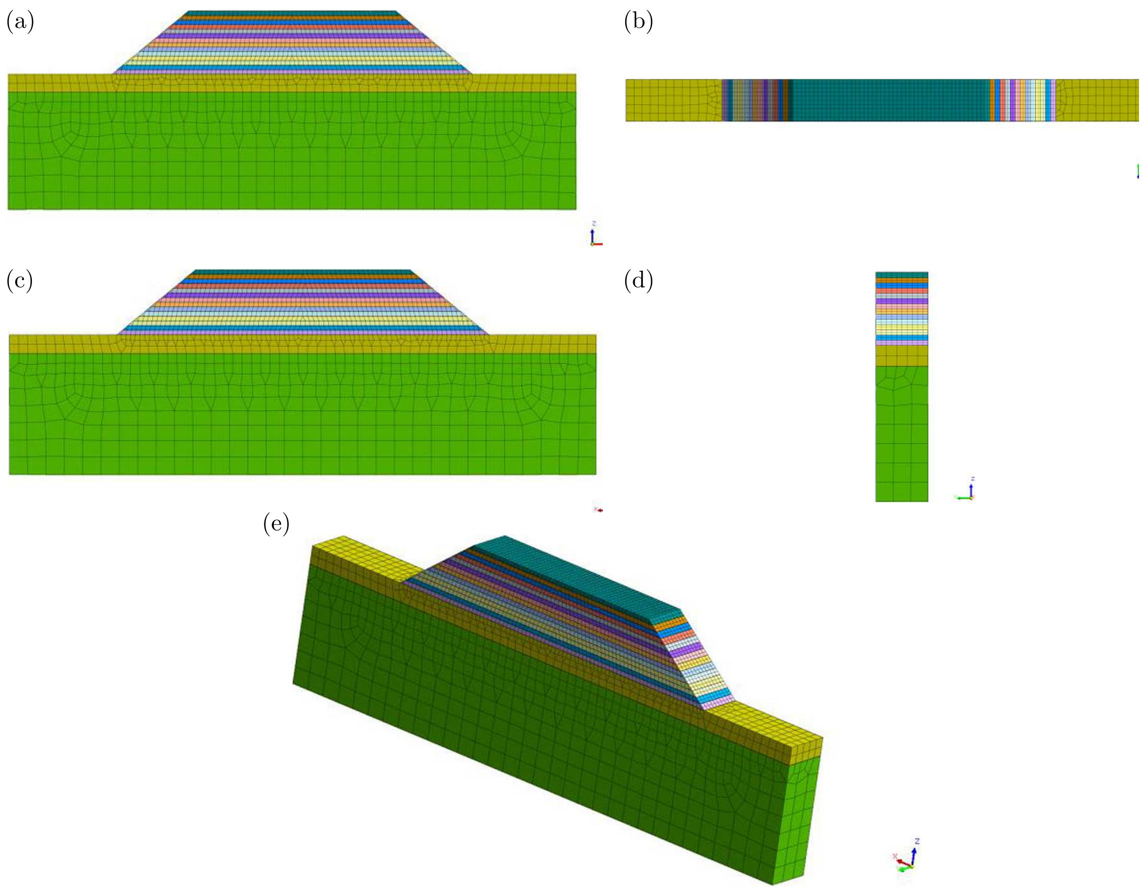

Fig. 4. Geometric model: (a) front view, (b) vertical view, (c) rear view, (d) side view, (e) graphic model

The model is generated by a hybrid grid, with the grid size transiting from 0.5 m to 2 m. The coal gangue subgrade is divided into fine grids and coarse foundations with a total of 15615 units including 9284 units for the coal gangue subgrade. The bottom of the model adopts fixed boundaries with the X-direction displacement limited on the left and right sides, and Y-direction displacement limited on the front and rear sides.

3.3. Physical and mechanical parameters

According to the laboratory test analysis, the physical and mechanical parameters of coal gangue and stratum in the calculation model are shown in Table 2. The porosity is set to 0.5.

Table 2. Material parameters of subgrade soil

Soil type	Thick-ness [m]	Elastic modulus [GPa]	Modulus of deformation [MPa]	Gravity [kN/m^3]	Poisson's ratio	Force of cohesion [kPa]	Angle of internal friction [°]
Coal gangue	7.0	1.1	–	18.5	0.3	75	45
Silty clay	2.0	–	15	18	0.35	15	23
Stone	13.0	–	60	22.5	0.35	40	30

3.4. Boundary conditions

The boundary conditions of the model are as follows: the fixed boundary is used at the bottom of the model, and the displacement in the X-direction is limited on both sides, and the displacement in the Y-direction is limited on both sides. The model boundary conditions are shown in Fig. 5.

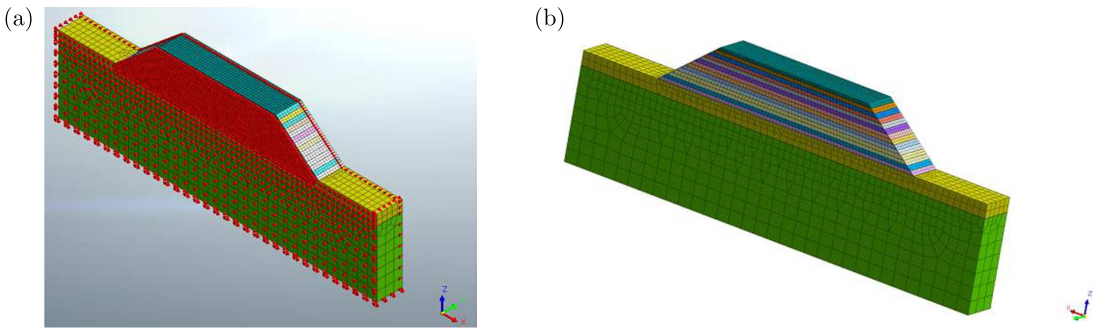

Fig. 5. Model boundary conditions: (a) boundary division, (b) mesh subdivision

3.5. Calculation model scheme

In order to better study the stress characteristics of the high-porosity coal gangue subgrade filling process, the calculation condition of coal gangue layered filling is 0.5 m, and the specific calculation model scheme is shown in Table 3.

Table 3. Calculation model scheme

Model calculation conditions	Calculation contents
Condition 1	Initial stress equilibrium
Condition 2	Filling to 0.5 m
Condition 3	Filling to 7.0 m

4. Mechanical characteristics analysis of the high-porosity coal gangue subgrade during construction

4.1. Initial stress balance

When the numerical calculation model starts to calculate the first step, the initial stress balance is needed, that is, to eliminate deformation caused by the self-weight stress. As shown in Fig. 6, when $Z = 0$, the gravity stress is zero. When $Z = 15$ m, the gravity stress is $3.17 \cdot 10^2$ kN/m^2. It can be seen from Fig. 5.b that when the silty clay $Z = 0$ on the surface and the gravel layer $Z = 10$ m at the bottom of the stratum, the deformation is zero.

(a) (b)

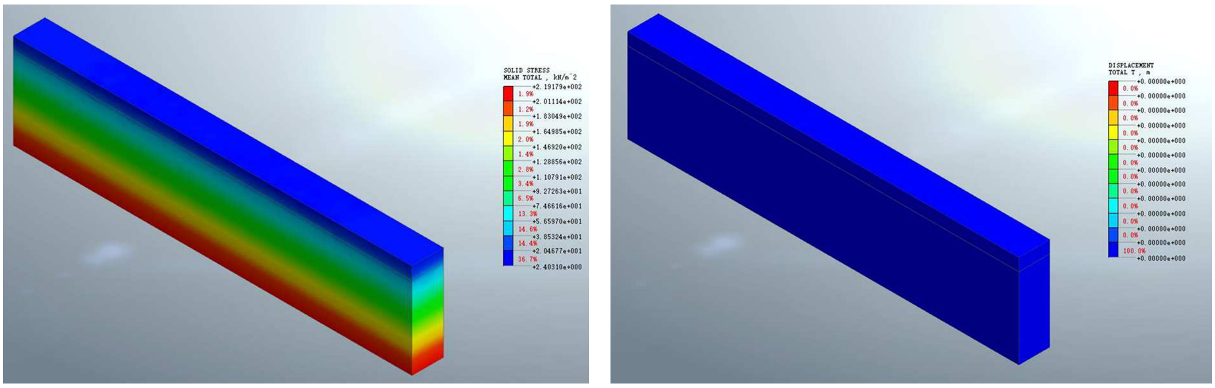

Fig. 6. Initial cloud images of the model: (a) stress cloud, (b) deforming cloud

4.2. Coal gangue subgrade first layer (0.5 m) filling

4.2.1. Stress nephogram

According to the numerical calculation results, the stress and deformation nephogram of the first layer of coal gangue filling are extracted. The center position at the bottom of the subgrade and the slope foot position at the bottom of the subgrade are mainly analyzed.

From Figs. 7a to 7c, it can be seen that when the layered filling height of coal gangue is 0.5 m, the total stress at the center of the subgrade bottom is 2.08 kPa, the horizontal (S-XX direction) stress is 1.37 kPa, and the vertical (S-ZZ direction) stress is 3.02 kPa. The total stress at the bottom slope foot of subgrade is 2.06 kPa, the horizontal (S-XX direction) stress is 1.58 kPa, and the vertical (S-ZZ direction) stress is 3.37 kPa.

Analysis of Figs. 7d-7f shows that when the height of coal gangue layered filling is 0.5 m, the total displacement of the center of the subgrade bottom is 1.64 mm, the horizontal (TX direction) displacement is $8.37 \cdot 10^{-4}$ mm, and the vertical (TZ direction) displacement is 1.63 mm. The total displacement at the bottom slope foot of the subgrade is 0.41 mm, the horizontal (TX direction) displacement is $5.87 \cdot 10^{-2}$ mm, and the vertical (TZ direction) displacement is 0.32 mm.

4.2.2. Differential settlement

Analysis of Fig. 8 shows that when the height of coal gangue layered filling is 0.5 m, the line at the bottom of the subgrade is extracted as the research object. The maximum settlement at the center of the subgrade bottom is 1.54 mm, and the maximum settlement at the foot of the subgrade bottom is 0.585 mm. It can be seen that an uneven settlement occurs between the bottom slope toe of the subgrade and the center of the subgrade bottom, and the differential settlement is 0.955 m.

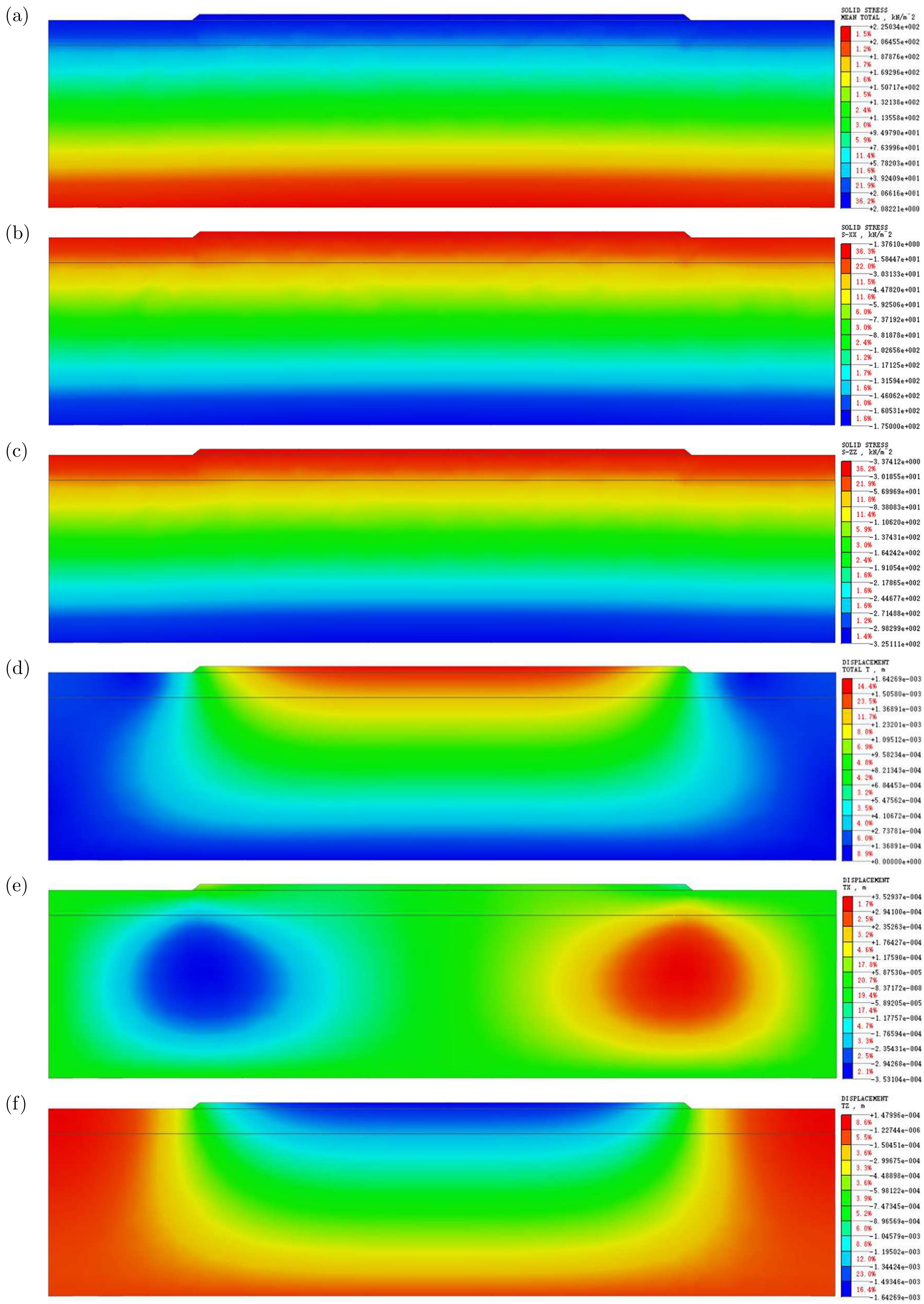

Fig. 7. Stress and deformation nephogram of the coal gangue filling first floor: (a) total stress, (b) horizontal (S-XX direction) stress, (c) vertical (S-ZZ direction) stress, (d) total displacement (T), (e) horizontal (TX direction) displacement, (f) vertical (TZ direction) displacement

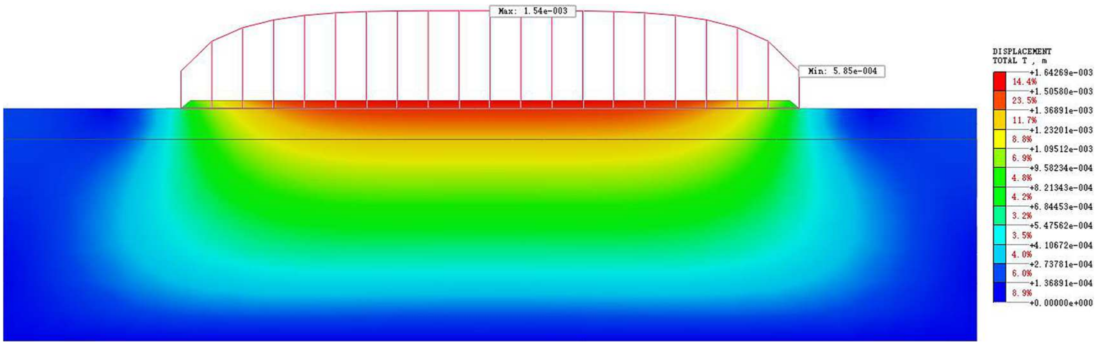

Fig. 8. Settlement curve between the slope toe and subgrade center

4.3. Filling of a 14th floor (7.0 m) of coal gangue subgrade

4.3.1. Stress nephogram

According to the numerical results, the stress and deformation nephogram of the fourteenth layer of coal gangue filling are extracted. The center position at the bottom of the subgrade and the slope foot position at the bottom are mainly analyzed.

From Figs. 9a to 9c, it can be seen that when the layered filling height of coal gangue is 7.0 m, the total stress at the center of the subgrade bottom is 74.90 kPa, the horizontal (S-XX direction) stress is 48.20 kPa, and the vertical (S-ZZ direction) stress is 125.00 kPa. The total stress at the bottom slope foot is 11.20 kPa, the horizontal (S-XX direction) stress is 12.20 kPa, and the vertical (S-ZZ direction) one is 12.60 kPa.

Analysis of Figs. 9d-9f shows that when height of the coal gangue layered filling is 7.0 m, the total displacement at the center of the bottom of the subgrade is the largest, which is 21.90 mm, and the maximum horizontal (TX direction) displacement is 3.17 mm, which appears on both sides of the subgrade center, and the maximum vertical (TZ direction) displacement is 21.90 mm. The total displacement at the bottom slope foot is 3.71 mm, the horizontal (TX direction) displacement is 2.48 mm, and the vertical (TZ direction) displacement is 3.05 mm.

4.3.2. Differential settlement

Analysis of Fig. 10 shows that when height of the coal gangue layered filling is 7.0 m, the line at the bottom of the subgrade is extracted as the research object. The maximum settlement at the center of the subgrade bottom is 21.90 mm, and the maximum settlement at the foot of the subgrade bottom is 3.05 mm. It can be seen that uneven settlement occurs between the bottom slope toe and the center of the bottom, and the differential settlement is 18.85 mm.

5. Study on the evolution of stress characteristics of the coal gangue filled subgrade construction process

With an increase of coal gangue filling height, the stress at the bottom of the subgrade, the slope foot and the middle line will increase, as shown in Fig. 11. The change curves of total stress, S-XX and S-ZZ in the process of coal gangue filling are extracted. The results show that the vertical stress (S-ZZ) of the middle line of the subgrade occupies the dominant position of the stress change. As the main control factor of stress growth, it is the first principal stress in the stress redistribution and particle incarceration of the subgrade. The stress of the coal gangue subgrade increases linearly from 0 m to 7 m, and the vertical stress (S-ZZ) reaches 125 kPa. The change of the vertical stress (S-ZZ) at the slope toe of the subgrade is the smallest, and it grows slowly in the process of coal gangue filling. The third principal stress plays a role in the stress redistribution and particle embedding of the subgrade. During the filling process of the

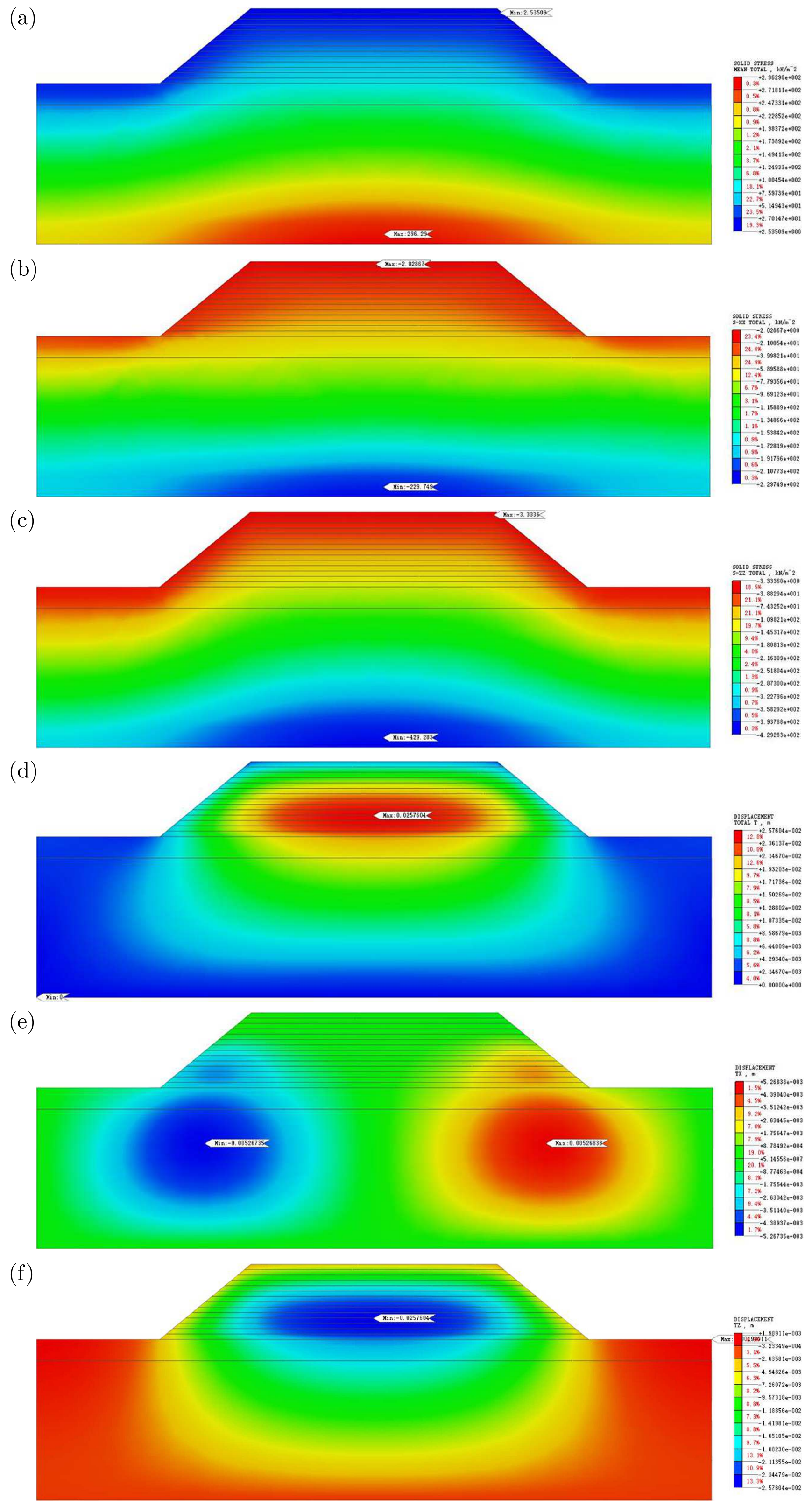

Fig. 9. Stress and deformation nephogram of coal gangue filling of the 14th floor: (a) total stress, (b) horizontal (S-XX direction) stress, (c) vertical (S-ZZ direction) stress, (d) total displacement (T), (e) horizontal (TX direction) displacement, (f) vertical (TZ direction) displacement

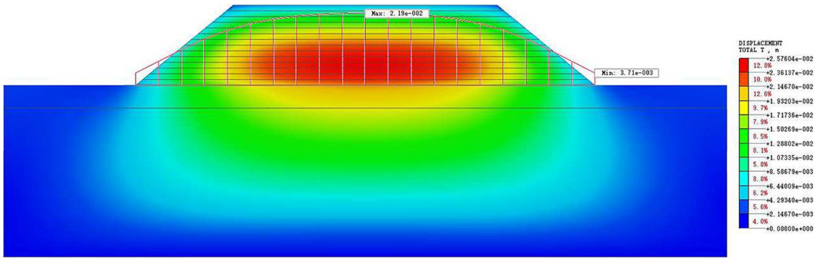

Fig. 10. Settlement curve between the slope toe and subgrade center

coal gangue subgrade from 0 m to 7 m, the stress shows a linear growth trend, and the vertical stress (S-ZZ) of subgrade slope toe reaches 12.2 kPa. The vertical stress change of the middle line of the subgrade is 10 times that of the slope toe, and the stress change directly affects the rigidity of the coal gangue subgrade, which varies the distribution of stress.

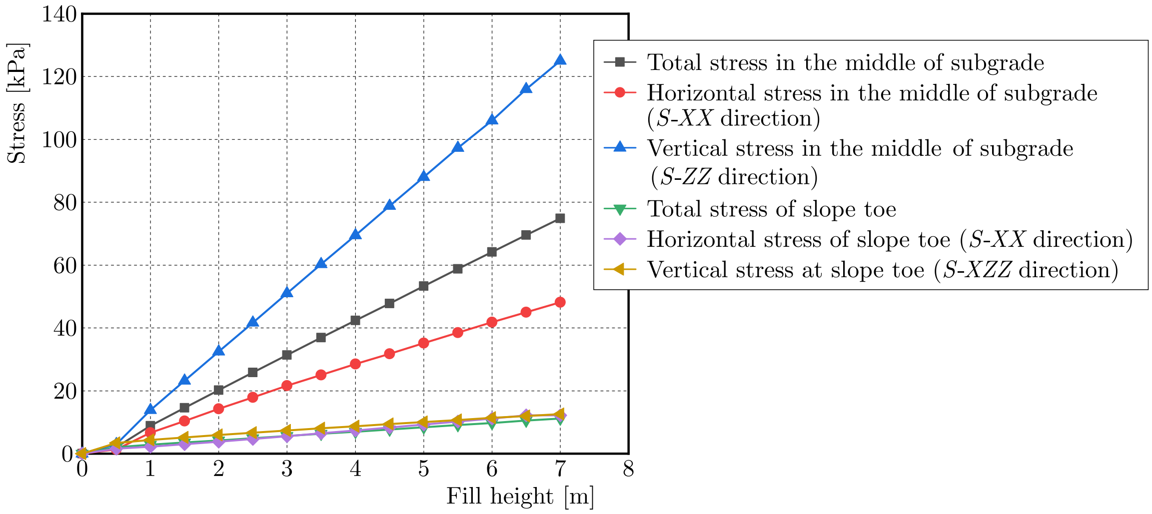

Fig. 11. Curve of stress variation with filling height

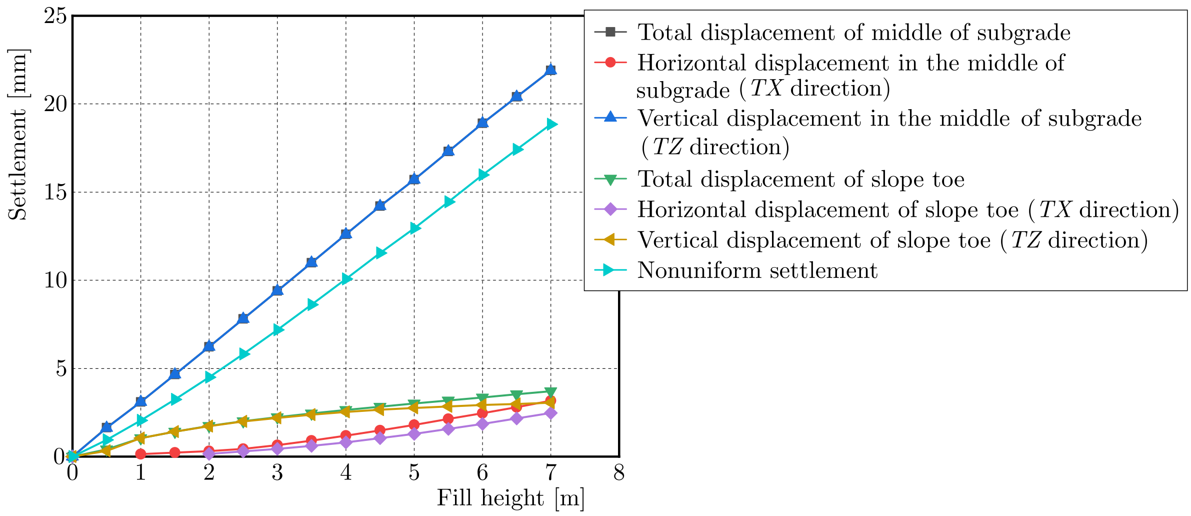

Fig. 12. Curve of settlement variation with filling height

With an increase of coal gangue filling height, the displacement at the bottom of the subgrade, the slope foot and the middle line will increase, as shown in Fig. 12. The change curves of total displacement, TX and TZ during the coal gangue filling process are extracted. The results show that the vertical displacement TZ of the subgrade midline occupies the dominant position of deformation, which plays an important role in the uneven deformation of the subgrade as the main control factor of deformation growth. The displacement of the coal gangue subgrade increases linearly from 0 m to 7 m, and the vertical displacement TZ reaches 21.9 mm. The horizontal displacement of the subgrade slope toe TX changes minimum, and it grows slowly in the process of coal gangue filling. The displacement of the coal gangue subgrade increases linearly from 0 m to 7 m, and the slope TX reaches 2.48 mm. The vertical displacement of the middle line is 10 times of the horizontal displacement of the slope toe. The change of displacement directly affects the overall safety and stability of the coal gangue subgrade, and it is easy to achieve variable settlement, which results in cracking defects of the subgrade.

With an increase of coal gangue filling height, the uneven settlement of the bottom slope foot and the bottom center of the subgrade will increase, as shown in Fig. 13. The variation curves of the total displacement and the total displacement of the bottom slope foot and the center of the bottom during the filling process of coal gangue are extracted. The results show that the variation of uneven settlement shows a linear growth trend. In the range of 5 m of coal gangue filling, the variation rate of uneven settlement is fast. When the height reaches 7 m, the settlement tends to be stable, and the stable value is 18.85 mm.

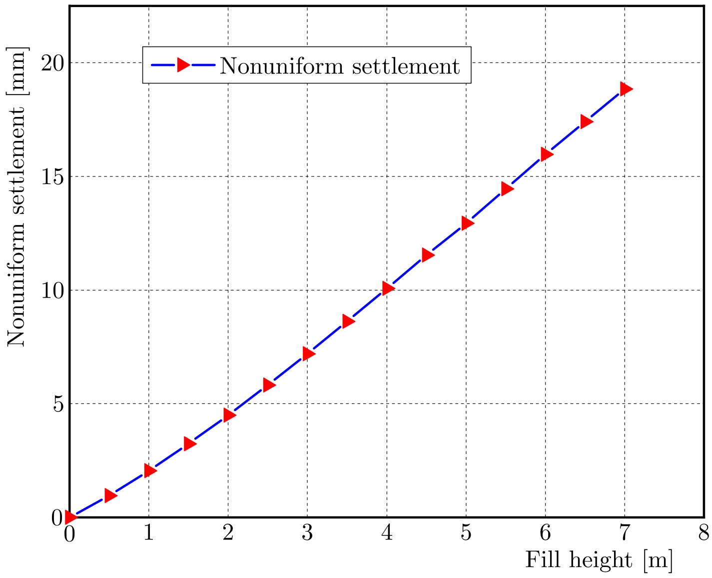

Fig. 13. Variation curve of differential settlement

6. Field stress and deformation monitoring

6.1. Field monitoring

In order to detect the state of coal gangue subgrade, it is necessary to control the coal gangue subgrade. According to the existing norms and standards, the settlement variation, elastic modulus and deflection value of coal gangue can be detected. However, the above is only the traditional detection method. In order to directly reflect the filling quality of coal gangue, the authors propose to use a set of key technologies for quality detection of coal gangue.

During the filling of the coal gangue subgrade, there are three test components, namely, earth pressure box, pore water pressure gauge and fixed inclinometer probe. The on-site coal gangue monitoring and sampling adopts a solar panel wireless transmission automatic monitoring system. After installation, the flow card is used to realize computer receiving data at any position, as shown in Fig. 14a.

Through data collection and analysis of the above test elements, it is concluded that the coal gangue subgrade structure is stable and there is no quality problem, as shown in Fig. 14b.

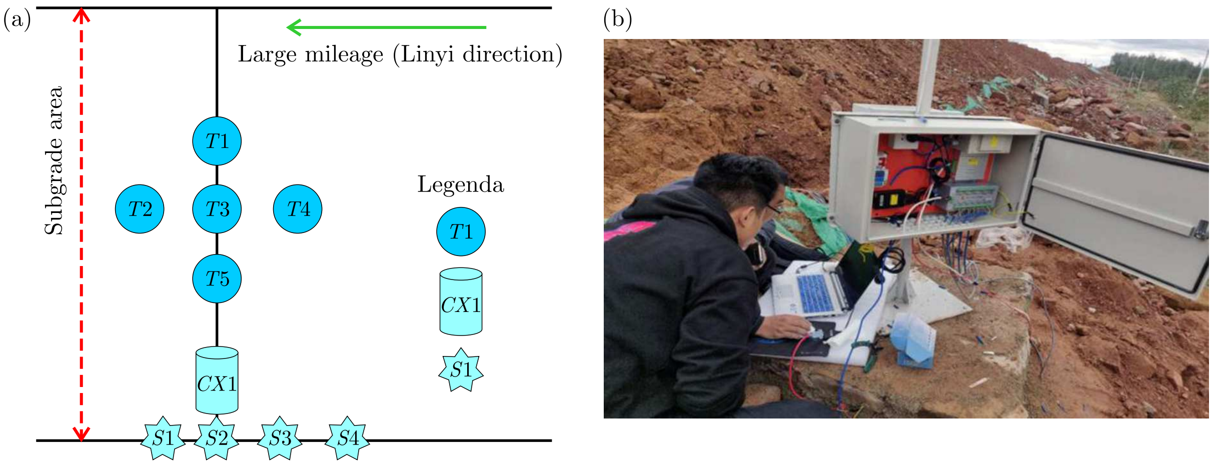

Fig. 14. (a) Setting diagram of test elements at each section, (b) data collection

6.2. Monitoring data analysis

Analysis of Fig. 15 shows that after nearly a year of monitoring data it turns out that the coal gangue subgrade does not occur groundwater infiltration and better guarantee its stability and safety.

Analysis of Fig. 16 shows that during the construction of the coal gangue subgrade the soil pressure increased sharply, after 100 days it stabilized, and the stable value is 185 kPa-207 kPa.

Figure 17 shows that the deformation of coal gangue subgrade is mainly reflected in the horizontal displacement and settlement change. The horizontal displacement and settlement change rate are faster in the early stage of subgrade construction. After completion of subgrade construction, the settlement reaches a stable state, with a horizontal deformation of 4.83 mm and settlement of 15.66 mm. And with construction of the base and surface layer, the load of the subgrade increases, which directly continues the deformation of the subgrade to increase. When the frequency of coal gangue subgrade monitoring is 400 d, the horizontal displacement and settlement reach a stable state. The horizontal displacement is maintained at 8.4 mm, and the settlement at 17.5 mm. The monitoring results show that the settlement of coal gangue subgrade is stable and the settlement is small, which ensures safety of the subgrade.

7. Conclusions

By analyzing geological conditions of the coal gangue filling subgrade, a three-dimensional geological mechanical model of coal gangue is established. Based on the Mohr-Coulomb failure criterion, stress characteristics and settlement changes during the filling process of the coal gangue roadbed are simulated. By extracting the stress and deformation cloud images of each layer of coal gangue filling, the stress and deformation curves of the center position at the bottom of the subgrade and the slope toe position at the bottom of the subgrade are analyzed. The following conclusions are drawn:

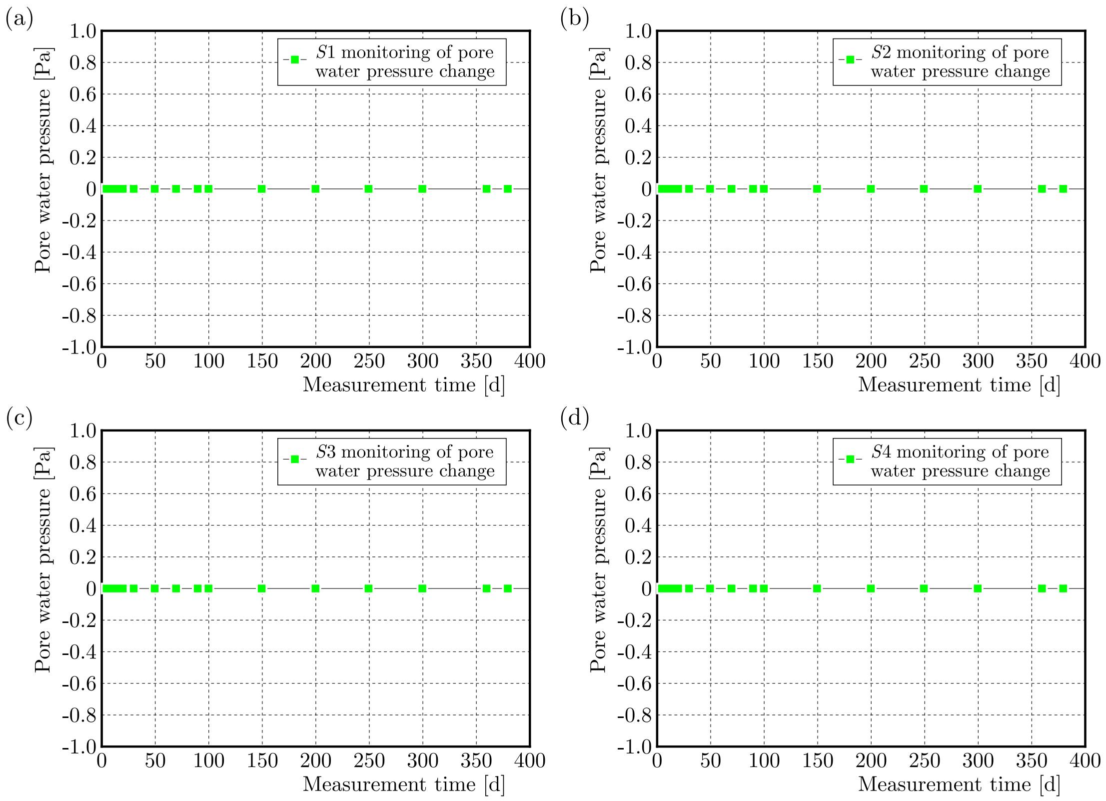

Fig. 15. Monitoring of pore water pressure variation of the coal gangue subgrade: (a) $S1$ pore water pressure, (b) $S2$ pore water pressure, (c) $S3$ pore water pressure, (d) $S4$ pore water pressure

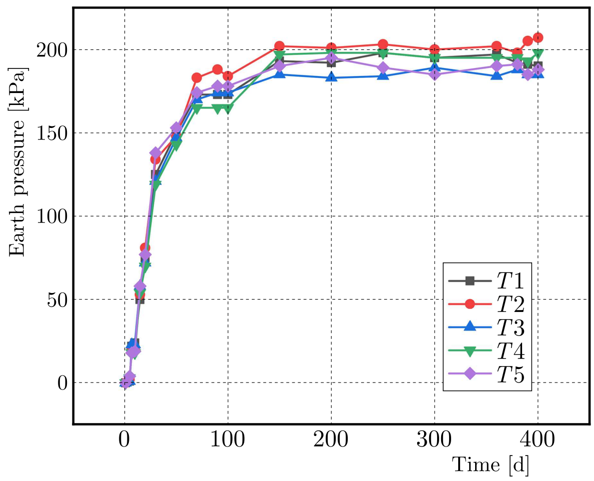

Fig. 16. Monitoring of earth pressure variation of the coal gangue subgrade

- As height of the coal gangue filling increases, the stress at the base of the road, the foot of the roadbed slope, and the center line of the roadbed will increase, and the settlement will also increase accordingly.
- During the filling process, the vertical stress (S-ZZ) plays a primary role in the stress redistribution and particle squeezing of the roadbed. The vertical stress change in the centerline of the roadbed is 10 times that of the vertical stress change at the foot of the roadbed slope, and the vertical displacement change in the centerline of the roadbed is 10 times that of the horizontal displacement change at the foot of the roadbed slope.

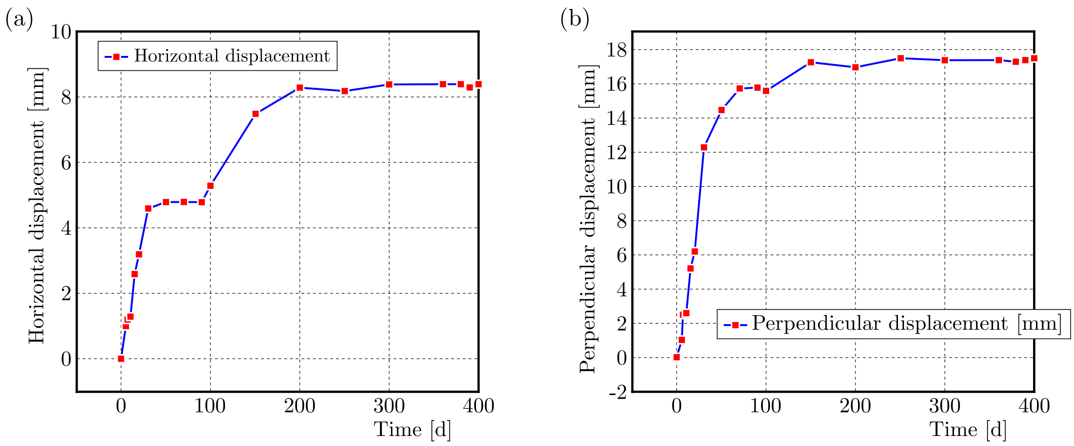

Fig. 17. (a) Monitoring of horizontal displacement change of the coal gangue subgrade, (b) monitoring of settlement change of the coal gangue subgrade

- As height of the coal gangue filling increases, the uneven settlement between the foot of the road base slope and the center of the road base will increase. The uneven settlement during the filling process shows a linear growth trend, and within the 5 m range of the coal gangue filling, the uneven settlement change rate is faster. When reaching a height of 7 m, the settlement tends to stabilize, and the stable value is 18.85 mm.
- The deformation of the coal gangue roadbed is mainly reflected in horizontal deformation and settlement changes. After completion of the roadbed construction, the horizontal deformation is 4.83 mm, and the settlement is 15.66 mm. With construction of the base and surface layers, the horizontal deformation increased to 8.4 mm and the settlement remained at 17.5 mm. The monitoring results indicate that the settlement of the coal gangue roadbed is stable and the settlement amount is small, ensuring safety of the roadbed.

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