Stability analysis of water-filled dump slope under the couple effect of seepage and damage

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Abstract

The stability problem of water-filled dump slope becomes one of the geotechnical engineering problems needed to be resolved. Especially, the couple effect of seepage and damage has a great influence on the dump slope. Using a combination of theoretical analysis and numerical calculation methods, the seepage-damage coupled mathematical model of coal rock mass based on pressure and shear type and open type is established, the permeability tensor effected by fracture damage of coal rock mass is studied. Taking Heidaigou dump slope for example, the stability of water-filled dump slope under the couple effect of seepage and damage is numerical analyzed. The results show that: (1) the pore water pressure of water-filled dump is not fully dissipated under high-stress load, and the damage degree of dump bed and the instability chance of dump slope are increasing. (2) as the water level rises, the pore water pressure increase, the safety factor of dump slope is reducing. The effective internal friction angle and the shear strength decrease when the settling velocity greater than the pore water pressure dissipation rate. But, the shear strength decrease significantly when the pore water pressure dissipation too late. The research results provide strong guidance for the stability of water-filled dump slope.

Keywords: seepage-damage coupled model, water-filled bed, dump slope, stability, numerical calculation

Introduction

The stability problem of water-filled dump slope becomes one of the geotechnical engineering problems needed to be resolved. Especially, the couple effect of seepage and damage has a great influence on the dump slope. Domestic and foreign researchers have carried out a lot of research work for the deformation of water-filled coal rock. The law of seepage characteristics with the variation of the stress state was obtained through a series of field and laboratory test by CL.LOUIS[1]. The seepage characteristic of joint surface affected by shear deformation was studied by BARTON[2]. The exponential relationship which determined by the deformation of the joints between the stress and the permeability coefficient is revealed by CHEN ShengHong[3]. The water filling factors of Baiyinhua open-pit coal mine 3# was researched by WEN dejuan[4], the open-air type of hydro-geological and pit water filling factor were obtained. However, previous studies mostly consider the structural stability of the single factor, the evolution of coal rock deformation under the couple effect of seepage and damage is still in its infancy. Therefore, considering the impact of seepage and damage, the study of stability of water-filled dump slope under the couple effect of seepage and damage has important theoretical significance and practical value.

Using a combination of theoretical analysis and numerical calculation methods, the seepage-damage coupled mathematical model of coal rock mass based on pressure and shear type and open type is established, the permeability tensor effected by fracture damage of coal rock mass is studied. Take Heidaigou dump slope for example, the stability of water-filled dump slope under the couple effect of seepage and damage is numerical analyzed. The results of the pore water pressure dissipation law of water-filled dump and the stability of dump slope influenced by pore water pressure can provide strong guidance for the stability of dump slope.

Seepage-damage coupled mathematical model

Pressure and shear type seepage-damage coupled model

(1) considering the action of normal stress and the osmotic pressure, the fracture surface deformation as follows:

$$\Delta b_1 = -b_0\left[1 - e^{-\frac{\sigma_n - \beta p}{K_n}}\right] \tag{1}$$

The average opening width of cracks as follows:

$$\Delta b_2 = \frac{2(1-\nu^2)}{E}\left[\frac{4a\tau_{eff}\cos\theta}{\pi l}\int_0^l\left(\frac{l}{x}+\sqrt{\left(\frac{l}{x}\right)^2-1}\right)dx - \frac{\pi}{2}\sigma_3 l\right] \tag{2}$$

Where, θ is the angle between cracks france direction and σ_3, l is the crack. length.

The total deformation of fracture surface as follows:

$$\Delta b=\Delta b_1+\Delta b_2=-b_0\left[1-e^{-\frac{\sigma_n-\beta p}{K_n}}\right]+\frac{2(1-\nu^2)}{E}\left[\frac{\frac{4a\tau_{eff}\cos\theta}{\pi l}}{\int_0^l\left(\frac{l}{x}+\sqrt{\left(\frac{l}{x}\right)^2-1}\right)dx-\frac{\pi}{2}\sigma_3 l}\right] \quad (3)$$

The fracture surface permeability tensor as follows:

$$k_{ij}=\sum_{k=1}^{n}\frac{\frac{g(b^{(k)}+\Delta b^{(k)})^3}{12\mu C^{(k)}}\pi}{(a+l)^{(k)^2}\lambda^{(k)}\rho_V^{(k)}\left(\delta_{ij}-n_i^{(k)}n_j^{(k)}\right)} \quad (4)$$

(2) tension and shear state: $K_I<K_{IC}$, the fracture surface deformation as follows:

$$\Delta b_3=\frac{16(1-\nu^2)}{3\pi E}a\left(\sigma_n+p\right) \quad (5)$$

The coal rock mass permeability tensor is:

$$k_{ij}=\sum_{k=1}^{n}\frac{\frac{g(b^{(k)}+\Delta b^{(k)})^3}{12\mu C^{(k)}}\pi}{a^{(k)^2}\lambda^{(k)}\rho_\nu^{(k)}\left(\delta_{ij}-n_i^{(k)}n_j^{(k)}\right)} \quad (6)$$

(3) $K_I>K_{IC}$, intensity factor of crack tip stress under tension and shear can obtained by the following formula:

$$K_I=\frac{5.18a(\tau_{eff}\sin\alpha+\sigma_3\cos\alpha)}{\sqrt{\pi l}}+1.12\sigma_3\sqrt{\pi l} \quad (7)$$

Where, α is the angle of fractured surface and σ_1. According to the Castigliano's Theorem:

$$\Delta b_4=\frac{16\sqrt{2}}{5\pi}\frac{(1-\nu^2)}{E}a\left(\sigma_n+p\right) \quad (8)$$

The coal rock mass permeability tensor is:

$$k_{ij}=\sum_{k=1}^{n}\frac{\frac{g(b^{(k)}+\Delta b_3^{(k)}+\Delta b_4^{(k)})^3}{12\mu C^{(k)}}\pi}{(a^{(k)}+l)^2\lambda^{(k)}\rho_\nu^{(k)}\left(\delta_{ij}-n_i^{(k)}n_j^{(k)}\right)} \quad (9)$$

The compatibility conditions of damage surface:

$$\dot{V}=-\frac{\frac{\partial G}{\partial\tau_\omega}\frac{\partial\tau_\omega}{\partial S_r}\mathrm{d}S_r\frac{\partial G}{\partial\tau_\omega}}{\frac{\partial G}{\partial L_V}\frac{\partial L_V}{\partial V}\frac{\partial G}{\partial\tau_\omega}} \quad (10)$$

Where, L_V is the humidifier injury strengthen parameters; G is the energy index; S_r is saturation.

Formula (4), (6), (9) and (10) together constitute the seepage-damage coupled model of coal rock mass.

open type seepage-damage coupled model

In accordance with the Betti energy reciprocity theorem, the initial damage compliance tensor [5, 6] is:

$$C_{ijkl}^{0-d-w}=C_{ijkl}^0+C_{ijkl}^d+C_{ijkl}^w \quad (11)$$

Where, C_{ijkl}^0 is the compliance tensor; C_{ijkl}^d is additional compliance tensor; C_{ijkl}^w is the osmotic pressure additional compliance tensor.

$$C_{ijkl}^0=\frac{1+\nu_0}{E}\delta_{ik}\delta_{jl}-\frac{\nu_0}{E}\delta_{ij}\delta_{jl}$$

$$C_{ijkl}^d=\frac{1}{E}\sum_{k=1}^{K}\left\{a^{(k)3}\rho_v^{(k)}\left[2G_1^{(k)}n_i^{(k)}n_j^{(k)}n_k^{(k)}n_l^{(k)}+\frac{1}{2}G_2^{(k)}\left(\delta_{il}n_j^{(k)}n_k^{(k)}+\delta_{ik}n_j^{(k)}n_l^{(k)}+\delta_{jl}n_i^{(k)}n_k^{(k)}+\delta_{jk}n_i^{(k)}n_l^{(k)}-4n_i^{(k)}n_j^{(k)}n_k^{(k)}n_l^{(k)}\right)\right]\right\}$$

$$C_{ijkl}^w=\frac{2}{3E}\sum_{k=1}^{K}\left\{a^{(k)3}\rho_v^{(k)}\left[G_1^{(k)}R^{(k)}(n_i^{(k)}n_j^{(k)}\delta_{kl}+n_k^{(k)}n_l^{(k)}\delta_{ij})+\frac{1}{3}G_2^{(k)}\delta_{ij}\delta_{kl}R^{(k)^2}\right]\right\}$$

Where, a is the radius; ρ_v is the density of fractures; K is the number of fractured group; $G_1=\frac{8(1-{\nu_0}^2)}{3},G_2=\frac{16(1-{\nu_0}^2)}{3E(2-\nu_0)},n_i(1,2,3)$; δ_{ij} is Kronecker symbol; $R=\frac{p}{\delta}$; p is osmotic pressure; $\delta=\frac{1}{3}\delta_{ii}$.

If $C_{ijkl}^w=0$, the initial damage compliance tensor is:

$$C_{ijkl}^{0-d-w}=C_{ijkl}^0+C_{ijkl}^d \quad (12)$$

The constitutive equation can be expressed as:

$$\varepsilon'_{ij}=\varepsilon_{ij}+\varepsilon_{ij}^w=C_{ijkl}^{0-d}\sigma_{kl}+C_{ijkl}^w\sigma_{kl}+C_{ijkl}^{0-d-w}\delta_{kl}p \quad (13)$$

$$\varepsilon_{ij}=C_{ijkl}^{0-d}\sigma_{kl} \quad (14)$$

$$\varepsilon_{ij}^w=C_{ijkl}^w\sigma_{kl}+C_{ijkl}^{0-d-w}\delta_{kl}p \quad (15)$$

Considering the solid deformation, the seepage control equation is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial p}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial p}{\partial x}\right)=n\alpha\rho\frac{\partial p}{\partial t}+\rho\frac{\partial e}{\partial t}+w \quad (16)$$

Where, K_{ij} is the permeability tensor; p is the pressure; e is the solid deformation; w is the source and sink terms; n is the porosity; α is water compressibility coefficient; ρ is the density of water.

The seepage-damage coupled model expressed as:

$$\varepsilon'_{ij} = C_{ijkl}^{0-d-w}\sigma_{kl}$$

$$\varepsilon_{ij} = C_{ijkl}^{0-d-w-ad}\sigma_{kl}$$

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial p}{\partial y}\right)+$$

$$\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial p}{\partial x}\right)=n\alpha\rho\frac{\partial p}{\partial t}+\rho\frac{\partial e}{\partial t}+w$$

Stability analysis of water-filled dump slope

Take Heidaigou dump slope for example, the stability of water-filled dump slope under the couple effect of seepage and damage is numerical analyzed. The dump which final elevation is 1260m covers an area of 5.06km^2. The dump(loose coefficient 1.15, slope angle 21°) height is 100m~120m, and the step height is 15m. The deepest water storage of the reservoir area is about 4.5m. The water storage area is about 8.3×10^4 m^2. The water storage is about 3×10^5 m^3.As the high reservoir level, the dump bed which infiltrated by water has been severely weakened. Engineering site photos are shown in Fig.1. Deformation area plane and computing profile position is shown in Fig.2. Fig.3 shows the calculation model.

Fig.1 Engineering site photos

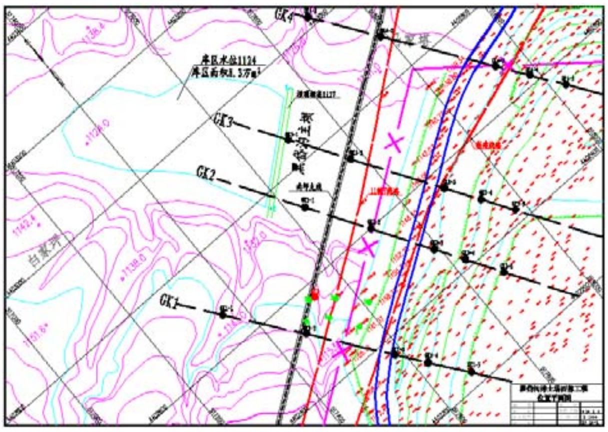


Fig.2 Deformation area plane and computing profile position

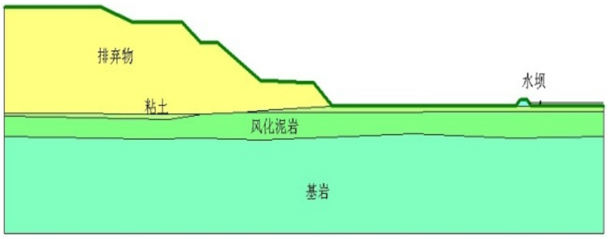


Fig.3 Calculation model

Water-filled weakening process of dump bed

Take dump GK2 for example, considering upstream water infiltration and saturation line uplift, the deformation evolution of dump slope is simulated.

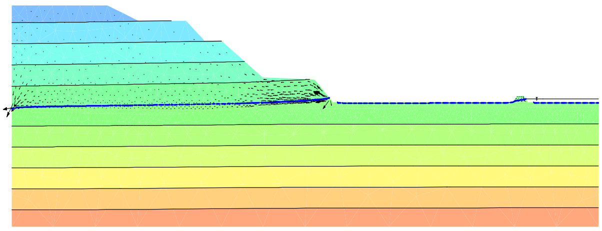


Fig.4 Vectogram of ponded water infiltration 10th step

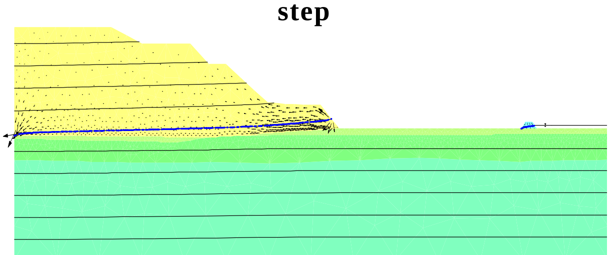


Fig.5 Vectogram of ponded water infiltration 20th step

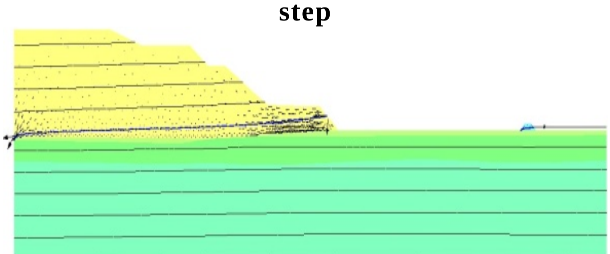
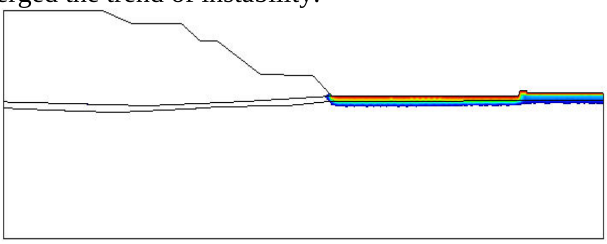


Fig.6 Vectogram of ponded water infiltration 30th step

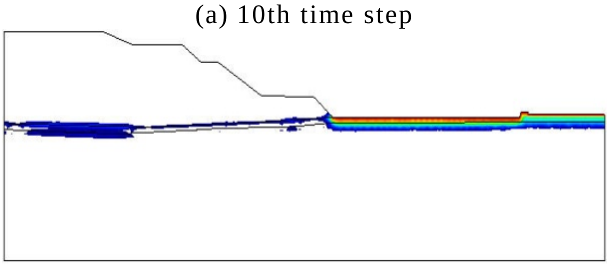
The vectogram of ponded water infiltration calculation results are shown in Fig.4～Fig.6. Stagnant water infiltrate into the dump bed under water pressure. On the one hand, water move to the downstream under the effect of hydrostatic pressure, on the under hand, water molecule rose and the saturation line got higher under the effect of capillary water. The rising speed is the fastest at the initial stage and it got slower and slower, as to say the speed and height change at unit time got smaller as time increased. At the same time, the slope stability would be seriously affected because of the effect of water-filled damage.

Water-filled Damage Simulation

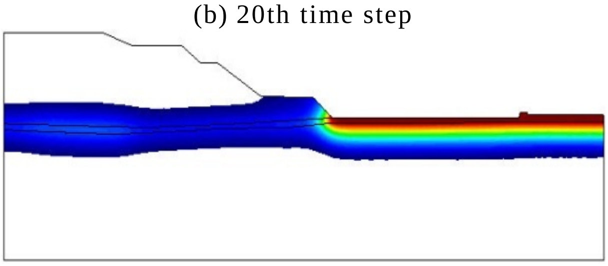
The calculation results of Fig.7 showed the whole process of waste dump basement water-filled damage. As the clay layer (including clayey rocks) of the dump bed is soft layer, the soft layer is changed into aquifer in the process of water filling and under the long-termed effect of water. The water content of the basement layer got larger and larger under the effect of high stress load dump and the shielding waste dump. The effective stress7-9 of waste dump got smaller and the soft layer weaken seriously caused by pore water pressure without got no dissipation. The former dump bed which the inclination angle 1°～3° is anti-tilt slope. This structure Is good for slope stability in theory, but as continued infiltration and weakening of water, the soft layer got thicker and thicker, it would afford to offset the advantage of stability caused by anti-tilt. As the dumping continues to row of abandoned and continued effect of water10, the damage degree of bed increased constantly, the slope stability declined remarkably and emerged the trend of instability.



(a) 10th time step



(b) 20th time step



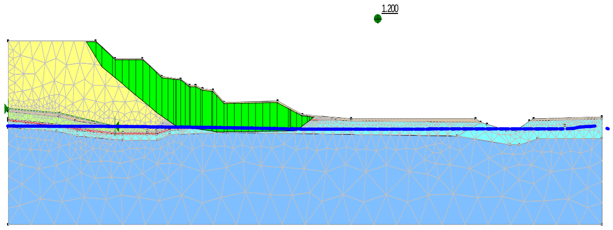
(c) 30nd time step

Fig.7 Diffusion diagram of ponded water infiltration

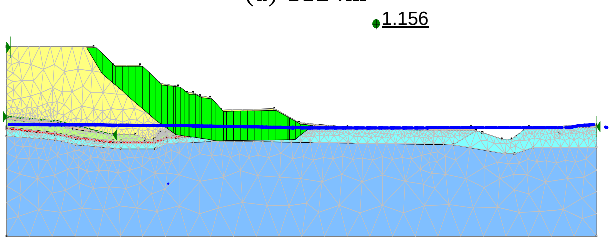
Stability analysis of dump slope under filling water damage

The damage of dump bed is mainly strength injury, its rock and soil strength significantly reduced under the action of seepage-damage coupling, and as the acting by external hydrostatic pressure caused by the rise of underground water level, the dump slope11,12 stability is effected seriously. This section uses finite reduction method on deformation and stability of GK1-GK4 profile in the region under the different water levels for quantitative calculations. The calculation result of dump slope stability effected by water level rising is shown in Fig.8～Fig.11.

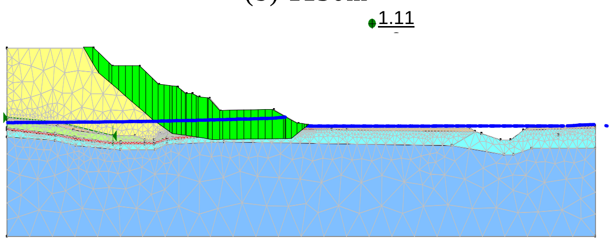
(1) Stability analysis of dump slope under the GK1 water level rise



(a) 1124m



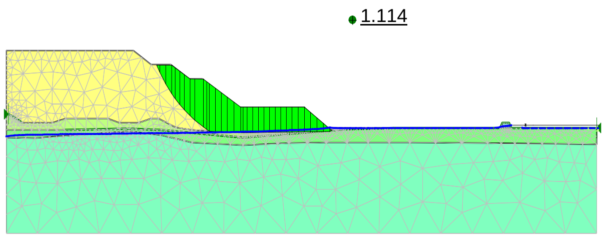
(b) 1130m



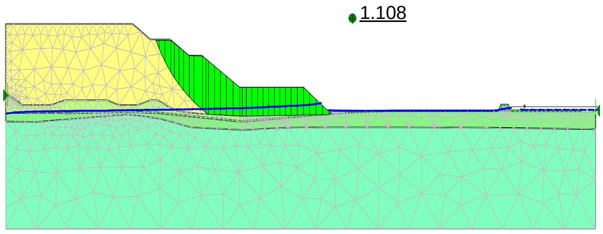
(c) 1135m

Fig.8 Stability calculation diagram of dump slope(GK1)

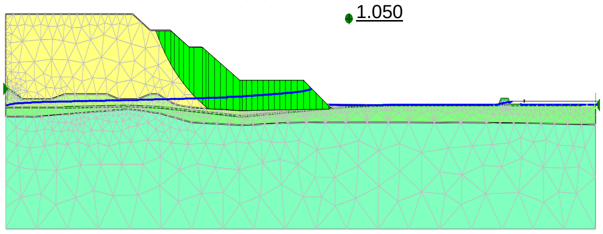
(2) Stability analysis of dump slope under the GK2 water level rise



(a) 1124m



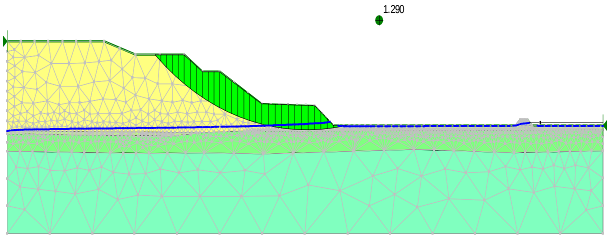
(b) 1130m



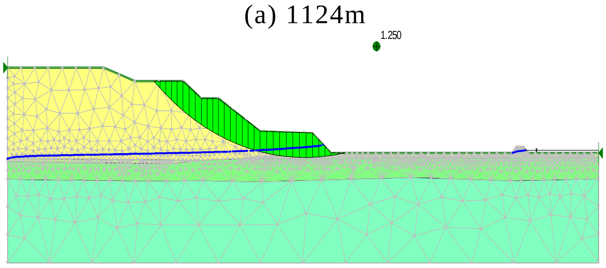
(c) 1135m

Fig.9 Stability calculation diagram of dump slope(GK2)

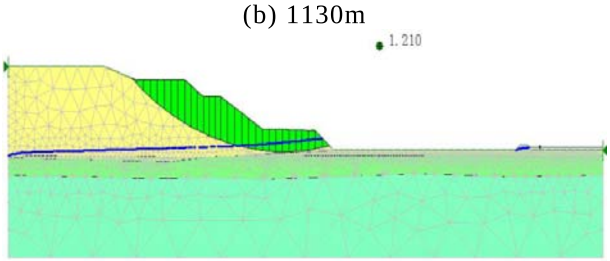
(3) Stability analysis of dump slope under the GK3 water level rise



(a) 1124m



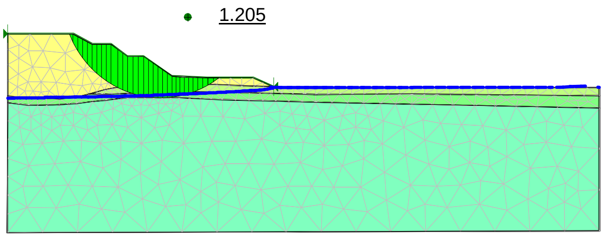
(b) 1130m



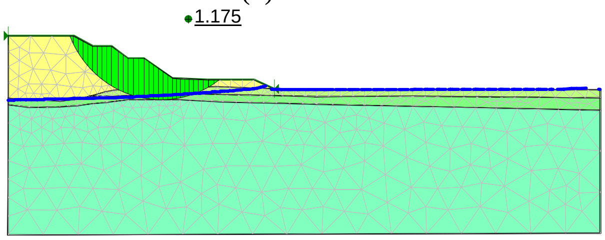
(c) 1135m

Fig.10 Stability calculation diagram of dump slope(GK3)

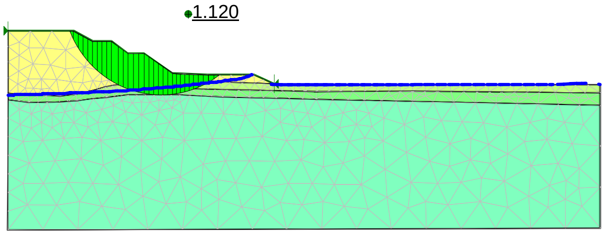
(4) Stability analysis of dump slope under the GK4 water level rise



(a) 1124m



(b) 1130m



(c) 1135m

Fig.11 Stability calculation diagram of dump slope(GK4)

The stability of dump slope under different water level were calculated by M-P method. The calculated results are shown in Table1. The results showed that: safety factor decrease as the water level rises, slope stability factor is less than the minimum factor of safety regulatory requirements. Under the effect of external loads, the additional stress of foundation soil were shared by soil effective normal stress and pore water pressure, soil effective normal stress increased only when the pore water pressure dissipated constantly, and the foundation soil strength is gradually increased. In the rainy season, the settling velocity got faster or higher intensity discharge for a short time caused the soil stress increase and as well as the speed of the settlement. Decline in the effective angle of internal friction and shear strength reduction were caused when excretion rate of settling velocity is greater than the water in the soil (or dissipation of pore water pressure of speed). The soil shear strength reduce marketable when settling velocity reach pore water pressure. Landslides may occur if continue to develop. To reduce further weakening of dump substrate, measures should be taken as soon as possible.

Table1 The impact of water-level rise on overall slope stability

Safety factor / Profile	1124 m	1130 m	1135 m
GK1	1.200	1.156	1.112
GK2	1.114	1.108	1.050
GK3	1.290	1.250	1.210
GK4	1.205	1.175	1.112

Conclusion

Through the stability analysis of water-filled dump slope under the couple effect of seepage and damage, the following conclusions:

(1) the seepage-damage coupled mathematical model of coal rock mass based on pressure and shear type and open type is established, the permeability tensor effected by fracture damage of coal rock mass is studied.

(2) the saturation line also will be increased as the dump bed water filled. Water-filled damage affected the slope stability.

(3) the pore water pressure of water-filled dump is not fully dissipated under high-stress load, and the damage degree of dump bed and the instability chance of dump slope are increasing.

(4) the effective internal friction angle and the shear strength decrease when the settling velocity greater than the pore water pressure dissipation rate. But, the shear strength decrease significantly when the pore water pressure dissipation too late. The research results provide strong guidance for the stability of water-filled dump slope.

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