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Seepage–damage coupling study of the stability of water-filled dump slope

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ABSTRACT

The stability of water-filled dump slope has been one significant geotechnical engineering problem that needs to be urgently resolved. The coupling effects of seepage and damage on the dump slope are critically important for stability analysis. In this paper, a seepage–damage coupled mathematical model is developed for fractured coal rock mass, and the permeability tensor effects from the fracture damage of coal rock mass are investigated. Numerical simulations are conducted for Dongming and Heidaigou dump slope on the stability of water-filled dump slope under the coupling effects of seepage and damage. Numerical results show that the high pore pressure can reduce the positive pressure of the sliding surface and the friction, and can lead to the strength loss of water-filled coal rock mass. It is also demonstrated that with the propagation of the slope crack, the pore pressure gradually dissipate to larger areas, and approaches the slope table. This will result in the further damage of the table rock of slope and the decrease of support force, has a serious impact on the overall slope stability of the system. With the development of seepage, the opened cracks increase gradually. The water pressure not only has restructured the fracture network of coal rock, but also has a huge impact on the main fracture deformation. It is demonstrated that if pore water pressure is difficult to dissipate, effective stress decreases and weak surface increases, and this further leads to instability of coal rock slope. The results also reveal that it is easy to cut out at the foot of the slope. Two failure models of “arc” or “located-sliding” are observed. The numerical results further reveal the percolation mechanism of the softening of coal rock slope.

1. Introduction

The deformation and damaging of coal rock is a discontinuous and non-even process, while the inherent pore and fracture space can speed up the process. If water within pore and fracture space is not evacuated smoothly, the water pore pressure can accumulate to be very high. This can reduce the positive pressure of the sliding surface and the friction, and can lead to the strength loss of water-filled coal rock mass. Therefore pore pressure has a great influence on the stability of coal rock slope and is one significant geotechnical engineering problem that needs to be urgently resolved.

Domestic and foreign researchers have carried out a lot of research work on the deformation of water-filled coal rock mass. Louis investigated the mechanism of seepage characteristics with the variation of the stress state through a series of field and laboratory tests [1]. Barton et al. studied the seepage characteristic of joint surface affected by shear deformation [2]. Wen et al. provided an investigation on water filling factors of Baiyinhua open-pit coal mine #3. The open-air type of hydro-geological and pit water filling factor were obtained. However, previous studies generally consider the structural stability of coal rock slope [3,4] based on single factor. In fact, the deformation and damaging process is closely related to the coupling effects of seepage and damage as well as water-filled filled weakening of coal rock mass, which are still in the infant stage.

In this paper, a mathematical model considering seepage–damage coupling effects in fractured coal rock mass shall be developed. Numerical simulations on water pressure dissipation of water-filled coal rock slope under the coupling effect of seepage and damage will be conducted for a practical engineering problem of water-filled coal rock slope of Dongming open pit. The obtained numerical results further reveal the percolation mechanism of the softening of coal rock slope.

2. Rupture–seepage coupling mechanism of coal rock

The penetration of coal rock slope is related to pressure difference, coefficient of permeability and storage. The corresponding

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mathematical model can be expressed as

$$\frac{\partial}{\partial x}\left(T\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial z}\left(T\frac{\partial H}{\partial z}\right)=S\frac{\partial H}{\partial t} \tag{1}$$

Head boundary

$$H(x,z,t)|_{\Gamma_1}=\varphi(x,z,t), \quad (x,z)\in\Gamma_1$$

Flow boundaries

$$T\frac{\partial H}{\partial n}\Big|_{\Gamma_2}=q(x,z,t), \quad (x,z)\in\Gamma_2$$

Initial conditions

$$H(x,z,t)|_{t=0}=H_0(x,z), \quad (x,z)\in D$$

where, T is the coefficient of permeability; H is the total head; S represents the coefficient of storage; q denotes the vertical recharge per unit width on Γ_2, and it is a known function; n is the outward normal direction of Γ_2; φ is a known function.

Assuming that the dissipation potential caused by penetration of coal rock mass is

$$\phi_V=\phi_V(Y,V) \tag{2}$$

The changes of water content have an effect on structural parameters, structural strength and matric suction.

Define a potential function

$$G=G(\tau_\omega,L_V) \tag{3}$$

where, L_V is a strengthening parameters, and stands for a function of V; G is the humidification energy indicators and can expressed as $\tau_\omega(S_r)$, where S_r represents the saturation.

The flow rule is

$$dV=d\lambda_V\frac{\partial G}{\partial \tau_\omega} \tag{4}$$

Compatibility condition is

$$dG=\frac{\partial G}{\partial \tau_\omega}d\tau_\omega+\frac{\partial G}{\partial L_V}dL_V=\frac{\partial G}{\partial \tau_\omega}d\tau_\omega+\frac{\partial G}{\partial L_V}\frac{\partial L_V}{\partial V}dV=0 \tag{5}$$

Obtained from the above equation

$$\dot{V}=-\frac{\dfrac{\partial G}{\partial \tau_\omega}\dfrac{\partial \tau_\omega}{\partial S_r}\,\mathrm{d}S_r\dfrac{\partial G}{\partial \tau_\omega}}{\dfrac{\partial G}{\partial L_V}\dfrac{\partial L_V}{\partial V}\dfrac{\partial G}{\partial \tau_\omega}} \tag{6}$$

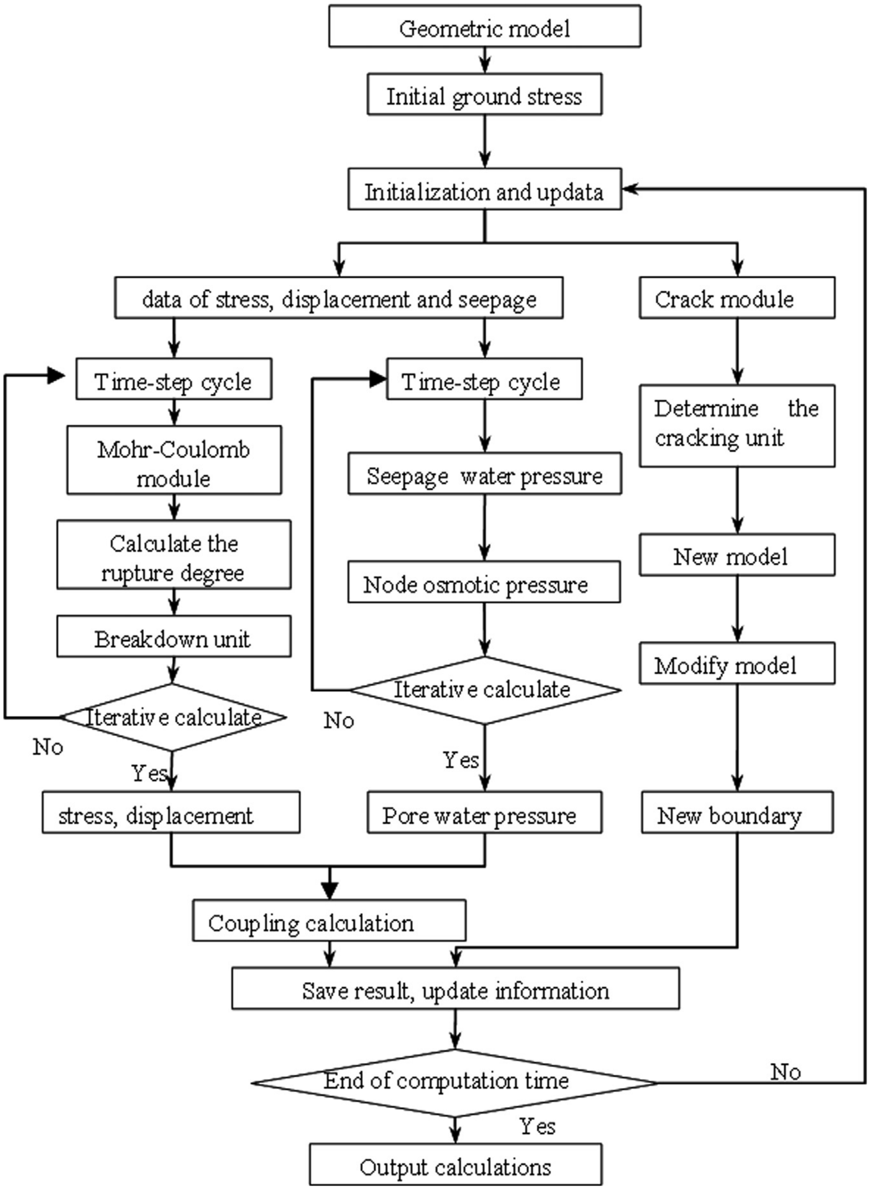

Fig. 1. The flow chart of seepage–damage coupled analysis.

3. Seepage–damage coupling model of fractured coal rock mass

In accordance with the Betti energy reciprocity theorem, the initial damage compliance tensor [5,6] can be written as

$$C_{ijkl}^{0-d-w} = C_{ijkl}^{0} + C_{ijkl}^{d} + C_{ijkl}^{w} \tag{7}$$

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.

$$C_{ijkl}^{0} = \frac{1+\nu_0}{E}\delta_{ik}\delta_{jl} - \frac{\nu_0}{E}\delta_{ij}\delta_{jl} \tag{8}$$

$$C_{ijkl}^{d} = \frac{1}{E}\sum_{k=1}^{K}\left\{\begin{array}{l} a^{(k)3}\rho_v^{(k)} \\ \left[\begin{array}{l} 2G_1^{(k)} n_i^{(k)} n_j^{(k)} n_k^{(k)} n_l^{(k)} + \\ \frac{1}{2}G_2^{(k)}\left(\begin{array}{l} \delta_{il} n_j^{(k)} n_k^{(k)} + \delta_{ik} n_j^{(k)} n_l^{(k)} + \\ \delta_{jl} n_i^{(k)} n_k^{(k)} + \delta_{jk} n_i^{(k)} n_l^{(k)} - \\ 4 n_i^{(k)} n_j^{(k)} n_k^{(k)} n_l^{(k)} \end{array}\right) \end{array}\right] \end{array}\right\} \tag{9}$$

$$C_{ijkl}^{w} = \frac{2}{3E}\sum_{k=1}^{K}\left\{ a^{(k)3}\rho_v^{(k)} \left[\begin{array}{l} G_1^{(k)} R^{(k)} (n_i^{(k)} n_j^{(k)} \delta_{kl} + \\ n_k^{(k)} n_l^{(k)} \delta_{ij}) + \\ \frac{1}{3}G_2^{(k)} \delta_{ij}\delta_{kl} R^{(k)^2} \end{array}\right]\right\} \tag{10}$$

where, a is the radius; ρ_v is the density of fractures; K is the number of fractured group;

$$G_1 = \frac{8(1-{\nu_0}^2)}{3}, \quad G_2 = \frac{16(1-{\nu_0}^2)}{3E(2-\nu_0)}, \quad n_i(1,2,3)$$

δ_{ij} is the Kronecker symbol; $R = p/\delta$; p is the osmotic pressure; $\delta = (1/3)\delta_{ii}$.

If $C_{ijkl}^{w} = 0$, the initial damage compliance tensor can be written as

$$C_{ijkl}^{0-d-w} = C_{ijkl}^{0} + C_{ijkl}^{d} \tag{11}$$

The constitutive equation can be expressed as

$$\varepsilon'_{ij} = \varepsilon_{ij} + \varepsilon_{ij}^{w} = C_{ijkl}^{0-d}\sigma_{kl} + C_{ijkl}^{w}\sigma_{kl} + C_{ijkl}^{0-d-w}\delta_{kl}p \tag{12}$$

$$\varepsilon_{ij} = C_{ijkl}^{0-d}\sigma_{kl} \tag{13}$$

$$\varepsilon_{ij}^{w} = C_{ijkl}^{w}\sigma_{kl} + C_{ijkl}^{0-d-w}\delta_{kl}p \tag{14}$$

Considering the solid deformation, the seepage control equation is

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial p}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial p}{\partial x}\right) = n\alpha\rho\frac{\partial p}{\partial t} + \rho\frac{\partial e}{\partial t} + w \tag{15}$$

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

$$\varepsilon'_{ij} = C_{ijkl}^{0-d-w}\sigma_{kl} \tag{16}$$

$$\varepsilon_{ij} = C_{ijkl}^{0-d-w-ad}\sigma_{kl} \tag{17}$$

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial p}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial p}{\partial x}\right) = n\alpha\rho\frac{\partial p}{\partial t} + \rho\frac{\partial e}{\partial t} + w \tag{18}$$

4. Finite element program of coupling calculation

Through coupling displacement, stress and water pressure, it is reasonable that the time elapsed at each loading step is small compared to the entire failure process of coal rock slop. The iterations at each loading step can cause changes on stress and displacement, and therefore can lead to redistribution of water pressure, which further changes stress and displacement. It is possible to judge the changing level of various physical, and to locate breaking units or elements in the coal rock. Finally, the dissipate situation of rupture and seepage field can be determined. It is able to simulate non-continuous media through processing mesh and generating new boundaries. The flowing chart of the finite element program is given in Figs. 1 and 2.

5. Numerical analysis of water pressure dissipation and the effect of seepage and damage of coal rock slope

The Dongming coal mine was founded in 2005, and it is an open pit with a yearly production scale of 1.8 million ton. The length, width and area are 2.10 km, 1.90 km and 4.0089 km^2, respectively. The geologic situation of Dongming coal mine is very complicated. Due to the inherent large amount of water, the strength of the mudstone is very low. With the production of open pit coal mine, the overhead area gradually increases, and the stability and safety of coal rock slope can be increasingly prominent. Fig. 3 shows the slope profile and Table 1 lists related parameters of the coal rock mass.

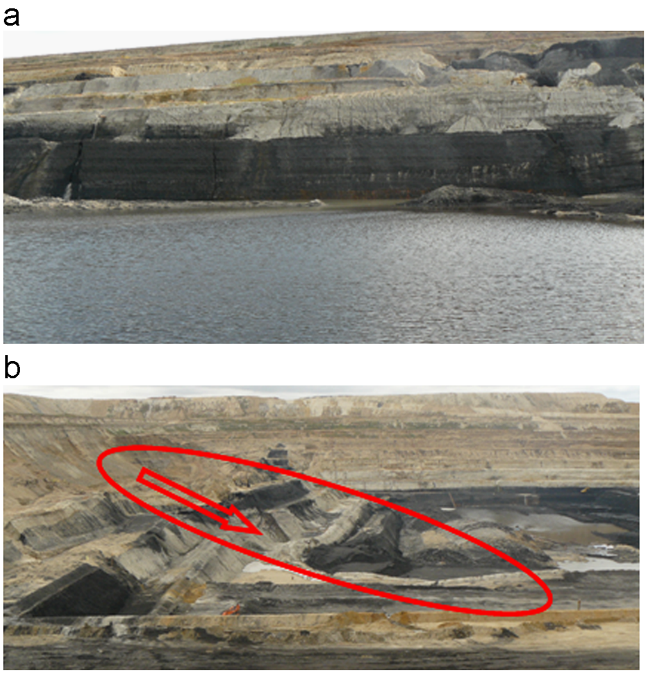

Fig. 2. The south of open pit mine. (a) water in the pit and (b) the south part of the pit after landslide.

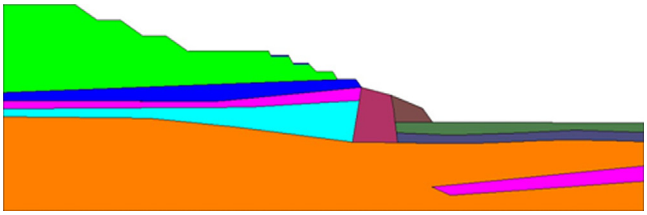

Fig. 3. The slope profile.

6. Water pressure dissipation of water-filled slope

The high pore pressure caused by discontinuous deformation [7,8] of coal rock mass can reduce the positive pressure of the sliding surface and the friction, lead to the strength loss of water-filled coal rock mass, and therefore can have great influences on the stability of coal rock slope. Fig. 4 shows the process of water pressure dissipation of water-filled slope with the deformation and failure of coal rock.

It can be observed from the numerical results that the infiltration process is closely related to the process of damage-fracture. The rate of water infiltration is higher than the diffusion rate in the inherent cracks at earlier stages. With the expension of damage area and damage degree, the coal rock slope occur to tensile failure. Also, the seepage and water pressure accelerated the degree of cracking of coal rock. The water pressure dissipation simulation results (see Fig. 4) also indicate that the dissipation of pore pressure gradually expands and approaches the slope table with the slope [9] crack propagation, resulting in further damage of the table rock of slope and the decrease of support force. It is therefore has a serious impact on the overall slope stability of the system.

Table 1
Parameters of coal rock mass.

Rock properties	E/MPa	μ	γ/(kN m^{-3})	C/10^3 Pa	ϕ/°	K/(m s^{-1})
Abandoned objects	540	0.3	1.42	6.75	23.7	2–5 × 10^{-4}
Glutenite	1180	0.33	1.78	6.75	34.5	5–10 × 10^{-4}
Mudstone	570	0.29	1.65	3.00	1.7	5–10 × 10^{-9}
Coal	540	0.3	1.28	67	25.4	1–10 × 10^{-6}
Fracture zone	300	0.4	1.64	5.46	14.6	5–10 × 10^{-4}

7. Seepage–damage coupling analysis of water-filled slope

Fig. 5 shows the evolution of the degree of damage and injury unit of slope at different computing time steps. The results indicate that damages first occur at the foot of slope due to the infiltration of precipitation to the slope body [10]. This leads to the damage and displacement of water-filled mudstone and the movement of the upper part of fault rock [8,11]. At the same time, damaged zone appears at the upper steps of fault rock. When time marches, the damage zone, damage degree and damage unit expands under the coupling effect of seepage and damage. It can be seen from the ninth step and tenth step that serious damages appear at the fault and the foot of slope, and a landslide is basically formed.

As the development of seepage, the opened cracks gradually increase. The water pressure not only has transformed the structure of the fracture network of coal rock, but also has a huge impact on the main fracture deformation. The simulation results show the damage state of coal rock and the deformation of main fracture and further reveal the percolation mechanism of the softening of coal rock slope.

8. Rupture evolution analysis of coal and rock slope

Take Heidaigou dump slope as an example, the stability of water-filled dump slope under coupling effects of seepage and damage is numerical analyzed. The final elevation of dump is

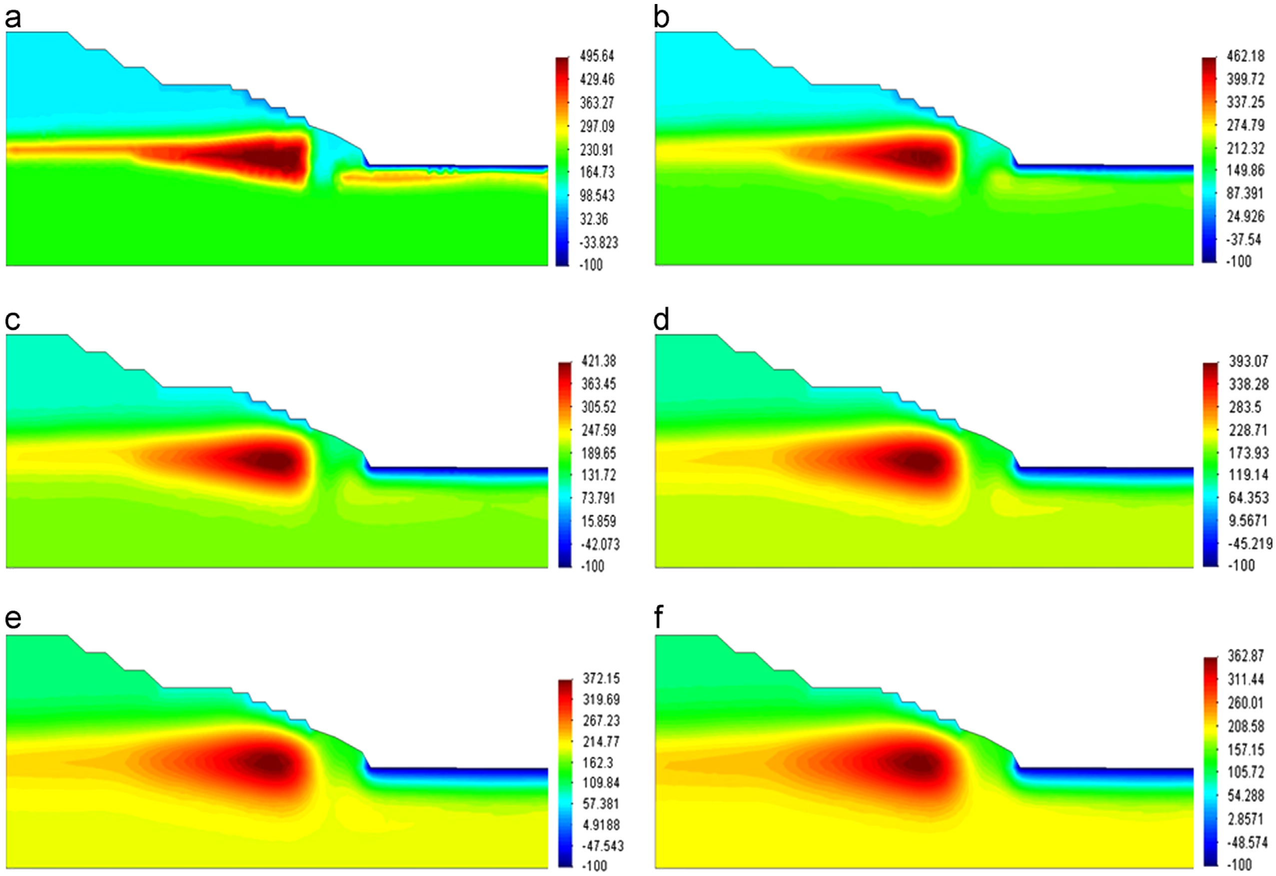

Fig. 4. Step chart of water pressure dissipation. (a) Step 1, (b) Step 3, (c) Step 5, (d) Step 7, (e) Step 9 and (10) Step 10.

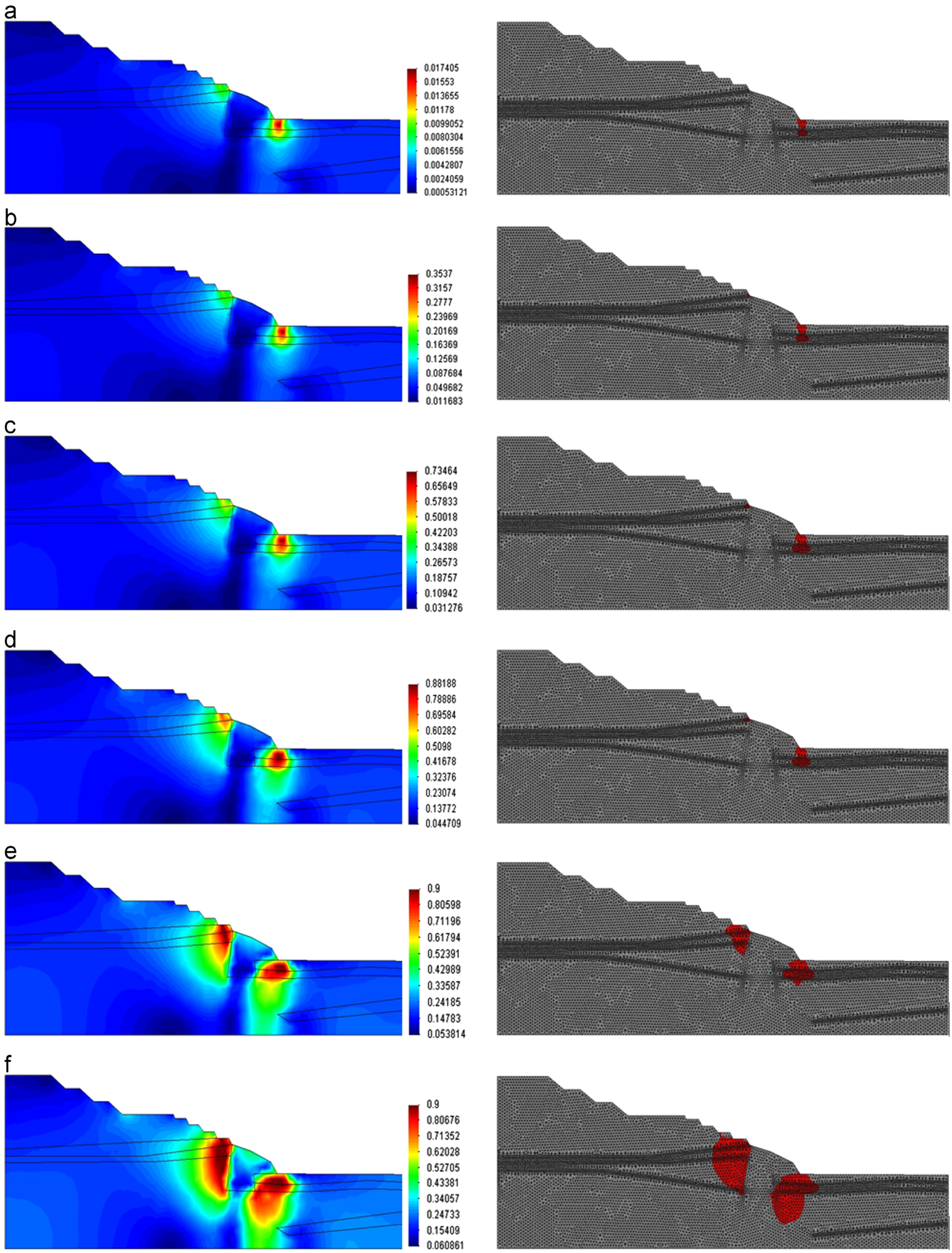

Fig. 5. The damage degree and damage unit. (a) Step 1, (b) Step 6, (c) Step 7, (d) Step 8, (e) Step 9 and (f) Step 10.

1260 m and the dump covers an area of 5.06 km^2. The dump (loose coefficient 1.15, slope angle 21°) height is 100–120 m, and the step height is 15 m. The deepest water storage of the reservoir area is about 4.5 m. The water storage area is about 8.3×10^4 m^2. Also, the water storage is about 3×10^5 m^3. Due to the high reservoir level, the dump bed has been infiltrated by water and has been severely

Fig. 6. Engineering site photos.

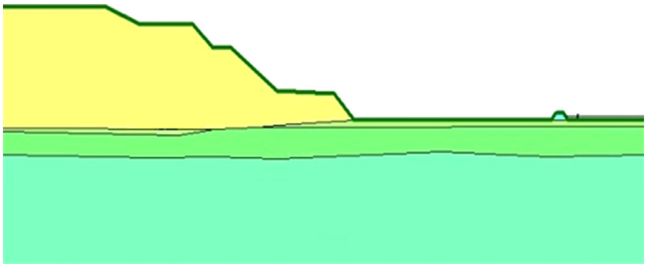

Fig. 7. Numerical simulation model.

weakened. An engineering site photo is given in Fig. 6, while Fig. 7 shows the numerical simulation model.

Fig. 8 gives the simulation results of tensile fracture process of slope. The simulate result indicate that the slope leads to displacement along the weak surface with strength reduction. As the displacement increases, tensile stress [12] concentration and tensile fractures appear at the first step ((b) and (c)). With the development of the deformation of weak layer, cracks increase in number and depth. Because slope [13] has lower tensile strength, the damage zone is extended to the slope edge ((d)). Meanwhile, the damage zone is expanded to the deep slope. And this shows the trend of tensile fractures penetration to the weak layer. It is clear that the crack shown in (e) and (f) appears in the edge of slope. If the infiltration problems of pore water is not well treated in a timely manner, the slope deformation will further develop, or can even result in slope instability. The slope deformation and failure mode can be judged from the simulation results. The slope failure simulation results also show that it is easy to cut out at the foot of the slope. In addition, the slope displays an failure model of “arc” or “located-sliding”.

9. Conclusions

This paper presents a seepage–damage coupling mathematical model for numerical simulation of coal rock mass and the permeability tensor effects from the fracture damage of coal rock mass. Numerical simulations are conducted for Dongming dump slope on the stability of water-filled dump slope under the coupling effects of seepage and damage. After analyzing water pressure dissipation of water-filled coal rock slope under the coupling effect of seepage and damage, it is found that:

(1) the high pore pressure can reduce the positive pressure of the sliding surface and the friction, and thus can lead to the strength loss of water-filled coal rock mass.
(2) when the dissipation of pore pressure gradually expands and approaches the slope table with the propagation of the slope crack, it will result in further damage of the table rock of slope and the decrease of support force, and therefore has a serious impact on the overall slope stability of the system.
(3) the water pressure not only has transformed the structure of fracture network of coal rock, but also have a huge impact on the main fracture deformation. The numerical results further reveal the percolation mechanism of the softening of coal rock slope.

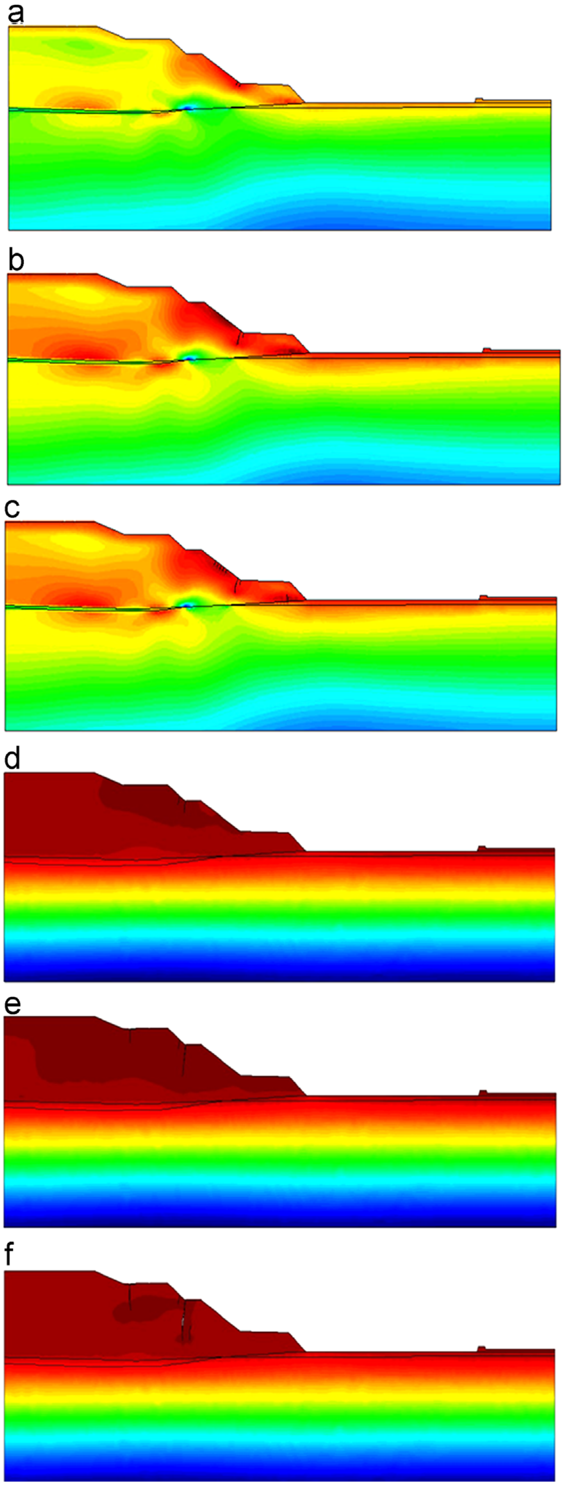

Fig. 8. The tensile rupture calculation result of dump slope. (a) the first step, (b) the third step, (c) the fifth step, (d) the seventh step, (e) the ninth step and (f) the eleventh step.

Acknowledgments

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