Study on sand particles creep model and open pit mine landslide mechanism caused by sand fatigue liquefaction

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Abstract. The sand particles in the sand-rock composite slope of the open pit mine occurs creep deformation and fatigue liquefaction under the action of vehicle load vibration and hydraulic gradient, which causes landslide geological disasters and it destroys the surface environment. To reveal the mechanism, a mechanics model based on the model considering the soil structural change with a new “plastic hinge” element is developed, to improve its constitutive and creep curve equations. Data from sand creep experiments are used to identify the parameters in the model and to validate the model. The results show that the mechanical model can describe the rotation progress between the sand particles, disclose the negative acceleration creep deformation stage during the third phase, and require fewer parameters while maintaining accuracy. It provides a new creep model considering rotation to analyze sand creep mechanism, which provides a theoretical basis for revealing the open pit mine landslide mechanism induced by creep deformation and fatigue liquefaction of sandy soil.

1. Introduction

During the process of surface mining under geological conditions of thin bedrock overlying thick loose sand layer in Inner Mongolia Autonomous Region of China, the fine sand particles is carried out from the slope during the creep and seepage process under the action of vehicle load vibration and hydraulic gradient pressure. It causes a large area of water and sand mixture stacking around the open pit mine slope, resulting in landslide geological disasters and endangers the surface environment as well, reducing the open pit slope stability and endangers the safety of production in surface mining. It falls into the category of surface mining-induced sand fatigue liquefaction disasters in quaternary loose aquifer [1], and it is essentially caused by water-sand movement formed in loose layer under long-term effects of vehicle load vibration and hydraulic gradient. It is the problem of liquefaction under seepage and vibration essentially, while its mechanism is obviously different from the earthquake induced liquefaction, similar to the "sand boiling" phenomenon proposed by Wang Wenshao [2]. But its occurrence condition is more complex, while its mechanism is not clear. Although research on sand liquefaction induced by the earthquake has been more deeply, the mechanism of sand fatigue liquefaction has to be studied further. It causes the inner destruction of composite slope and instability and endangers the safety of production and the surrounding earth's surface environment. Once it occurs, it's difficult to control and restore, the study is becoming ever more important as a result.

There is relatively few specific studies on sand particles creep model and landslide mechanism induced by fatigue liquefaction, while much work is mainly focus on sand boiling mechanism [3-5],
the piping model test [6]. Sand piping process was simulated by PFC method combined with small scale model test [7]; and the flow of sand inrush phenomenon in the soil and mining disaster is studied [8-9]. The model and criterion of liquefaction of saturated sand were established by sand pore water two-phase medium interaction perspective, according to the sinking sand and pore water seepage process of relative motion of dynamic action [10].

Much work focuses mainly on piping, water sand inrush in mining, etc, while study on sand particles creep model and fatigue liquefaction induced landslide mechanism needs to be deep. Sand creep and fatigue liquefaction phenomenon in open pit mine composite slope is a progressive process of peristaltic deformation and fatigue liquefaction process between sand particles and water in pore. From the view point of micro feature structural unit it is a process that a grain of sand is separated from the sand clumps and losing weight. From the analysis of mechanical behavior on the strong force chain between sand particles, it is a slowly progressive deformation and movement process including elastic, elastic viscous, elastic plastic deformation, plastic deformation, formation of hinge and rotation. To clarify the creep mechanism of interaction between sand particles, the key is to reveal the mechanism of sand creep and fatigue liquefaction phenomenon in open pit mine composite slope.

2. Force analysis of sand particles characteristic structural unit
The objective of scientific research should start with the smallest basic characteristic structure unit [11-12], so the work starts from taking sand particle as the research object, by constructing simplified creep model by the old and new elements and its combination to describe the micro particle mechanical behavior.

From the microscopic point of view, Granular particles are multi-particle dispersion void structure of different gradation of particles. Sand is a typical particulate matter, and it forms a complex system under the interaction between the particles. In recent years the research on particulate matter tends to focus on its fine mechanical behavior, and a large number of experimental observations and numerical simulation is carried out, but for the static and dynamic behavior of particles in the system still can not be explained with the classic solid and fluid mechanics clearly. Particulate matter and turbulence were enumerated as one of the 100 scientific problems in Science. How to build links between the micro and macro is also a bottleneck of the research on macro-microscopic particulate matter. At present, study on the movement and balance of particulate matter system and its application is forming a new discipline of particulate matter mechanics.

The characteristic structural element of the saturated sand was selected to make the mechanical analysis of single sand. A single sand particle is mainly withstand gravity, buoyancy, the normal contact force, tangential contact force and penetration force. (in Fig. 1)

3. The improved Putin model based on “plastic to hinge” element
3.1 Model improvement
Putin (1974) in the literature "thin retaining wall", it is recommended to use a series of elastic and viscous component elements and certain nonlinear deformation structural element to establish Putin model [13] which can reflect the structural change process of soil deformation, (as shown in Fig. 2)
The structural element has the characteristic that can reflect the change of the particle direction during the deformation progress and its deformation speed is changed accordingly. The particle direction change is simulated by the structural element. The viscous element is subject to the formula \( \tau = \eta \dot{\gamma} \), The deformation of the structural element can be described by a nonlinear relationship in the formula (1):

\[
\dot{\gamma}_s = \gamma^* \tan \left( \frac{\tau_i}{\eta_s} \right)
\]

where \( \gamma^* = \gamma^p / \sin \theta_s \), \( \gamma^p \) is equivalent to the shear strain when the structure is completely re distributed. \( \theta_s \) is the rotation limit angle of the structural unit S. The model also includes two Saint Venant components, SV1 and SV2. Its flow limit are \( \tau_{T1} \) and \( \tau_{T2} \) respectively.

The model equations are derived from the conditional formula (2) and formula (3), which read

\[
\gamma = \gamma_s + \gamma^N
\]

\[
\tau = \tau_s = \tau^N
\]

Creep does not occur when \( \tau < \tau_{T1} \); the decay creep occurred in the reorientation of soil particles when \( \tau > \tau_{T1} \); It is can be written as

\[
\gamma = \gamma^* \tan \left( \left[ \left( \tau - \tau_{T1} \right) / \eta_s \right] \right)
\]

The decay creep described by the formula (4), which stops when the particle is reoriented when \( \theta = \theta_{np} \), the further deformation may be stable. It is can be written as

\[
\tau = \tau_{T(2)} + \tau_{T(1)} + \eta \dot{\gamma}
\]

Occurrence condition :

\[
\tau_{T(1)} < \tau < \left[ \tau_{T(1)} + \tau_{T(2)} \right]
\]

Taking into account the existing slide element can not describe the process of the rotation after the occurrence of plastic deformation in certain local regions where plastic hinge formed, proposed a new member of improved slider element to replace the vane element and it’s a new simplified model element (in Fig.3). When the element does not reach the maximum shear strength is still sliding element, but when the components meet and exceed the maximum shear strength of sliding, as the plastic zone extended and formed plastic hinge, the element of a sliding piece change to plastic hinge, it is called “plastic to hinge” element.
The element $SV_1$ in classical Putin model can not reflect the rotating, and when the plastic element is in the sliding stage, plastic hinge can be used to describe the mechanical behavior of the plastic zone after the plastic zone is formed. The bending moment at the plastic hinge tends to zero, while the position of the hinge is only connected by force, it can be divided into x, y two directions. In order to describe the plastic deformation of the rock and soil in the third creep stage, in which the rotation state of the plastic hinge is formed. Replacing the traditional plastic sliding element $SV_1$ with the "plastic to hinge" element to improve the classic Putin model, as shown in Fig.4. The element $SV_1$ in the improved Putin model can truly reflect the rotation process of the development of plastic deformation of soil to a certain degree.

Biyarov stressed that the formula given by the mechanical model is only a qualitative reflection of the actual rheological process in the soil [13]. Generally speaking, the model is not consistent with the experimental data. One of the reasons is that most of the equations describing the creep curve derived from the model are derived from the most primitive differential equations (6), which read

$$\tau + T_1 \dot{\gamma} = G_0 \dot{\gamma} + G_\infty \gamma$$  \hspace{1cm} (6)

The linear elastic viscosity equation is studied in M.Leuer, A.P.Lennonic and Ischykin’s monograph. The general form of the linear visco-elastic state equation given by Hayesmarshall and Prague is written as

$$\alpha_0 + \alpha_1 \tau + \alpha_2 \dot{\tau} = \beta_1 \dot{\gamma} + \beta_2 \gamma$$  \hspace{1cm} (7)

where $\alpha_0 = -\tau_r$ , it is ultimate shear stress (based on Bingham model); $\alpha_1 = 1$; $\alpha_2 = T_r = \frac{\eta}{G_0}$, it is the relaxation time; $\beta_2 = \eta$ (Coefficient of viscosity); When $\beta_1 = G_\infty$, substituting the above condition into the equation (7) results in Equation (6). $G_0$ and $G_\infty$ is respectively instantaneous shear modulus and long-term shear modulus limit. Equation (6) is the equation (7) when $\tau_f = 0$.

Therefore the formula (6) can be used to describe elastic aftereffect and relaxation process. At the same time, considering the instantaneous deformation, the stress relaxation process can be described to a final value, rather than zero, so the formula (6) can be used to describe the rheological state equation of the integrated elastic viscous material.

The general solution of differential equation (6) according to any law the stress $\tau(t)$ and deformation $\gamma(t)$ is written as
\[
\gamma = \gamma_0 e^{\frac{\beta_1}{\beta_2} + \frac{\alpha_1}{\alpha_2} \int_t^\infty \tau(\nu) + \frac{\alpha_2}{\alpha_t} \hat{\tau}(\nu) e^{\frac{\alpha_t}{\beta_t} (\tau - \nu)} d\nu}
\]

(8)

Formula (9) is obtained by integration by parts, it read
\[
\gamma = \frac{1}{G_0} \left[ \tau(t) + \int_0^t \tau(\nu) K(t - \nu) d\nu \right]
\]

(9)

In the formula (9) \[ K(t - \nu) = \frac{G_0 - G_{\infty}}{G_p T_p} e^{\frac{(t - \nu)}{\tau_p}} \]

is the kernel of integral relation formula.

Where \[ G_{\infty} = \beta_1 / \alpha_1, G_0 = \beta_2 / \alpha_2, T_p = \beta_1 / \beta_2, T_r = G_0 / G_{\infty}, T_t = \alpha_2 / \alpha_t \]. The corresponding force solution of Formula (6) is
\[
\tau = G_0 \left[ \gamma(t) - \int_0^t \gamma(\nu) R(t - \nu) d\nu \right]
\]

(10)

Where \[ R(t - \nu) = \frac{G_0 - G_{\infty}}{G_0^2 T_r} e^{\frac{(t - \nu)}{\tau_r}} \]

which is the kernel of integral relation in formula (10).

Creep process can be divided into attenuation and non-attenuation creep according to the development trend, as shown in Fig. 5 and Fig. 6. In the two case, the deformation is equal to the sum of the two parts of the relative instantaneous deformation and the deformation with the development of time occurs immediately after the load. It read
\[
\gamma = \gamma_0 + \gamma(t)
\]

(11)

Fig. 5 Attenuation creep curve
Fig. 6 Nonattenuation creep curve

There is a normal acceleration creep stage CE in the third stage of the non-attenuation creep curve and the non-attenuation creep rate curve and also a negative acceleration of the creep stage ED. For this kind of creep properties of sand in the non-attenuation creep stage III, it is due to sand contact friction and deformation movement by analysis.

3.2 Model identification
To verify the reliability and validity of improved Putin model, the model and parameter identification are verified by the experimental results [14]. Lanzhou fine sand was selected to make a cylindrical specimen of 11cm high and diameter 11.28cm, and the shear creep test was carried out. The creep curves of four specimens under constant shear load at different temperatures are given, as shown in Fig. 7.
It can be seen from several groups curves that when the temperature falls below -10 C, the three creep stages of curves under low stress conditions are more obvious. There is a certain difference between the third stage creep curves of temperature at -10℃ and -15℃. When the temperature is at -10℃, in the third stage of creep it enters the accelerated creep stage until failure after plastic yield; When the temperature is at -15℃, creep is accelerated under low stress condition after the two plastic yield appears. Test results is close to the law in Fig.8, it proved that there is a positive acceleration and negative acceleration creep stage during the third creep process. Positive acceleration of the soil accelerated approaching to the deformation and ultimate strength, and the trend of soil acceleration deformation is slowed down by the negative acceleration creep, so that the yield limit appears hysteresis phenomenon, the creep stage is the direct cause of the frozen soil creep.

Under the low stress level of 3.61MPa at the temperature of -15℃, the test creep curve is close to the three stage of creep, therefore, the test data are used to fit the model parameters, and the optimal algorithm is used to fit and parameter identification, and the fitting results and model parameters are shown in tab.1.

Table. 1 Model parameter identification

| Model types   | sin θ | γp | ηs | τT(1) | Tp | Go | G0 | τT | Fitting Relevanc e |
|---------------|-------|----|----|-------|----|----|----|----|-------------------|
| Improved Putin model | 0.361 | 2.001 | 3.815 | -0.05 | | | | | 0.9725 |
| Bivarov model | 0.000 | 1223.2 | 1.546 | 1.525 | 3.7 | | | | 0.9526 |
| Putin model | 0.372 | 2.188 | 1.823 | -0.04 | | | | | 0.9668 |

4. Conclusions
A sand creep mechanics model of improved Putin model based on a new “plastic to hinge” element was proposed. The constitutive equation and creep equation was presented, and it reveals the acceleration and negative acceleration creep process in the third creep stage due to the plastic zone extension and sand contact deformation caused by friction and rotation. It can describe the rotation process of sand particle with the new “plastic to hinge” element in the new sand creep model. The new sand creep model based on the improved Putin model was validated through the model validation and parameter identification with the sand creep test data. Compared with other models, the result showed that its accuracy could meet the requirements basically with less parameters. It demonstrates the reliability and validity of the improved model. It provides a new model for the analysis of the creep seepage mechanism of sands in the surface mining composite slope during the process of seepage sands carrying.
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