NUMERICAL ANALYSIS OF DEGRADATION EVOLUTION OF STRUCTURAL LOESS UNDER LOADING AND WETTING BY DISCRETE ELEMENT METHOD

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Abstract An evaluation of degradation evolution for unsaturated structured loess under loading and wetting is studied by means of discrete element method (DEM). Firstly, an adaptable three-dimensional (3D) contact model is presented for unsaturated structured loess by considering the effects of adhesive force and chemical cementation. micromechanics theory and microscopic deformation for bonded geomaterials is established according to the bonding effect at contacts. Then, the breakage parameter λ_s , which is used to characterize the degradation evolution, is introduced based on the micromechanics theory. Finally, the equivalent plastic strain coefficient is defined to consider the effect of water content. The formula for the breakage parameter under different stress and wetting paths is proposed. The results show that the formula can predict the evaluation of breakage parameter λ_s for structured loess under loading and wetting well.

1 INTRODUCTION

Unsaturated structured loess which is different from unbonded geomaterials is a typical structured soil due to the bonding effect at contacts[1-3]. The bond breakage will cause the progressive failure for the bonded geotechnical material under loading [4-5] (the breakage of the structured loess under loading or wetting). Therefore, the establishment of a constitutive model of structured soil requires a reasonable description of the bonding effect.

In order to describe the effect of degradation evolution in the constitutive model, one method is to express the difference or ratio of the macroscopic mechanical properties of the structured and remoulded soil as a function of stress or strain, and introduce it into the hardening law. Therefore, a structured model based on classical elastoplastic constitutive model (modified elastoplastic model) [6-8] is established. Another method is to consider the stress sharing by bond and the friction (unbonded contact) at contacts. It is assumed that the sharing ratio of two as a function of stress or strain, thereby a binary medium model is established [9-12]. In terms of physical meaning, although the former model is not as clear as the latter, the parameters are less and more practical. Both of the modelling methods above make different assumptions about the breakage parameters, usually by assuming a function of stress or strain, and obtaining the parameters by fitting the laboratory test results. However, even the advanced measurement techniques, such as x-ray [13], particle image velocimetry (PIV) [14] are difficult to accurately determine the microscopic information. DEM is an effective tool for studying and analyzing granular materials [15-17]. Studies have shown that DEM can provide microscopic information on bond breakage [18].

The effect of attractive forces is introduced into a three-dimensional contact model incorporating rolling resistance. The evolution of the breakage parameters is obtained by a series of numerical tests under loading and wetting, and the formula for the breakage parameters is investgated in this paper.

2 INTRODUCTION OF CONTACT MODEL

An adaptable three-dimensional (3D) contact model is introduced to simulate the macroscopic and microscopic mechanical behavior of unsaturated structural loess by considering the effects of adhesive force and chemical cementation based on the contact model proposed by Jiang et al. [19]. Interparticle adhesive force is composed of van der Waals attractions and capillary forces. Both bond stiffness and strength are associated with the bond size to represent unrecoverable chemical cementation. By using the relationships between water content and suction, a new 3D contact model for loess is established considering the coupling effects of water content-void ratio-suction [20].

2.1 Particle contact force and moment

The calculation of interparticle contact force and contact moment is based on the model proposed by Jiang et al [19], but the effect of interparticle adhesive force has to be taken into account, thus reproducing compaction of Loess by Van der Waals force in the process of Loess weathering. It is noted that the normal contact force is calculated according to formula (1):

$$F_n^l = \begin{cases} k_n u_n - F_a & u_n \ge 0 \\ 0 & u_n < 0 \end{cases} \tag{1}$$

Where k_n denotes the normal stiffness, u_n denotes overlap, F_a denotes interparticle adhesive force.

The following parameters should be determined (1) stiffness parameters: the interparticle contact equivalent modulus E^* and the stiffness ratio of normal to tangential κ^*; (2) strength parameters: friction coefficient μ and interparticle adhesive force; (3) interparticle contact radius coefficient β. The specific calculation methods can be referred to literature [19]

2.2 Bonding force and cementing moment

In order to consider the effect of bond size, the simplified formulas based on Shen et al [21] for calculating the bonding forces and moments are suggested in literature proposed by Li [20].

The following parameters should be determined (1) stiffness parameters: the bond equivalent modulus E^* and the bond stiffness ratio of normal to tangential κ_b; (2) strength parameters: bond compressive σ_c^b and the ratio of bond tensile-compression strength η_σ; (3) bond size parameters： bond thickness h_0^b , bond radius coefficient λ_b and bond critical thickness coefficient g_c。 The specific calculation methods and physical meaning can be referred to literature [20]

3 UNSATURATED STRUCTURED LOESS NUMERICAL TEST

3.1 Specimens preparation

DEM specimen preparation is divided into three steps: (i) A homogeneous and loose unbonded loess specimens is prepared by using the Muti-layer with Undercompaction Method (UCM) The basic principle and implementation steps of UCM are detailed in the literature [22]. A five-layer cubic test specimens contains 42180 particles in Fig.1. (ii) After specimens preparation, the friction coefficient μ=0.5, and the specimens are pre-compaction at vertical pressure of 12.5 kPa to simulate the in-situ stress state of loess. A three-dimensional contact model for unsaturated structured loess proposed by Li [20], which takes the van der Waals force into account according to formula (2).

$$F_v = \frac{H_a \beta^2}{96 h^3} D^2 = \sigma_{van} D^2 \tag{2}$$

Where H_a denotes Hamaker constant, which is 6.5×10−20J; β denotes the contact radius coefficient, which is about 0.1~0.4; D is the diameter of the particle, h is the micro-separation at contact, taken as about 1nm~4nm, we choose σ_{van}=4kPa in this paper.

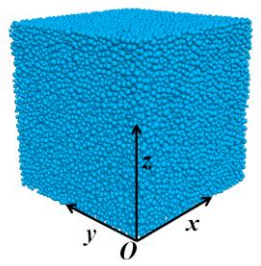

Fig.1 Numerical assemblies

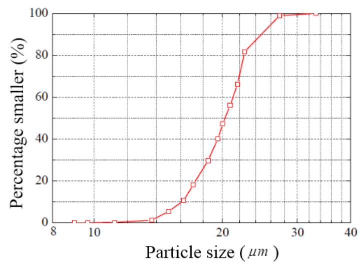

Fig.2 particle size distribution of the numerical assemblies

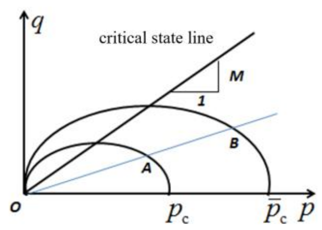

Fig.3 Remoulded soil and structured soil yield surface

The particle size distribution of the numerical assemblies is shown in Fig.2. the particle density is 2710 kg/m^3, and the local damping coefficient is 0.7, Particle equivalent modulus E^*=800 MPa, particle normal-tangential stiffness ratio is κ^*=1.5, particle contact radius coefficient β=0.21.

3.2 Parameter calibration

In view of the limited experimental data and the representativeness and generality of the microscopic parameters, comprehensively the test results of various loess are considered, the representative microscopic parameters are calculated according to formula (3).

$$F_a = \sigma_a d_{50}^2 = \left(\frac{s_u}{\xi_a \left(1 + \left(s_u / \left[c_{a1} \exp(c_{a2} e_0)\right]\right)^{b_s}\right)^{1-1/b_s}} + \sigma_{van} \right) d_{50}^2 \tag{3}$$

Where σ_a is the normalized particle attraction; S_u is the matrix suction, the effect of particle attraction on the cohesive force ξ_a=0.24; the parameters c_{a1}=750kPa, c_{a2}=-4.5, b_s=1.6.

The relationship between matric suction and effective saturation is established by describing the soil-water characteristic curve using the van Genuchten model [23], namely:

$$S_e = \frac{1}{\left(1 + (s_u / a_{sw})^{b_s}\right)^{1-1/b_s}} \tag{4}$$

Where a_{sw} , b_s are fitting parameters, taken as $a_{sw} = c_{s1}\exp(c_{s2}e)$ （c_{s1}=400kPa, c_{s2}=−4.7） and b_s=1.6, and e is void ratio.

The bond compressive strength σ_c^b is calibrated by the laboratory one-dimensional consolidation test relative simulation results, which can be expressed by formula (5):

$$\sigma_c^b = \frac{c_{y1}\exp(c_{y2}S_e e_0^2) - c_{un}(1 - S_e)}{\xi_b} \tag{5}$$

Where c_{y1}、c_{y2} are fitting parameters, c_{y1}=1350kPa, c_{y2}=-3.1, e_0 is the initial void ratio, S_e is effective Saturation, c_{un}=300kPa, ξ_b=0.018. The detailed process of particle and bond contact parameter calibration and physical meaning related parameters are referred to literature [20].

The calibration results are summarized as shown in Table 1. The bond thickness h_0^b can be automatically given by the program when the bond is formed., the bond thickness is zero, When the particles have an overlap amount.

Table 1. Parameters for unsaturated structured loess contact model

parameters	E^* /MPa	κ^*	$\mu_{ballball}$; $\mu_{ball-wall}$	F_a	β	$\bar{E}^*$ /MPa	η_E	k_b	σ_c^b	η_σ	λ_b	g_c
Numerical value	800	1.5	0.5； 0	Formula (2)	0.21	200	0.2	2.0	Formula (4)	0.1	0.35	0.1

2.3 Numerical test scheme

In order to obtain the degradation evolution for structured loess under loading and wetting, one-dimensional consolidation, isotropic compression and common stress ratio, quick wetting (primary wetting to saturation) and gradual wetting (multi-stage wetting up to saturation) tests for unsaturated structured loess are carried out by DEM and the calibration parameters.

4 BREAKAGE PARAMETERS FOR UNSATURATED STRUCTURED LOESS

The stress for structured soil can be regarded as composed of unbonded particle assemblies and bonded particle assemblies. The proportion of bonded particle assemblies is gradually decreased for structured soil under loading and wetting, which is the process of structured soil gradually transforming into remoulded soil. As shown in Fig.3, the yield surface for the structured soil should be above the yield surface for the corresponding remoulded soil based on the elastoplastic theory, In the figure, p_c and $\bar{p}_c$ are used to indicate the size of the yield surface respectively. The yield surface determined by p_c is the structural yield surface (or superloading yield surface [6]).

Draw any straight line from the origin and it intersects at points A and B, which are on the yield surface of remolded soil and structured soil respectively. The stress states of these two points can be expressed as $\bar{\sigma}_{ij}^d$, $\bar{\sigma}_{ij}$. the sharing ratio between bond and unbonded part can be defined in the macroscopic scale as shown following formula.

$$p_c / \bar{p}_c \doteq \bar{\sigma}_{ij}^d / \bar{\sigma}_{ij} \tag{6}$$

Parameter B_0 is proposed by Jiang et al [24].

$$B_0 = \lambda \cdot \bar{\sigma}_{ij}^{d} \Big/ \bar{\sigma}_{ij} \tag{7}$$

Where B_0 denotes breakage parameter based on binary medium theory.

According to formula (6) and (7), we can conclude:

$$\frac{p_c}{\bar{p}_c} \doteq \frac{B_0}{\lambda} = \lambda_s \tag{8}$$

Where λ_s is the breakage parameter defined by the modified elastoplastic method, the physical meaning is to represent the ratio of the local stress of the unbonded granulars to the average stress. λ_s has an initial value (nonzero), With the loading or wetting process of the structured soil, λ_s will increase continuously, and the structured soil completely evolves into remolded soil when it reaches the limit value 1.

5 DEGRADATION EVOLUTION OF BREAKAGE PARAMETER λ_S

The degradation evolution rate for structured loess relates to the water content by DEM simulation analysis. The lower the water content, the slower the structured breakage rate. Therefore, the equivalent plastic strain coefficient soil is defined the ratio of the equivalent plastic strain to the structured yield stress of the structured loess (measured by the isotropic compression test), namely $E_d^p = \varepsilon_d^p / \sigma_y{}'$, among them, $\varepsilon_d^p = \sqrt{(\varepsilon_v^p)^2 + (\varepsilon_s^p)^2}$ is the equivalent plastic strain. λ_s is assumed by the following formula:

$$\lambda_s = 1 - \frac{1}{c_a E_d^p + c_b} \tag{9}$$

Making $E_d^p = 0$, substituting it into formula (9):

$$\lambda_s = 1 - \frac{1 - \lambda_{s0}}{1 + v_s (1 - \lambda_{s0}) E_d^p} \tag{10}$$

Where $v_s = c_a$ denotes the rate of degradation evolution. λ_{s0} denotes the initial value of breakage parameter.

5.1 Performance of breakage parameter λ_s under loading

The variation of the structured breakage parameters λ_s with the equivalent plastic strain coefficient of the stress-compression test and the one-dimensional consolidation test of the structured loess numerical samples with various water contents are given. It shows that the structure is damage. The breakage parameters λ_s can be fitted well in compression tests and one-dimensional consolidation tests with different stress ratios. For structured loess numerical samples of different water contents, breakage parameters λ_s increase rapidly and then slowly with the equivalent plastic strain increases. Figure 4(b) puts the evolution of breakage parameters under two water contents on a graph. The influence of parameters is normalized by proposing the equivalent plastic strain coefficient. The breakage parameters of the two water contents samples are similar with the equivalent plastic strain coefficient. Figure 4(c) summarizes the breakage parameters of different water contents. The influence of water content can be reasonably considered by the equivalent plastic strain coefficient. It can be found by fitting (Fig. 4(d)), the formula can fit the breakage parameters λ_s in the constant stress ratio compression test and equivalent plastic strain coefficient.

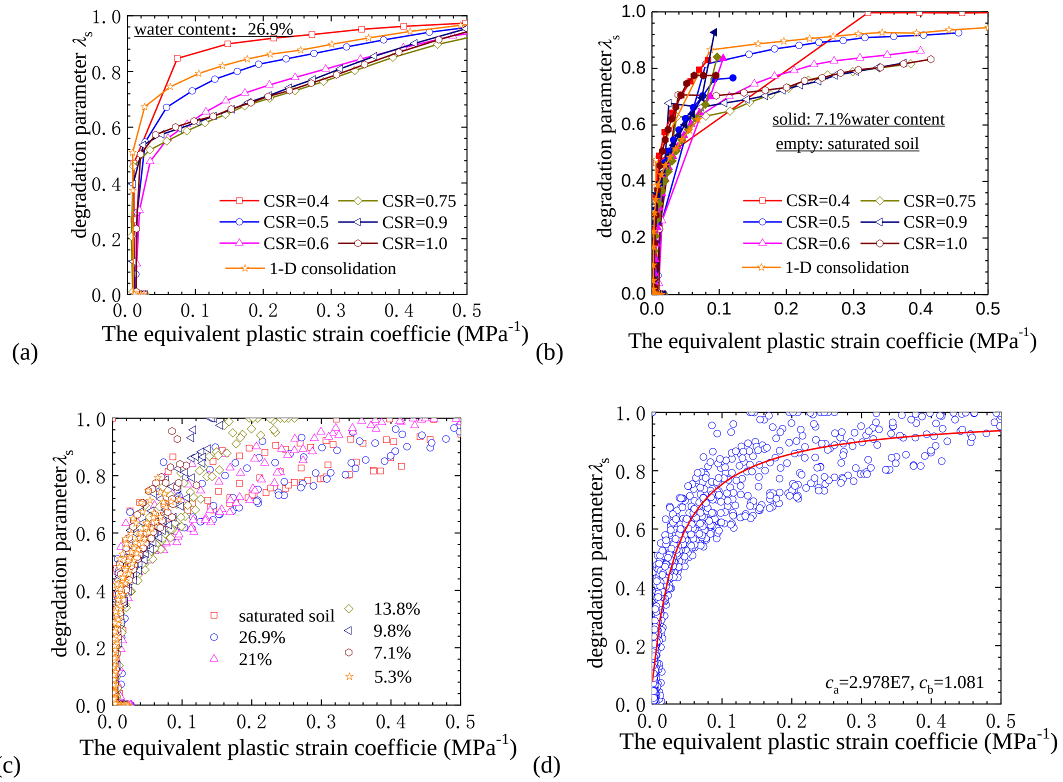

Fig. 4 Evolution law of structured breakage parameter λ_s with equivalent plastic strain coefficient: (a) water content: 26.9%; (b) water content: 7.1% and saturated structured loess; (c) summary map; (d)Fitting map

5.2 Performance of breakage parameter λ_s under wetting

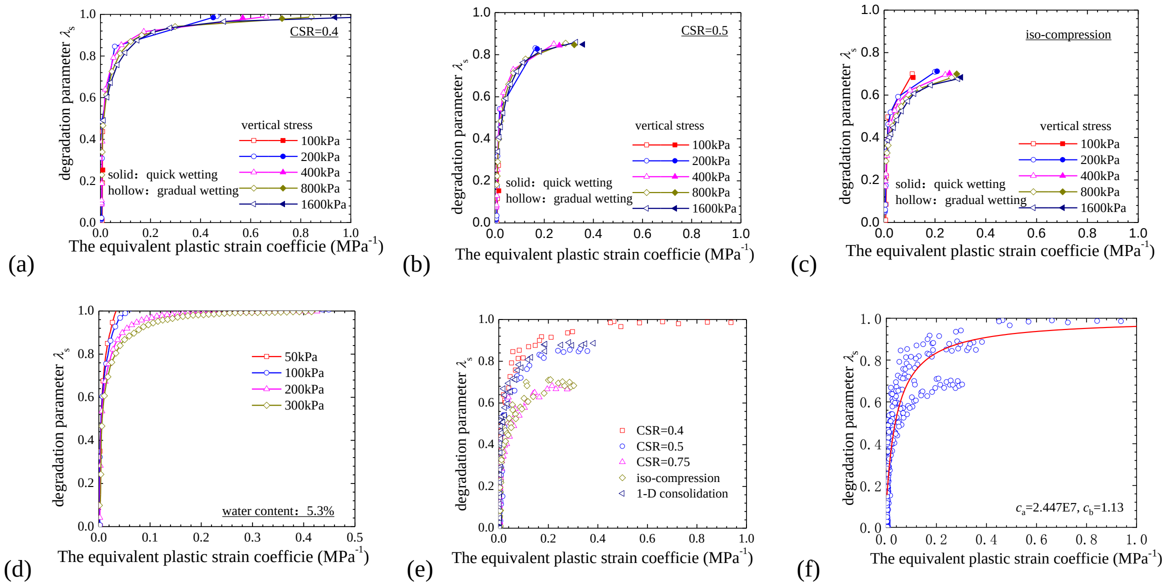

Fig.5 The evolution law of structured breakage parameter λ_s with equivalent plastic strain coefficient: (a) CSR=0.4; (b) CSR=0.5; (c) CSR=1 (isotropic compression); (d) one-dimensional consolidation; (e) summary map; (f) fit map

Isotropic compression and one-dimensional consolidation wetting tests are carried out on numerical sample of 7.1% water content. Fig.5 gives out the relationship between degradation evolution parameter λ_s and equivalent plastic strain coefficient. As mentioned earlier, the evolution of the parameter λ_s with the equivalent plastic strain is more complicated and obviously affected by the wetting pressure. However, after the equivalent plastic strain coefficient is introduced, the breakage parameters λ_s of the sample after wetting under different vertical pressures. And the degree of normalization of the evolution process is significantly improved. As for the difference between two wetting methods, the breakage parameters λ_s of quick wetting differ from the results of gradual wetting to saturation, and the equivalent plastic strains after the end of wetting exist some differences, but they are all on the normalized curve of breakage parameters λ_s with equivalent plastic strain coefficients. By summarizing (including quick wetting results) and fitting, the equivalent plastic strain coefficient is introduced, and formula (8) can reflects the evolution of breakage parameters λ_s in the isotropic compression test.

6 CONCLUSIONS

In this paper, a series of numerical tests for structured loess are carried out under loading and wetting. Based on the contact relationship and the microscopic deformation beheaviors, the formula of degradation evolution parameters is presented . Then, the equivalent plastic strain coefficient is defined. (The ratio of equivalent plastic strain to structured yield stress). In order to consider the effect of water content, a formula of the breakage parameter based on micromechanics theory under various stress and wetting paths is established. The conclusions are as followed:

(1) An adaptable three-dimensional (3D) contact model is presented to simulate the macroscopic and microscopic mechanical behaviors of unsaturated structural loess by considering the effects of adhesive force and chemical cementation.

(2). The physical meaning and the numerical solution for the breakage parameters λ_s in the frame of the modified elastoplastic constitutive model are given based on the macroscopic and microscopic theory for unsaturated structured loess.

(3) The structured breakage rate becomes slower as the water content is lower. By introducing the equivalent plastic strain coefficient, the effect of water content can be considered well. And the formula of degradation evolution parameters is verified.

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