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The Structural Damage Properties of Loess under Loading and Moistening

A Z Luo[1] S J Shao[2]

[1]School of Civil and Architecture Engineering, Guizhou University of Engineering Science, Bijie, Guizhou 551700, China

[2]Institute of Geotechnical Engineering, Xi'an University of Technology, Xi'an, Shaanxi 710048, China

Abstract: Based on the deformation properties of intact loess under the tri-axial loading and moistening, and starting from the loess structural damage and development caused by the moistening, iso-directional consolidation as well as moistening and shearing deformation, this paper seeks to obtain the variation with the stress-strain curve initial tangential modulus to reflect to intact structure damage and the secondary structure development by the moistening and consolidation as well as reflect to the moist shearing structure damage and the secondary structure development by the ideal hyperbola variation of the iso-structure stress-strain corresponding to the different stress-strain states during the process of shearing deformation, in which the whole development process are revealed, the intact loess structure varies are derived from the action of loading and moistening. Meanwhile, this paper proposed the structural damage property parameters of the intact structure damage development law that can completely the collapsible loess under the varying conditions of water content fields and stress fields; and they are used to establish the stress-strain equation for the structural loess.

1. Introduction

Collapsible loess is a kind of structure soil, Ding-yi Xie(1999,2001)think that whose structure properties show that maintaining its structure stabilization ability before the structural connection is not damaged and the structural changeability after the structural connection is damaged. The changes of the stress field and water content field caused by external loading and humidity variation will occur simultaneously in the loess body, the stress field and humidity field are the functions of time distributions and space distributions. Generally speaking, since the stress increase is likely to cause the variations in soil structure, and water content increase is likely to make soil structure connection weaken that soil displays, their dynamic variations in inter-coupling can cause structural changes within soil body, further resulting in the deformation and changes in various kinds of mechanical effects (Zu-dian Liu, 1996). Because of the structural properties of collapse loess, that is, structural states are in correspondence with a certain stress and water content states. Accordingly, both can change simultaneously or either of one will change; and soil grain arrangement within soil body and colloidal state can change, the micro-structural change can cause the changes of macro-mechanical behaviors in the loess. It is just the loess strong structural behaviors that make loess soil be very sensitive to water content and stress condition changes so that moistening and loading processes are also the process of loess original structure damage and softening (Sheng-jun Shao, 2004). The most of existing non-linear constitutive models or elastic-plastic models can only describe the process of deformation change, or modify the existing models with an aim at structural soil behaviors without considering the structural damage evolution laws caused by moistening and loading. Accordingly, it is hard for them to reflect the real mechanical characteristics of structural soil and stress-strain changing laws. To summarize the above description, this paper deals with the intact loess deformation characteristics acted by moistening and loading under the conditions of tri-axial tests, discusses the damage evolution laws of structural loess under the conditions of moistening, iso-directional compress and moistening and shearing stress, and seeks for a parameter which is able to reflect intact structure damage evolution law of the collapsible loess in an overall way under the varying conditions of water content field and stress field, and establishes the stress-strain equation based on the structural damage parameters.

2. Research Ideas of Loess Structural Damage Behaviors Under the Tri-Axial Shearing Conditions

On the whole, the people analyze damage behaviors of the loess in view of damage properties of the mechanical composite materials, that is, the stress borne by the damage loess with a certain trait can be shared by the intact loess and completed damage loess in terms of a certain proportion, and the same deformation occur on the intact loess and completed damage loess. Based on this hypothesis, the stress sharing can be described as follows:

$$\{\sigma\} = (1-\omega)\{\sigma_i\} + \omega\{\sigma_d\} \quad (1)$$

Where, σ_i and σ_d are the intact loess and complete damage loess sharing stress; ω is the damage ratio. Owing to the intact loess and complete damage loess having the same deformation, which is actual deformation of the damage loess, thus, the following equation can be derived:

$$E = (1-\omega)E_i + \omega E_d \quad (2)$$

Where, E, E_i and E_d are the whole magnitude modulus and sharing stress of the intact loess and complete damage loess respectively. If the whole magnitude modulus of the damage loess can be decided, the damage parameter can be obtained.

Based on the viewpoint that moistening and loading can cause damages (Sheng-jun Shao, 2004), damage parameters of the collapse loess, being able to reflect the loess structural damage changes in the case of moistening and consolidation confining pressure, are established by the changing law which occur between the initial tangent modulus and consolidation confining pressure and water content. However, the damage parameters established in such a way can not reflect the damage changes in the shearing process, that is, under different conditions of the humidity and consolidation pressure, it is not only different of the initial shearing modulus, but also different of the whole magnitude modulus (the cutting modulus) in the shearing process. The modulus changing has been proved by the test results can also reflect the damage changes of soil structure in shearing process. It can be seen that loading damage should be further distinguished into the consolidation damage and shearing damage in order to reflect the structure changes in the shearing process, and both can cause the structure damage coupled with moistening.

As to the normal consolidation loess, it is no consideration, in general, that the structure changes effect on the stress-strain relation, the stress-strain relation curve can be expressed as follows:

$$\sigma_1 - \sigma_3 = \varepsilon_1/(a + b\varepsilon_1) \quad (3)$$

Where, a, b are soil feature parameters, the reciprocal of a is the initial tangent modulus, which mainly reflects the effect of pressure hardening caused by the consolidation pressure, the reciprocal of b is the approximation value of stress-strain curve, which reflect soils anti-shearing strength. However, under the effect of the coupling with consolidation pressure and moistening, there is not only the compressible hardening in the structural loess, but also the highlighting compressible damage. Under the effect of the coupling with shearing pressure and moistening, there is not only shear-contraction hardening in the structural loess, but also the projected shear damage. That is to say, a not only relates to the initial consolidation pressure, but also to the changes of water content. At the same time, because the structure strength continues to change, the shearing strength reflected by b continues to change in the shearing process. If soil structure is no change in the shearing deformation process, b value is fixed, the shearing stress-strain relationship of the loess with a certain structure, being similar to the saturated normal consolidated soil, can still be described by the hyperbola pattern. The structural changes can be described by the hyperbola relation with different b values in the shearing process. Namely, **a** value reflects the moistening-pressure damage caused by moistening and consolidation pressure; **b** value is a changing quantity with the shearing deformation, reflecting that moistening-shearing damage caused by the moistening and shearing pressure. Supposing that when shearing starts, the approximation value of the fitting hyperbola is b_0, and damaged, the approximation value of the fitting hyperbola is b_R, the varying laws of b value reflect the changes of shearing strength on different structures soil body in the sharing process. Basing on the varying of b value with shearing deformation, the stress-strain relationship curve region can be divided into the hardening type curve and softening type curve.

Based on the above analysis, when the initial water content and consolidation pressure are fixed, **a** value is constant in Eq. (3), stress and strain state can be determined by corresponding to **b** value in the shearing deformation process, but **b** value varies with the strain development. When $\mathbf{b_0<b_R}$, this indicates that the anti-shearing strength of loess under the shearing initial structural conditions is larger than under the strain failure structural conditions so that the corresponding stress-strain curve can be judged to fall into the softening type curve. When $\mathbf{b_0>b_R}$, this indicates that the anti-shearing strength of loess under the shearing initial structural conditions is smaller than under the strain secondary structural conditions so that the stress-strain curve can be judged to fall into the hardening type curve. It can be seen that the process of moistening and loading is the successively damaging variation process in the soil body structure. Whether the stress-strain curves are the hardening or softening types, they can be expressed by a family of hyperbolas drawn by **a** value determined with the initial water content and consolidation stress and **b** value varying between $\mathbf{b_0}$ and $\mathbf{b_R}$. Therefore, based on the tri-axial shearing testing results under the different humidity conditions, if the parameter, which are **a,** $\mathbf{b_0}$ and $\mathbf{b_R}$, varying laws of structural loess can be obtained, the secant modulus of structural loess in the different damages state in Eq. (2) can be derived. Therefore, the equation can be derived from Eq. (3):

$$E = (\sigma_1 - \sigma_3)/\varepsilon_1 = 1/(a + b\varepsilon_1) \quad (4)$$

Here, E is the secant modulus corresponding ideal hyperbola with a certain **b** value under a certain structural condition in actual strain states, it reflects the degrees of consolidation pressure, humidity and damaging failures as well as the effect of shearing deformation development, which can be described and expressed by the following Eq.

$$E = F(\sigma_{3c}, w, \omega, \varepsilon_1) \quad (5)$$

It can be seen from this that when the modulus is obtained under any certain consolidation pressure, humidity and strain state, the damage parameters for loess under the complete damage states can be decided based on Eq. (2) by the modulus corresponding to the intact loess.

3. Results of Tri-Axial Shearing tests and Analysis of Collapsible Loess

3.1. Results of Tri-Axial Shearing Tests

All experiments in this study conducted on Xi'an Q_3 loess samples, the dry density is 1.30g/cm^3. Testing equipment is the conventional tri-axial shearing apparatus. Consolidation drainage tests are adopted. Consolidation pressures are 100-300kPa to reflect the effect of consolidation pressure upon structural properties. Intact soil moisture contents are 3.1%, 6%, 10%, 14%, 22% and 26% to reflect the effect of water content upon structural properties and structural parameters.

Test results are shown in Fig.1. The results indicate that although Q_3 loess is loose in texture, and good in porosity development, its humidity (water content) is so small (w=3.1%) that its structural properties are apparent, and the stress-strain curves appear to be softening patterns. With the growth of consolidation pressure (100kPa – 300kPa), the compressing-hardening feature are enhanced, and the softening feature of stress-strain curves is weakened. When water content increased, the compressing-hardening feature will become more prominence with an increase of consolidation pressure. Meanwhile, with the enhancement of compressing-hardening feature and the secondary structure, the stress-strain relationship curves appear gradually to be weak softening type in the shearing process. When water content and confining pressure are high, the intact structure is damaged to great extent, but the secondary structure develop and shearing contraction enhances under the consolidation action; and in the shearing process, the stress-strain curves gradually develop from the weak hardening type into strong hardening type. Obviously, when water content is low, consolidation pressure can bring weak damage to the intact structure, and the intact structure can display the apparent changes in the shearing process, there are obvious peak values and residual strength. When water content increase, the coupling of moistening and consolidation pressure will enhance the damage of intact structure, but the varying of intact structure will reduce in the shearing process, and the compressing-hardening and the secondary structure feature can gradually enhance. In addition, it can be seen from Figs that consolidation pressure has greater effect upon the residual stress, with consolidation pressure increasing, the residual stress increases, this indicates that increasing the consolidation pressure can improve soil residual strength under the same conditions of water content in the shearing process.

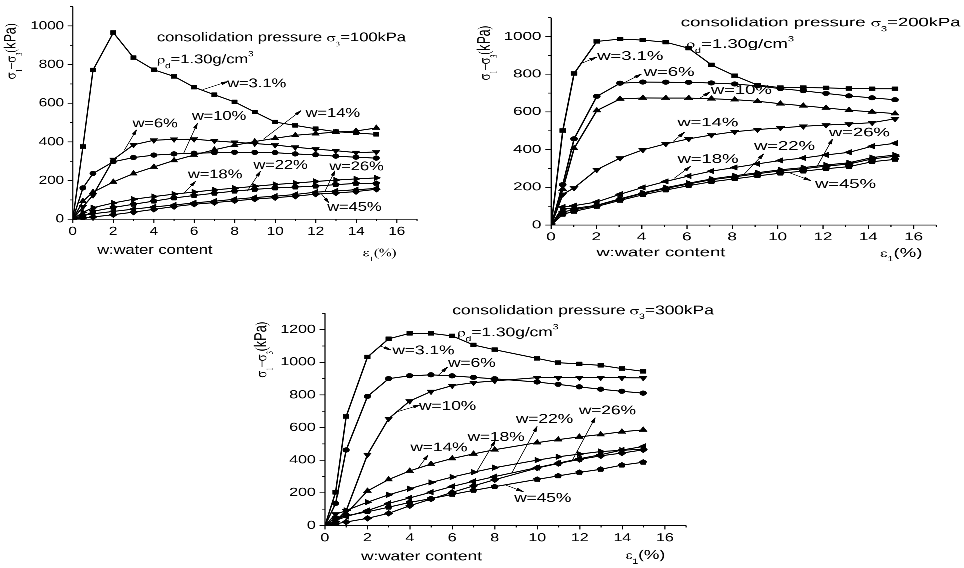

Fig. 1 The stress-strain curve of the same initial consolidation pressure

3.2. Varying Law of the Initial Tangent Modulus

By analyzing different humidity and stress-strain curves under the different conditions of water content and consolidation pressure, the varying laws of the initial tangent modulus can be obtained, as shown in Fig.2. It can be seen that the initial tangent modulus decreases with an increase in water content in the structural damaging evolution process of collapsible loess, this illustrates that changes of water content (humidity) is one of the most important factors that structural damage changes. Meanwhile, with an increase in consolidation pressure, the initial tangent modulus represent a descending tendency, this indicates that structure feature of the collapsible loess weakened with an increase in consolidation pressure. That is, the changes of the initial stress can also yield the same damage to the structure of the loess. This is the obvious features that intact loess is different from of remodel loess. When water content increases to a certain extent, the initial modulus has tended to the

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horizon or level line with the variation of initial consolidation pressure, it is illustrated that soil structural properties have released fully by moistening at this time. With an increase of water content, shearing contract features become more and more apparent.

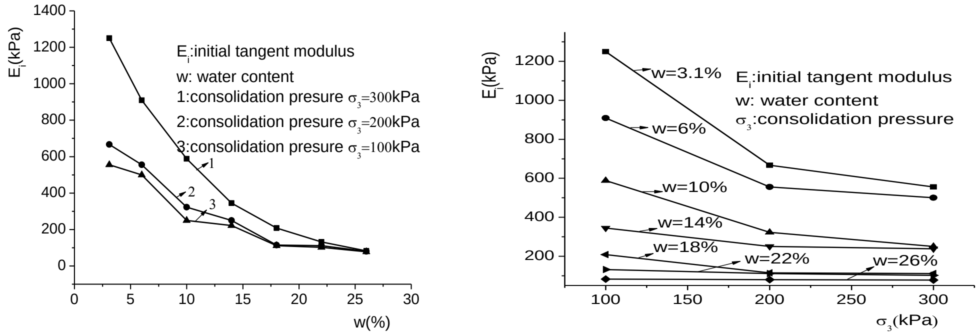

Fig.2 The curve of initial tangent modulus and water content and consolidation pressure.

The varying laws of the initial tangent modulus with water content increasing indicate that loess structure gradually suffers from damage under the coupling action of moistening and consolidation, and structural damage caused by moistening and compressing develops gradually so that the secondary structure and compressing hardening are gradually enhanced, thus, the initial tangent modulus reduce gradually, and tend to a certain fixed value in the end. Moistening can dissolve parts of colloids and salt base, and make sucking connection loss its function at the same time. The wedging function of water membrane renders all the expansion and contraction potential energy released and damages the solid-chemical bounding linkage among grains as a result of accelerating the damage of loess structure. Consolidation pressure has had a certain effect upon loess structure. With initial stress field increasing, the damage of loess structure increases gradually.

In analyzing the relation curves among the initial tangent modulus and water content as well as consolidation pressure, they can be expressed by the following equation:

$$E_i^w = K_w Pae^{-n_w} \tag{6}$$

When the varying scope of consolidation confining pressure is within 100kPa – 300kPa, K_w=692.11 – 1860.64, n_w=9.1 – 12.0

The relation of initial tangent modulus with consolidation pressure can be expressed by the following equation:

$$E_i^\sigma = K_\sigma Pa(\sigma_{3c} / Pa)^{-n_\sigma} \tag{7}$$

Where, when the varying scope of water content is within 3.1% - 26%, K =82.8 – 1215.3, n =0.571 – 0.7563.

In considering comprehensively the effect of water content and consolidation pressure, the following comprehensively-unified equation is present:

$$E_i^{w\sigma} = KPa(\sigma_{3c} / Pa)^{-n_\sigma} \cdot \exp(-n_w \cdot w) \tag{8}$$

In this paper, modulus number K=1863.1 is suggested; n is suggested to take 0.8636, and n_w= -0.03096 +14.6997. the varying laws of initial tangent modulus are determined, that is, **a** value in Eq. (2) is derived.

3.3 Varying Laws of b Value

Under the conditions of consolidation stress and humidity, when **a** value is decided, **b** value can be obtained in terms of Eq. (2) under different shearing stress states. As to the softening type curves, the changing laws **of b** value with the axial strain is shown in Fig.3. This paper suggests the following power function equations to describe the changing laws of the softening type curves:

$$b = A_1 \varepsilon^{B_1} \tag{9}$$

Where, A_1, B_1 are the test parameters; and they are related to the initial consolidation pressures and water contents.

A vast number of test data show that the initial structure damage is protruding and the secondary structure growth is more apparent than the intact structure with the enhancement in the coupling of both initial consolidation pressures and moistening, so that the stress-strain relation curve shows the hardening features. But, soil body still has suffered from structural damage in the shearing process. As to the hardening type curves, its changing laws **of b value** with axial strain **is** shown in Fig.4. Also, this paper suggests that the power function is used to describe the varying regulations of the damage development of the hardening type curves in the following:

$$b = A_2 \varepsilon^{-B_2} \tag{10}$$

Where, $A_{2,}$ B_2 are the test parameters. They are also related to the initial consolidation pressures and water contents.

It can be seen that the hardening type curve of structural collapsible loess can not be simply considered as the ideal hyperbola, but the ideal hyperbola used to study the hardening type hyperbola of structural collapsible loess is great difference.

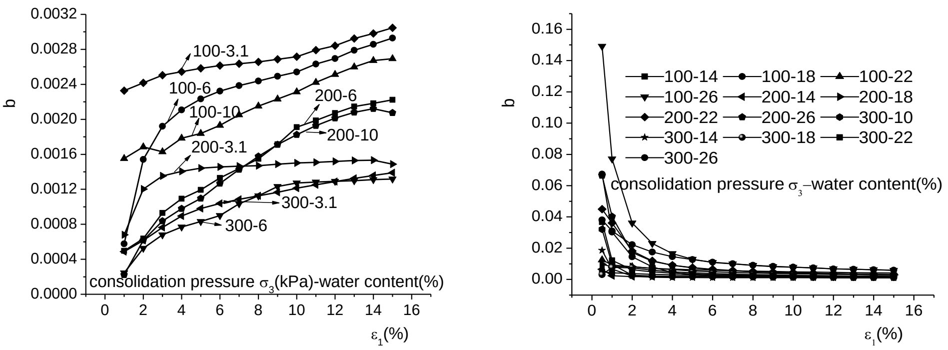

Fig.3 The curve of b and axis strain of stress-strain curve

3.4 The Judging whether Softening or Hardening Type Curves

Since there are different changing laws of b value on the softening type curves and hardening type curves, it is necessary to make different judging to the b value. Through taking consider the properties of the stress-strain relationship curves under the same consolidation pressure and water content in the shearing process, the curves, given the b value, can be determined under the **a** value. Where, $\mathbf{b_o}$ is the **b** value of the initial shearing damage in the shearing process; $\mathbf{b_R}$ is the corresponding damage state **b** value when strain reaches the damage, the relationship curves with $\mathbf{b_o}$ and $\mathbf{b_R}$ under different consolidation pressures and water contents are shown in Fig.5 and Fig.6.

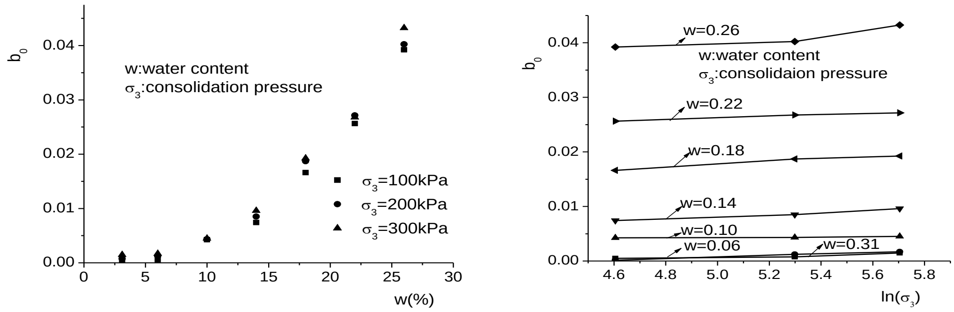

Fig.4 The relationship between b_o and water content and consolidation confining pressure

Based on the above curve features, $\mathbf{b_o}$ and $\mathbf{b_R}$ can be described using the following function equations:

$$b_o = A_o \exp(-B_o w) + C_o \ln(\sigma_{3c}) + D_o \quad (11)$$

$$b_R = A_R \exp(-B_R w) + C_R \ln(\sigma_{3c}) + D_R \quad (12)$$

Where, $\mathbf{A_o}$, $\mathbf{B_o}$, $\mathbf{C_o}$, $\mathbf{A_R}$, $\mathbf{B_R}$, $\mathbf{C_R}$, $\mathbf{D_R}$ are the testing parameters, which can be determined by the conventional tri-axial tests.

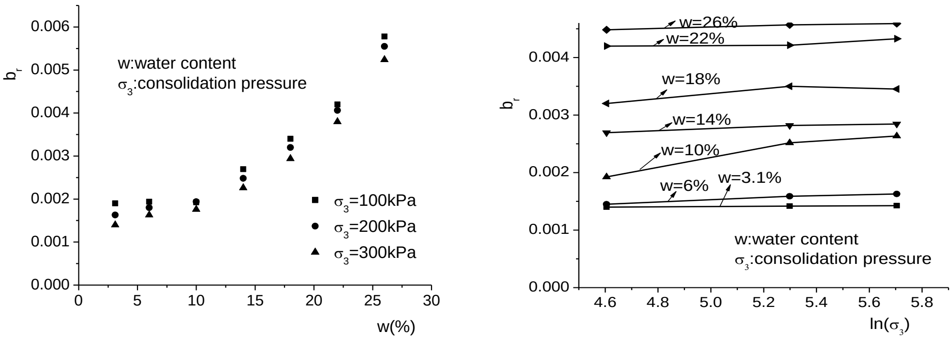

Fig.5 The relationship between b_R and water content and consolidation pressure

4. The Damage Changing Laws of Loess Under the Actions of Loading and Moistening

4.1 Definition for Damage Ratio

In terms of above descriptions, under the coupling of loading and moistening, structural loess damage process includes not only the effect of compressing-moistening damage to soil structure for consolidation pressures and moistening, but also the moistening-shearing damage effect for moistening shearing damage. It includes not only the damage of intact structure, but also the growth of secondary structure. The damage of intact structure and growth of secondary structure are always accompanied in the process of consolidation and shearing deformation under some given moistening conditions. Accordingly, the structure damage parameters defining must reflect compressing-moistening damage and shearing -moistening damage as well as the growth of secondary structure. Based on Eq. (2), damage ratio can be described by the difference values among the initial tangent modulus of the undamaged intact loess and some strain corresponding to damage loess secant modulus, and the difference value ratio among the intact loess initial tangent modulus and corresponding to the complete damage secant modulus. As following:

$$\omega = (E_i - (E)_{\varepsilon_1}) / (E_i - (E_d)_{\varepsilon_1}) \quad (13)$$

Where, E_i is the initial tangent modulus of intact loess; $(E)_{\varepsilon 1}$ is the secant modulus of damage loess under some strain condition; $(E_d)_{\varepsilon 1}$ is the secant modulus of complete damage loess under the same strain condition. Eq. (4) can be used to determine modulus: parameter **a** can reflect the moistening damage of intact structure and the growth effect of the secondary structure, and parameter **b** can reflect the shearing-moistening damage of intact structure and the growth effect of secondary structure.

4.2 Changing Laws of the Modulus

Owing to the different of compressing-moistening damage of intact structure and the growth of secondary structure in the compressing deformation process, and the different of shearing-moistening damage of intact structure and the growth of secondary structure in the shearing deformation process, the shearing stress-strain curves appear to be the different softening type or hardening type curves. They can be differentiated by the changing laws of **b** value determined by the hyperbola relationship under different shearing states, and they can be also determined by comparing the initial $\mathbf{b_o}$ with the damage strain state $\mathbf{b_R}$ in the shearing process.

The secant modulus equation of softening type curves should be as follows:

$$E = \frac{1}{1/\{KPa(\sigma_{3c}/Pa)^{-n_\sigma}\exp(-n_w w)\} + A_1\varepsilon_1^{B_1+1}} \tag{14}$$

The secant modulus equation of hardening type curves should be as follows

$$E = \frac{1}{1/\{KPa(\sigma_{3c}/Pa)^{-n_\sigma}\exp(-n_w w)\} + A_2\varepsilon_1^{-B_2+1}} \tag{15}$$

4.3Damage Ratio and Stress-Strain Equation

When the damage ratio is determined in terms of Eq. (13), the secant modulus of the intact loess and the complete damage loess are needed. In this paper, based on the test results of the stress-strain under the conditions of different water contents (3.0-26%) and consolidation pressures (100-300kPa) and the hyperbola distribution of different structural states reflected in the shearing process, when water content is 3.0% and consolidation pressure is 100kPa, the moisture pressure is the minimum and the initial tangent modulus is the maximum and $\mathbf{b_0}$ value is the minimum; when water content is 26.0% and consolidation pressure is 100kPa, the moisture pressure is the maximum and the initial tangent modulus is the minimum and $\mathbf{b_0}$ value is the maximum. Accordingly, the initial hyperbola of the initial shearing-moistening damage states can be served as stress-strain curves of the intact loess and stress-strain curves of the completed damage loess. Respectively, the complete loess is defined under the conditions of that water content is 26.0%, and consolidation pressure is 300kPa.

The modulus of intact loess is as follows:

$$E_i = 1863.1Pa \cdot \exp(-11.61w) \tag{16}$$

The modulus of complete damage loess is as follows:

$$E_d = \frac{1}{1/(1863.1Pa \cdot \exp(-11.61 \times 0.26)) + A_2\varepsilon^{B_2+1}} \tag{17}$$

Based on Eq. (13), (14), (15), the damage ratios can be determined respectively in the process of softening and hardening type shearing deformation, that is, when $\mathbf{b_0} < \mathbf{b_R}$, the damage ratio is as follows:

$$\omega = \frac{\exp(-11.61w) - \dfrac{\exp(-11.61w)}{1+1863.1Pa\cdot\exp(-11.61w)\cdot A_1\varepsilon^{B_1+1}}}{\exp(-11.61w) - \dfrac{\exp(-11.61w)}{1+1863.1Pa\cdot\exp(-11.61w)\cdot A_2\varepsilon^{B_2+1}}} \quad (18)$$

When $\mathbf{b_0}>\mathbf{b}_R$, the damage ratio is as follows:

$$\omega = \frac{\exp(-11.61w) - \dfrac{\exp(-11.61w)}{1+1863.1Pa\cdot\exp(-11.61w)\cdot A_2\varepsilon^{B_2+1}}}{\exp(-11.61w) - \dfrac{\exp(-11.61w)}{1+1863.1Pa\cdot\exp(-11.61w)\cdot A_2\varepsilon^{B_2+1}}} \quad (19)$$

And then, in terms of the view of composite materials in the damage mechanics, based on Eq. (1), the stress-strain equation can be described as the increment equation:

$$\{\Delta\sigma\} = (1-\omega)[D_i]\{\Delta\varepsilon) + \omega[D_d]\{\Delta\varepsilon\} - (\{\sigma_i\} - \{\sigma_d\})\Delta\omega \quad (20)$$

Where, $[D_i]$ and $[D_d]$ are the intact loess and damage loess tangent radial matrix respectively. Application of the above equation, the actual deformation process of the collapsible loess can be obtained under loading and moistening process.

5. Conclusions

(1) Under the coupling of loading and moistening, the collapsible loess structure appears to be the changing and developing process that intact structure damage and the secondary structure grows. In the process of tri-axial consolidation and shearing deformation, there are the damage of intact structural and growth of the secondary structure caused by compressing-moistening as well as the shearing-moistening.

(2) The degrees are different of compressing-moistening damage of intact and the growth of the secondary structure, and the shearing stress-strain curves are different. Supposing when the stress-strain curves without structural changes in the shearing process, are the ideal hyperbola variations, the changing of loess structure can be revealed by the different hyperbola distribution determined by the actual shearing stress-strain states in the shearing process.

(3) Based on the changing of the hyperbola distribution that can reflect different structural in the shearing process, the stress-strain curves under the different humidity and consolidation pressure can be classified into the softening and hardening types. The former indicates that the compressing-moistening damage is smaller, but the structural variation is obvious in moistening-shearing process; the latter indicates that the compressing-moistening pressure damage is projected, and the growth of secondary structure is apparent in the shearing moistening process.

(4) Based on the viewpoint of composite materials in the damage mechanics, it is suggested that the changing of the damage ratio between compressing-moistening damage and shearing- moistening damage should be taken into consideration, so that the corresponding stress-strain equation is established, which is able to reflect the changing of loess structural damage in the loading and moistening process.

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