Volumetric Deformation of Natural Clays

M. D. Liu[1] and J. P. Carter[2]

Abstract: A theoretical framework to describe the behavior of natural clay is proposed in a new four-dimensional space, consisting of the current stress state, stress history, the current voids ratio, and a measure of the current soil structure. A key assumption of the proposed framework is that both the hardening and the destructuring of natural clay are dependent on plastic volumetric deformation. Two different assumptions about how this destructuring occurs are proposed, based on which two versions of a complete constitutive model have been formulated. The behavior of reconstituted soil can also be simulated by the proposed model as a special case where the structure of soil has no effect on soil deformation. Characteristics of the proposed model are demonstrated through systematic simulations of the influence of soil structure on clay behavior. The simulated behavior of natural clay is compared qualitatively with widely available experimental data. It is seen that the proposed model successfully represents the main features of natural clays with various soil structures.

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Introduction

By the late 1940s, the mathematical theory of plasticity for metals was well established (Hill 1950). These developments in metal plasticity theory, together with the analogy between the mechanical behavior of metals and some soils, were responsible for stimulating much research interest in the related field of constitutive modeling of soil (e.g., Drucker et al. 1957; Mroz et al. 1978; Desai 2001). The formulation of the concept of the Cam Clay model by the Cambridge Soil Mechanics Group during the 1950s marked a milestone in soil mechanics and lead to the establishment a body of theory known widely as ''Critical State Soil Mechanics'' (e.g., Schofield and Wroth 1968). Perhaps the most important contribution as well as the most distinguishing feature of the critical state framework was the introduction of the voids ratio into constitutive modeling of soil behavior. Current stress state, stress history, and voids ratio are the three dimensions in which the behavior of soil was defined, allowing the unification into one simple descriptive framework of the behavior of various soil types under a variety of stress paths (e.g., Muir-Wood 1990).

Cam Clay and other constitutive models of the critical state framework generally represent successfully the behavior of reconstituted soils (e.g., Scott 1985; Desai et al. 1986; Yu 1998). However, the performance of these models is much less satisfactory for natural soils, where there is a fourth factor of some importance, which has not generally been included in critical state models. This factor is the structure of the natural soil. The term ''soil structure'' is used here to denote the arrangement and bonding of soil constituents, and for simplicity it encompasses all features of a soil that are different from those of the corresponding reconstituted soil. There have also been developments in formulating constitutive models incorporating the influence of soil structure, such as those proposed by Whittle (1993), Wheeler (1997), and Kavvadas and Amorosi (2000). However, while there have been useful contributions in recent years, much more progress in both understanding and modeling the influence of soil structure and destructuring is still needed.

In this paper, a theoretical framework for natural clay behavior is developed in a new 4D space, namely, the current stress state, stress history, voids ratio, and soil structure. A basic assumption of the proposed framework is that both the hardening and destructuring of natural clays are dependent on plastic volumetric deformation. Modeling the behavior of reconstituted soils under the assumption of volumetric hardening has been studied in detail in an earlier paper by the writers (Liu and Carter 2000a). The work described in this paper provides an extension of the previous framework, which allows specifically for the inclusion of the influence of soil structure on the behavior of natural clays. The proposed framework is evaluated by simulating the behavior of a variety of natural clays.

Modeling Behavior of Natural Clays

The formation and development of soil structure often produces anisotropy in the mechanical properties of soil. In order to concentrate on introducing the concepts of the framework and to avoid unnecessary complexity of mathematical detail, only the isotropic effects of soil structure are included in the proposed theoretical framework. The extension to include the influence of soil anisotropy shall be a future research topic. The stress and strain quantities are defined in the same way as those adopted by Liu and Carter (2000a). Following the suggestion of Burland (1990), the properties of a reconstituted soil are called the intrinsic properties, and are denoted by the symbol* attached to the relevant symbols.

Isotropic Compression

The work by Liu and Carter (1999, 2000b) on the virgin compression behavior of natural (structured) clays is adopted as a starting

[1]Dept. of Civil Engineering, The Univ. of Sydney, N.S.W. 2006, Australia. E-mail: m.liu@civil.usyd.edu.au

[2]Dept. of Civil Engineering, The Univ. of Sydney, N.S.W. 2006, Australia.

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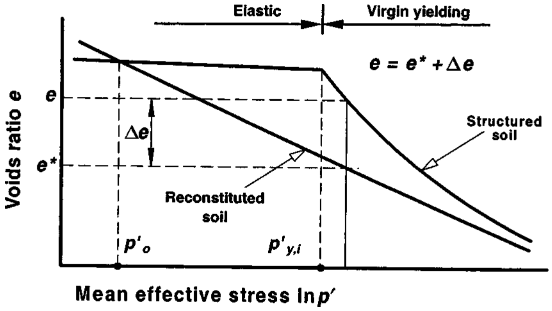

Fig. 1. Idealization of the compression behavior of reconstituted and structured clays

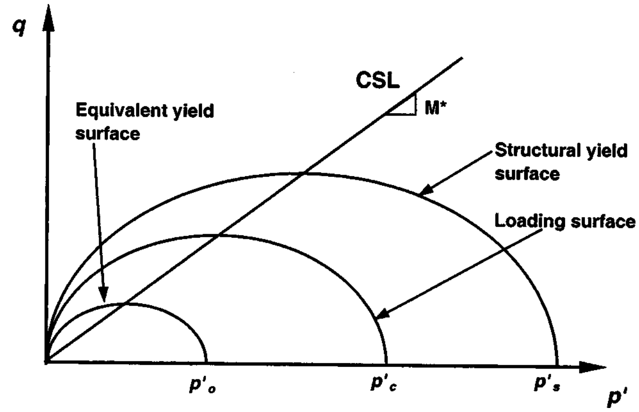

Fig. 2. Three surfaces for a structured soil

point for the current study. The proposed material idealization for the isotropic compression (IC) behavior of clay is shown in Fig. 1. In this figure, p' is the mean effective stress; e represents the voids ratio for a structured soil; e^* is the voids ratio for the corresponding reconstituted soil at the same stress state during virgin yielding, $p'_{y,i}$ is the mean effective stress at which virgin yielding of the structured soil begins, and Δe, the additional voids ratio, is the difference in voids ratio between a structured soil and a sample of soil of the same mineralogy and stress level in the reconstituted condition.

Liu and Carter (2000b) proposed the following general equation describing the isotropic virgin compression equation of natural clay

$$e = e^*_{\mathrm{IC}} + \Delta e_i \left(\frac{p'_{y,i}}{p'} \right)^b - \lambda^* \ln p' \tag{1}$$

where Δe_i=the initial additional voids ratio sustained by the soil structure; b=a parameter quantifying the rate of destructuring, termed the destructuring index. It has been demonstrated that the compression Eq. (1) has the capacity to describe effectively the destructuring during virgin compression of both soft and stiff structured clays, as well as fissured clays and clay shales (Liu and Carter 2000b).

Volumetric Hardening and Destructuring

The following conclusions were drawn from an earlier study by the writers on reconstituted clays (Liu and Carter 2000a): (1) the magnitude of plastic volumetric deformation is dependent on the change in size of the yield surface but independent of the stress path; (2) there is a one-to-one relationship between the yield surface and the plastic volumetric strain; (3) because the elastic volumetric deformation is dependent on the current stress state only, the current yield surface can be linked to the current voids ratio and the current stress state. Similarly, a fundamental assumption of the theoretical framework proposed here for natural soils is that both the hardening and the destructuring of structured clay are dependent on plastic volumetric deformation. As stated, only the isotropic effect of soil structure is of concern here, and the hardening and destructuring of natural clays is modeled by the change in size of the yield surface.

The following consequences flow from this fundamental assumption: (1) the magnitude of plastic volumetric deformation of natural clay is dependent on the change in size of the yield surface, irrespective of the stress path; and (2) the yield surface for natural clay is dependent on the current soil structure, the current voids ratio, and the current stress state.

Experimental evidence for the dependence of hardening and destructuring on volumetric deformation may be found in studies such as those by Calabresi and Scarpelli (1985), Graham and Li (1985), Clayton et al. (1992), and Cotecchia and Chandler (2000).

Surfaces in $p' - q$ Space

The two-surface theory for modeling the elastoplastic deformation of materials (e.g., Dafalias and Popov 1976; Hashiguchi 1980) is adopted and extended in this research. The two surfaces are the yield surface and the loading surface. However, an additional reference surface is also introduced, i.e., the equivalent yield surface. Hence, for a structured soil associated with a given state, three significant surfaces may be defined in stress space, as illustrated in Fig. 2.

Based on the assumption of volumetric hardening, the yield surface for a reconstituted soil is uniquely dependent on the current voids ratio and stress state (Liu and Carter 2000a). The equivalent yield surface for a structured soil is defined as the yield surface for the same soil in a reconstituted state with the same voids ratio and the same stress state. The size of the equivalent yield surface is denoted by p'_o. It is well known that the relationship between p'_o and the voids ratio e can be expressed by the following equation:

$$e = e^*_{\mathrm{IC}} - \kappa^* \ln p' - (\lambda^* - \kappa^*) \ln p'_o \tag{2}$$

Consequently, p'_o can be written as

$$p'_o = \frac{e^{((e_{\mathrm{IC}} - e)/(\lambda^* - \kappa^*))}}{p'^{(\kappa^*/(\lambda^* - \kappa^*))}} \tag{3}$$

The yield surface for a structured soil is described as the "structural yield surface." The size of a structural yield surface is denoted by p'_s, the value of which is determined by the current soil structure, voids ratio, and stress state. The smallest possible structural yield surface is the equivalent yield surface.

Following an earlier suggestion of Hashiguchi (1980), the loading surface is defined as the surface on which the current stress state always stays. The size of the loading surface is denoted by p'_c, and clearly p'_c is determined entirely by the current stress state. In the notation to be adopted here, a further subscript N will often be used to indicate the stress point with which a surface is associated. For example, $p'_{s,N}$ represents the size of the structural yield surface for a soil at state N. For a reconstituted soil, only two surfaces are necessary to describe soil behavior, because $p'_o \equiv p'_s$. Therefore, the difference between p'_o and p'_s is an indication of the influence of soil structure.

Similar to the proposal by Roscoe and Burland (1968), the yield surface in $p'-q$ space for a reconstituted clay is assumed to be elliptical (Fig. 2) and can be expressed as

$$f = q^2 - M^{*2} p'(p'_o - p') \quad (4)$$

where q=the generalized deviator stress and M^*=the stress ratio at the critical state of deformation and is an intrinsic material property. The equivalent yield surface is identical to the yield surface for a reconstituted soil (Fig. 2).

Because the effects of anisotropy are not studied in this paper, only the variation in the size of the yield surface due to soil structure is modeled. Hence, the structural yield surface in the $p'-q$ space is also assumed to be elliptical in shape with the aspect ratio being equal to M^* (Fig. 2). The value p'_s, which represents the size of the structural yield surface, is the non-zero value of p' where the ellipse intersects the p' axis. Similarly, the loading surface is assumed to be elliptical and with the same aspect ratio M^* (Fig. 2). The mathematical forms for the structural yield surface and the loading surface are the same as Eq. (4).

Destructuring

There are many factors that may alter the structure of a soil, such as ageing, leaching, loading, and weathering. In this study, only the destructuring of natural clay resulting from stress variation is of interest. It is assumed that the destructuring resulting from stress variation is a monotonic and irrecoverable process and is dependent only on the plastic volumetric deformation. For purely elastic deformation, there is no plastic deformation, and consequently, there can be no destructuring.

For simplicity of presentation, two assumptions or idealizations about the destructuring process are presented. The first is the simpler assumption, but it should become evident that it may be regarded merely as a particular form of the more general second idealization proposed for destructuring.

In the first assumption, destructuring idealization I, soil is regarded as an elastic and virgin yielding material. The yield surface varies isotropically with the change in plastic volumetric deformation. Soil behavior is assumed to be elastic for a stress change inside the structural yield surface. Virgin yielding occurs for a stress change originating on the current structural yield surface and causes it to expand. During virgin yielding, the structural yield surface is coincident with the loading surface.

Destructuring idealization I is illustrated in Fig. 3, and it should be noted that in Fig. 3(a) the horizontal axis is p'_c, the size of the loading surface, but in Fig. 3(b), it is p', the mean effective stress. Given the assumed mathematical form of the loading surface, its size is numerically equal to the mean effective stress only if the soil is in an isotropic state. At Point B [Fig. 3(b)], the size of the loading surface $p'_{c,B}$ is equal to $p'_{y,i}$, the size of the initial yield surface produced by soil structure. For any loading inside the initial structural yield surface $p'_{y,i}$, only elastic deformation is induced. There is no destructuring, and the structural yield surface remains unchanged.

For loading at Point B with $dp'_c > 0$, virgin yielding occurs, and destructuring is associated with plastic deformation. Destructuring tends to cause shrinkage of the yield surface, but at the same time the compressive plastic volumetric deformation tends to cause it to expand. It is proposed that for virgin yielding $p'_{s,C} = p'_{c,C}$. As a result, soil behaves elastically for loading along stress path AB (Fig. 3), and the structural yield surface remains

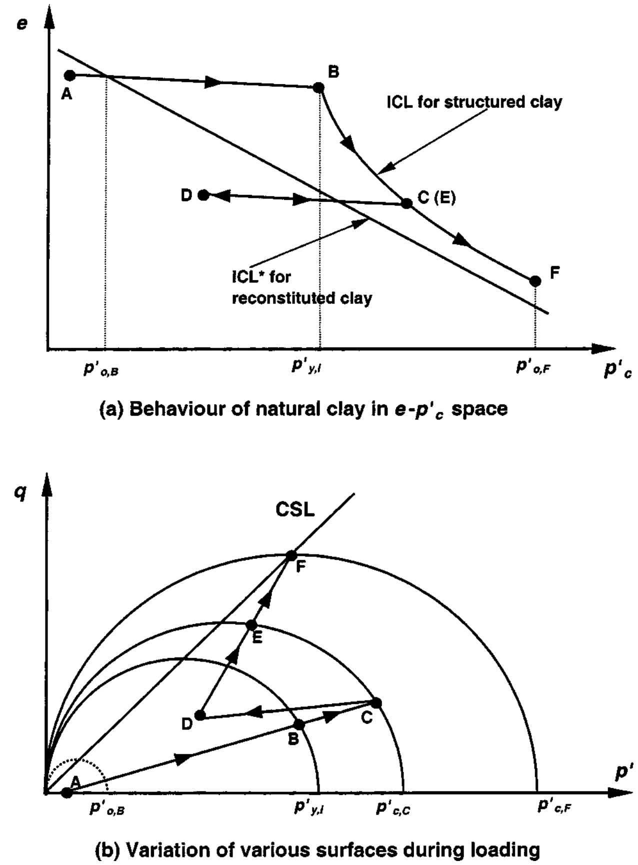

Fig. 3. Destructuring idealization I

the same for all points along AB. Virgin yielding starts at Point B and continues along the stress path BC. The structural yield surface expands and is coincident with the loading surface for loading along BC. The soil is unloaded from C to D and subsequently is reloaded again from D to E. The soil behaves elastically for stress path C→D→E. For further loading along stress path DE, virgin yielding starts again at point E where $p'_{c,E} = p'_{s,E} = p'_{s,C}$.

Fig. 3 is drawn to illustrate some of the features of the destructuring process that are determined by plastic volumetric deformation. However, it may be noticed that there are some deficiencies in the figure. The position indicated in Fig. 3(a) describes soil behavior in terms of the size of the loading surface p'_c and the voids ratio. Because elastic deformation is dependent on the change in stress state and not the size of the loading surface, it is not possible to represent correctly in this figure, the magnitude of the elastic deformation for both purely elastic behavior and virgin yielding, except for isotropic stress states where $p' = p'_c$. However, the plastic volumetric deformation and the destructuring effects demonstrated in the figure are reasonable, at least qualitatively.

In the second assumption, destructuring idealization II, soil is idealized as a subyielding and virgin yielding material. Plastic deformation is generally induced by a stress change inside the structural yield surface, as well as by a stress change originating on the current yield surface causing it to expand. The former is referred to as subyielding and the latter as virgin yielding. The structural yield surface varies isotropically with the change in plastic volumetric deformation. During virgin yielding, the structural yield surface expands and is coincident with the loading surface. During subyielding, the variation of the yield surface is

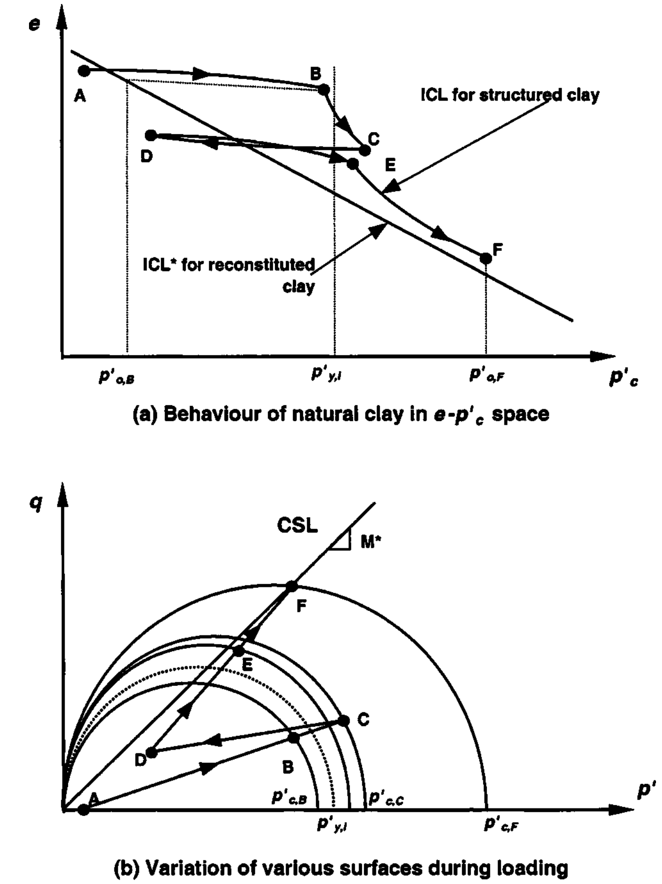

Fig. 4. Destructuring idealization II

dependent on destructuring as well as hardening, both of which are assumed to be determined by plastic volumetric deformation.

Destructuring idealization II is presented in Fig. 4. Suppose the initial state for a clay in situ is Point A in Fig. 4, and its initial structural yield surface is defined by its size $p'_{y,i}$. For loading inside the structural yield surface, subyielding occurs. The structural yield surface varies as both hardening and destructuring of the yield surface are normally induced by the plastic deformation. As loading continues along stress path AB, the loading surface expands. Suppose that the loading surface and the structural yield surface coincide at Point B, that is, $p'_{c,B}=p'_{s,B}$, then, virgin yielding will commence at Point B. Generally, $p'_{c,B}\neq p'_{y,i}$. For virgin yielding along stress path BC, the structural yield surface coincides with the loading surface. Suppose unloading occurs at Point C and continues along the stress path CD, i.e., $dp'_c<0$. Consequently, subyielding occurs with unloading along path CD, and the current loading surface turns inside the current structural yield surface and contracts. Suppose the stress path changes direction again at Point D with $dp'_c>0$. Reloading then commences and continues along stress path DE. The structural yield surface varies during both unloading and reloading. Suppose at Point E the loading surface coincides with the structural yield surface, i.e., $p'_{c,E}=p'_{s,E}$. In this case, virgin yielding recommences at Point E and continues for loading along stress path EF.

As indicated previously, destructuring idealization II is a more general form of destructuring idealization I. The second assumption allows for the presence of subyielding while the former does not. A major feature of destructuring idealization II is its ability to determine the variation of the structural yield surface during subyielding. As a special case, when the soil has no structure the yield surface and the equivalent yield surface are identical. The variation of the yield surface during subyielding is dependent on the plastic volumetric deformation and can be determined by Eq. (3).

The variation of the structural yield surface is determined by two factors: the hardening mechanism and the destructuring mechanism. Both mechanisms are dependent on plastic volumetric deformation. It is assumed that the effects of the two mechanisms can be modeled independently, and the change in the current yield surface can be expressed in terms of the hardening effect dH and the destructuring effect dD by the following equation

$$dp'_s=dH-dD \tag{5}$$

Various hardening and destructuring functions can be formulated within the proposed framework of subyielding and virgin yielding, as described later.

Stress-Strain Model

A model for the mechanical behavior of natural clays is now formulated based on destructuring idealization II described previously. Clearly, the general form of this model will collapse to a simpler form if the assumption of subyielding is abandoned and unloading and reloading inside the structural yield surface remains purely elastic.

Elastic Behavior

It is assumed that the deformation of clay can be decomposed into elastic and plastic components. A large body of experimental data is available on the influence of soil structure on the elastic properties and particularly on the swelling-recompression index κ^* (e.g., Lambe and Whitman 1969; Wallace 1973; Hight et al. 1992; Burland et al. 1996). It is found that although the change of elastic properties has been observed for some clays the difference in soil behavior attributed for most naturally structured clays is not very significant, except for situations such as those where soil deformation at very small strains is of particular interest (Liu and Carter, unpublished report, 2000). It is therefore assumed that the elastic properties of a soil are independent of soil structure and are therefore intrinsic soil properties. For simplicity, the following equations for elastic deformations, expressed in terms of the recompression index κ^* and Poisson's ratio ν^*, are adopted

$$d\varepsilon_v^e=\left(\frac{\kappa^*}{1+e}\right)\frac{dp'}{p'} \tag{6}$$

$$d\varepsilon_d^e=\frac{2(1+\nu^*)}{9(1-2\nu^*)}\left(\frac{\kappa^*}{1+e}\right)\frac{dq}{p'} \tag{7}$$

where $d\varepsilon_v^e$ and $d\varepsilon_d^e$ represent the elastic increments of volumetric and deviatoric strains, respectively. Because of their simplicity Eqs. (5) and (6) are widely employed in geotechnical engineering for calculating the elastic deformation of soils (Potts and Zdravkovic 1999; Desai 2001). However, it should be noted that these equations have limits, and rational elastic models may be derived from principles of thermomechanics (Collins and Kelly 2002).

Flow Rule

Compared to reconstituted clay, during virgin yielding more compressive plastic volumetric deformation will be produced by structured clay (Graham and Li 1985; Allman and Atkinson 1992; Lagioia and Nova 1995). Destructuring accompanies yielding, and the additional voids ratio sustained by soil structure will diminish steadily. To represent the influence of destructuring, a new, nonassociated flow rule is proposed by modifying the associated flow rule adopted in the Modified Cam Clay Model (Roscoe and Burland 1968), i.e.

$$\frac{d\varepsilon_d^p}{d\varepsilon_v^p}=(1-0.5\Delta e/\Delta e_i)\left(\frac{\partial f/\partial q}{\partial f/\partial p'}\right)=\frac{2(1-0.5\Delta e/\Delta e_i)\eta}{M^{*2}-\eta^2} \quad (8)$$

Virgin Yielding and Softening

Virgin Yielding

Virgin yielding occurs for a loading with $p_c'=p_s'$ and $dp_c'>0$. Based on the assumption that both the hardening and the destructuring of natural clay are dependent only on plastic volumetric deformation and virgin isotropic compression defined by Eq. (1), a general equation describing plastic volumetric deformation for soil during virgin yielding can be derived.

Eq. (1), describing virgin isotropic compression, can be rewritten in terms of elastic and plastic parts as follows:

$$e=e_{\mathrm{IC}}^*-\kappa^*\ln p'+\Delta e_i\left(\frac{p_{y,i}'}{p'}\right)^b-(\lambda^*-\kappa^*)\ln p' \quad (9)$$

The plastic part of the voids ratio change is dependent on the size of the current yield surface, not the mean effective stress. Hence p' in the third and fourth terms of Eq. (9) should be substituted by the size of the current structural yield surface p_s'. Noticing that for isotropic compression the size of the yield surface is numerically equal to the mean effective stress, Eq. (9) can be rewritten as

$$e=e_{\mathrm{IC}}^*-\kappa^*\ln p'+\Delta e_i\left(\frac{p_{y,i}'}{p_s'}\right)^b-(\lambda^*-\kappa^*)\ln p_s' \quad (10)$$

Eq. (10) describes the change of voids ratio, and there are three basic terms in the equation. The first, $\kappa^*\ln p'$, describing the change associated with elastic deformation, is valid for loading along general stress paths. The third term, $(\lambda^*-\kappa^*)\ln p_s'$, describes the change associated with plastic deformation for clay in a reconstituted state. This term is the same as that appearing in the Cam Clay model for describing the voids ratio change associated with plastic deformation under general loading (Schofield and Wroth 1968). The second term $\Delta e_i(p_{y,i}'/p_s')^b$, describes the change associated with the additional voids ratio sustained by soil structure and is a plastic deformation. It was suggested previously that the magnitude of plastic volumetric deformation of natural soil is dependent on the change in size of the yield surface, irrespective of the stress path. Therefore, the second term is also valid for loading along general stress paths. Consequently, Eq. (10) is valid for loading along general stress paths.

Taking the differential form of Eq. (10) and dividing both sides by $(1+e)$, the following equation for the total volumetric strain increment is obtained:

$$d\varepsilon_v=\frac{\kappa^*}{1+e}\left(\frac{dp'}{p'}\right)+[(\lambda^*-\kappa^*)+b\Delta e]\frac{dp_s'}{(1+e)p_s'} \quad (11)$$

where Δe is the current additional voids ratio sustained by soil structure for loading along general stress paths. By examining the geometrical relationships presented in Fig. 1 and in particular considering the linear relationship for the elastic and plastic parts of the volumetric deformation in e-$\ln p_c'$ space, the following expression for Δe can be obtained:

$$\Delta e=(\lambda^*-\kappa^*)\ln\left(\frac{p_s'}{p_o'}\right) \quad (12)$$

The first part of Eq. (11) represents elastic deformation. The plastic strain increment $d\varepsilon_v^p$ can therefore be expressed as

$$\begin{aligned} d\varepsilon_v^p&=\left[(\lambda^*-\kappa^*)+b\Delta e_i\left(\frac{p_{y,i}'}{p_c'}\right)^b\right]\frac{dp_s'}{(1+e)p_s'}\\ &=(\lambda^*-\kappa^*)\left[1+b\ln\left(\frac{p_s'}{p_o'}\right)\right]\frac{dp_s'}{(1+e)p_s'} \end{aligned} \quad (13)$$

Alternatively

$$dp_s'=\frac{(1+e)p_s'd\varepsilon_v^p}{(\lambda^*-\kappa^*)\left[1+b\ln\left(\frac{p_s'}{p_o'}\right)\right]} \quad (14)$$

Eq. (14) defines the hardening function for natural clay during virgin yielding. The plastic deviatoric strain increment can be computed from the flow rule, Eq. (8). Noting that the elastic component is given by Eq. (7), the total deviatoric strain increment can be written as

$$\begin{aligned} d\varepsilon_d=&\frac{2(1+\nu^*)}{9(1-2\nu^*)}\frac{\kappa^*}{1+e}\frac{dq}{p'}+\frac{2(1-0.5\Delta e/\Delta e_i)\eta}{M^{*2}-\eta^2}\\ &\times\left[1+b\ln\left(\frac{p_s'}{p_o'}\right)\right]\frac{(\lambda^*-\kappa^*)dp_s'}{(1+e)p_s'} \end{aligned} \quad (15)$$

Eq. (14) is also applicable for a reconstituted clay, where $\Delta e \equiv 0$ because such a soil has no structure. Hence, for a reconstituted clay

$$dp_o'=\frac{(1+e)p_o'd\varepsilon_v^p}{(\lambda^*-\kappa^*)} \quad (16)$$

Softening

When the current stress state reaches the virgin yield surface with $\eta>M^*$, softening occurs if the boundary conditions allow the adjustment of the stress state. Otherwise, catastrophic failure will be predicted. During a controlled softening process, the yield surface shrinks, and the current stress state remains on it. Therefore, in principle, the constitutive equations derived for the virgin yielding behavior of soil, Eqs. (13) and (15), should be applicable for the softening process. However, because during softening dp_c' is negative, it is noticed that the volumetric deformation associated with the additional voids ratio will be negative for a positive value of Δe. This leads to an increase of the additional voids ratio sustained by soil structure during the softening process, which is unrealistic. Consequently, the absolute value of dp_c' is taken when computing the plastic volumetric deformation associated with softening, and the following modified equation is the result:

$$d\varepsilon_v^p=[dp_c'+b\ln(p_s'/p_o')|dp_c'|]\frac{(\lambda^*-\kappa^*)}{(1+e)p_c'} \quad (17)$$

where the notation $|\ |$ represents the absolute value of a scalar quantity. The flow rule, Eq. (8), is still valid. However, it may be seen from Eq. (17) that $d\varepsilon_v^p$ can be either compressive or expansive. To ensure that the deviatoric plastic strain increment vector will always point outside the yield surface, the following equation is used to compute the plastic deviatoric strain increment:

$$d\varepsilon_d^p = -\frac{2(1-\Delta e/\Delta e_i)\eta}{M^{*2}-\eta^2}|d\varepsilon_v^p| \tag{18}$$

Hardening and Destructuring

For a reconstituted soil, the change in size of the yield surface is induced purely by plastic hardening. It is assumed that Eq. (16) is also suitable to describe the hardening of a structured soil during subyielding. In this equation, p_o' is the size of the current equivalent yield surface. Therefore

$$dH = \frac{(1+e)p_o' d\varepsilon_v^p}{(\lambda^*-\kappa^*)} \tag{19}$$

It may be seen from Eq. (1), $\Delta e \equiv \Delta e_i$ if $b=0$. That is, the additional voids ratio sustained by soil structure remains the same during virgin yielding. Therefore, it can be interpreted that there is no destructuring for a structured soil with $b=0$. The corresponding variation of the yield surface for a structured soil with $b=0$ during virgin yielding can be recovered from Eq. (14) as follows:

$$dp_s' = \frac{(1+e)p_s' d\varepsilon_v^p}{(\lambda^*-\kappa^*)} \tag{20}$$

The variation of the yield surface during virgin yielding with destructuring is given by Eq. (14), and therefore the effect of destructuring dD can be obtained as

$$dD = dp_s'|_{\text{no destructuring}} - dp_s'|_{\text{destructured}}$$

$$= \frac{(1+e)p_s' d\varepsilon_v^p}{(\lambda^*-\kappa^*)[1+b\ln(p_s'/p_o')]} b \ln(p_s'/p_o') \tag{21}$$

It is assumed that Eq. (21) is also valid for general stress paths including both virgin yielding and subyielding. Considering that expansive plastic volumetric strain also results in the removal of soil structure, the absolute value of plastic strain increment $d\varepsilon_v^p$ should be employed in the destructuring function. Therefore

$$dD = \frac{(1+e)p_s' |d\varepsilon_v^p|}{(\lambda^*-\kappa^*)[1+b\ln(p_s'/p_o')]} b \ln(p_s'/p_o') \tag{22}$$

Based on Eq. (5), the following equation for dp_s' for subyielding can be obtained

$$dp_s' = dH - dD = \frac{(1+e)p_o' d\varepsilon_v^p}{(\lambda^*-\kappa^*)} - \frac{(1+e)p_s' |d\varepsilon_v^p|}{(\lambda^*-\kappa^*)[1+b\ln(p_s'/p_o')]} b \ln(p_s'/p_o') \tag{23}$$

Subyielding

Subyielding may occur for a stress excursion inside the current yield surface. The basic idea for modeling subyielding is to link the plastic volumetric deformation at a subyielding state to that at a corresponding virgin yielding state and then calculate the plastic deviatoric strain with the flow rule given by Eq. (8) with or without modification. The exact forms for the mathematical equations adopted for subyielding are based on comparisons with experimental data.

The volumetric plastic strain increment during subyielding for reconstituted soils proposed by Liu and Carter (2000a) is modified for natural clays as follows:

$$d\varepsilon_v^p = \left(1-\frac{\eta}{M^*}\right)\left[\frac{\alpha(\lambda^*-\kappa^*)dp_c' + \alpha^3 b \Delta e |dp_c'|}{(1+e)p_s'}\right] \tag{24}$$

This modification is made based on the following observations: (1) although during virgin yielding natural clay is usually much more compressible than the same soil in a reconstituted state, there is no evidence that during subyielding a natural soil is more compressible than the reconstituted soil (Wallace 1973; Graham and Li 1985; Burland et al. 1996); and (2) the plastic volumetric deformation contributed by destructuring is irrecoverable during cyclic loading. For example, it is rational that this part of deformation should be nonexpansive for a soil with positive Δe.

A simple scalar expression for α, similar to the proposal by Liu and Cater (2000a), is adopted

$$\alpha = \begin{cases} \left(\dfrac{p_c'-p_u'}{p_s'-p_u'}\right) & \text{if } dp_c' \geqslant 0 \\ \left(1-\dfrac{p_c'}{p_s'}\right) & \text{if } dp_c' < 0 \end{cases} \tag{25}$$

in which p_u' is the minimum size of the loading surface previously attained, i.e., $p_u' = \min(p_c')$. When the stress state returns to virgin yielding, the memory of the previous loading is lost, and $p_u' = p_c'$.

It should be pointed out that Eq. (25) provides an approximate scalar equation for describing the influence of stress history on soil behavior. Generally, α takes a value between 0 and 1, with $\alpha=0$ corresponding to purely elastic deformation, and $\alpha=1$ corresponding to virgin yielding. To describe the Bauschinger effect accurately, the Mroz-Iwan theory of work hardening (Mroz 1967; Iwan 1967) could be used to determine the value of α. It may also be noted that the transition between subyielding and virgin yielding is generally not smooth except when $\eta=0$. The flow rule, Eq. (8), is assumed to be valid for subyielding with $dp_c' \geqslant 0$, i.e., reloading, and thus, the plastic deviatoric strain increment during subyielding can be written as

$$d\varepsilon_d^p = \frac{2[1-0.5(\Delta e/\Delta e_i)]\eta}{M^*(M^*+\eta)} \frac{\lfloor \alpha(\lambda^*-\kappa^*)dp_c' + \alpha^3 b \Delta e |dp_c'| \rfloor}{(1+e)p_s'} \tag{26}$$

For subyielding with $dp_c' < 0$, i.e., unloading, a modification to the flow rule [Eq. (8)] is made and the following plastic deviatoric strain is proposed:

$$d\varepsilon_d^p = \frac{2[1-0.5(\Delta e/\Delta e_i)](\eta_u-\eta)}{M^*(M^*+\eta)} \times \frac{\lfloor \alpha(\lambda^*-\kappa^*)dp_c' + \alpha^3 b \Delta e |dp_c'| \rfloor}{(1+e)p_s'} \tag{27}$$

where η_u is the stress ratio at which unloading commences. The current structural yield surface varies during subyielding. The change of the structural yield surface dp_s' can be computed directly from Eq. (23).

Table 1. Model Parameters

Parameter	M^*	λ^*	κ^*	e^*_{IC}	v^*
Value	1.2	0.16	0.05	2.176	0.25

Applications

In this section, numerical simulations using the proposed stress-strain model are presented in order to demonstrate some of the important features of the model. The simplified version of the stress-strain model (incorporating destructuring idealization I) was employed to simulate mostly the behavior of naturally structured soft clays under monotonic loading or stress paths with simple stress reversals. The more general form of the stress-strain model (incorporating destructuring idealization II) was employed to simulate the behavior of naturally structured clays under more complicated forms of cyclic loading.

Model Parameters

Four groups of simulations were designed. They are (1) cyclic isotropic compression; (2) virgin shearing of samples from the same initial stress state and structural yield surface; (3) shearing of over-consolidated clays; and (4) uniform cyclic shearing. The stress paths for all simulations follow those that can be performed on soil samples in conventional triaxial apparatus under fully drained conditions.

It is noted that the two forms of the stress-strain model are identical to models derived by Liu and Carter (2000a) for reconstituted clays, provided of course that the structure of the soil has been removed completely, i.e., $\Delta e_i = 0$. Thus the proposed models have the capacity to describe features of soil behavior qualitatively similar to those of reconstituted clay. Therefore, the simulations presented here are focused on the features of natural clays that are characteristically different from their reconstituted soil types.

Seven parameters are required to define the model completely. They are M^*, λ^*, κ^*, e^*_{IC}, v^*, $p'_{y,i}$, and b. The values M^*, λ^*, κ^*, e^*_{IC}, and v^* are intrinsic soil properties and are standard parameters used in the original and the Modified Cam Clay Model (Schofield and Wroth 1968; Muir-Wood 1990). Values of the intrinsic soil properties adopted in the simulations are listed in Table 1. For the simulations presented in this paper, $b = 1$ is assigned for the simplified form of the model, because this value is typical for most natural soft clays (Liu and Carter 1999).

Cyclic Isotropic Compression

In this example, the stress state of the soil remains isotropic. The initial stress state is defined by $p' = 10$ kPa, and the initial voids ratio is $e = 1.955$ (denoted by Point A on Fig. 5). The size of the initial structural yield surface is 100 kPa. Based on Eq. (1), it is found that the initial additional voids ratio is 0.4, i.e., $\Delta e_i = 0.4$. The isotropic stress path applied to the element of soil is defined as follows: a stress increase to $p' = 110$ kPa (Point B), followed by a reduction to $p' = 50$ kPa (Point C), another increase to $p' = 150$ kPa (Point D), another reduction to $p' = 130$ kPa (Point E), followed by an increase to $p' = 300$ kPa (Point F), another reduction to $p' = 11$ kPa (Point G), and finally an increase to $p' = 3{,}000$ kPa (Point H).

Simulations are shown in Figs. 5 and 6 for the simplified and more general forms of the model, respectively. For comparison, the virgin compression behavior of the corresponding reconstituted soil is also shown in these figures marked as A^*H^*. For the general model, four cases were simulated with different values of b, viz., $b = 0$, 0.5, 1, and 5. The performance of both versions of the model for virgin isotropic loading is the same as that predicted by Eq. (1), whose ability to predict the virgin compression behavior of structured clays has been shown previously to be satisfactory for over 30 different types of clays (Liu and Carter 1999, 2000b). Hence, the model simulation of virgin compression of natural clays can be considered as reliable.

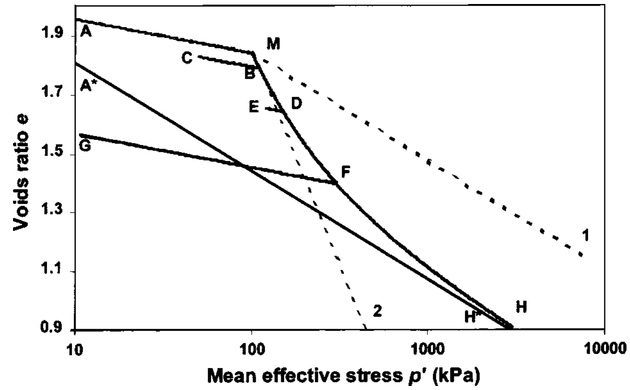

Fig. 5. Soil behavior under cyclic isotropic loading simulated by the simplified model

It is clearly seen from the performance of the simplified model shown in Fig. 5 that two zones of clay behavior are predicted, elasticity and virgin yielding, and these are sharply divided. There is no Bauschinger effect. Two types of structured soil behavior have also been simulated. In one simulation, marked as M1 in Fig. 5 by a broken line, the structured soil is assumed to compress linearly in the e-ln p' space with the same compression index λ^* as its reconstituted soil type. M is the point where virgin yielding starts for loading along stress path AB. In the other simulation, marked as M2 and shown by a broken line, the structured soil is assumed to compress linearly in the e-ln p' space with the com-

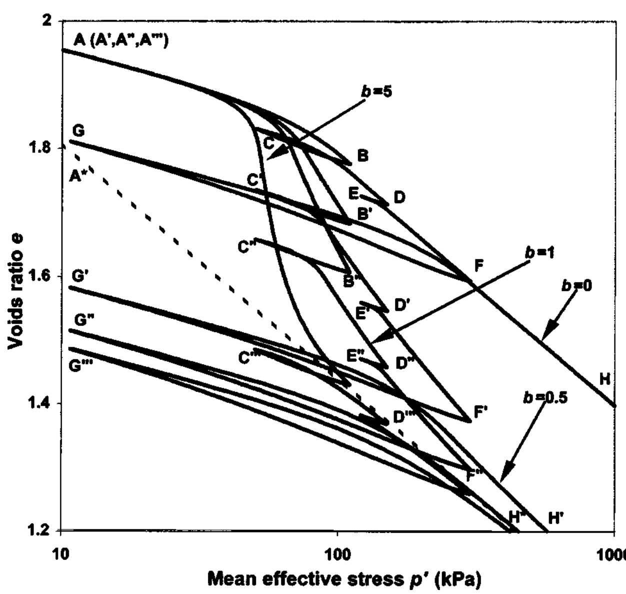

Fig. 6. Soil behavior under cyclic isotropic loading simulated by the general model

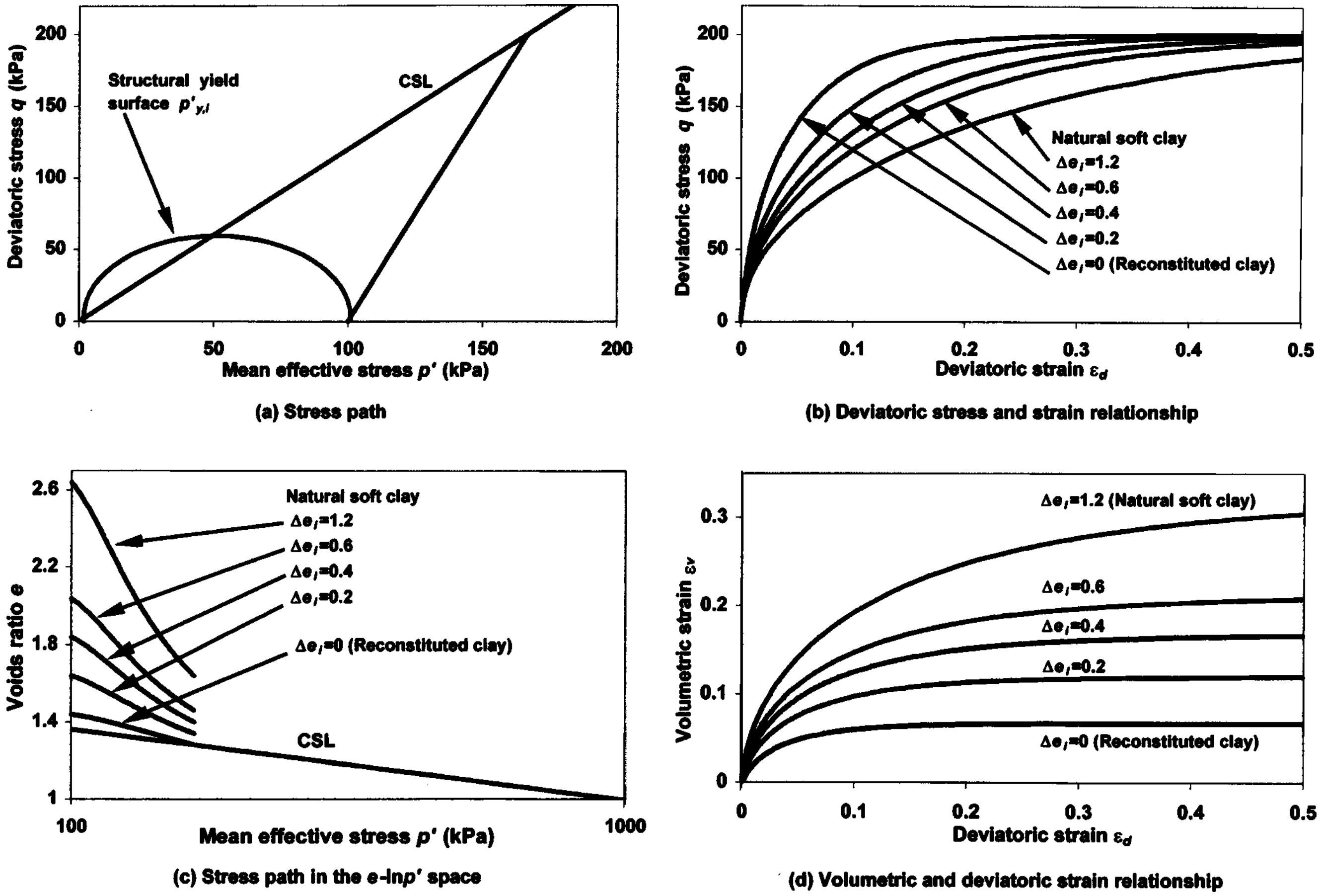

Fig. 7. Virgin shearing behavior of natural soft clay with different Δe_i simulated by simplified model

pression index being equal to the initial tangent compression index of the structured soil at the point where virgin yielding starts.

Based on the comparison of simulation MBDFH and simulation M1, it can be seen that the compressibility of natural soft clays during virgin yielding may be significantly underestimated if the compression index measured in laboratory tests on a reconstituted sample is used directly to predict the behavior of the clay in situ. This potential problem has been reported previously (e.g., Walker and Raymond 1969; Landva et al. 1988). Based on the comparison of the simulations MBDFH and M2, it can also be concluded that a linear representation of the virgin compression behavior of natural soft clay in the e-$\ln p'$ space is generally not a suitable description.

A quantitative examination of destructuring during the first loading AB is also of interest. The size of the initial yield surface is 100 kPa for all four cases. The sizes of the yield surface at the start of virgin yielding during loading AB are 101.6 kPa for $b=0$, 75 kPa for $b=0.5$, 67.5 kPa for $b=1$, and 52.1 kPa for $b=5$. For the case with $b=0$, there is no destructuring effect, and the change in the yield surface is attributed entirely to the hardening effect resulting from the plastic volumetric compression produced during subyielding. For the other three cases, the structural yield surface shrinks during subyielding. As expected, the higher the destructuring index b, the higher the magnitude of reduction in the structural yield surface. It may also be noticed that for the case with $b=5$ the additional voids ratio sustained by soil structure is reduced to less than 0.01 at $p'=110$ kPa during first loading AB because of its relatively high destructuring index. The structure of the soil is effectively removed at this stage of loading, and the soil behaves essentially the same as a reconstituted soil during further loading. Similar behavioral features have been observed in laboratory tests on natural clays, e.g., the structure of Osaka clay was removed almost completely after one cycle of isotropic loading (Adachi et al. 1995).

It is seen that in some cases the absolute value of the total volumetric expansion during unloading may be much smaller than the compression that occurs on reloading along the same stress path. Hence the hysteretic loop may be very small or may not even exist. This is because plastic volumetric deformation resulting from destructuring is monotonically compressive for both unloading and reloading. This observation is also consistent with experimental data (Carter et al. 2000; Butterfield and Baligh 1996).

Virgin Shearing from Same Initial Stress State and Yield Surface

Simulations were made of the shearing behavior of structured clay samples with the same initial stress state and the same structural yield surface. The initial stress state was isotropic with $p'=100$ kPa, and the size of the initial structural yield surface was $p'_{y,i}=100$ kPa. The stress paths were the same for all tests, with samples being loaded axially to failure while the confining stress remained constant. Thus all samples start deforming with virgin yielding.

Each soil sample has the same mineralogy but a different structure. The differences in soil structure are reflected by the

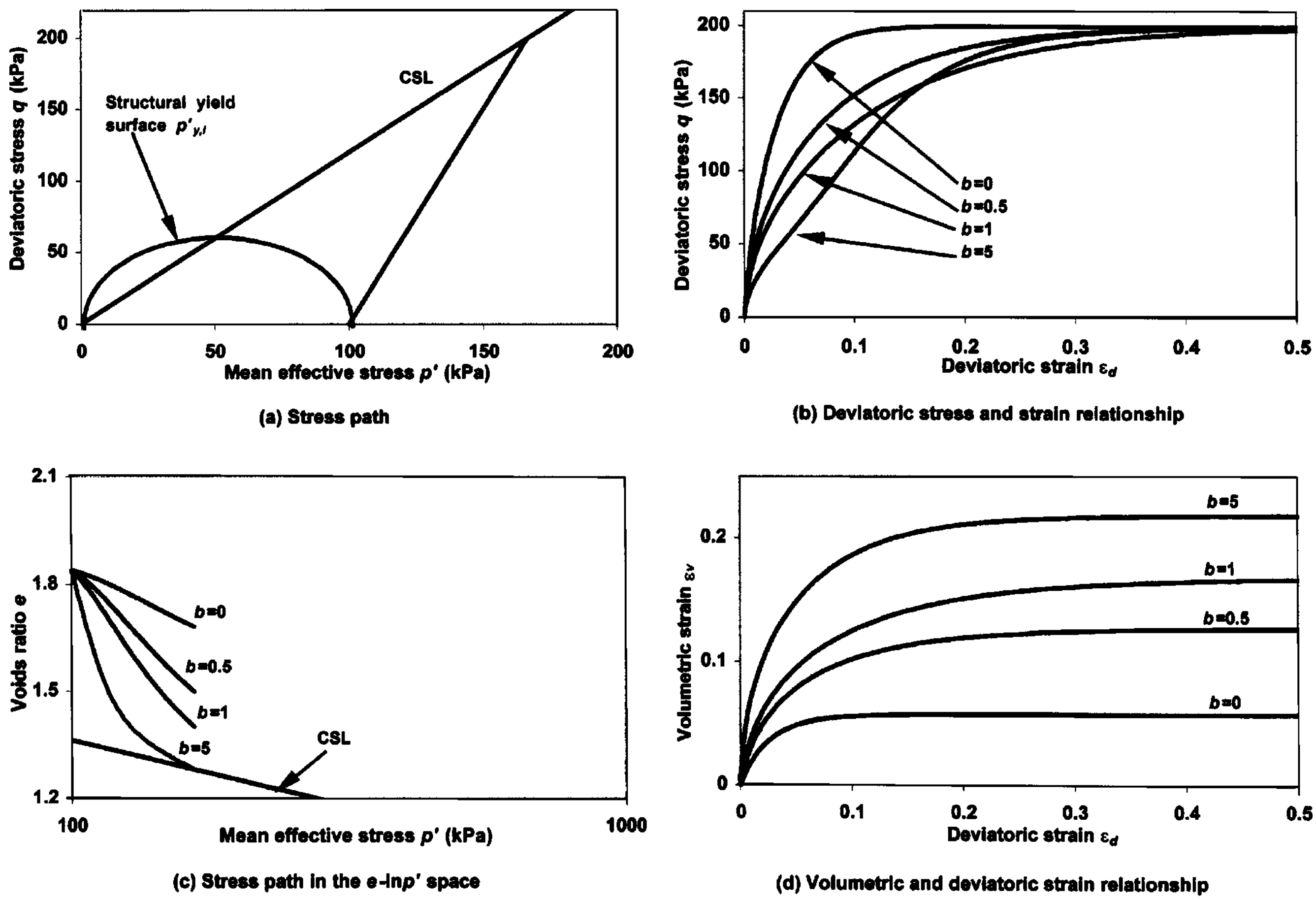

Fig. 8. Virgin shearing behavior of natural soft clay with different Δe_i simulated by general model

initial values of the additional voids ratios. Five cases were considered with the simplified model and $b=1$. For these cases, $\Delta e_i=0$, 0.2, 0.4, 0.6, and 1.2. According to Eq. (1), the initial voids ratios for the samples are 1.44, 1.64, 1.84, 2.04, and 2.64, respectively. The influence of the destructuring index was also examined using the more general form of the model and adopting values of $b=0$, 0.5, 1, and 5. The additional voids ratio for each of these cases was $\Delta e_i=0.4$, and the corresponding initial voids ratio was 1.84. The simulations using the simplified model are shown in Fig. 7, and those obtained using the more general model are shown in Fig. 8. The following features of soil behavior have been simulated:

1. For virgin shearing, curvature of the stress and strain relationship is observed. Like reconstituted soil, structured soil hardens steadily in the deviatoric stress and strain space until failure occurs, and compressive volumetric deformation is exhibited during drained loading.
2. Quantitatively, the behavior is dependent on soil structure. Unlike reconstituted clay, the virgin shearing behavior of structured clay plotted in the $\eta-\varepsilon_d-\varepsilon_v$ space cannot be normalized into one unique line. Soil structure exerts the following two main influences on the soil response to loading.
   • During virgin yielding, the stiffness of the deviatoric response decreases with the increase of additional voids ratio. Hence, clay in a reconstituted state has the highest deviatoric stiffness during virgin yielding.
   • It is seen that for a given change in stress state during virgin yielding, the magnitude of overall volumetric deformation increases with the additional voids ratio Δe and also increases with the destructuring index b. Consequently, the accumulated volumetric deformation increases with both Δe_i and b.

The influence of the destructuring index b on the overall shear stiffness appears to be complicated [see Fig. 8(b)]. This is because the shear stiffness of structured clay during virgin yielding is dependent on both b and the value of the current additional voids ratio, Δe. At the start of virgin yielding, all four samples shown in Fig. 8 had the same additional voids ratio. Hence, the differences in soil behavior directly reflect the influence of b. It is seen that the higher the value of b the quicker the destructuring and the lower the shear stiffness. Consequently, the additional voids ratio for clay with a higher value of b will reduce more quickly. Accordingly, the overall shear stiffness will actually increase during shearing due to the decrement in Δe. For example, the clay sample with $b=5$ initially has the lowest shear stiffness, but later, after Δe has been reduced considerably, it has a secant shear stiffness higher than the clay with $b=1$. The following conclusions can be drawn about the influence of b and of soil structure generally.

1. During virgin yielding, deviatoric stiffness decreases with an increase in the destructuring index.
2. The final strength of a structured soil, either expressed in terms of stress ratio or deviatoric stress, is independent of soil structure. The final stress ratio at failure is equal the critical state stress ratio, which is an intrinsic soil property.
3. The voids ratio at the final failure state is dependent on soil

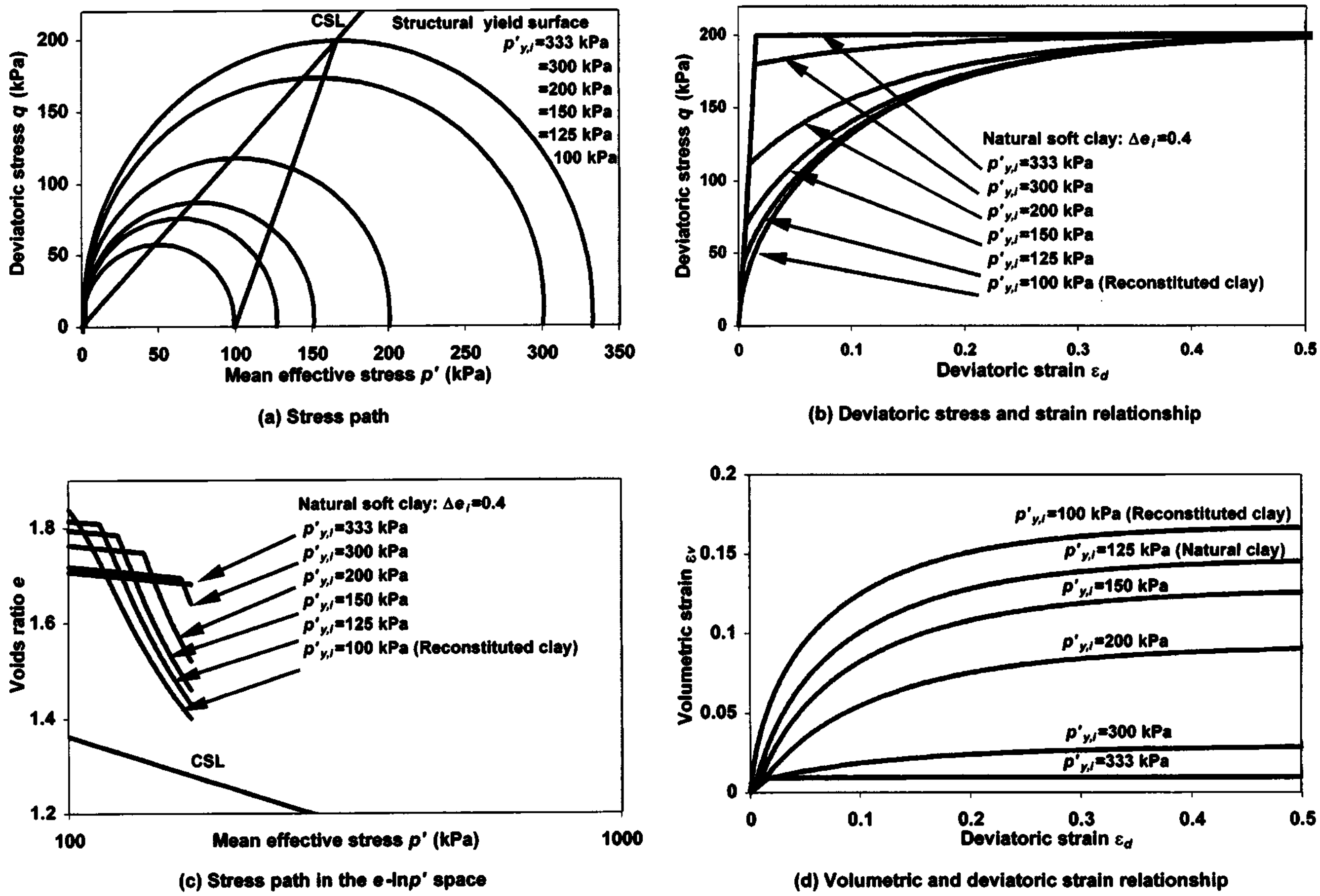

Fig. 9. Shearing behavior of lightly overconsolidated clay with different $p'_{y,i}$ simulated by simplified model

structure [Figs. 7(c) and 8(c)]. Therefore, the structure of a soil may not be removed completely when the soil is sheared to its final failure stress state.

The features of structured clay behavior simulated by the model are generally consistent with experimental observations. It has long been demonstrated that the virgin shearing behavior of a reconstituted clay, plotted in the $p' - q - \varepsilon_d - \varepsilon_v$ space for both drained and undrained conditions, can be normalized into a unique line by a single parameter (Wroth and Loudon 1967; Muir-Wood 1990; Allman and Atkinson 1992). The selected parameter for normalizing may be dependent on the value of the current voids ratio. In contrast, experimental evidence suggests that the virgin shearing behavior of structured clay cannot be normalized into one unique line by the same parameter (Allman and Atkinson 1992; Adachi et al. 1995; Cotecchia and Chandler 2000).

The greater compressibility and compliance of natural clays during virgin shearing, as compared to a reconstituted sample of the same soil, have been widely reported (Graham and Li 1985; Burland 1990; Lagioa and Nova 1995). It has also been demonstrated that a positive (negative) increment of pore pressure will occur under undrained conditions if the soil tends to contract (expand) when full drainage is permitted (Muir-Wood 1990). It can also be seen from experimental data, such as that published by Olson (1962), Allman and Atkinson (1992), and Huang (1994), that much higher positive pore pressures are generated for structured soils during virgin shearing than for reconstituted samples of the same soil. This is also evidence that naturally structured clays during virgin yielding are usually more compressive than the same soil in a reconstituted state.

It has been demonstrated extensively by researchers such as Burland (1990) and Novello and Johnston (1995) that the final strength of structured clay is independent of soil structure and can be treated as an intrinsic soil property. This is predicted by the proposed models. It should be noticed that the models proposed here predict that the voids ratio of a structured soil, although approaching that of the reconstituted soil with destructuring, may not be the same as the latter at the final critical state of deformation and is therefore dependent on soil structure. This prediction is mainly attributed to the basic assumption of the proposed framework that both the hardening and destructuring of natural clay are dependent on plastic volumetric deformation. As a result, the reduction of the additional voids ratio is dependent only on the size change of the yield surface. Thus, the additional voids ratio does not diminish when the soil is theoretically at a state of being continuously remoulded, i.e., the critical state of deformation.

From a significant amount of experimental data it may be interpreted, at least from a theoretical viewpoint, that the final critical state of a soil, in terms of stress state and voids ratio, is independent of soil structure, and soil properties at these states are intrinsic soil properties (Burland 1990; Leroueil and Vaughan 1990; Gens and Potts 1988; Carter et al. 2000). To represent this feature of soil behavior, the assumption of pure volumetric-deformation-dependent destructuring is not sufficient, and an in-

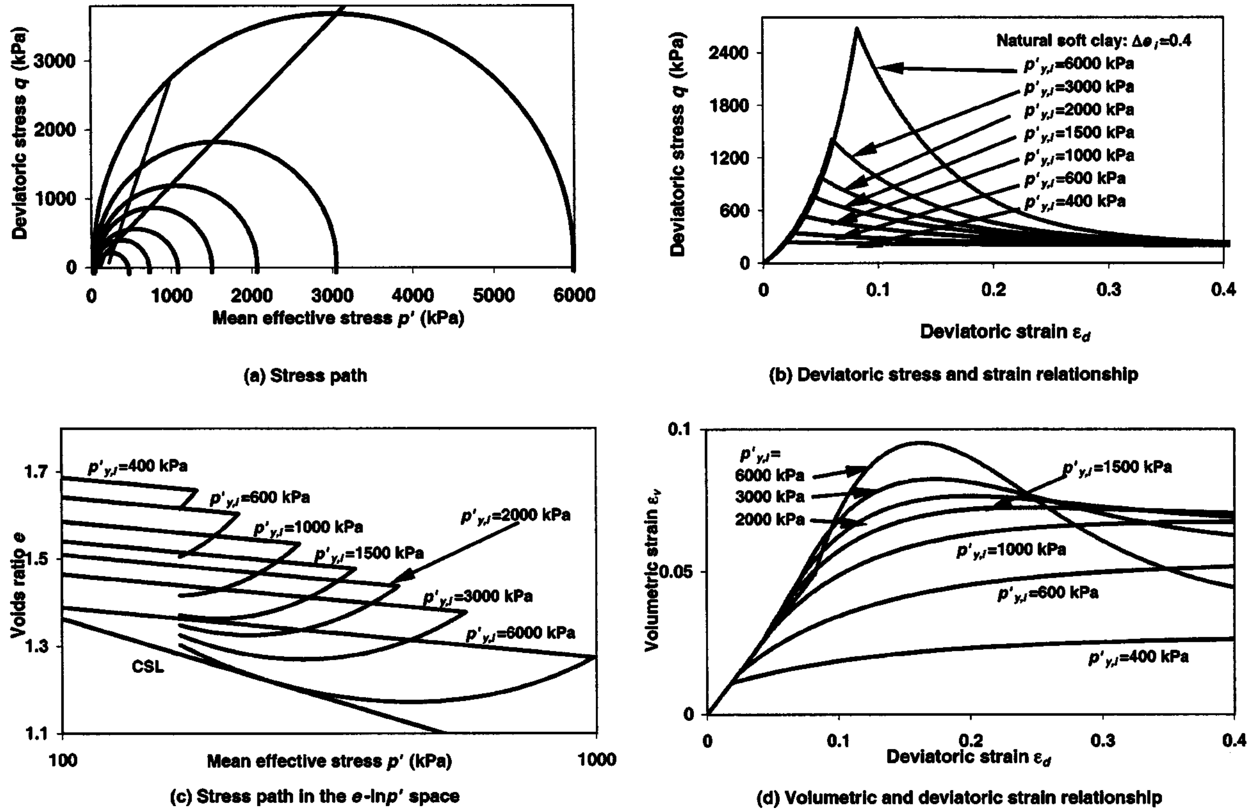

Fig. 10. Shearing behavior of heavily overconsolidated clay with different $p'_{y,i}$ simulated by simplified model

troduction of plastic-deviatoric-deformation-dependent destructuring is needed. Nevertheless, a comprehensive and theoretical investigation of soil behavior under the assumption of pure volumetric-deformation-dependent hardening and destructuring is still useful for understanding the mechanism of soil behavior under such circumstance, and can form a useful basis for further study. On the other hand, there are also quite a number of reported experiments that show clearly that the voids ratio of structured soils at the final critical state does depend on structure (Little 1988; Cotecchia and Chandler 2000; Doanh and Ibraim 2000; Hoeg et al. 2000). It is believed that the model performance is acceptable, at least for engineering purposes, in a significant number of cases.

Shearing of Overconsolidated Clays

The concept of overconsolidation ratio (OCR), which is widely used in geotechnical engineering practice, was originally defined as the ratio of the maximum stress a soil has ever experienced in its stress history to its current stress level. A generalized concept of OCR is introduced, and OCR is defined as the ratio of the size of the initial yield surface $p'_{y,i}$ to the current mean effective stress p'

$$\mathrm{OCR}=\frac{p'_{y,i}}{p'} \tag{28}$$

In the set of simulations considered now, the behavior of overconsolidated structured soils with the same initial stress state and additional voids ratio is computed. The stress paths are the same for all cases and follow that of a conventional drained triaxial test. The soil is loaded axially to failure from an original isotropic stress state with $p' = 100\,\mathrm{kPa}$. The additional voids ratio is $\Delta e_i = 0.4$.

Thirteen cases were simulated using the simplified model with $b=1$, and the differences between these cases are the sizes of the initial structural yield surface. They are 100 kPa (OCR=1), 125 kPa (OCR=1.25), 150 kPa (OCR=1.5), 200 kPa (OCR=2), 300 kPa (OCR=3), 333 kPa (OCR=3.3), 400 kPa (OCR=4), 600 kPa (OCR=6), 1,000 kPa (OCR=10), 1,500 kPa (OCR=15), 2,000 kPa (OCR=20), 3,000 kPa (OCR=30), and 6,000 kPa (OCR =60). According to Eq. (1), the corresponding initial voids ratios for these specimens are 1.839, 1.815, 1.795, 1.763, 1.718, 1.707 1.687, 1.642, 1.586, 1.541, 1.5, 1.465, and 1.389. The simulations are presented in two sets of figures, i.e., Fig. 9 for tests with OCR≤3.3 and Fig. 10 for tests with OCR>3.3. Such a division is made merely for clarity of presentation. It may also be seen that the soil behavior presented in Fig. 9 is characterized by only one strength, the final strength, while that depicted in Fig. 10 is characterized by a peak strength and the final strength. In geotechnical engineering, it is found that the former behavior is often characteristic of lightly overconsolidated clays and the latter of heavily consolidated clays.

Three groups of simulations involving 10 different cases were made using the more general form of the model. For the first group there are four cases. The size of the initial structural yield surface was 200 kPa, and the initial voids ratio was 1.763, which corresponds to $\Delta e_i = 0.4$. Different values of the destructuring index were adopted, viz., $b=0$, 0.5, 1, and 5. These simulations are presented in Fig. 11, while Fig. 12 shows the same predictions of the deviatoric stress and strain relationships at a different scale. For the second group, there are also four cases. The size of the initial structural yield surface was 2,000 kPa, and the initial voids ratio was 1.51, which corresponds to $\Delta e_i = 0.4$. As before, the values selected for the destructuring index are $b=0$, 0.5, 1, and 5. These simulations are presented in Fig. 13. For the third group there are two cases. The initial condition for the first case was

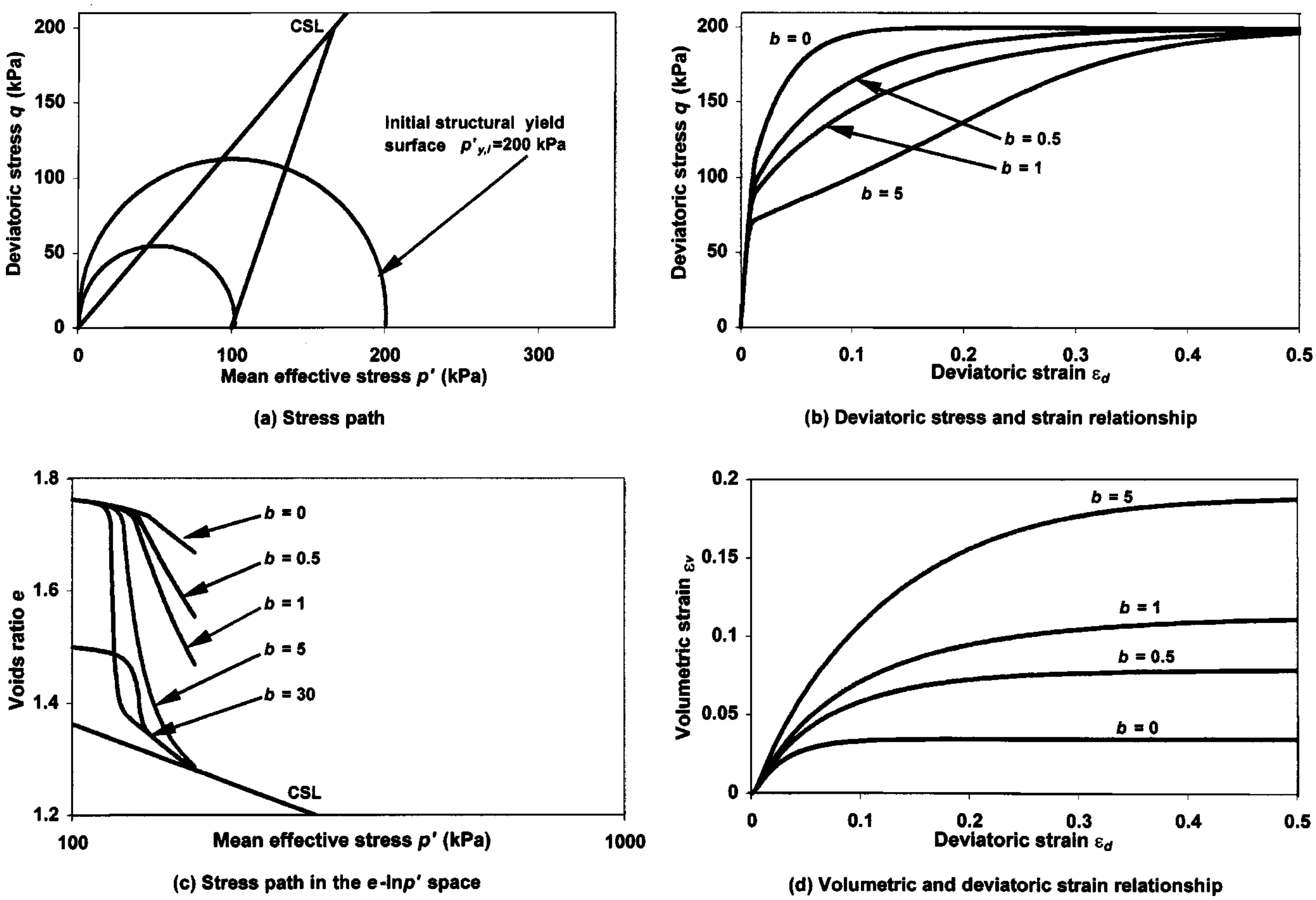

Fig. 11. Shearing behavior of lightly overconsolidated clay with different $p'_{y,i}$ simulated by general model

$p'_{y,i}=200$ and $e_i=1.763$ (which corresponds to $\Delta e_i=0.4$). The initial condition for the second case was $p'_{y,i}=250$ and $e_i=1.5$ (which corresponds to $\Delta e_i=0.16$). The value of the destructuring index for both cases is the same with $b=30$. The simulations are presented in Fig. 14.

For the purposes of comparing the model predictions with real soil behavior, some experimental data on the behavior of structured clays are shown in Fig. 15 (Georgiannou et al. 1993), Fig. 16 (Lo 1972), and Fig. 17 (Lagioia et al. 1998). In Fig. 15, the shearing behavior of reconstituted London clay is also included. It may also be noted that the experimental data in Fig. 15 are from direct shear tests, and, accordingly, the data are presented in the form of vertical effective stress σ'_v, shear stress ratio τ/σ'_v, and horizontal and vertical displacements. Soil deformation in a direct shear test has similar features to the behavior of the same soil in a conventional drained triaxial test. The shear stress ratio τ/σ'_v and the horizontal displacement relationship are analogous to the deviatoric stress ratio η and deviatoric strain relationship. The horizontal and vertical displacement relationship is similar to the deviatoric and volumetric strain relationship.

The following features are described by both versions of the model for the behavior of overconsolidated structured clays under monotonic shearing.

1. The behavior of an overconsolidated structured clay under monotonic shearing may be divided into two types of behavior: the behavior of lightly overconsolidated soil and that of heavily overconsolidated soil. For lightly overconsolidated clay behavior, the clay hardens monotonically until failure is reached, and only one strength is observed, the final critical state of strength, and only compressive volumetric deformation is produced under monotonic shearing (Figs. 9,11,14). This feature of structured clay behavior is qualitatively the same as that of a reconstituted soil.
2. For heavily overconsolidated clay behavior, the clay initially hardens to a peak strength and then softens to the final critical state strength (Figs. 10,13).

Strictly speaking, such division should be made based on the pattern of the deviatoric stress ratio and deviatoric strain relationship. For drained tests carried out using a conventional triaxial apparatus with the confining stress kept constant, the pattern of the deviatoric stress and strain relationship is the same as that of the deviatoric stress ratio and deviatoric strain relationship. Hence, in the following discussion, attention is paid to the deviatoric stress and strain relationship.

3. For heavily overconsolidated clay behavior, compressive volumetric deformation may be found during softening [Figs. 10(d) and 13(d)]. This feature of structured soil behavior is fundamentally different from that of a reconstituted soil.

It has been reported widely that compressive volumetric deformation may occur for structured clays during softening (Nambiar et al. 1985; Lagioa and Nova 1995; Arces et al. 1998; Wong 1998). It can also be seen in Fig. 15 that monotonic compressive volumetric deformation is induced for the test with $\sigma'_v=310\,\text{kPa}$. On the contrary, for the test with $\sigma'_v=100\,\text{kPa}$, the

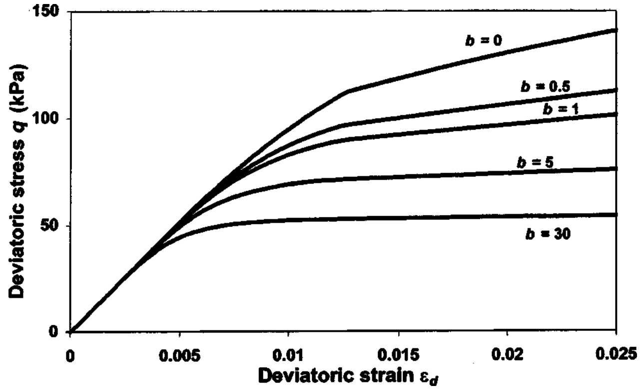

Fig. 12. Deviatoric stress and strain relationship under small strain simulated by general model

observed volumetric deformation is eventually expansive but of smaller magnitude when compared to the same soil under the same test but in a reconstituted state. These observations are consistent with the model simulations.

4. In some cases for heavily overconsolidated clay, a small dilative deformation is observed near the peak strength, and, thereafter, contractive deformation is observed. Thus the volumetric deformation has the feature of an initial compression, followed by expansion and then compression again.

This feature has been reported in a large body of experimental observations. (For drained tests, e.g., Fig. 16 by Lo 1972; Lefebvre 1981; Calabresi et al. 1985; Nambiar et al. 1985; Burland 1990; Georgiannou et al. 1993. For undrained tests, e.g., Anagnostpoulo et al. 1991; Burland et al. 1996; Carter et al. 2000.)

The volumetric deformation of structured clay is dependent on the additional voids ratio Δe_i, OCR, the destructuring index, and the stress path. As may be seen from this simulation as well as the equations describing the volumetric deformation, i.e., Eqs. (11) and (17), the pattern of behavior of natural clay is the same as that of its reconstituted soil type if $\Delta e_i = 0$ or $b = 0$. With increases in the value of either Δe_i or b, the pattern of soil behavior is changed.

5. For a structured soil, the reduction in soil strength after the peak is attributed to two factors: softening and destructuring. Therefore, the peak strength of a structured soil degenerates more rapidly with straining than a reconstituted sample of the same soil. For engineering design, a safety factor higher than that for a reconstituted soil should be considered if the peak strength contributed by soil structure is to be used.

The rapid drop in peak strength for structured soils can be seen from experimental data such as those reported by Skempton and Petley (1967), Clough et al. (1981), and Graham and Au (1985).

6. At critical state, the final stress state is independent of soil structure but the voids ratio is dependent on the initial soil structure and the stress path of the test.

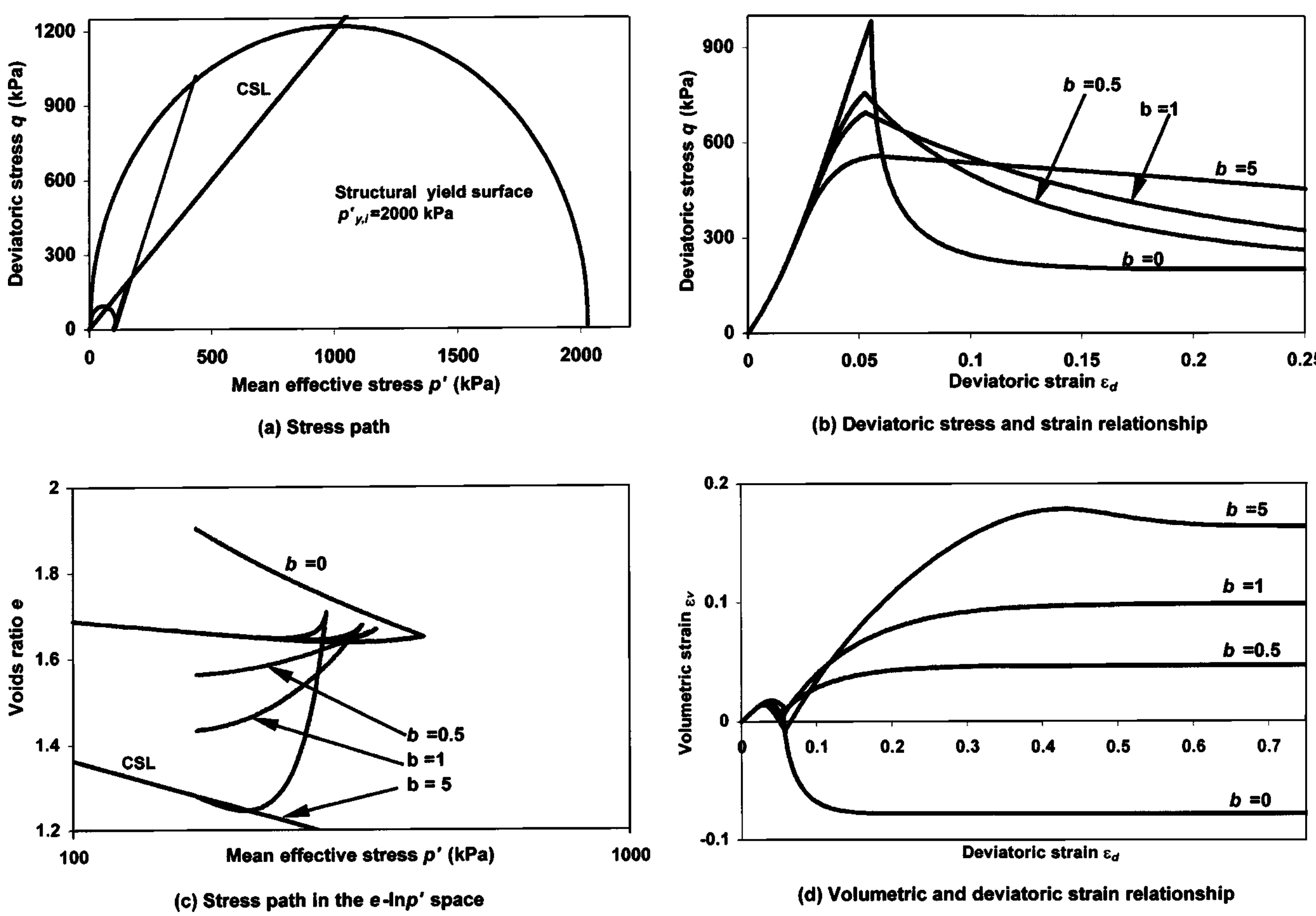

Fig. 13. Shearing behavior of heavily overconsolidated clay with different $p'_{y,i}$ simulated by general model

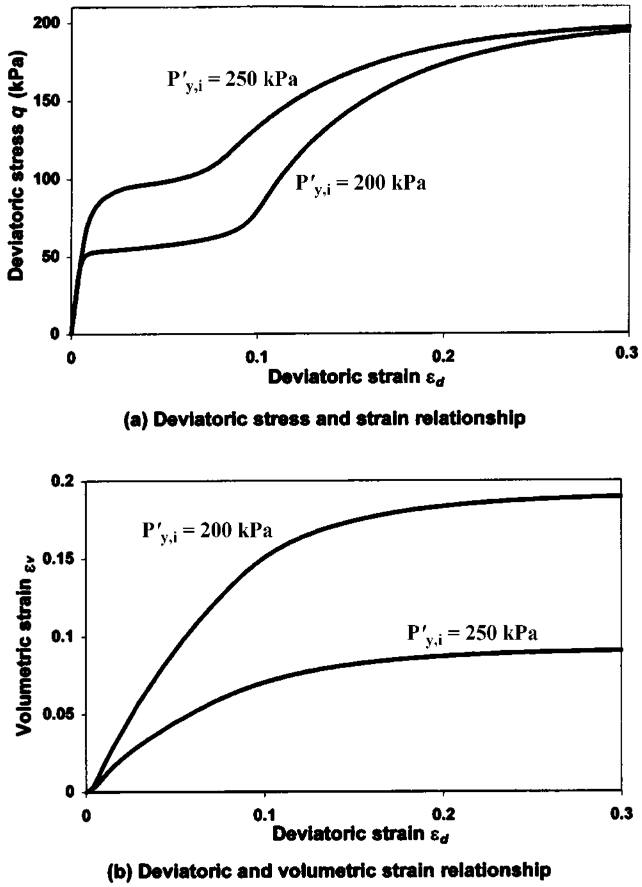

Fig. 14. Shearing behavior of highly sensitive soft clay simulated by general model

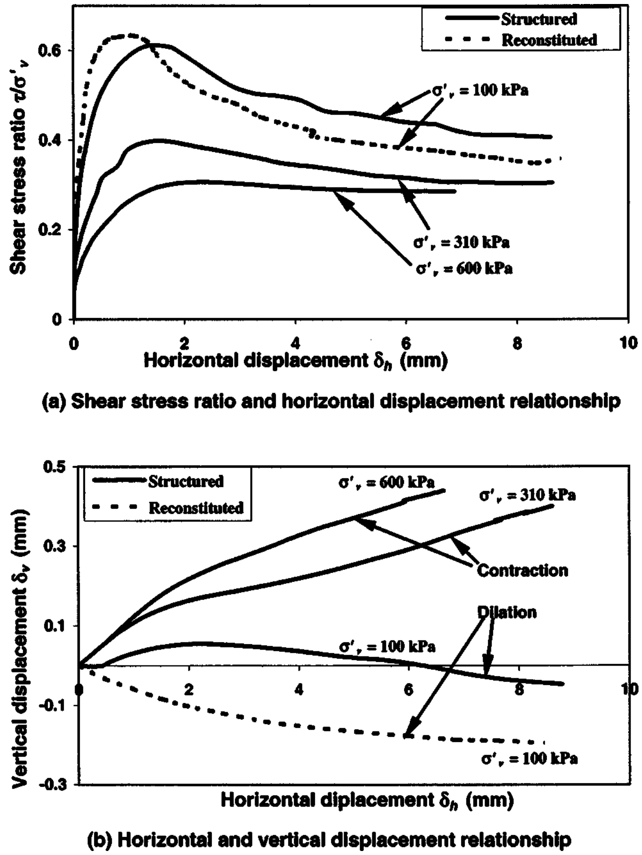

Fig. 15. Behavior of natural London clay in direct shear test (test data after Georgiannou et al. 1993)

Subyielding and destructuring are described by the general form of the model for loading inside the current yield surface. The following influences of the destructuring index may be observed.

7. Based on the assumed values of model parameters, for subyielding with $\varepsilon_d < 0.5\%$, the differences in the simulated soil responses for soils with different values of b are very small. This is attributed to the fact that elastic deformation is the dominant component of soil deformation during this range of behavior (Fig. 12). After the initial loading period, the stiffness decreases with b.
8. The higher the value of the destructuring index b, the more compliant the overall response of the clay will be to shearing and the higher the volumetric deformation.

The variation of the initial structural yield surface resulting from subyielding can be studied from the three groups of simulations (Figs. 11,13,14). Only one group is examined here. For tests shown in Fig. 11, virgin yielding commences at $p'_c = 155\,\text{kPa}$ for $b=5$, $p'_c = 173\,\text{kPa}$ for $b=1$, $p'_c = 181\,\text{kPa}$ for $b=0.5$, and $p'_c = 201\,\text{kPa}$ for $b=0$. The size of the initial yield surface for all four cases was the same with $p'_c = 200\,\text{kPa}$. The shrinkage of the structural yield surface during subyielding is mainly contributed by destructuring. For the fourth case, there is no destructuring effect because $b=0$, and the yield surface hardens due to the plastic compressive volumetric deformation.

It is also observed in the simulations for the two cases with $b=30$ (Fig. 14) that both the deviatoric and the volumetric strains increase virtually at constant stress at the moment when virgin yielding occurs and that a large amount of plastic deformation is accumulated at the end of this process. These simulations are consistent with experimental observations of natural soil behavior where the soils have a very high destructuring index (e.g., Fig. 17 for Gravina calcarenite from Lagioia et al. 1998; Westerberg after Rouainia and Muir-Wood 2000; Arces et al. 1998). The model is therefore able to predict this special behavioral feature of clays with very sensitive structures.

Uniform Cyclic Shearing

The behavior of structured soil under uniform cyclic shearing has been simulated using the general form of the model, and the results are presented in this section. Three cases with the same initial state and initial structural yield surface but with the different values of b were considered, namely, $b=0.5$, 1, and 5. The size of the initial structural yield surface was 100 kPa. The initial stress state was isotropic with $p' = 4$ kPa (Point A in Fig. 18). The initial value of the additional voids ratio is 0.4, which gives the initial voids ratio as 2. Uniform cyclic shearing, under fully drained conditions, was applied to the soil element until the sample failed. During shearing, the stress paths follow a straight line between stress state A ($p' = 4$ kPa, $q=0$) and state B ($p' = 8$ kPa, $q = 12$ kPa).

The simulated relationships between the deviatoric stress q and deviatoric strain ε_d are shown in Fig. 18, and those between the voids ratio e and the mean effective stress p' are presented in Fig. 19. It is seen that the structure of the clays is removed progressively during yielding in each case. The size of the structural yield surface shrinks continuously with the number of cycles.

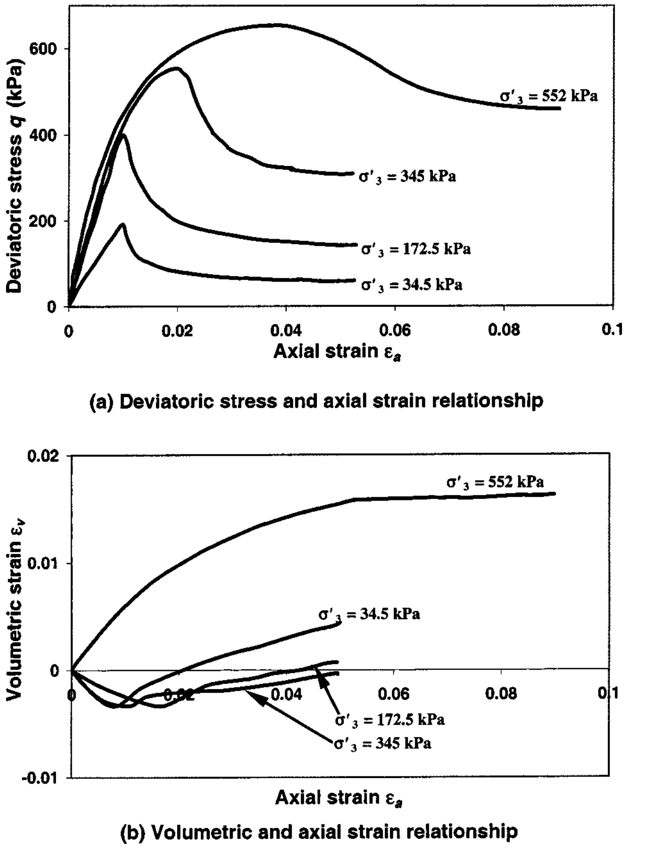

Fig. 16. Behavior of natural Nanticoke clay (test data after Lo 1972)

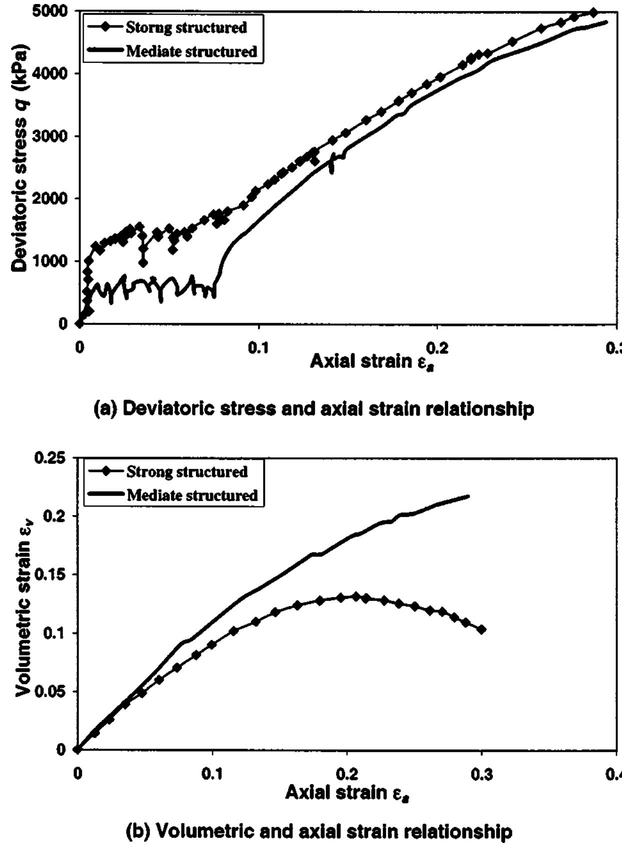

Fig. 17. Behavior of a natural calcarenite (test data after Lagiaoia et al. 1998)

Finally, the current stress state reaches the current yield surface at a stress state with $\eta > M^*$. Softening occurs and the sample fails. The numbers of cycles needed to induce failure are 108, 41, and 4 for the cases with $b = 0.5$, 1, and 5, respectively. It is seen in the simulations that both the volumetric deformation and deviatoric deformation increase with the destructuring index b. It has been reported by Santos et al. (1997) and Leroueil (2001) that cyclic loading inside the current yield surface induces the destructuring of soil and eventually leads to failure. The monotonic reduction of voids ratio for natural soft clay resulting from destructuring during cyclic freezing and thawing has also been reported, e.g., by Graham and Au (1985), and Eigenbrod (1996).

Comments

For the simplified model, it is assumed that soil behavior is purely elastic for stress excursions inside the current yield surface. This assumption was made for simplicity, and, generally, this form of the model is suitable for providing engineering solutions to problems where virgin yield is the major feature of soil deformation, and the details of soil behavior under stress reversals are not so important. However, it should be pointed out that this assumption of purely elastic deformation within the current yield surface is able to provide highly accurate descriptions of some natural clays. For example, linear elastic compression behavior within the current yield surface is found to be appropriate for many natural soft clays during simple stress reversals (e.g., Holtz et al. 1986; Lagioa and Nova 1995; Wong 1998; Arces et al. 1998; Carter et al. 2000; Rao et al. 2000).

As indicated previously, anisotropic effects of soil structure have not been considered in the current study, and the yield surface of natural structured clay is assumed to be elliptical, as it is for reconstituted soil. An elliptical yield surface is found to provide acceptable predictions for many natural clays (e.g., Graham and Li 1985; Anagnostopoulos et al. 1991; Huang 1994; Lagioia and Nova 1995; Carter et al. 2000; Cotecchia and Chandler 2000). It may be concluded that although the complexity of natural clays should not necessarily be ignored there are situations where their behavior can be described adequately by a relatively simple model.

Conclusions

Based on an extensive review of the available experimental data, a new theoretical framework to describe the mechanical behavior of natural clays has been proposed. A fundamental hypothesis of the framework is that hardening and destructuring of natural clays are dependent on plastic volumetric deformation, which provides a premise for the derivation of the constitutive equations. In the proposed framework, the response of soil to a stress change is defined in 4D space, namely, the current stress state, the stress history, the current voids ratio, and the current soil structure.

Based on two idealizations of soil destructuring, two different forms of a constitutive model have been formulated. The simpler form of the model is suitable for describing the behavior of natural clays under monotonic loading and simple stress reversals. In this simpler version, it is assumed that soil behaves elastically for any stress excursion inside the current structural yield surface. The more general form of the model is suitable for describing the behavior of various natural clays under monotonic and cyclic

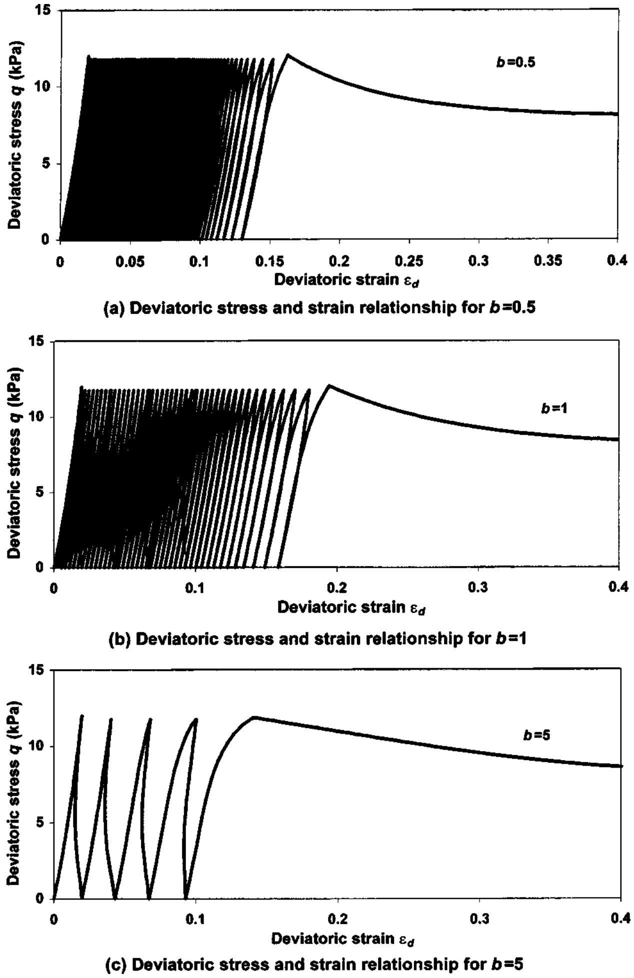

Fig. 18. Behavior of structured clay under uniform cyclic loading

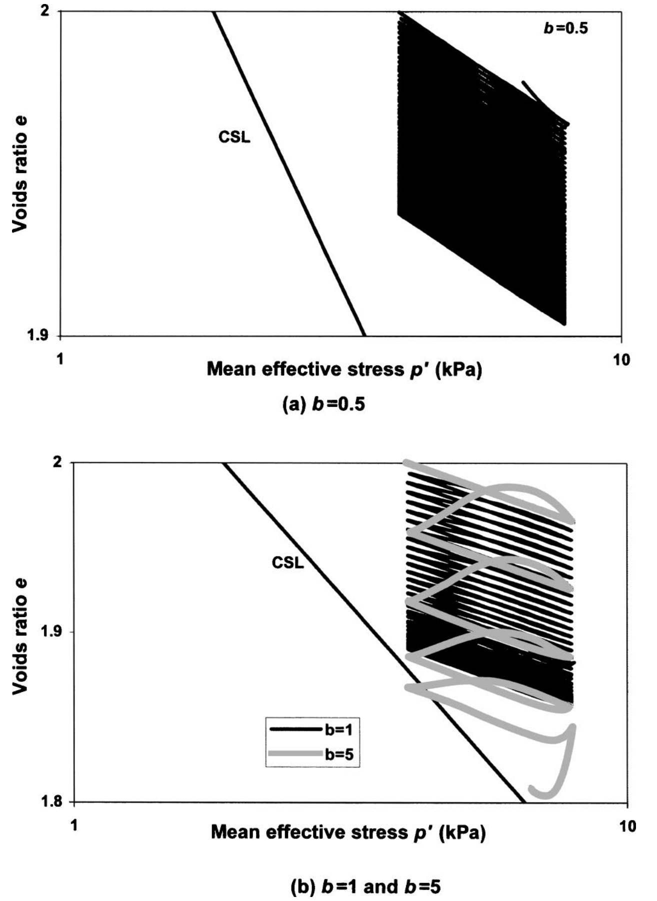

Fig. 19. Behavior of structured clay under uniform cyclic loading in the e-$\ln p'$ space

stress paths. In this version of the model, subyielding occurs for stress excursion inside the structural yield surface, and the associated destructuring is described. The simpler model becomes the Modified Cam Clay Model if soil has no structure, or the effects of soil structure are considered to be negligible.

The two versions of the model were employed to simulate the behavior of natural clays along various triaxial stress paths. The performance of the models was analyzed and compared qualitatively with experimental data. These comparisons suggest that the proposed model provides a simple and coherent description of the effects of structure on soil behavior and captures satisfactorily the main features of the behavior of structured soil.

The work presented in this paper was focused on the conceptual modeling of soil structure, and the simulations were made to provide a comprehensive picture of the performance of the model. Some further research work is still required and should include quantitative predictions of natural soil behavior under both drained and undrained situations and the extension of the theory to include anisotropy, including the formation and development of induced and inherent anisotropy.

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