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TECHNICAL NOTE

Modelling the destructuring of soils during virgin compression

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KEYWORDS: calcareous soils; clays; compressibility.

INTRODUCTION

The important influence of soil structure on the mechanical properties of soil has long been recognized (e.g. Casagrande, 1932; Mitchell, 1976). The term 'soil structure' is used here to mean the arrangement and bonding of the soil constituents, and for simplicity it encompasses all features of a soil that cause its mechanical behaviour to be different from that of the corresponding reconstituted soil. The removal of soil structure is referred to as 'destructuring', and this is usually a progressive process.

In recent years there have been numerous studies in which a theoretical framework for describing the behaviour of structured soils has been formulated (e.g. Burland, 1990; Leroueil & Vaughan, 1990; Gens & Nova, 1993; Cotecchia & Chandler, 1997). The authors have also made a study of the virgin compression behaviour of structured soils (Liu & Carter, 1999), and in particular have proposed the hypothesis that, during virgin compression, the additional voids ratio sustained by soil structure is inversely proportional to the current mean effective stress. It was found that this hypothesis gives reasonable predictions of the virgin compression behaviour of many soft structured soils, although discrepancies were observed for some soils. The influence of destructuring, as well as the development of soil structure on the compression properties of soft clays, have been successfully quantified, and it was demonstrated that the hypothesis may be employed as a basis for formulating a complete stress–strain model for structured soils. In this article, the previous hypothesis is generalized so that the virgin compression behaviour of stiff clay, clay shale and fissured clay can also be described accurately. A general discussion on the modelling of destructuring of soils is also given.

THE GENERALIZED HYPOTHESIS

Following the suggestion of Burland (1990), the properties of a reconstituted soil are called the 'intrinsic properties', and are denoted by an asterisk (*) attached to the relevant symbols. Hence, under all stress conditions, the influence of soil structure can be measured by comparing its behaviour with the intrinsic behaviour. A material idealization for the compression behaviour of soil is shown in Fig. 1, where 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 its corresponding reconstituted soil. Hence, the virgin compression behaviour of a structured soil can be expressed by the following equation:

$$e = e^* + \Delta e \tag{1}$$

In order to model the variation in the destructuring rate for a

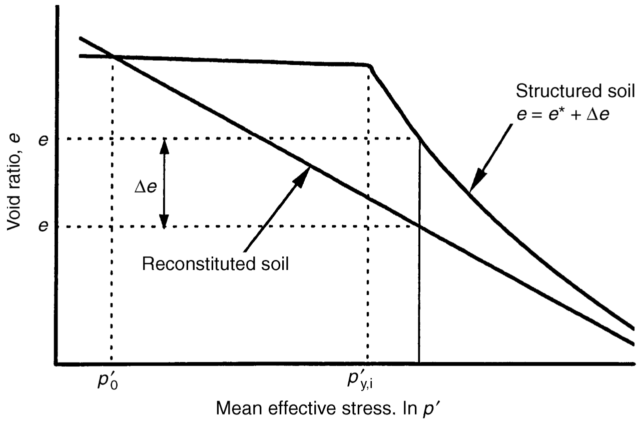

Fig. 1. Idealization of the compression behaviour of reconstituted and structured soils

variety of structured soils during virgin compression, a new equation is proposed as follows:

$$\Delta e = \Delta e_i \left(\frac{p'_{y,i}}{p'}\right)^b \quad \text{for } p' \geqslant p'_{y,i} \tag{2}$$

Δe_i is the additional voids ratio at $p' = p'_{y,i}$, where virgin yielding begins (Fig. 1). The compression destructuring index b is a new parameter quantifying the rate of destructuring. Appropriate values for the index b are studied in detail here. The valid range for b is

$$0 \leqslant b < \infty \tag{3}$$

A quantitative illustration of the influence of b on the virgin compression behaviour of structured soils is shown in Fig. 2. The following features may be observed in this figure:

(*a*) The rate of reduction in the additional voids ratio increases with the magnitude of the compression destructuring index (i.e. the more rapid the destructuring, the higher the value of *b*).

(*b*) Two extreme cases can be identified:

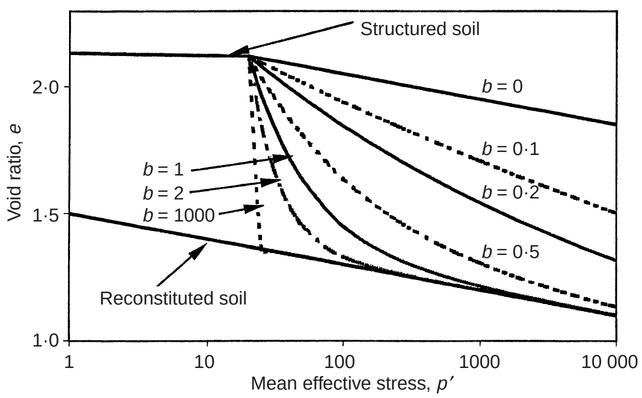

Fig. 2. Destructuring of soils during compression

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(*i*) $\Delta e \equiv \Delta e_i$ for $b = 0$ (i.e. the additional voids ratio sustained by soil structure remains unchanged during virgin compression). Consequently, no destructuring occurs during the virgin compression.

(*ii*) For $b \to \infty$, $\Delta e \equiv 0$ if $p' > p'_{y,i}$ (i.e. the structure of a soil collapses immediately after the virgin yield stress is reached).

(*c*) The hypothesis proposed previously by Liu & Carter (1999) is a special case of the generalized hypothesis and corresponds to $b = 1$.

It is usually convenient to substitute the vertical effective stress σ'_v for the mean effective stress p' when describing one-dimensional compression behaviour. Consequently, for one-dimensional compression behaviour, equation (2) can be written as

$$\Delta e = \Delta e_i \left(\frac{\sigma'_{vy,i}}{\sigma'_v} \right)^b \quad \text{for } \sigma'_v \geqslant \sigma'_{vy,i} \tag{4}$$

where $\sigma'_{vy,i}$ is the initial vertical yield stress. For a given type of soil structure it is assumed that the compression destructuring index b will take the same value in equations (2) and (4). It may be noticed that this assumption implies the following constraint on the stress state in the soil during a compression test:

$$\frac{p'}{\sigma'_v} = \frac{p'_{y,i}}{\sigma'_{vy,i}} \tag{5}$$

where $p'_{y,i}$ and $\sigma'_{vy,i}$ are two stress quantities that refer to the same yielding stress state. Condition equation (5) is the definition of pure compression loading, and may only be satisfied approximately for one-dimensional compression tests.

EXPERIMENTAL EVALUATION

The generalized hypothesis was applied in the simulation of the results of 15 tests on 11 different soils. The results of the compression tests have been obtained from the literature, and the individual soils are listed in Table 1. Individual test results are plotted in Figs 3–9. In the earlier study by Liu & Carter (1999), the previous hypothesis ($b = 1$) was applied to simulate the results of 27 tests on 20 different soils. Only one test on an artificially bonded soil has been employed in both simulations (the test by Maccarini (1987), see Fig. 9). With the one exception noted, the data considered in this paper have not been considered previously by the authors, and their consideration now has led to the generalization given by $b \neq 1$.

The initial yield stress, $p'_{y,i}$ or $\sigma'_{vy,i}$, has been identified directly from the compression curves plotted in the (e, $\ln p'$) or (e, $\ln \sigma'_v$) coordinates. The method used to determine $p'_{y,i}$ or $\sigma'_{vy,i}$ is shown schematically in the inset in Fig. 7. The value of Δe_i is determined by selecting the appropriate value of the voids ratio at the state where virgin yielding takes place. The value of parameter b has been determined by finding the best match of the test data for virgin yielding with equation (2) for test results presented in the e–p' form or with equation (4) for one-dimensional compression. The difference in voids ratio between a structured soil and the reconstituted soil can be measured directly from the results of two tests (i.e. the com-

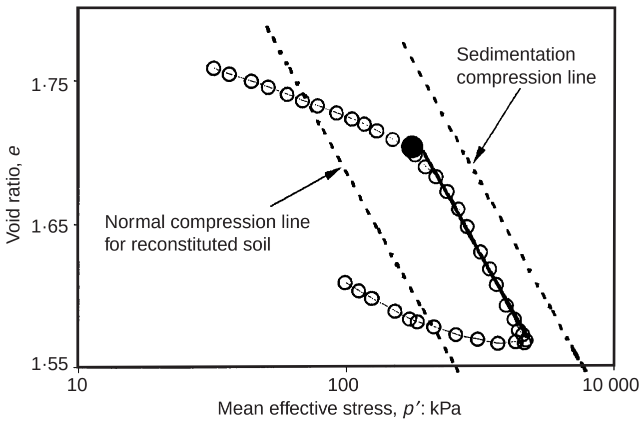

Fig. 3. Compression behaviour of stiff Vallericca clay (test data after Amorosi & Rampello (1998))

Table 1. Details of the compression tests

Figure	Soil	Reference	Δe_i	$p'_{y,i}$ or $\sigma'_{vy,i}$: kPa	b	Comments*
Fig. 3	Stiff Vallericca clay	Amorosi & Rampello (1998)	0·111	$p'_{y,i} = 1800$	0	NCL*: $e = 2{\cdot}69 - 0{\cdot}145 \ln p'$ SCL: $e = 2{\cdot}85 - 0{\cdot}145 \ln p'$
Fig. 4	A hard fissured lodgement till	Lehane *et al.* (1998)	−0·082	$\sigma'_{vy,i} = 1250$	0·15	NCL*: $e = 0{\cdot}58 - 0{\cdot}0417 \ln \sigma'_v$
Fig. 5	Four stiff clays: Todi Pietrafitta Vallericca Corinth marl	Burland *et al.* (1996)	 0·35 C_c^* 0·5 C_c^* 0·46 C_c^* 0·8 C_c^*	$\sigma'_{vy,i} =$ 13 000 750 1600 2300	 0·2 0·6 0·2 0·1	 NCL*: $I_v = 1{\cdot}39 - 0{\cdot}369 \ln \sigma'_v$ SCL: $I_v = 2{\cdot}05 - 0{\cdot}369 \ln \sigma'_v$ C^*: intrinsic material constant
Fig. 6	Soft Louiseville clay Lime content: 10% 5% 2%	Locat *et al.* (1996)	 8·5 9 9·5	 $\sigma'_{vy,i} =$ 24·5 4·2 0·37	 0·43 0·34 0·3	Louiseville clay was mixed with various quantities of lime
Fig. 7	Sault Ste Marie clay: Sample: 3·51 m Sample: 6·55 m Sample: 9·75 m Sample: 12·8 m	Burland (1990)	 1·3 C_c^* 1·95 C_c^* 1·55 C_c^* 1·6 C_c^*	$\sigma'_{vy,i} =$ 205 103 120 188	 0·38 0·6 1 0·85	NCL*: $I_v = 2{\cdot}45 - 0{\cdot}1285 \ln \sigma'_v + 0{\cdot}015(\ln \sigma'_v)^3$
Fig. 8	Soft Nagasaka clay (artificial)	Murakami (1979)	0·049	$p'_{y,i} = 225$	3·5	NCL*: $e = 3{\cdot}765 - 0{\cdot}28 \ln p'$
Fig. 9	Artificially bonded soft soil	Maccarini (1987)	0·225 0·225	$p'_{y,i} = 117$ $p'_{y,i} = 117$	3 1	Two simulations are made with $b = 3$ and $b = 1$
Fig. 9	A soft calcarenite soil	Fontana *et al.* (1998)	0·155	$p'_{y,i} = 2400$	30	NCL*: $e = 2{\cdot}57 - 0{\cdot}208 \ln p'$

* NCL, normal compression line; SCL, sedimentation compression line.

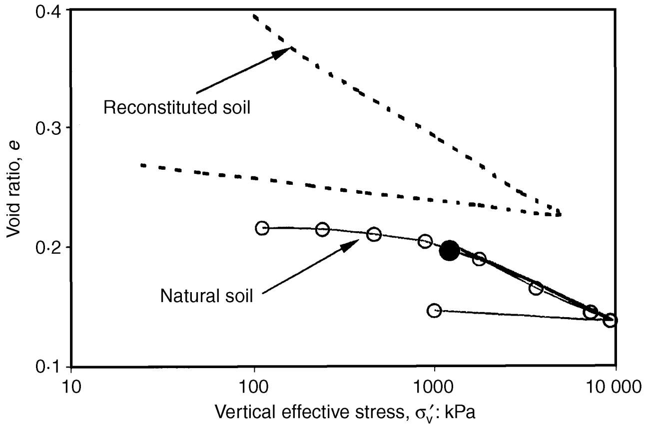

Fig. 4. Compression behaviour of a hard fissured lodgement fill (test data after Lehane *et al.* (1998))

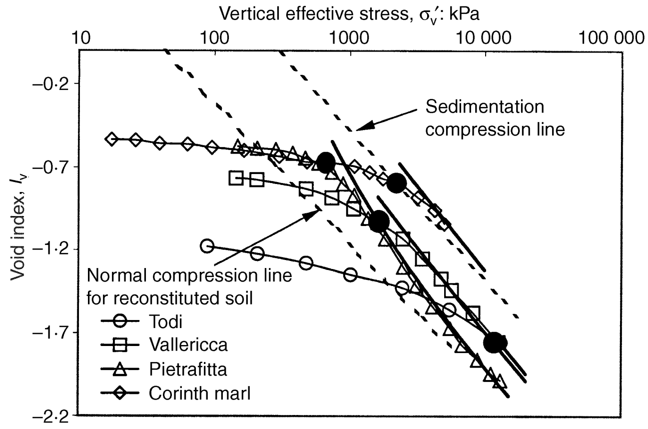

Fig. 5. Compression behaviour of four stiff clays (test data after Burland *et al.* (1996))

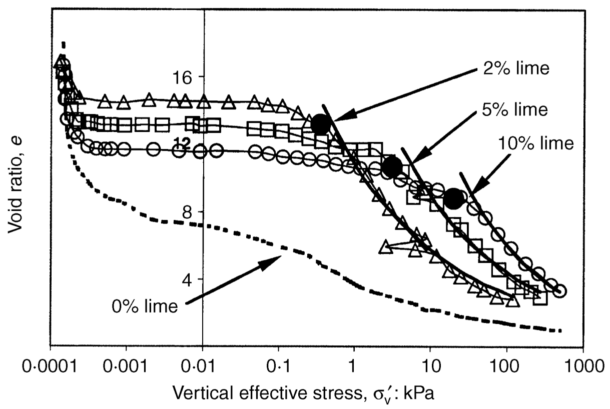

Fig. 6. Compression behaviour of soft Louiseville clay treated with lime (test data after Locat *et al.* (1996))

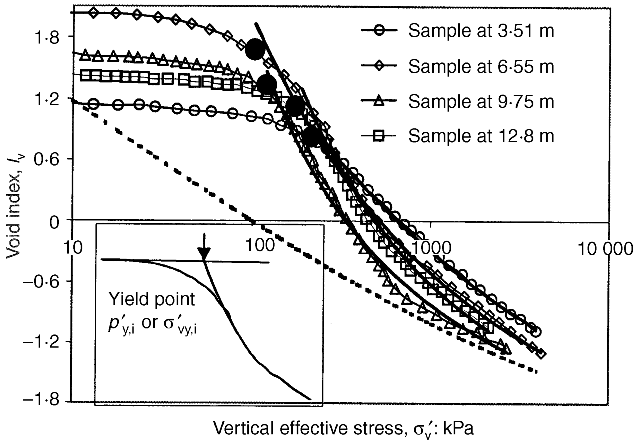

Fig. 7. Compression behaviour of Sault Ste Marie clay (test data after Burland (1990))

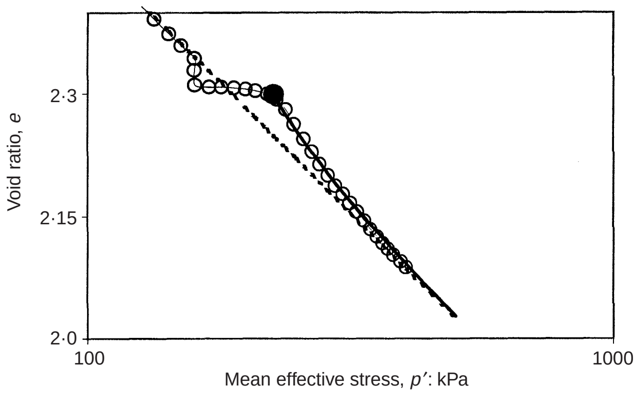

Fig. 8. Compression behaviour of soft Nagasaka clay (test data after Murakami (1979))

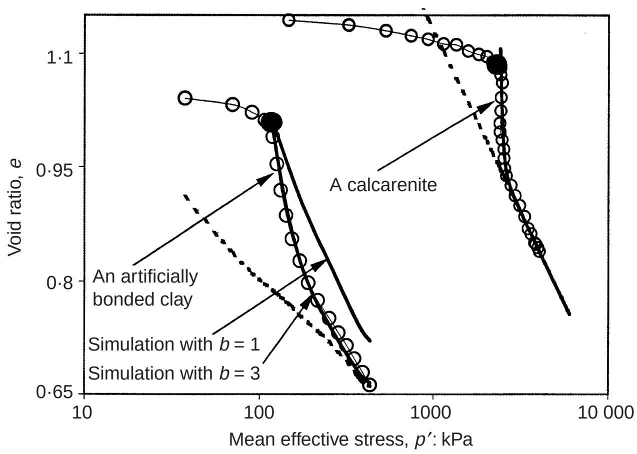

Fig. 9. Compression behaviour of an artificially bonded soft clay (test data after Maccarini (1987) and a soft calcerenite (test data after Fontana *et al.* (1998))

pression test on the structured soil and that on the reconstituted soil).

All values of the parameters determined in this way are also listed in Table 1. The stress units adopted here are kilopascals. NCL represents the normal compression line, and SCL represents the sedimentation compression line. Comparisons between the theoretical equations and the experimental data are shown in Figs 3–9. The selected initial yield point is indicated on the plots by a large solid circle on the experimental curve. The theoretical curves are represented by solid lines. The experimental curves for the behaviour of structured soil are represented by open circles or squares which are linked by thin solid lines, and the curves for reconstituted soil are represented by thicker broken lines. In order to concentrate exclusively on the virgin yielding behaviour of structured soils, the compression behaviour before the initial yield point was not investigated.

In Figs 5 and 7, the voids index is used instead of the voids ratio. The relationship between the two parameters can be found in the paper by Burland (1990). To illustrate the improved accuracy of the new generalized equation, two simulations were done for an artificially bonded soil with $b = 3$ and $b = 1$ (Fig.

9). It can be seen that the reduction in the additional voids ratio resulting from the destructuring in virgin compression is simulated by the generalized hypothesis with good accuracy over a wide range of applied stress, and for a number of different materials.

DISCUSSION

Compression destructuring index

The sensitivity index S_t was defined by Terzaghi (1944) (as quoted by Skempton & Northey (1952)) as the ratio of the strength of an undisturbed structured soil over that of the same soil at a corresponding reconstituted state (i.e. at the same voids ratio). Generally speaking, S_t, a direct measurement of the difference in soil strength between the structured and the reconstituted soil, may provide an indication of the difference between the behaviour of a structured soil and that of its corresponding reconstituted soil type. Meanwhile, the destructuring index b, the rate of the reduction in the additional voids ratio sustained by soil structure, may provide an indication of the rate of reduction, with respect to loading, of the difference between the behaviour of a structured soil and that of its corresponding reconstituted soil type. Therefore, it appears that S_t and b form a set of parameters that could provide a complete quantitative description of the effects of soil structure, and hence may be basic parameters for constitutive modelling of structured soils.

For the soils discussed in this study, it was found that $0 \leqslant b \leqslant 30$. Generally speaking, $b \geqslant 1$ for soft structured soils and $b < 1$ for stiff soils. It can be seen from the simulation of the experimental data that the rates of destructuring do vary with soil type and structure. For example, there are four tests on samples of Sault Ste Marie clay taken from the same location, but at different depths below the surface (see Fig. 7). The values of b are found to be different for the four specimens, ranging from 0·38 to 1. It is also seen that the value of parameter b increases with lime content for soft Louiseville clay (see Fig. 6). In order to describe the destructuring process for engineering application it is essential that the parameter b can be determined conveniently. It has not been possible to perform a systematic and detailed study of the parameter b due to the lack of experimental data. Until this can be done, a more pragmatic approach is required, in which values of b are determined for each individual engineering problem. For example, parameter b may be expressed as function of the lime content for the soft Louiseville clay reported by Locat *et al.* (1996). For clay of a given mineralogy taken from the same location with similar geological stress history but at different depths below the surface, b may depend mainly on the liquidity index.

Over the stress range investigated, the value of the compression destructuring index was found to be 0 for the stiff Vallericca clay (see Fig. 3). During the virgin compression from $p' = 1800$ kPa to $p' = 4700$ kPa, the additional voids ratio sustained by soil structure basically remains constant, although the occurrence of virgin yielding is clearly observed. Therefore, there would appear to be no destructuring effect on the virgin compression of the Vallericca clay for this range of stress.

It is also noted that simulations for which $b < 0{\cdot}5$ are approximately linear when plotted on $(e, \ln p')$ or $(e, \ln \sigma'_v)$ coordinates, over a range of stress equivalent to at least an order of magnitude change (see Figs 4 and 5). This is consistent with earlier experimental observations that the compression behaviour of some structured soils in the $(e, \ln p')$ or $(e, \ln \sigma'_v)$ coordinates may be assumed to be approximately linear (e.g. Yudhbir, 1973; Diaz-Rodriguez *et al.*, 1992).

Negative additional voids ratio

The additional voids ratio Δe is one means of identifying the influence of soil structure. It usually has a positive value, which means that a larger voids ratio can be sustained due to the effects of soil structure. However, negative values of Δe have also been reported for some structured soils (e.g. Maccarini, 1987; Stark & Duncan, 1991; Picarelli & Olivares, 1998). Most of the natural clays or clay shales for which negative values of Δe have been reported are very stiff and fissured. An example is given in Fig. 4. It is obvious that only after generalization of the compression equation, of the type proposed here, can this type of soil behaviour be described accurately.

CONCLUSIONS

An expression describing the virgin compression behaviour of many structured soils has been proposed. The ability of this expression to simulate the response of the following structured soils during virgin compression has been demonstrated: soft and stiff structured clays, fissured clays and clay shales, and structured calcareous soil. Some discussion on the rate of destructuring for soils during virgin compression has been given.

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