Liu, M. D. & Carter, J. P. (1999). *Géotechnique* **49**, No. 1, 43–57

Virgin compression of structured soils

M. D. LIU* and J. P. CARTER*

This paper describes a study of the virgin compression behaviour of both naturally and artificially structured soils under one-dimensional compression or isotropic compression. It is proposed that during virgin compression, the additional voids ratio sustained by soil structure is inversely proportional to the current mean effective stress. The proposed formula has been verified for 20 different naturally and artificially structured soils, and it is seen that the proposal describes well the behaviour of all these soils. Finally, a general discussion on soil structure and its features is presented, and the proposed compression equation is extended to describe the compression of structured soil along a general stress path.

KEYWORDS: clays; compressibility; structure of soil.

Cet exposé est une étude du comportement d'une consolidation vierge sur des sols structurés de manière naturelle et artificielle, avec une consolidation unidimensionnelle ou isotrope. Nous avançons que pendant la consolidation vierge, le taux de pore additionnel subi par la structure du sol est inversement proportionnel à la contrainte effective moyenne actuelle. La formule proposée a été vérifiée sur vingt sols structurés de manière artificielle et naturelle et l'on voit que la proposition décrit bien le comportement de tous ces sols. Enfin, nous présentons une étude générale de la structure du sol et de ses caractéristiques et nous développons l'équation de consolidation proposée pour décrire la consolidation du sol structuré le long d'une trajectoire de contrainte générale.

INTRODUCTION

When encountered in situ, most natural soils exhibit some form of 'structure'. It is usually accepted that the structure is formed during their depositional history, where complicated influences such as mechanical, chemical and biological factors are brought into action (Mitchell, 1986; Leroueil & Vaughan, 1990). Stress history may alter the structure of a soil and may overlay on a soil deposit a distinct 'fabric'. The general 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 are different from those of the corresponding reconstituted soil.

There is a significant body of experimental data to suggest that soil structure, as well as stress history, are influences of first importance on the mechanical behaviour of natural soil (e.g. Rowe, 1972; Silva, 1974; Skempton, 1985; Burland, 1990; Leroueil & Vaughan, 1990). It is also well recognized that disturbances, such as weathering or sampling or loading, generally modify the original structure of soil. A method of describing the effects of structure and how those effects change with disturbance would be very useful in geotechnical practice.

In this paper, virgin compression behaviour of structured soils is examined. A basic compression equation is suggested, which is a generalization of the well-known and widely accepted linear relationship between voids ratio, e, and the logarithm of mean effective stress, $\ln p'$, used to describe the compression of reconstituted soils. A new compression parameter to describe soil structure is introduced, together with the concept of a virgin yield stress associated with soil structure. The proposed compression equation is compared with available data for 20 different soils. Important features of the compression behaviour of structured soils are discussed and the influences of stress level and other factors on destructuring are briefly investigated.

VIRGIN COMPRESSION EQUATION FOR STRUCTURED SOILS

Compression curves for a soil with different degrees of structure are illustrated in Fig. 1 (Wang & Wei, 1996). The soil is a clay from Guang-shen in China. In this figure, curve (a) represents the compression behaviour for a high-quality undisturbed sample, curve (b) represents the compression

Manuscript received 30 June 1997; revised manuscript accepted 6 May 1998.
Discussion on this paper closes 7 May 1999; for further details see p. ii.
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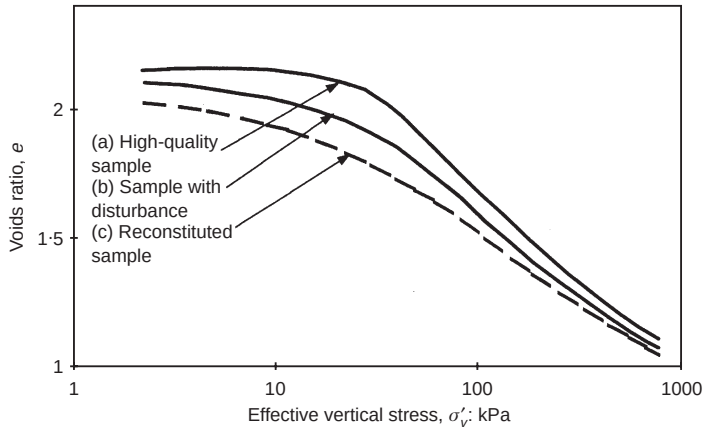

Fig. 1. One-dimensional compression tests on Guang-shen clay (Wang & Wei (1996))

behaviour for a sample that has undergone a degree of disturbance (or 'destructuring'), and curve (c) represents the compression behaviour for a completely reconstituted sample of the same soil. The following features can be observed in Fig. 1.

(*a*) For a given vertical stress, σ'_v, the voids ratio for a natural, structured soil is higher than that of the reconstituted soil of the same mineralogy. When soil undergoes destructuring, the additional voids ratio sustained by soil structure decreases.

(*b*) As σ'_v increases, the compression curves corresponding to the structured soils appear to be asymptotic to the curve for the reconstituted soil; that is, the influence of soil structure tends to diminish as σ'_v increases. Progressive destructuring accompanies the plastic yielding (irrecoverable deformation) that is associated with the virgin compression.

A material idealization of the compression behaviour of structured soils is shown in Fig. 2. The

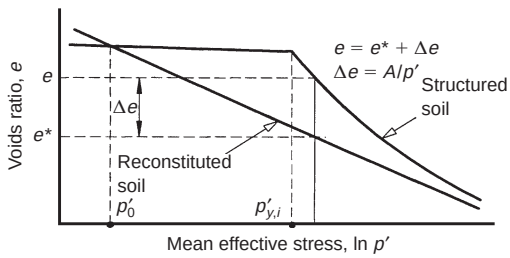

Fig. 2. Idealization of the compression behaviour of reconstituted and structured soils

voids ratio for a structured soil, e, can be expressed in terms of the corresponding voids ratio for the reconstituted soil, e^*, and the component due to the structure, Δe, that is

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

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. Hence, under all conditions the influence of soil structure can be measured by comparing its behaviour with the intrinsic behaviour. The behaviour of reconstituted soil is regarded as the reference behaviour, and the associated properties are regarded as the reference properties in this study. The difference, Δe, identifies the effect of soil structure. Usually, Δe is positive, which means that a larger voids ratio can be sustained due to the effects of soil structure.

Following an examination of a large body of experimental data for both naturally and artificially structured soils, a basic principle for the compression behaviour of structured soils is proposed as follows:

> During virgin compression, the additional voids ratio sustained by soil structure is inversely proportional to the current mean effective stress.

This principle implies that the virgin compression behaviour of structured soils can be expressed as

$$e = e^* + \frac{A}{p'} \text{ for } p' \geqslant p'_{y,i} \tag{2}$$

A is a new parameter, described here as the 'structural compression factor', which is a constant for a given soil under a given type of compression,

p' is the current mean effective stress, and $p'_{y,i}$ is the mean effective stress at which virgin yielding of the structured soil begins (Fig. 2). The stress $p'_{y,i}$ represents effectively a yield point produced by the soil structure, and its value is likely to have been determined by the processes that formed the soil during its geological history. It should be noted that this yield point is not necessarily the same as that produced by stress history, as observed in many reconstituted soils.

Equation (2) is an expression for the virgin compression behaviour, that is, for compression with $p' \geqslant p'_{y,i}$. For $p' < p'_{y,i}$, available evidence suggests that soils behave stiffly and approximately elastically.

For reconstituted soils, it is widely accepted that there is a linear relationship between the voids ratio e and $\ln p'$ over a broad range of effective stress. Consequently, the behaviour of a structured soil may be described by

$$e = e^*_{IC} + \frac{A}{p'} - \lambda^* \ln p' \tag{3}$$

where e^*_{IC} and λ^* are standard or intrinsic compression parameters for the reconstituted soil. If the soil has no structure, or the influence of soil structure is negligible, then $A = 0$. In this case, equation (3) becomes the familiar compression equation for a reconstituted soil.

In this study, the additional part of the voids ratio sustained by soil structure is of major interest, that is, the component given by

$$\Delta e = \frac{A}{p'} \tag{4}$$

The applicability of the proposed hyperbolic relationship between the additional voids ratio and the current mean effective stress will be demonstrated in the following section using widely available experimental data.

It is obvious that A is not a fundamental soil structure parameter, and its value is dependent on the initial virgin yield stress as well as the deformation constraints imposed during the compression. The currently available test data do not enable the derivation of an explicit and definitive expression for A. In view of this fact, a simple equation for A is suggested:

$$A = Sp'_{y,i} \ln p'_{y,i} \tag{5}$$

or

$$\Delta e = S\left(\frac{p'_{y,i}}{p'}\right) \ln p'_{y,i} \tag{6}$$

where S is a new soil parameter, described as the 'structure index'.

Hence the virgin compression behaviour of a structured soil can be rewritten as

$$e = e^*_{IC} + S\left(\frac{p'_{y,i}}{p'}\right) \ln p'_{y,i} - \lambda^* \ln p'$$

$$\text{for } p' \geqslant p'_{y,i} \tag{7}$$

In the verification of the hyperbolic relationship, the value of structure index S is also evaluated and the validity of equation (5) is examined where the available test data permit.

EXPERIMENTAL DATA

The results of 27 compression tests on 20 different soils are now considered in order to verify the proposed hyperbolic relationship. The results of the compression tests have been obtained from the literature, and the individual soils are listed in Table 1. All the tests involve one-dimensional compression, and in most cases the mean effective stresses are not given in the original papers. This means that mostly it has not been possible to demonstrate the validity of equations (4) and (6) directly, but instead a form of these equations suitable for one-dimensional conditions has been examined. In the verification of one-dimensional compression tests, the mean effective stress p' has been replaced by vertical stress σ'_{v}. Hence, equations (4) and (6) may be rewritten as

$$\Delta e = \frac{A_{\mathrm{v}}}{\sigma'_{\mathrm{v}}} \tag{8}$$

and

$$\Delta e = S_{\mathrm{v}}\left(\frac{\sigma'_{\mathrm{v}y,i}}{\sigma'_{\mathrm{v}}}\right) \ln \sigma'_{\mathrm{v}y,i} \tag{9}$$

where σ'_{v} is the vertical effective stress, $\sigma'_{\mathrm{v}y,i}$ is the vertical stress at which virgin yielding commences, and A_{v} is the structural compression factor corresponding to one-dimensional conditions. The advantage of this substitution is that the difficulty in determining the values of the horizontal effective stresses in the tests is avoided. In four tests, the values of p' are known, and so direct identification of the values of $p'_{y,i}$, A and S has been possible. A justification of the substitution for the remaining cases is proved below.

For one-dimensional virgin compression, p' is approximately linearly proportional to σ'_{v} (Wroth, 1984). Suppose then that

$$\frac{p'}{\sigma'_{\mathrm{v}}} = K \tag{10}$$

Consequently, the following relationships can be obtained:

$$\frac{p'_{y,i}}{p'} = \frac{\sigma'_{\mathrm{v}y,i}}{\sigma'_{\mathrm{v}}} \tag{11}$$

Table 1. Details of compression tests

Test and Fig. numbers	Soil	Reference	$\sigma'_{vy,i}$: kPa	A_v: kPa	S_v	Comments
1 Fig. 3	Artificially bonded soil	Maccarini (1987)	$p'_{y,i} = 117$	$A = 21{\cdot}4$	$S = 0{\cdot}038$	Bond formed artificially; p' known
2a 2b Fig. 4	Bothkennar clay	Smith *et al.* (1992)	83·8 66·9	37·9 21·3	0·102 0·076	Different sampling methods and depths
3 Fig. 5	Champlain clay	Tavenas *et al.* (1974)	47·5	23·5	0·128	
4 Fig. 5	Leda clay	Yong & Nagaraj (1977)	168·6	100·7	0·116	
5 Fig. 6	Eberg clay	Janbu (1985)	103	18·2	0·038	
6a 6b Fig. 7	Guang-shen clay	Wang & Wei (1996)	35·5 28·3	12·4 5·8	0·099 0·062	Different disturbance
7 Fig. 8	Grande Baleine clay	Locat & Lefebvre (1985)	80	57	0·163	
8 Fig. 9	Highland soil	Wallace (1973)	313	18·9	0·011	
9 Fig. 9	Winnipeg clay	Graham & Li (1985)	215·1	40·0	0·035	
10 Fig. 10	Laboratory sedimented clay	Leonards & Altschaeffl (1964)	61	26·9	0·107	Sample at rest for 90 days
11a 11b Fig. 11	Java residual soil	Wesley (1974)	466·7 65	315 20·6	0·110 0·076	Sample 11b sedimented in slurry, difficult to define yielding
12 Fig. 12	Jonquiere clay	Leroueil (1996)	17·8	2·3	0·045	Sample at rest for 120 days
13 Fig. 13	Mattagami mines clay	Sangrey (1972)	$p'_{y,i} = 105$	$A = 92$	$S = 0{\cdot}188$	p' known
14 15 Figs 14, 15	Mexico City clay	Terzaghi (1953)	$p'_{y,i} = 324$ 92	$A = 472$ 321	$S = 0{\cdot}252$ 0·772	Very high voids ratio; p' known
16 Fig. 14	Mexico City clay	Mesri *et al.* (1975)	86·1	328·6	0·856	Very high voids ratio
17 Fig. 16	Osaka clay	Adachi *et al.* (1995)	62·9	19·2	0·074	Effect of destructuring clearly seen
18 Fig. 17	Rigaud clay	Silvestri (1984)	161·3	99·7	0·122	
19 Fig. 18	Saguenay Fjord sediment I	Perret *et al.* (1995)	14·5	6·7	0·161	
20 Fig. 18	Saguenay Fjord sediment II	Perret *et al.* (1995)	43·8	22·5	0·136	
21a 21b Fig. 19	Troll field clay	Burland (1990)	58·4 209	$67C_c^*$ $212C_c^*$	$0{\cdot}28C_c^*$ $0{\cdot}19C_c^*$	C_c^*: an intrinsic material constant
22a 22b Fig. 20	Vasby clay	Leroueil & Kabbaj (1987)	47·9 30·5	35·4 18·9	0·191 0·181	

$$\frac{A_v}{\sigma'_v} = K\frac{A_v}{p'} = \frac{A}{p'} \tag{12}$$

and

$$S_v\left(\frac{\sigma'_{vy,i}}{\sigma'_v}\right)\ln\sigma'_{vy,i} = S_v\left(1 - \frac{\ln K}{\ln p'_{y,i}}\right)\left(\frac{p'_{y,i}}{p'}\right)\ln p'_{y,i} \tag{13}$$

Therefore,

$$A = KA_v \tag{14}$$

and

$$S = S_v\left(1 - \frac{\ln K}{\ln p'_{y,i}}\right) \tag{15}$$

It can be seen from the above equations that the proposed hyperbolic relationship is independent of the substitution, provided the ratio of p' to σ'_v is kept constant during virgin compression of the structured soil. However, it should be noted that the values of both A_v and S_v are dependent on the ratio p'/σ'_v. It also appears from equation (15) that the value of S_v is not a material constant, but dependent on the value of $p'_{y,i}$.

For the test data examined in this study, the values of the initial yield stress, $\sigma'_{vy,i}$, have been identified directly from the compression curves plotted in the $e-\ln\sigma'_v$ coordinates. The method used to determine $\sigma'_{vy,i}$ is shown schematically in the inset on Fig. 3. The value of parameter A_v has been determined by finding the best match of equation (8) with the test data for virgin yielding. The difference in voids ratio between structured soil and the reconstituted soil can be measured directly from the results of two tests, that is, the compression test on the structured soil and that on the reconstituted soil. It is worth noting that the values of $\sigma'_{vy,i}$ and A_v have been determined independently, and the values of S_v have been determined subsequently from these values of A_v and $\sigma'_{vy,i}$. The theoretical curves corresponding to equation (8) have been superimposed on the experimental data, using only the values determined for A_v. Thus, comparisons between the theoretical and experimental compression curves provide a straightforward evaluation of the assumption of a hyperbolic relationship between the additional voids ratio and the current mean effective stress.

All values of the parameters determined for virgin yielding of the structured soils are listed in Table 1. The stress units adopted here are kPa. Comparisons between the theoretical equations and the experimental data are shown in Figs 3–20. In each case 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 solid circles or squares which are linked by broken lines, and the curves for reconstituted soil are represented by open circles or squares linked by broken lines. In order to concentrate exclusively on the virgin yielding behaviour of structured soils, compression behaviour before the initial yield point is not investigated here.

Virgin compression behaviour of resedimented soil is adopted as the reference condition to measure the influence of soil structure for the Jonquiere clay in Fig. 12, and Mexico City clay in Fig. 14 for test data from Mesri *et al.* (1975). The

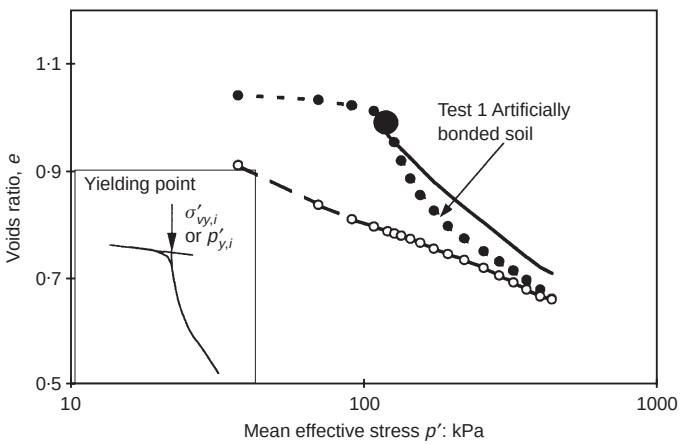

Fig. 3. One-dimensional compression tests on an artificially bonded soil (test data after Maccarini (1987))

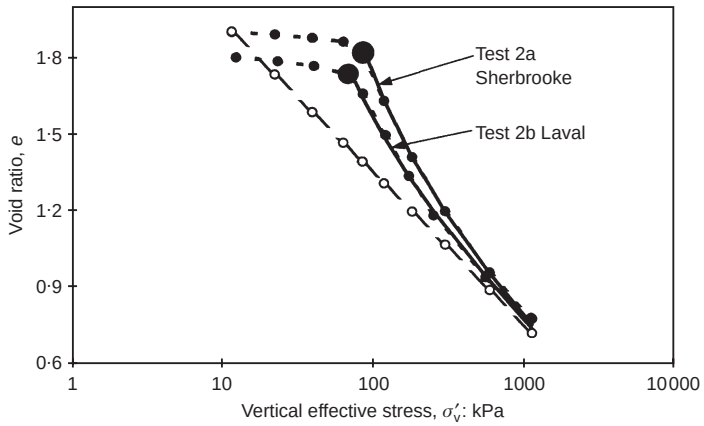

Fig. 4. One-dimensional compression tests on Bothkennar clay (test data after Smith *et al.* (1992))

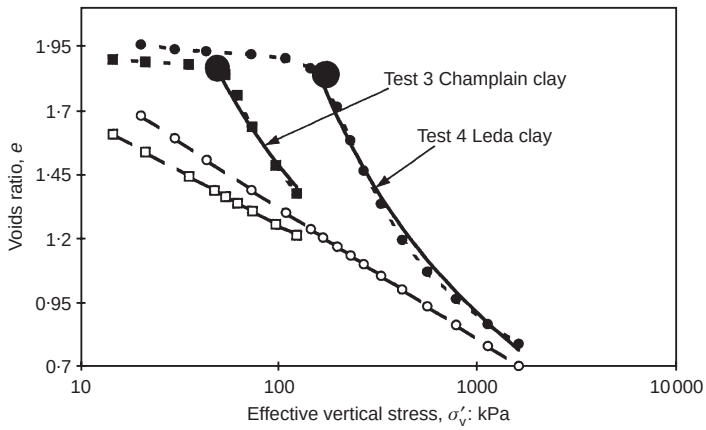

Fig. 5. One-dimensional compression tests on Champlain clay and Leda clay (test data after Tavenas *et al.* (1974) and Yong & Nagaraj (1977))

proposed hyperbolic relationship should not be influenced by the adoption of this reference, although the values of A_v and S_v may be affected. In Fig. 19 for the Troll field clay, voids index is used instead of voids ratio. The relationship between the two parameters can be found in the paper by Burland (1990).

The authors have been unable to find information on the behaviour of reconstituted samples of Eberg clay (Fig. 6), Grande Baleine clay (Fig. 8), Mattagami mines clay (Fig. 13), Saguenay Fjord sediments (Fig. 18) and Vasby clay (Fig. 20). The liquid limit values for two of the clays are known, that is, $w_L = 34$ for Grande Baleine clay, and $w_L = 78$ for Mattagami mines clay. Hence, the intrinsic one-dimensional compression curves for these clays are estimated by the empirical method suggested by Burland (1990). For the other three clays, linear virgin compression lines for the reconstituted soils have been assumed. The position of these lines is defined by assuming that the behaviour of a structured soil is asymptotic to that of the reconstituted soil. The compression lines thus decided are speculative. In the remaining cases, where there are data for reconstituted soil samples, it is seen that in most cases the relationships between e and $\ln p'$ or $\ln \sigma'_v$ are reasonably linear over the range of stresses considered. However, in some cases the linear relationship is not accurate at very low and very high stress levels; for example, see Fig. 7 for Guang-shen clay, Fig. 11 for Java residual clay, and Figs 14 and 15 for Mexico City clay.

The development of soil structure has been

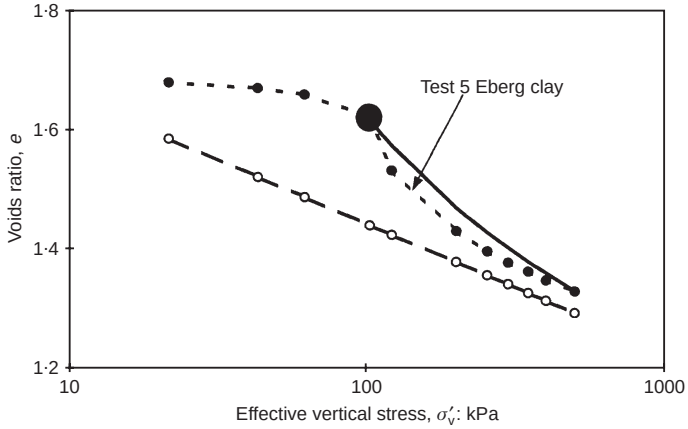

Fig. 6. One-dimensional compression tests on Eberg clay (test data after Janbu (1985))

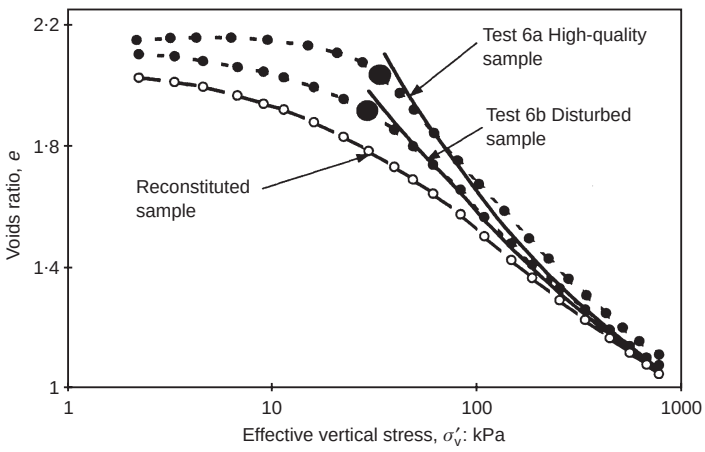

Fig. 7. One-dimensional compression tests on Guang-shen clay (test data after Wang & Wei (1996))

clearly demonstrated in two sets of test data. Fig. 12 shows the data for a reconstituted sample of Jonquiere clay (Leroueil, 1996) that was first consolidated to a vertical effective stress of 10 kPa. This compression pressure was then held constant for 120 days. Subsequently, the sample was subjected to further compression under increasing vertical effective stress. The results during the subsequent compression loading are typical of those for a soil that has developed a structure. In fact, the subsequent compression response indicates that the soil behaves as if it had been previously loaded to a stress state with $\sigma'_v = 18$ kPa, not the actual value of $\sigma'_v = 10$ kPa. Hence, during the 120-day period of constant effective stress, the reconstituted soil apparently developed a structure producing a subsequent yield point which is larger than that produced by its stress history alone.

The other example of a developed structure is shown in Fig. 10 for a laboratory-sedimented residual clay (Leonards & Altschaeffl, 1964). The reconstituted soil sample was first isotropically loaded to 49 kPa, and then was held at rest for 90 days. After that, the sample was loaded again. The virgin yield stress was increased to 61 kPa because of the development of soil structure.

The Mexico City clay, shown in Figs 14 and 15, has an in-situ voids ratio as high as 14. During the loading from $\sigma'_v = 100$ kPa to $\sigma'_v = 3000$ kPa, the voids ratio is reduced to 2·7. It can be seen from

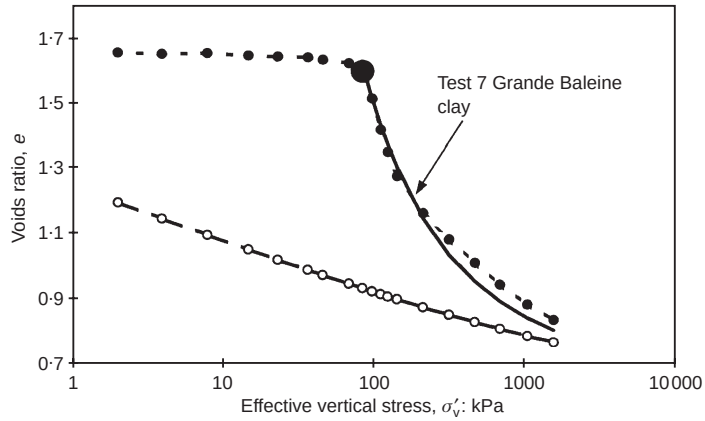

Fig. 8. One-dimensional compression tests on Grande Baleine clay (tests data after Locat & Lefebvre (1985))

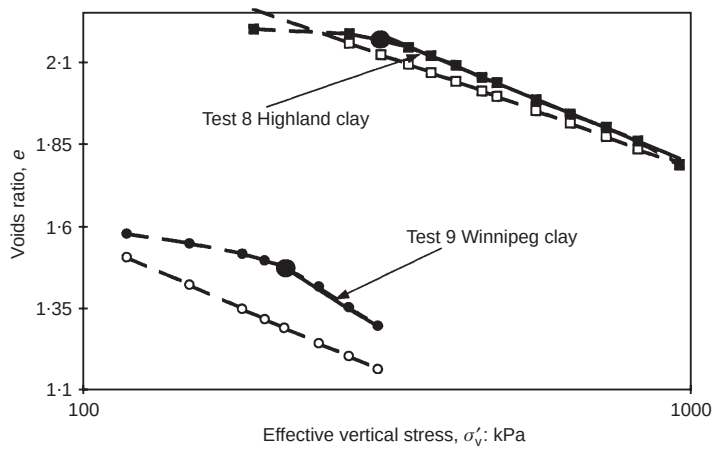

Fig. 9. One-dimensional compression tests on a Highland clay and Winnipeg clay (test data after Wallace (1973) and Graham & Li (1985))

the data that the difference in the compressibility between the 'undisturbed' in-situ soil and that of the reconstituted sample is very large.

Figure 16 indicates the compression and swelling behaviour of structured and reconstituted Osaka clay. Each sample was loaded to a vertical effective stress of $\sigma'_v = 178$ kPa, and then unloaded to $\sigma'_v = 7$ kPa, followed by reloading to $\sigma'_v = 960$ kPa. During the portion of the reloading curve that is clearly associated with virgin yielding, the behaviour of the natural soil is very close to that of the reconstituted soil. The cycle of loading, unloading and reloading has clearly contributed to the destructuring of the natural material.

DISCUSSION

From the above review of the available experimental data on the compression of structured soils, the following observations may be made.

Soil structure

The formation of soil structure is an extremely complicated process that is dependent on the geological and stress histories of the soil. These are features which usually cannot be traced accurately for most natural soils. However, it has been observed in all the data quoted here that the influence of soil structure, at least for the compression behaviour, can be adequately modelled in terms of

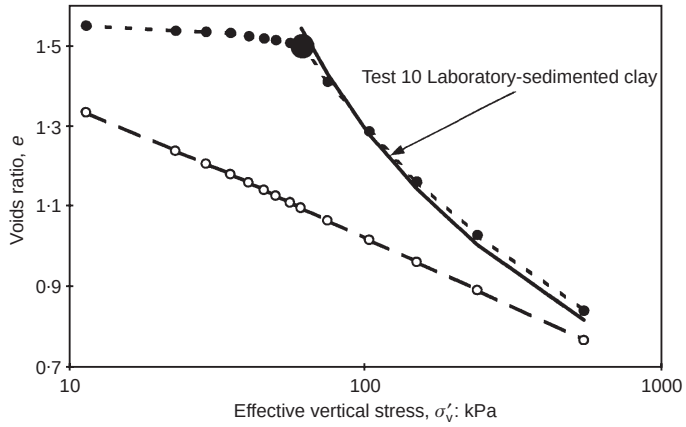

Fig. 10. One-dimensional compression tests on a laboratory-sedimented residual clay (test data after Leonards & Altschaeffl (1964))

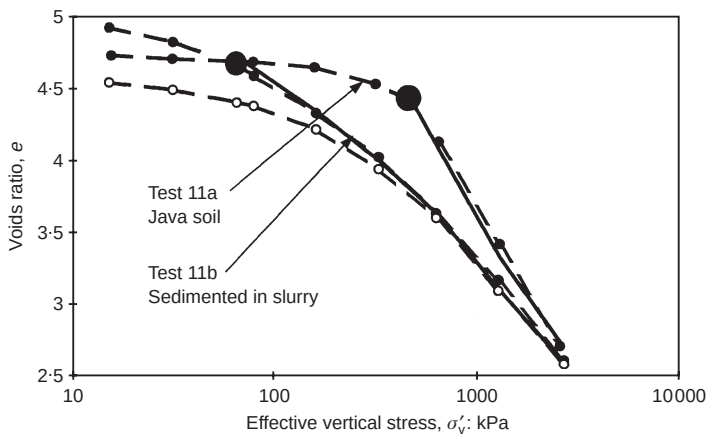

Fig. 11. One-dimensional compression tests on Java residual soil (test data after Wesley (1974))

an initial yield stress and a scalar constant, either S or A, irrespective of the origin of the structure. The behaviour of a soil with structure differs from that of the same soil type in a reconstituted condition in at least three respects.

(*a*) Soil structure creates a material that initially is quite stiff at relatively low stress levels. Beyond this region of stiff behaviour, virgin yielding occurs. The region can be represented by $p'_{y,i}$, the mean effective stress at which virgin yielding commences. The value of $p'_{y,i}$ is generally higher than the mean effective stress for the corresponding reconstituted soil at the same value of voids ratio, that is, the maximum mean effective stress p'_0, determined by stress history, as illustrated in Fig. 2.

(*b*) Soil with structure sustains a higher voids ratio than that of the corresponding reconstituted soil.

(*c*) During virgin yielding, structured soil is generally more compressible than the reconstituted soil. The behaviour of a structured soil moves closer to that of the reconstituted soil as destructuring progresses.

The proposed principle

The applicability of the principle proposed for describing the behaviour of structured soils has been examined with 20 different types of soils over 27 compression tests, covering effective stress levels from 10 to 3000 kPa, and voids ratios ranging from 0·5 to 14·0. By comparing the predictions of

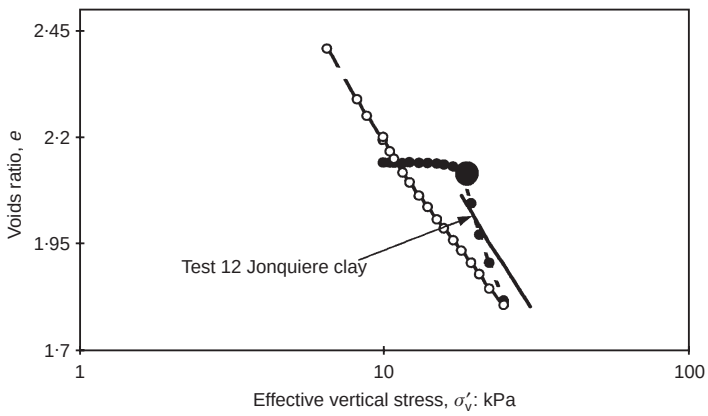

Fig. 12. One-dimensional compression tests on Jonquiere clay (test data after Leroueil (1996))

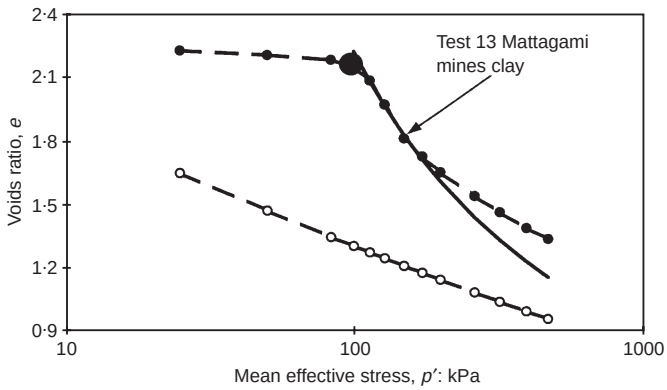

Fig. 13. One-dimensional compression tests on Mattagami mines clay (test data after Sangrey (1972))

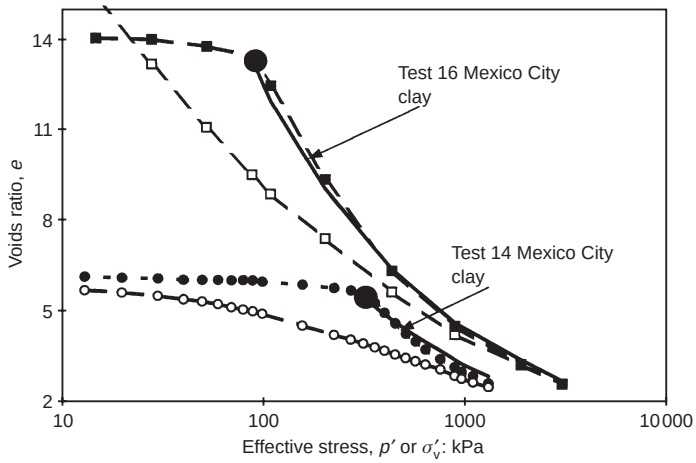

Fig. 14. One-dimensional compression tests on Mexico City clay (test data after Terzaghi (1953) and Mesri *et al.* (1975))

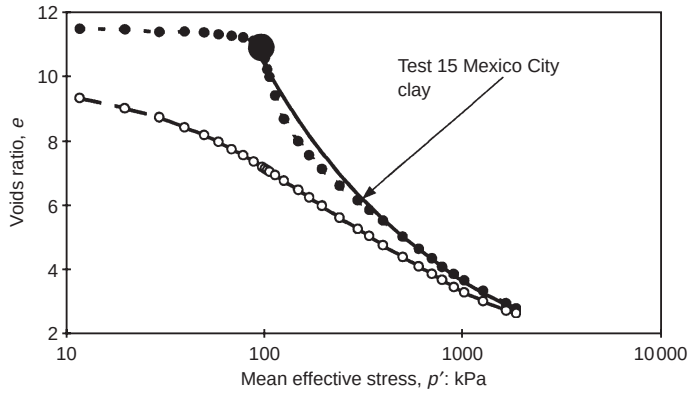

Fig. 15. One-dimensional compression tests on Mexico City clay (test data after Terzaghi (1953))

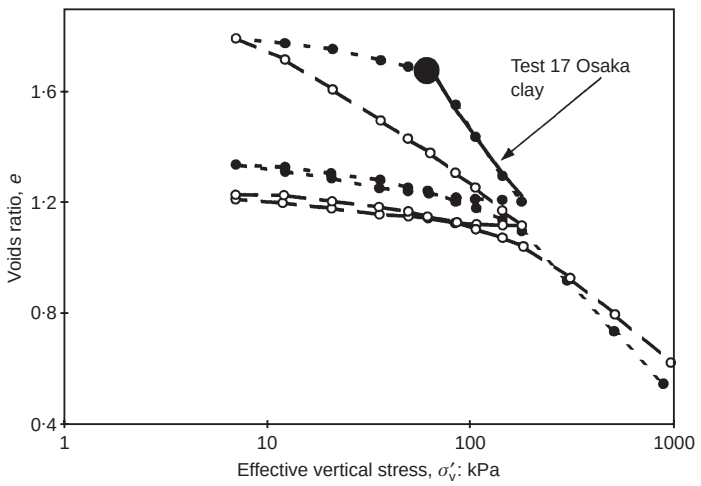

Fig. 16. One-dimensional compression tests on Osaka clay (test data after Adachi *et al.* (1995))

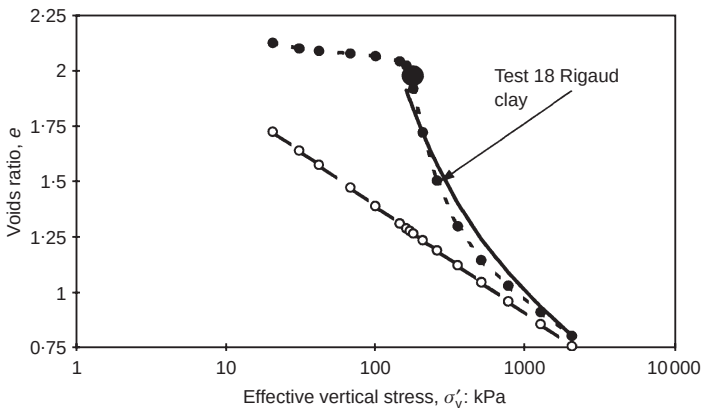

Fig. 17. One-dimensional compression tests on Rigaud clay (test data after Silvestri (1984))

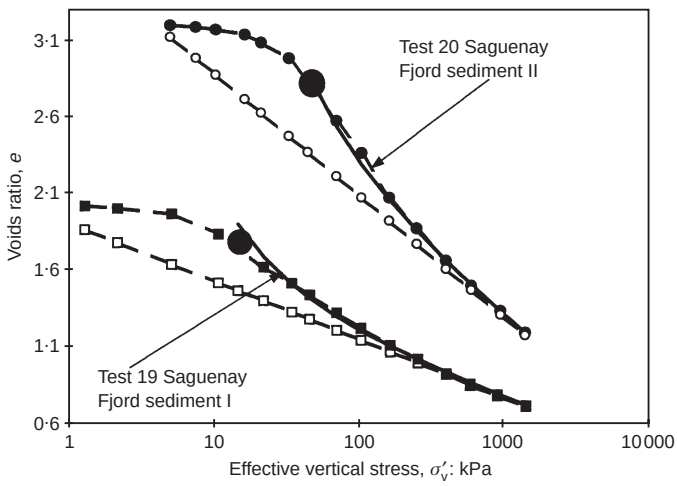

Fig. 18. One-dimensional compression tests on Saguenay Fjord sediments I and II (test data after Perret *et al.* (1995))

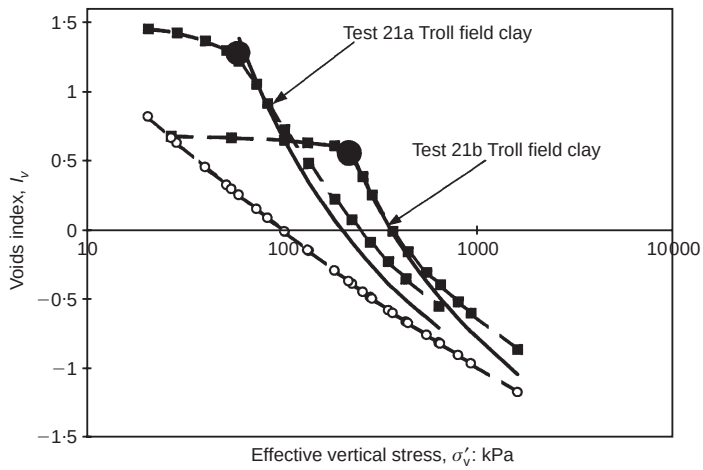

Fig. 19. One-dimensional compression tests on Troll field clay (test data after Burland (1990))

the model and the experimental data, it can be seen that the proposed assumption describes the additional voids ratio sustained by soil structure very well.

Structure index, S

Equations (6) and (9) indicate that the virgin compression of a structured soil can be described in terms of a 'structure index', S or S_v. The range of values for the parameter S_v, introduced in equation (9), deduced from the test results considered here, is generally from 0·01 to 0·2. The one exception is the Mexico City clay, which has an unusually high voids ratio, and therefore a value of S_v as high as 0·856, consistent with a more highly developed structure. In four cases, different tests have been performed on samples of the same clay with similar geological history. These are Bothkennar clay, Guang-shen clay, Troll field clay and Vasby clay. For Bothkennar clay and Vasby clay, it appears that the proposed equation (9) provides a reasonably consistent relationship between the parameter A_v, the initial virgin yield stress $\sigma'_{vy,i}$ and the structure index S_v. As a result, equations (6) and (9) may be used to provide a reasonable

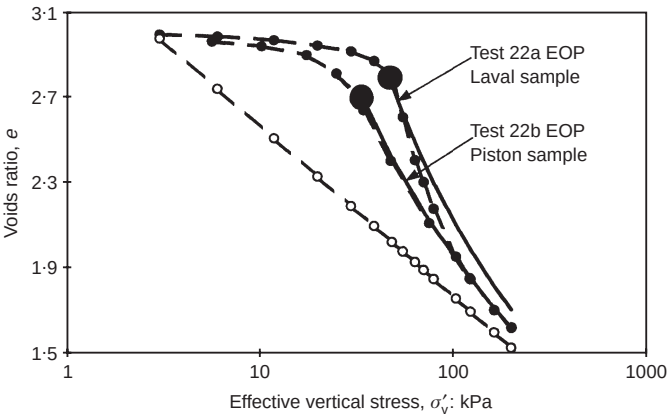

Fig. 20. One-dimensional compression tests on Vasby clay (test data after Leroueil & Kabbaj (1987))

estimate of the virgin compression behaviour of natural soils, if a more accurate expression for parameter A is not available.

For Guang-shen clay, soil samples had undergone different degrees of disturbance, and it seems that the value of S_v has been influenced by the disturbance. For tests on Troll field clay, soil samples were taken from the same location but at different depths. The values of S_v for the same clay from different depths are different. It appears that the values of S_v proposed in equation (9) and S in equation (5) are dependent on the type and the degree of soil structure. Generally speaking, however, there is a lack of experimental data either to verify equations (5) or (9) or to suggest some other equation. More experiments are needed to reveal the relationship of A with the initial yield stress $p'_{y,i}$, and the structure index, S.

Destructuring

As the value of the compression pressure increases, the difference between the behaviour of a structured soil and that of the reconstituted soil narrows, that is, destructuring takes place. Theoretically, the behaviour of the two samples should be identical when the structure is completely destroyed. According to the assumptions of critical state soil mechanics, the critical state of deformation is an example of a complete absence of structure. This conclusion is supported by the observation that the critical state strengths and the critical state voids ratios, for both structured and reconstituted soils, are dependent only on the mean effective stress at the critical state, as well as on the mineralogy of the soil (Henkel, 1959; Bolton, 1986; Been *et al.*, 1991; Novello & Johnston, 1995).

Destructuring takes place when plastic deformation is induced and, as a result, quantities associated with soil structure, such as additional voids ratio Δe^*, generally diminish. The process of destructuring with respect to stress variation is monotonic and irrecoverable. However, it should be pointed out that soil structure also varies with factors such as time and chemical changes, and thus it may be possible for a destructured soil to become restructured as a result of chemical bonding and the passage of time. In this study, two quantities were introduced to describe soil structure, that is, the initial yield stress associated with soil structure, $p'_{y,i}$, and the structure index, S. From the available data it is clear that the initial yield stress associated with soil structures is affected by destructuring. However, as discussed previously, the value of S may be assumed to be a constant for the same soil with similar geological and stress histories.

Compression along a general stress path

For conditions other than one-dimensional or isotropic compression, it is desirable to define a general stress quantity for the compression model of structured soil, such that the model parameters do not vary with the stress path. In the absence of sufficient data to suggest a definitive stress parameter, the following tentative suggestion is made.

A simple and obvious quantity to be used in the model is the mean effective stress, p'. However, a more rational selection can be derived from the hardening law for many soils. If the hardening of structured soil is assumed to be dependent on plastic volumetric deformation, all stress states that have the same accumulation of absolute plastic volumetric strain constitute one yield surface. In

such a model the plastic volumetric deformation is dependent on the change in size of the yield surface only. If the elastic deformation for a structured soil is assumed to be the same as that of the reconstituted soil, any change in the additional voids ratio sustained by soil structure is associated with plastic volumetric deformation. In this case, the change in the additional voids ratio is also dependent on the size of the yield surface. Consequently, the variable p' in equation (6) may be written in terms of the size of the current yield surface p'_c, as follows:

$$\Delta e = S\left(\frac{p'_{cy,i}}{p'_c}\right)\ln p'_{cy,i} \text{ for } p'_c \geqslant p'_{cy,i} \tag{16}$$

In the above equation, p'_c is the size of the current yield surface, that is, the non-zero intercept of the yield surface on the p' axis, and $p'_{cy,i}$ here is the size of the initial yield surface associated with the initial soil structure. The actual yield surface may be an ellipse or some other shape.

It is assumed that equation (16) is valid for compression of structured soil under any general stress path. According to critical state soil mechanics (Schofield & Wroth, 1968), for compression along a general stress path the volumetric deformation defined by $\lambda^* \ln(p')$ and associated with the intrinsic soil properties in equation (7) should be divided into two parts. The elastic part is defined by $\kappa^* \ln(p')$, which is dependent on the current mean effective stress, and the plastic part is given by $(\lambda^* - \kappa^*)\ln(p'_c)$, which is dependent on the size of the yield surface. The voids ratio for a structured soil during virgin compression along a general stress path is thus obtained as follows:

$$e = e^*_{IC} + S\left(\frac{p'_{cy,i}}{p'_c}\right)\ln p'_{cy,i} - (\lambda^* - \kappa^*)\ln p'_c - \kappa^* \ln p' \tag{17}$$

where κ^* is the standard soil parameter for elastic deformation, and e^*_{IC} is the voids ratio for the corresponding reconstituted soil when $p' = p'_c = 1$ during virgin isotropic compression.

The general compression equation (17) states that voids ratio for a structured soil during virgin compression is dependent on two parts, that is, the elastic part which is dependent on the current mean effective stress, and the plastic part which is dependent on the size of the current yield surface. The plastic part is again subdivided into two parts, that is, the part associated with the intrinsic properties of the soil and that associated with soil structure.

CONCLUSIONS

In this paper the virgin compression behaviour of both naturally and artificially structured soils has been considered. The influence of soil structure and the influence of destructuring on compression have been analysed. Following a suggestion of Burland (1990), the properties of reconstituted soils are adopted as the intrinsic properties. In this case, the difference in the behaviour between a structured soil and the corresponding reconstituted soil is reflected in the additional voids ratio sustained by soil structure, which is a direct indicator of soil structure. A hyperbolic relationship between the additional voids ratio and the current mean effective stress is proposed, and the proposal has been evaluated using the results of 27 compression tests on 20 different soils. It has been demonstrated that the hyperbolic relationship describes very successfully the virgin compression behaviour of structured soils. An attempt has been made to link the additional voids ratio with the initial yield stress through the structure index S, by way of equation (6). From the available data, it appears that equation (6) may provide a reasonable estimation of the voids ratio sustained by soil structure.

The proposed compression equation has been extended to describe the virgin compression behaviour of structured soil along a general stress path. This generalization must be considered as tentative at the present time, because test data to validate it are not yet available.

The authors plan to formulate a complete constitutive model for natural soils in a later paper. The proposed constitutive model will include both the compression and shearing behaviour of structured soils, and will also present a mathematical description of destructuring.

ACKNOWLEDGEMENTS

The work described in this paper forms part of an overall research programme investigating the constitutive behaviour of fissured and structured soils. This work is supported by a grant from the Australian Research Council.

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