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Estimation of the compression behaviour of reconstituted clays

Abstract

The void index is a relative quantity measuring the position of the current void ratio of a clay against the void ratios of the clay at two specific vertical effective stresses (i.e., $\sigma_v' = 100$ kPa and $\sigma_v' = 1000$ kPa). Based on this concept, a simple systematic tool is proposed for estimating the compression behaviour of reconstituted clays over a wide range of stresses and water contents. Following the practice of geotechnical engineering computation, the compression behaviour of clays is idealised as linear segments in the $I_v \sim \ln p'$ (or the void index and the mean effective stress) space. Considering the variation in the available data, there are three related but independent models for describing the compression behaviour of reconstituted clays. The accuracy of estimation increases with the level of available data. The proposed estimation is used to simulate the behaviour of a variety of reconstituted clays over a wide range of stresses and water contents. With different levels of available data, the estimation is evaluated on the basis of these simulations. The proposed estimation can take maximum use of available data and provide a simple yet practical tool for calculating the compression behaviour of reconstituted clays and a basic parameter for geotechnical engineering computations, the compression index. An empirical equation for the initial compression index is also suggested and verified.

Keywords

compression, behaviour, reconstituted, estimation, clays

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4 **ESTIMATION OF THE COMPRESSION BEHAVIOUR OF**
5 **RECONSTITUTED CLAYS**
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Estimation of the compression behaviour of reconstituted clays

by

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ABSTRACT

The void index is a relative quantity measuring the position of the current void ratio of a clay against the void ratios of the clay at two specific vertical effective stresses, i.e., $\sigma'_v = 100$ kPa and $\sigma'_v = 1000$ kPa.). Based on this concept, a simple systematic tool is proposed for estimating the compression behaviour of reconstituted clays over a wide range of stresses and water contents. Following the practice of geotechnical engineering computation, the compression behaviour of clays is idealised as linear segments in the $I_v \sim \ln p'$ (or the void index and the mean effective stress) space. Considering the variation in the available data, there are three related but independent models for describing the compression behaviour of reconstituted clays. The accuracy of estimation increases with the level of available data. The proposed estimation is used to simulate the behaviour of a variety of reconstituted clays over a wide range of stresses and water contents. With different levels of available data, the estimation is evaluated on the basis of these simulations. The proposed estimation can take maximum use of available data and provide a simple yet practical tool for calculating the compression behaviour of reconstituted clays and a basic parameter for geotechnical engineering computations, the compression index. An empirical equation for the initial compression index is also suggested and verified.

Keywords: Clay, compressibility, constitutive equations, reconstituted soil.

1. Introduction

Compression behaviour is a fundamental aspect of soil deformation, and modelling compression behaviour generally forms the base of modelling the stress-strain relationships of soils (e.g., Pestana and Whittle, 1995; Hong and Onitsuka, 1998; Potts and Zdravkovic 1999; Baudet and Stallebrass, 2001; Liu et al, 2011). Many practical geological and geotechnical engineering problems are often analysed based on soil properties determined from compression tests as key parameters. One example is the settlement computations of the surface of land, which can be induced by various factors such as the change of the levels of ground water, mining activities, mud flow, sedimentation, and earthquakes. . The understanding of compression behaviour has therefore always been important to geological and geotechnical engineering practice and research for many decades (e.g., Skempton, 1944; Bowles, 1989; Butterfield and Baligh, 1996; Desai, 2001; and Chai et al, 2004).

The inherent nature and diversity of the geotechnical process involved in soil formation are responsible for the compressibility of soils. The stresses to which soils have been subjected, the environments in which they are formed and the time that has lapsed on the geotechnical time scale over different stages of their formation have been recognised as potential factors in their compressibility. Soils age and creep over time; hence, bonds develop at particle contacts in natural clay, which can also be thought of as “structured clay” (Leonards, 1972; Leroueil et al., 1979; Michell, 1996; and Shibuya, 2000; etc.). The term “soil structure” refers to the particle associations and arrangements (fabric) and to inter-particle forces. The resistance of soil structure is responsible for the difference in the engineering behaviour of natural soils between the structured and the destructured (reconstituted) states (Leroueil et al., 1979 and 1983; Hanzawa and Adachi, 1983; Leroueil and Vaughan, 1990; Mitchell, 1996; and Shibuya, 2000). The development of a soil structure during depositional and

postdepositional processes has been documented by many researchers (Locat and Lefebvre, 1985; Mitchell, 1986; and Schmertmann, 1991). The compression curve of reconstituted clay is intrinsic (devoid of soil structure) and is usually used as a frame of reference for the behaviour of naturally and artificially structured soils (Burland, 1990; Nagaraj and Miura, 2001; Nagaraj et al., 1990 and 1998) and as a basis for modelling the behaviour of soils in the structured state (e.g., Liu et al, 2000; Masín, 2007; Hinchberger and Qu, 2009; Horpibulsuk et al, 2007, 2010; 2013; Suebsuk et al., 2010 and 2011). Moreover, reconstituted clay is typical used as a liner for landfill and a fill for reclaimed area, and the compressibility of the reconstituted clay is one of the required design parameters.

Burland (1990) proposed the concept of void index and demonstrated its ability to generalise the compression behaviour of reconstituted clays and the influence of natural soil structure. The concept has since been used widely in interpreting the compression behaviour of structured soils (e.g., Low et al, 2008; and Horpibulsuk et al, 2011). Based on Burland's work and many others, a further study is presented in this paper focusing on reconstituted clays.

A systematic tool is proposed for estimating the compression behaviour of reconstituted clays over a wide range of stresses and water contents in the void index I_v and mean effective stress p' space, i.e., the $I_v \sim \ln p'$ space. The objective of this study is to provide an estimation of the void ratio and compression index of clays during compression over a wide range of stress levels, from 1 kPa to 100,000 kPa, with the flexibility of implementing various levels of available data. The compression indexes in the $e \sim \log \sigma'_v$ space and the $e \sim \log p'$ space are essentially the same because their pattern similarity is widely observed (a discussion on the two curves can be found in a paper by Liu and Carter, 1999). Some numerical difference in σ'_v exists, but this difference is minimised by the normalisation. Values of $I_v = 0$ for 100 kPa

and $I_v = -1$ for 1000 kPa are observed in both cases. The proposed model is evaluated based on comparisons between model performance and experimental data.

2. Estimation of the compression behaviour of reconstituted clays

2.1 Burland's work on the compression behaviour of reconstituted soils

In his fortieth Rankine lecture, Burland (1990) introduced the concept of void index and performed a systematic study on the compression behaviour of clays via the void index. The current research is carried out based on Burland's original work and subsequent research by others (e.g., Amorosi and Rampello, 2007; Bobet et al, 2011; Hong et al, 2012). A change in approach is made in the current study: the behaviour of soil is described by the mean effective stress p' , not the vertical effective stress, σ'_v . To distinguish between soil parameters associated with p' and those associated with σ'_v , parameters associated with σ'_v are indicated by an italic and subscript v. Hence, e_v indicates the void ratio associated with the vertical effective stress. For two parameters introduced in this study, differences exist between the parameters used in the two systems: the parameters e_{100}^* (the void ratio of the soil in a reconstituted state at $p' = 100$ kPa) and e_{1000}^* (the void ratio at $p' = 1,000$ kPa). For the vertical effective stress, σ'_v , the corresponding values are denoted as $e_{v,100}^*$, $e_{v,1000}^*$ and $C_{c,v}^*$. However, the value of the numeric difference between e_{100}^* and e_{1000}^* , i.e., C_c^* , is the same as that between $e_{100,v}^*$ and $e_{1000,v}^*$, i.e., $C_{c,v}^*$.

147 The void index I_v is the relative magnitude of the void ratio calculated with the respect to the
 148 void ratio of the soil in the reconstituted state at $p' = 100$ kPa and at $p' = 1,000$ kPa, as shown
 149 below,

$$150 \quad I_v = \frac{e - e_{100}^*}{e_{100}^* - e_{1000}^*} = \frac{e_v - e_{v,100}^*}{e_{v,100}^* - e_{v,1000}^*} . \quad (1)$$

151 The properties of a reconstituted soil are referred to as intrinsic properties and are denoted by
 152 the symbol $*$ attached to the relevant symbols. The parameter C_c^* is used to represent the
 153 difference between e_{100}^* and e_{1000}^* , i.e.,

$$154 \quad C_c^* = e_{100}^* - e_{1000}^* . \quad (2)$$

155 Consequently, the void ratio and the void index are related by the following equation

$$156 \quad e^* = I_v C_c^* + e_{100}^* \quad (3)$$

157 Burland proposed the following equations to describe the compression behaviour of
 158 reconstituted soils (Fig. 1):

$$159 \quad I_v = 2.45 - 1.285 \log \sigma'_v + 0.015 (\log \sigma'_v)^3 . \quad (4)$$

160 This line is the intrinsic compression line of soil and it is the same for both isotropic
 161 compression tests and one-dimensional compression tests. To distinguish this line from the
 162 widely used isotropic compression line ICL^* in the $e \sim \ln p'$ space, this intrinsic void index
 163 compression line is denoted by $I_v CL^*$. As observed in Fig. 1, the $I_v CL^*$ is curved in the
 164 $I_v \sim \ln \sigma'_v$ space.

165 A set of empirical equations are also proposed by Burland for estimating $e_{v,100}^*$, and $e_{v,1000}^*$ as
 166 functions of the liquid limit void ratio, e_L .

$$e_{v,100}^* = 0.109 + 0.679e_L - 0.089e_L^2 + 0.016e_L^3, \quad (5)$$

$$e_{v,1000}^* = e_{v,100} - 0.256e_L + 0.04. \quad (6)$$

Based on the theoretical framework of the critical state soil mechanics, the following approximation can be made for e_{100}^* and e_{1000}^* .

$$e_{100}^* = e_{v,100}^* + \Delta, \quad (7)$$

$$e_{1000}^* = e_{v,1000}^* + \Delta, \quad (8)$$

where Δ is given by

$$\Delta = \left(\frac{C_{c,v}^*}{3} \right) \ln \left\{ \left(1 - \frac{2}{3} \sin \varphi_{cs} \right) \left[1 + \left(\frac{3 - \sin \varphi_{cs}}{6 - 4 \sin \varphi_{cs}} \right)^2 \right] \right\} \quad (9)$$

where φ_{cs} is the critical-state friction angle measured in a triaxial compression test. If the value of φ_{cs} is not known, $\varphi_{cs} = 20^\circ$ may be assumed. The method for the determination of Δ is similar to that for the void ratio at $p' = 1$ kPa from a one-dimensional compression test (e.g., Muir-Wood, 1990; Liu and Carter, 2002).

2.2 Experimental data

A summary of a large amount of experimental data is shown in Fig. 2. Some detailed information on the soils and the references are listed in Tables 1 and 2. These data were obtained from 68 tests on 25 reconstituted clays and 45 tests on four clays in reconstituted states but at various water contents. The following features of the compression behaviour of the reconstituted clays are observed.

- (1) The virgin compression behaviour of a reconstituted clay with a given mineralogy and water content has been successfully normalised into one unique line with less

dependence on the testing stress path. The compression behaviour of soil normalised by I_v is graphically identical for the $I_v \sim \ln p'$ space and for the $I_v \sim \ln \sigma'_v$ space. In this study, the soil behaviour in the $I_v \sim \ln p'$ space is described.

(2) The virgin compression line for different reconstituted clays can be reasonably normalized into one unique linear line in the region of approximately 100 kPa $< p' < 1,000$ kPa.

(3) Based on the physical meaning of void in soils and the experimental observations, it is obvious that this linearity of soil behaviour does not hold for all possible values of p' . For example, linearity suggests an infinitively large void ratio as p' approaches zero. The curvatures at the two ends of the compression line are dependent on the mineralogy and water content of the soil.

The main objective of this study is to propose a simple tool for the prediction of the void ratio and compression index of soil with consideration of the curvatures at the two ends when there are available data.

2.3 Proposed tool for estimation

Based on the above observation, a systematic tool is proposed to provide a simple way to estimate the compression behaviour of reconstituted clays over a wide range of stresses, i.e., for $1 \text{ kPa} \leq p' \leq 100,000 \text{ kPa}$, with the flexibility of application for various levels of available data. For geotechnical engineering computation of settlement and consolidation and for constitutive modelling, parameters that describe the deformation of soil are usually obtained by assuming that the compression behaviour is linear in the $e \sim \ln p'$ space (e.g., Desai and Toth, 1996; Liu and Carter, 2000; Horpibulsuk et al., 2010; Suebsuk et al 2010, 2011; Chai and Carter 2011). Therefore, soil behaviour is idealised by linear segments, indicating that

relevant soil parameters are dependent on the stress level. As a result, soil parameters obtained from the proposed method can be used for direct engineering calculation.

The minimum datum for using the model is e . The following data, if available, can be used in the model:

- (1) e_{100}^* : the void ratio of the soil in a reconstituted state at $p' = 100$ kPa;
- (2) e_{1000}^* : the void ratio of the soil in a reconstituted state at $p' = 1,000$ kPa;
- (3) (e_i^*, p'_i) : an initial soil state;
- (4) p'_y : the yielding mean effective stress or the maximum historical stress;
- (5) κ_i : the initial compression index (i.e., the gradient of the initial virgin compression curve in the $I_v \sim \ln p'$ space);
- (6) κ_e : the ending compression index (i.e., the gradient of the compression curve for $p' > 5000$ kPa in the $I_v \sim \ln p'$ space);
- (7) κ_u : the swelling index (i.e., the gradient of the unloading and reloading curve in the $I_v \sim \ln p'$ space).

Any of the above seven groups of data can be incorporated into the proposed tool. It is obvious that the accuracy of estimation increases as more data are available. Three related but independent models for the estimation are proposed based on the available data. As shown in Figs 2 and 3, the basic part of the estimation is the approximation of a unique bi-linear segments OAB: the compression line (ICL^{*}). The mean effective stress at the turning point A is 5,000 kPa. The gradient for line OA is 0.4343, and the gradient for AB is a quarter of the value of that for OA, i.e., 0.1086. OAB or ICL^{*}, the intrinsic compression line for reconstituted clays, is defined as follows:

$$\begin{cases} I_v = 2 - 0.4343 \ln p' & \text{for } p' \leq 5000 \text{ kPa} \\ I_v = -0.775 - 0.1086 \ln p' & \text{for } p' > 5000 \text{ kPa} \end{cases} \quad (10)$$

If there are reliable data available to make the calculation of κ_e possible, the ending compression index for $p' > 5,000$ kPa, the line OAB can be more accurately described as follows:

$$\begin{cases} I_v = 2 - 0.4343 \ln p' & \text{for } p' \leq 5000 \text{ kPa} \\ I_v = \kappa_e \ln(5000/p') - 1.699 & \text{for } p' > 5000 \text{ kPa} \end{cases} \quad (11)$$

The only difference between Equation (10) and Equation (11) is in the magnitudes of the compression index beyond $p' = 5000$ kPa. If the compression index beyond $p' = 5000$ kPa could be identified reliably for a given soil and its value is found to be different from 0.1086, equation (11) is recommended.

Model 1: If only e_{100}^* and e_{1000}^* for a given soil are known, measured or estimated via equations (7) and (8), the intrinsic compression line for reconstituted clays OAB, i.e., equation (10), is employed to represent the compression behaviour of the soil.

Model 2: Model 2 is applicable when an initial soil state (e_i, p'_i) is known in addition to the values of e_{100}^* and e_{1000}^* . A sketch of the model is shown in Fig. 3.

The position of the initial state, represented by (e_i, p'_i), in relation to the intrinsic compression line OAB, is identified by the following set of equations

$$\begin{cases} 2 - 0.4343 \ln p' - I_{v,i} > 0 & \text{Initial state above ICL}^* \\ 2 - 0.4343 \ln p' - I_{v,i} = 0 & \text{Initial state on ICL}^* \\ 2 - 0.4343 \ln p' - I_{v,i} < 0 & \text{Initial state below ICL}^* \end{cases} \quad (12)$$

where $I_{v,i}$ is the void index for the initial state.

The compression behaviour of the soil can be described by the set of constitutive equations, depending on the position of the initial soil state (Fig. 3).

For a soil with an initial state on ICL^* , the behaviour of the soil described by OAB or by Model 1 is consistent with available data. Equation (10) or (11) gives a reliable description of the soil behaviour.

If the initial state of a soil is below ICL^* , the behaviour of the soil is described by 1FAB (Fig. 3). The gradient of line 1F, denoted by κ_i , is the initial compression index. F is the point where the initial compression line and the intrinsic compression line intersect. p'_F is the mean effective stress at that point. The behaviour of the soil represented by 1FAB is described by the following set of constitutive equations

$$\begin{cases} I_v = I_{v,i} - \kappa_i \ln(p'/p'_i) & \text{for } p' \leq p'_F \\ I_v = 2 - 0.4343 \ln p' & \text{for } p'_F < p' \leq 5000 \text{ kPa} \\ I_v = -0.775 - 0.1086 \ln p' & \text{for } p' > 5000 \text{ kPa} \end{cases} \quad (13)$$

The mean effective stress at the intersection point F is expressed as follows:

$$p'_F = \exp\left(\frac{2 - I_{v,i}}{0.4343 - \kappa_i}\right). \quad (14)$$

For situations in which the value of the parameter κ_i is unknown, the following empirical equation is proposed

$$\kappa_i = 0.0125(1 + 0.5I_{v,i}^3) \quad \text{for } -0.9 \leq I_{v,i} \leq 5. \quad (15)$$

It is obvious that κ_i must always be greater than zero. Thus, based on experimental observation a condition for applicability of the equation, $-0.9 \leq I_{v,i} \leq 5$, is imposed.

The proposed equation is based on analysis of a set of experimental data. A comparison of the values of κ_i between those measured and those predicted via equation (15) is shown in

Fig 4. In the figure, data from fifty-six tests on eleven clays are shown. The experimental data are reported by Terzaghi (1953), Cotecchia (1996), Wang and Wei (1996), Suzuki et al (2007), Takemura et al, (2007), Hong et al (2011), Shipton and Coop, (2012). It should be noted that the parameter $I_{v,i}$ is used in equation (15) for simplicity and is a pragmatic approach. The methodology is similar to the usage of p'_e , the equivalent confining stress (Muir-Wood, 1990; Graham, 2006).

For a soil with an initial state above ICL^* (Fig. 3), the behaviour of the soil is described by 2CAB for $p'_i < 100$ kPa and $I_{v,i} > 0$, or is described by 3AB for $p'_i \geq 100$ kPa or $I_{v,i} \leq 0$.

For $p'_i < 100$ kPa and $I_{v,i} > 0$, the gradient for line 2C is denoted by κ_{2C} . The compression behaviour of the soil, passing through point C (100 kPa, 0), is described by the following set of constitutive equations

$$\begin{cases} I_v = I_{v,i} - \kappa_{2C} \ln(p'/p'_i) & \text{for } p' \leq 100 \text{ kPa} \\ I_v = 2 - 0.4343 \ln p' & \text{for } 100 \text{ kPa} < p' \leq 5000 \text{ kPa} \\ I_v = -0.775 - 0.1086 \ln p' & \text{for } p' > 5000 \text{ kPa} \end{cases} \quad (16)$$

Based on the values of the void index and mean effective stress for points 2 and C, the gradient κ_{2C} for line 2C is expressed as follows:

$$\kappa_{2C} = \frac{I_{v,2} - I_{v,100}}{\ln\left(\frac{100}{p'_2}\right)} = \frac{I_{v,2}}{4.605 - \ln p'_2} \quad (17)$$

For $p'_i \geq 100$ kPa or $I_{v,i} \leq 0$, the compression line cannot be assumed to pass through point C, because a negative compression index is indicated. Thus, the compression behaviour is assumed to be 3AB, and the gradient for line 3A is denoted by κ_{3A} . The compression behaviour of the soil is described by the following set of constitutive equations

$$289 \quad \begin{cases} I_v = I_{v,i} - \kappa_{3A} \ln(p'/p'_i) & \text{for } p' \leq 1000 \text{ kPa} \\ I_v = -0.775 - 0.1086 \ln p' & \text{for } p' > 5000 \text{ kPa} \end{cases} \quad (18)$$

290 Based on the values of the void index and mean effective stress for points 3 and A, the
 291 gradient κ_{2C} for line 3A is expressed as follows:

$$292 \quad \kappa_{3A} = \frac{I_{v,3} - I_{v,1000}}{\ln(1000/p'_3)} = \frac{I_{v,3}}{6.908 - \ln p'_3} \quad (19)$$

293 **Model 3:** Model 3 is applicable in situations in which all three sets of data are available,
 294 e^*_{100} and e^*_{1000} , an initial soil state (e^*_i, p'_i), and the yielding stress p'_y . Model 3 is an
 295 improvement over Model 2 in that it incorporates the influence of the yield stress on soil
 296 behaviour. Consequently, there is a change in the soil compression index around the yielding
 297 point, indicated as point Y in Fig. 5. The initial behaviour of the soil from p'_i and p'_y is
 298 described by the initial behaviour either with the initial compression index, if the soil
 299 experiences virgin yielding, or the unloading and reloading compression index, if the soil
 300 experiences subsequent loading. Beyond the yielding point p'_y , the soil behaviour is
 301 essentially the same as that described by Model 2. As shown in Fig 5, the soil behaviour is
 302 represented by the following four linear segments 4YCAB if the position of the yielding point
 303 p'_y is above ICL^* , with $p'_y < 100 \text{ kPa}$ and $I_{v,i} > 0$. The gradient for line YC is denoted by κ_{YC} .

$$304 \quad \begin{cases} I_v = I_{v,i} - \kappa_i \ln(p'/p'_i) & \text{for } p' \leq p'_y \text{ kPa} \\ I_v = I_{v,y} - \kappa_{YC} \ln(p'/p'_y) & \text{for } p'_y < p' \leq 100 \text{ kPa} \\ I_v = 2 - 0.4343 \ln p' & \text{for } 100 \text{ kPa} < p' \leq 5000 \text{ kPa} \\ I_v = -0.775 - 0.1086 \ln p' & \text{for } p' > 5000 \text{ kPa} \end{cases} \quad (20)$$

305 As a result, the value of the void index at the yield point Y can be determined by substituting
 306 the value of the stress at that point into the equation for line 4Y, and its value is given as
 307 follows:

$$I_{v,y} = I_{v,4} - \kappa_i \ln p'_y, \quad (21)$$

where $I_{v,i}$ is the void index at the initial point 4, and κ_i is the initial compression index.

Based on the values of the void index and the mean effective stress for points Y and C, the gradient κ_{YC} for line YC is determined as follows:

$$\kappa_{YC} = \frac{I_{v,Y} - I_{v,100}}{\ln\left(\frac{100}{p'_y}\right)} = \frac{I_{v,Y}}{4.605 - \ln p'_y}. \quad (22)$$

2.4 Discussion of the application of the proposed tool

2.4.1. p'_y : the yielding mean effective stress or the maximum historical stress

As noted in Section 2.2, the general shape of the compression curve in the $e \sim \ln p'$ space or the $I_v \sim \ln p'$ space is not a straight line, but rather an S-shape (Liu et al, 2013). If the actual compression curve is represented by a number of segmented lines, there will be a number of points at which the value of the compression index changes sharply, which falls into the definition of traditional yielding stress (e.g., Coop and Atkinson, 1993; Khalili et al, 2005; Airey et al, 2011). In this study, the term yielding is used to indicate a sharp change in the slope of the soil compression curve, irrespective of whether the change is due to the nature of the compression or by unloading or reloading. The difference in initial compression or unloading and reloading is normally modelled via the compression index.

2.4.2. Parameters for void ratio and for void index

The relationship between the void ratio and the void index is expressed by equation (3). A basic parameter in engineering computation and theoretical constitutive modelling is the constant compression index in the $e \sim \ln p'$ space. The index in the $e \sim \ln p'$ space, K_e , and that in the $I_v \sim \ln p'$ space, κ_{Iv} , are related by the following equation.

$$K_e = \kappa_v C_c^* \quad (23)$$

In this study, linear segmental compression behaviour for clays is suggested. Therefore, the compression index is dependent on the stress level. The corresponding index for the intrinsic compression line OAB is as follows:

$$\begin{cases} K_e = 0.4343 C_c^* & \text{for } p' \leq 5000 \text{ kPa} \\ K_e = 0.1086 C_c^* & \text{for } p' > 5000 \text{ kPa} \end{cases} \quad (24)$$

For a soil with an initial compression index calculated via equation (15), the index for deformation measured by the void ratio is given by the following equation:

$$K_{e,i} = 0.0125 \left(1 + 0.5 I_{L,i}^3 \right) C_c^* \quad (25)$$

2.4.3. Methods in the $I_v \sim \ln \sigma'_v$ space

As stated in Section 2.2, the compression behaviour of soil normalised by I_v is graphically identical in the $I_v \sim \ln p'$ space and in the $I_v \sim \ln \sigma'_v$ space. In geotechnical engineering, it is a common practice to substitute the vertical effective stress σ'_v for the mean effective stress p' when describing one-dimensional compression behaviour (e.g., Burland 1990; Liu et al, 2003; Chai and Carter, 2011). Consequently, the proposed models and the constitutive equations remain essentially the same when the mean effective stress p' is replaced by the vertical effective stress σ'_v . For example, the intrinsic compression line OAB in the $I_v \sim \ln \sigma'_v$ space is described by the following equation:

$$\begin{cases} I_v = 2 - 0.4343 \ln \sigma'_v & \text{for } \sigma'_v \leq 5000 \text{ kPa} \\ I_v = -0.775 - 0.1086 \ln \sigma'_v & \text{for } \sigma'_v > 5000 \text{ kPa} \end{cases} \quad (26)$$

Parameter $C_{c,v}^*$ is expressed as follows:

$$C_{c,v}^* = e_{100,v}^* - e_{1000,v}^* \quad (27)$$

Consequently, the void ratio and the void index are related by the following equation:

$$e_v^* = I_v C_{c,v}^* + e_{100,v}^* \quad (28)$$

and the compression index in the $e \sim \ln \sigma'_v$ space, $K_{e,v}$, and that in the $I_v \sim \ln p'$ space, κ_{Iv} , are related by the following equation.

$$K_{e,v} = K_{Iv} C_{c,v}^* \quad (29)$$

It should be noted that the compression index in the $e \sim \ln \sigma'_v$ space is identical to that in the $e \sim \ln p'$ space.

3. Validation of Proposed Models

3.1 Background

The proposed systematic tool has been applied to analysis of the behaviour of many different types of reconstituted clays. The simulations for six types of reconstituted clays, with 10 tests in total, are presented here. Details of tests can be found in the original reports and their references are listed in Table 2. The values of the soil parameters used in the theoretical simulations are also given in Table 2. Simulations are conducted for all three models. Comparisons between the experimental data and the theoretical simulation results are shown in Figs 6 to 15. Of the six groups of test results considered here, the mean effective stresses are reported for one group, Bisaccia clay. The results are shown in Fig. 13. The rest of the tests are one-dimensional compression tests and only the values of the vertical effective stress are reported.

The stress units adopted here are kilopascals (kPa). The proposed empirical equation for the initial compression index, i.e., equation (15), is employed for the simulations presented in this study. Because the void ratio is used directly in engineering computations, all the simulations

are presented in the e - $\ln p'$ space. The values of the initial yield stress have been identified directly from the original compression curves plotted in terms of e - $\ln p'$ or I_v - $\ln p'$ coordinates.

The experimental data are represented by solid symbols, such as circles or squares. The simulation results obtained via Model 1 are represented by dark solid lines, those obtained via Model 2 are represented by broken lines of dark dots, and those obtained via Model 3 are represented by dark broken lines without dots. It should be noted that the simulation results for Models 2 and 3 will usually be coincident with those for Model 1 for further loading after the compression curve meets OAB. As a result, only dark lines are shown in the figures after the other two models merge into Model 1. When the simulation results obtained using Model 1 and those obtained using Model 2 or Model 3 are identical, the simulation results are represented by one curve, the dark solid lines as indicated in the legends. Similarly, the simulation results are represented dark broken lines without dots when the simulation results obtained using Model 2 and those obtained using Model 3 are identical.

3.2 Evaluation and discussion

An overall view of the compression behaviour of various reconstituted clays is shown in Fig. 2. The test results selected for the simulation presentation are marked by solid symbols linked with thin lines, and the other tests are by marked by open symbols linked with thin lines. Soft Louisville clay and kaolin clay with initial void ratios of approximately 0.7 form the upper and lower bands of the collection and are selected for simulation. The stress levels for all the simulations vary from 0.1 kPa to 20,000 kPa. The stress ratio levels reach as high as 5,000 for soft Louisville clay and 8,000 for Lianyugang clay. The void index varies from -1.8 to 7.6. The void ratio varies from 0.3 to 24. All tests forming the bands of the ranges are selected for the simulations. The tests selected for the simulations are a reasonably good representation of

all the data collected.

Model 1 yields a good prediction of reconstituted clay behaviour in the range of 100 kPa to 1,000 kPa. Outside that range, Model 1 should only be used as a rough estimation. For some clays, considerable disagreement is expected between Model 1, or the proposed I_{CL}^* , and the actual soil behaviour. Generally speaking, the prediction via Model 1 is more reliable for stresses greater than 1,000 kPa than for stresses less than 100 kPa. A conclusion can be drawn that the intrinsic compression curves of reconstituted clays are dependent on the types of the clays and their initial water contents, especially for $p' < 100$ kPa.

In general, Model 2 provides a reasonably good estimation of the compression behaviour of clays over a very wide range of stresses and water contents. An additional information such as the initial stress and the void ratio state, can be implemented conveniently into the proposed model and will result in significant improvement in the engineering computations.

Because the yielding stress of the soil is known and implemented into Model 3, Model 3 yields an overall satisfactory description of the compression behaviour of reconstituted clays, and this model can be used reliably in engineering computations of soil void ratios and compression index values. Fig. 10 shows that for soft Louisville clay, a considerable difference between the simulation results and the experimental data exists. A major factor in this difference is that the value of the initial compression index, determined via the empirical equation (15), is not accurate. Consequently, the compression of soil is seriously over predicted from the initial state to the yielding point. Another special point about this simulation is that the stress starts at a very low level, 0.1 kPa. For comparison, the simulation with an accurate value of the index is also shown in Fig. 10. Because Model 3 allows the usage of an accurate initial compression index in the simulation (as described in equation 11), the model is able to represent the behaviour of reconstituted clays well.

The simulation results in Fig. 6 to Fig. 15 show that the I_{vCL}^* , or OAB, is the basis of all three models. The predictions made by using Model 2 and Model 3 eventually agree and coincide with the I_{vCL}^* . For five cases, the simulation results obtained via Model 2 and those obtained via Model 3 are identical. For two cases (Figs 12 and 13), there is no obvious yielding point and thus there is no difference between Model 2 and Model 3. For the other three cases (Figs 9, 11 and 14), the yielding state occurs in the vicinity of the I_{vCL}^* . Under these conditions, Model 2 and Model 3 predict the same turning point for the compression behaviour.

The proposed empirical equation for the initial compression index, i.e., Equation (15), is employed to simulate the initial behaviour of four clays in eight tests. For soft Louisville clay (Fig. 10), the initial void index is too high ($I_{v,i} = 7.6$) and the empirical equation for k_i is not applicable. Overall speaking, the simulations made via the proposed empirical equation provide acceptable estimates of the soil's initial behaviour when it diverges from the unique I_{vCL}^* . The maximum value of compression index of a clay usually occurs in the stress range from 100 kPa to 1,000 kPa; however, for clays with very high initial I_v , the initial compression index can be greater than the value that occurs in the range of 100 kPa to 1,000 kPa (e.g.; Burland et al, 1996; Liu et al, 2003; Khalili et al, 2005).

As shown Fig. 13 for Bisaccia clay, the unloading and reloading behaviour of reconstituted clay is simulated simply by following the same conventional compression model as that used for Cam Clay, which is assumed to behave linear elastically in the $e - \ln p'$ space in both unloading and reloading. The concepts and methods for describing conventional elastic behaviour can be incorporated straightforward into the proposed method.

Index properties of clayey soils are directly dependent on the mineralogy of the soils. Many studies have been reported on the correlations of the compressibility of clayey soils and index

properties (e.g., Skempton, 1944; Bowles, 1989; Muir Wood, 1990; Burland, 1990; Sridharan and Nagaraji, 2000; Horpibulsuk et al, 2013). Based on these studies, the virgin compression index of a clay can usually be estimated from the liquid limit or the initial void ratio of the soil. The proposed equation (15), though based on the void index concept, is in consistency with these works. It is seen that the proposed equation provides a reasonably good agreement with experimental data. Hence it seems possible that for the purpose of primary estimation the proposed models can be further developed with all model parameters estimated via index properties. It may also be possible to normalize the index properties by parameters such as $e_{v,100}^*$, and $e_{v,1000}^*$. Thus, the general feature of the compression behavior of reconstituted clays, i.e., a unique curve in the $I_v - \ln p'$ space for $p' \geq 100$ kPa, can be described. This will be a future study topic.

It should also be noted that the compression of clays even in the simplest states, reconstituted states, is very complicated. The proposed tool, which is based on limited experimental data may not be applicable to some clays. A study of the compression behaviour of reconstituted soils in terms of influential factors such as the clay minerals and the double layer characteristics may provide insight into the mechanisms and parameters of compression behaviour. This may be a topic of further research.

4. Conclusions

A simple systematic tool based on Burland's void index is proposed for use in estimating the compression behaviour of reconstituted clays. The compression behaviour of clays is idealised as linear segments in the $I_v \sim \ln p'$ space. Based on available data, three related but independent models are proposed for use in predicting the compression behaviour of clays, which is a key soil characteristic in engineering computation and constitutive modelling. The

proposed estimation is employed to simulate the behaviour of various reconstituted clays and the simulations are compared with experimental data. The proposed estimations make maximum use of the available data, and the accuracy of the estimation increases with the level of the available data. The proposed estimation is a simple yet practical tool for calculating the compression behaviour of reconstituted clays and the soil compression index and is suitable for use in describing clay compression behaviour over a wide range of stresses, i.e., $1 \text{ kPa} < p' < 100,000 \text{ kPa}$, and a wide range of water contents. An empirical equation for the initial compression index is also suggested. This equation has been found to be very useful in predicting the initial compression behaviour of clays, which is usually expected to diverge from the standard intrinsic compression line, I_{vCL}^* .

5. References

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622 *of soft clay. Proc. 2nd Int. Conf. Soft Soil Engng*, pp.120-125, Nanjing, China.
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624 **Table 1: Basic Data on Compression Tests of Reconstituted Soil from Previous Studies**

Soils	Reference	Known stresses	No. of tests	e^*_{100}	e^*_{1000}	Range of stresses (kPa)
Osaka clay	Adachi et al, 1995	σ'_v	1	1.26	0.61	5-1000
Baimahu Clay	Hong et al, 2000	σ'_v 14-Tests	$\omega=64\%$	1.23	0.75	0.5-1600
			$\omega=72\%$	1.25	0.71	0.5-1600
			$\omega=83\%$	1.33	0.68	0.5-1600
			$\omega=91\%$	1.33	0.73	0.5-1600
			$\omega=101\%$	1.39	0.77	0.5-1600
			$\omega=111\%$	1.50	0.80	0.5-1600
			$\omega=119\%$	1.45	0.82	0.5-1600
			$\omega=126\%$	1.52	0.81	0.5-1600
			$\omega=137\%$	1.54	0.78	0.5-1600
			$\omega=143\%$	1.58	0.86	0.5-1600
			$\omega=153\%$	1.62	0.86	0.5-1600
			$\omega=163\%$	1.68	0.90	0.5-1600
			$\omega=174\%$	1.70	0.92	0.5-1600
			$\omega=180\%$	1.72	0.95	0.5-1600
Lianyugang Clay	Hong et al, 2000	σ'_v 14-Tests	$\omega=50\%$	0.99	0.62	0.5-1600
			$\omega=59\%$	1.05	0.68	0.5-1600
			$\omega=68\%$	1.13	0.73	0.5-1600
			$\omega=78\%$	1.26	0.78	0.5-1600
			$\omega=85\%$	1.28	0.74	0.5-1600
			$\omega=92\%$	1.28	0.73	0.5-1600
			$\omega=96\%$	1.35	0.74	0.5-1600
			$\omega=104\%$	1.37	0.81	0.5-1600
			$\omega=114\%$	1.34	0.77	0.5-1600
			$\omega=119\%$	1.36	0.79	0.5-1600
			$\omega=127\%$	1.43	0.79	0.5-1600
			$\omega=135\%$	1.45	0.81	0.5-1600
			$\omega=142\%$	1.51	0.83	0.5-1600
			$\omega=146\%$	1.54	0.83	0.5-1600
Keman	Hong et al, 2000	σ'_v 14-Tests	$\omega=43\%$	0.91	0.62	0.5-1000
			$\omega=48\%$	0.95	0.64	0.5-1000
			$\omega=57\%$	0.95	0.65	0.5-1000
			$\omega=62\%$	0.98	0.65	0.5-1000
			$\omega=66\%$	1.04	0.67	0.5-1000
			$\omega=72\%$	1.04	0.70	0.5-1000
			$\omega=80\%$	1.11	0.66	0.5-1000
			$\omega=87\%$	1.17	0.71	0.5-1000

			$\omega=91\%$	1.21	0.76	0.5-1000
			$\omega=99\%$	1.26	0.76	0.5-1000
			$\omega=106\%$	1.25	0.75	0.5-1000
			$\omega=110\%$	1.32	0.79	0.5-1000
			$\omega=116\%$	1.34	0.82	0.5-1000
			$\omega=122\%$	1.37	0.82	0.5-1000
Mexico city clay	Terzaghi, 1953	p'	1	7.17	3.35	10-1900
Guang-shen clay	Wang et al, 1996	σ'_v	1	1.53	0.98	1-1000
Fissured lodgement	Lehane et al, 1998	σ'_v	1	0.40	0.29	100-5000
Tian An clay	Takemura et al, 2007	σ'_v	2	1.54	0.89	1-1100
				1.57	0.94	1-1100
Can Tho	Takemura et al, 2007	σ'_v	4	1.08	0.75	10-1300
				0.9	0.65	10-1300
				0.83	0.59	10-1300
				0.98	0.57	10-1300
London clay	Gasparre, 2008	σ'_v	2	0.99	0.61	500-7000
				1.08	0.69	2000-6000
Landslide clay	Suzuki et al, 2007	p'	2	0.63	0.29	10-1000
				0.35	0.17	10-600
Kaolin	Suzuki et al, 2007	p'	1	1.43	1.01	10-1300
Langjokull sediment	Altuhafi et al, 2011	σ'_v	1	0.59	0.55	100-20000
Marine soil	Fukue et al, 2009	p'	1	5.40	1.88	1-1000
Kaolin	Shipton et al, 2012	σ'_v	1	1.16	0.83	1-4000

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Table 2: Compression Test Results for the Validation of Proposed Models of prediction for Compression Index

Soils	Reference	Stress known	No. of tests	e^*_{100}	e^*_{1000}	Initial soil state		Yield stress (kPa)	Stress range (kPa)	Simulations
						e^*_i	p'_i (kPa)			
Lianyugang Clay	Hong et al, 2000	σ'_v 4-Tests	$\omega=50\%$	0.99	0.62	1.37	0.50	10.3	0.5-1600	Methods 2 and 3 the same
			$\omega=85\%$	1.28	0.74	2.31	0.51	3.80	0.5-1600	
			$\omega=114\%$	1.34	0.77	3.05	0.51	2.20	0.5-1600	
			$\omega=142\%$	1.51	0.83	3.73	0.51	1.60	0.5-1600	
Bisaccia clay	Onofrio et al,1998	p'	1	2.71	1.89	3.01	50.96	N/A	50-8000	Methods 2 and 3 the same
Mexico city clay	Mesri et al 1975	σ'_v	1	9.08	4.09	23.97	2.39	N/A	1-3000	Methods 2 and 3 the same
Pleistocene stiff clay	Cotecchia et al, 1997	σ'_v	1	1.33	0.79	1.28	18.8	100	10-20000	Methods 2 and 3 the same
Soft Louisenville	Locat et al, 1996	σ'_v	1	1.39	0.79	6.16	0.07	1.2	0.1-500	Very low stress, $p'=0.1$ kPa
Reconstituted Kaolin	Shipton et al, 2012	σ'_v	2	1.28	0.92	3.33	1.72	7.80	1-2000	Methods 2 and 3 the same
				1.23	0.87	3.46	1.56	6.65	1-4000	

Estimation of the compression behaviour of reconstituted clays

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Fig. 1 Burland's equation and some experimental data (after Burland ,1990)

Fig. 2 A Comparison of experimental data, Burland's equation and the proposed I_vCL^* (References for data listed in Tables 1 and 2)

Fig. 3 Method 2 for estimating soil compression behaviour

Fig. 4 Empirical equation proposed for the initial compression index

Fig. 5 Method 3 for estimating soil compression behaviour

Fig. 6 Compression behavior of Lianyugang clay with $\omega=146\%$ (Data after Hong et al, 2000)

Fig. 7 Compression behavior of Lianyugang clay with $\omega=114\%$ (Data after Hong et al, 2000)

Fig. 8 Compression behavior of Lianyungang clay with $\omega=85\%$ (Data after Hong et al, 2000)

Fig. 9 Compression behavior of Lianyugang clay with $\omega=50\%$ (Data after Hong et al, 2000)

Fig. 10 Compression behavior of Soft Louisville clay (Data after Locat et al, 1996)

Fig. 11 Compression behavior of Pleistocene stiff clay (Data after Cotecchia et al, 1997)

Fig. 12 Compression behavior of Bothkennar clay (Data after Burland, 1990)

Fig. 13 Compression behavior of Bisaccia clay (Data after Onofrio et al,1998)

Fig. 14 Compression behavior of Kaolin with $e_i=1.72$ (Data after Shipton et al, 2012)

Fig. 15 Compression behavior of Kaolin with $e_i=1.49$ (Data after Shipton et al, 2012)