Relationship Between Coefficient of Consolidation and Over-consolidation Ratio from Piezo-cone and Oedometer Testing

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ABSTRACT: The rate of consolidation can be theoretically estimated using the coefficient of consolidation, c_v, which is not a material constant, but varies with consolidation pressure. Although a number of analytical solutions have been proposed for non-linear consolidation rate, all of them consider a variable c_v indirectly based on the combined effects of soil permeability k and compressibility m_v. In particular, the accurate determination of k needs a hydraulic conductivity test, which is relatively costly and time consuming for clay soils. This paper documents the results of c_v estimated from piezo-cone testing conducted at a number of soft soil sites in Australia. The c_v -OCR relationships for these field data are presented, and shown to be represented by a power function: $c_v = c_{v\,(NC)}\,OCR^{\Lambda}$, in which the normally consolidated $c_{v\,(NC)}$ at OCR = 1, and the parameter Λ that controls the rate of increase of c_v, are material specific and can be related to soil index properties.

1 INTRODUCTION

It has long been recognised that laboratory consolidation tests underestimate the coefficient of consolidation c_v in the field. This is generally due to the presence of macro fabric in the sedimentation such as sand lenses, which give rise to faster drainage in the field. Moreover, c_v is dependent on the over-consolidation ratio (OCR). It is higher in the over-consolidated (OC) stress range than in the normally consolidated (NC) range. The OCR of soils varies with depth, and again changes as the load is applied. Therefore, c_v is not an intrinsic soil property. Although a number of analytical solutions have been proposed for non-linear consolidation rate, all of them consider variable c_v indirectly based on the combined effects of soil permeability k, and compressibility m_v. The accurate determination of k needs a hydraulic conductivity test, which is relatively costly and time consuming for clays.

This paper documents the results of c_v measured from piezocone tests conducted at a number of soft soil sites in Australia. The relationships of c_v -OCR for the tested sedimentary soils with different index properties are presented. While the relationships are inevitably site and material specific, it can be shown that certain patterns may be established and used to predict change in c_v with OCR.

2 STRESS HISTORY DEPENDENT c_v

According to Terzaghi's theory of 1D consolidation, c_v is theoretically related to m_v and k by:

$$c_v = \frac{k}{m_v \gamma_w} \tag{1}$$

where γ_w is the unit weight of water. For 1D consolidation, m_v can be defined in terms of the compressibility index c_c, or the recompression index c_r, depending on the vertical effective stress σ'_v relative to the preconsolidation pressure, σ'_p, as follow:

$$m_v = \frac{1}{1+e_0}\frac{\partial e}{\partial \sigma'_v} \begin{cases} m_v = \dfrac{0.434 C_r}{\sigma'_v(1+e_0)} & \text{for } \sigma'_v \le \sigma'_p \\ m_v = \dfrac{0.434 C_c}{\sigma'_v(1+e_0)} & \text{for } \sigma'_v > \sigma'_p \end{cases} \tag{2}$$

where e_0 is the initial void ratio. Tavenas et al (1983) indicated k can be related to e by:

$$e = e_0 + c_k \log (k / k_0) \tag{3}$$

where c_k and k_0 are defined in Figure 1b. This linear $e - \log k$ relationship holds irrespective of stress history. Substituting the equations (2) and (3) into (1), and following the derivation similar to that given in Walker et al (2012), a theoretical c_v vs. σ'_v curve can be obtained as shown in Fig. 1c. For the NC stress range, both k and m_v decrease rapidly with decreasing void ratio (i.e. with increasing σ'_v), hence c_v is fairly constant and is consistent with the general understanding about the variation of c_v with pressure (e.g. Terzaghi and Peck, 1967). For the OC stress range, the soil has a smaller reduction of m_v with decreasing e whilst the rate of change of k with e remains the same as for the NC stress range. This results in higher c_v values for the soils in the OC stress range than in the NC range.

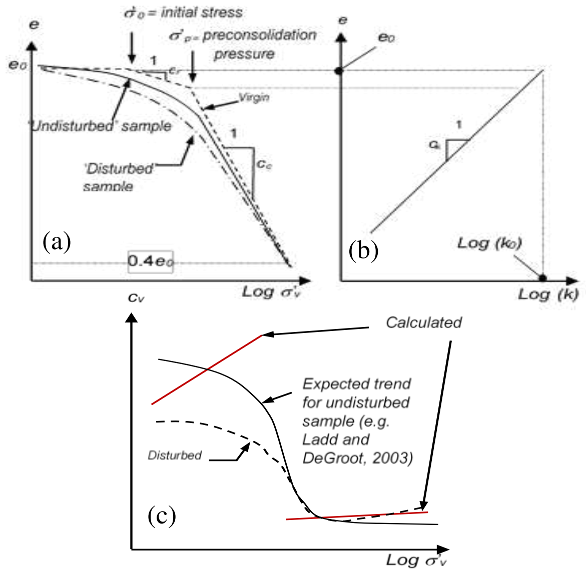

Fig. 1 Soil model with void ratio dependent (a) compressibility (b) permeability, and (c) calculated c_v

In the OC stress range, the theoretical c_v curve (Fig 1c) shows to increase with σ'_v, then followed by a sudden drop of c_v as the loading changes from recompression (OC) to virgin compression (NC). This calculated c_v appears to be contradictory with the expected trend outlined in Fig. 1c (cited Ladd and DeGroot, 2003), which shows that $c_{v\,(OC)}$ decreases to a fairly constant $c_{v\,(NC)}$ value as the stress level increases up to σ'_p. Therefore, the soil model may overestimate the consolidation rate when the soil is slightly over-consolidated. The authors considered likely that this inconsistency could be due to the use of the simplified bi-linear recompression and compression e –log σ'_v model. Should a non-linear e –log σ'_v equation is adopted, the resulting c_v could be more in line with expectation.

Fig. 2a shows a typical example given by Davies and Humpheson (1981) for a soft silty clay of high plasticity present at a trial embankment site in Belfast. The results from piezocone tests, in-situ permeability tests and oedometer tests all suggest a reduction of c_v with increasing σ'_v up to σ'_p and beyond which c_v is fairly constant. Fig. 2b replot the data in terms of c_v vs. OCR, in which OCR is calculated based on a σ'_p of about 130 kPa. The data can be represented by a linear log c_v–log OCR (i.e. power function) in the form:

$$c_{v\,(OC)} = c_{v\,(NC)}\, OCR^{\Lambda} \qquad (4)$$

The y-intercept of equation (4) is the $c_{v\,(NC)}$ at OCR = 1, and 'Λ' controls the rate of increase of c_v with OCR and may be influenced by material types. In order to substantiate the above c_v–OCR relationship and to assess the effect of soil types and soil index properties on this trend line, data from three soft soil sites along the east coast of Australia were assessed as described below.

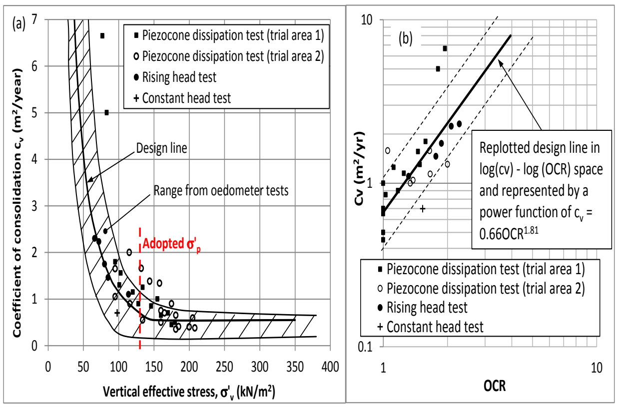

Fig. 2 (a) c_v vs σ'_v (Davies and Humpheson,1981); (b) Replotting 2(a) in log c_v–log OCR space

2.1 *Soft soil site 1 – Nambucca Floodplain*

Situated in the Mid North Coast region of New South Wales, Australia, the 2.5 km wide Nambucca Floodplain is on the southern side of the Nambucca River near Macksville. The soil profile comprises generally soft Holocene alluvial clay to a depth of about 15 m, then underlain by about 5 m thick soft/firm Holocene alluvial sandy clay. Towards Nambucca River, the sub-soil profile, comprises about 15 m thick soft/firm Holocene sandy clay, followed by the Pleistocene sandy deposits. The characterisation of the alluvial clay and the sandy clay within the Holocene sediments are summarised as: *Alluvial clay* – Liquid limit (LL) = 35-50%; Plasticity index (PI) = 10-30%; Compression ratio [CR= $c_c/(1+e_0)$] = 0.18; Recompression ratio [RR= $c_r/(1+e_0)$] = 0.025. *Sandy clay* – LL = 20-40%; PI = 5-20%; CR = 0.11; RR = 0.016.

Piezocone tests were carried out to assess the field c_v, undrained shear strength s_u and OCR profiles. For the c_v assessment, the horizontal coefficient of consolidation (c_h) is firstly assessed from the piezocone dissipation tests using Teh and Houlsby's (1991) method with a rigidity index of 100. Published literature and our experience in the region generally suggest that c_h/c_v is between 1.5 and 2, hence an average value of 1.75 is adopted.

The OCR can be assessed from the piezocone inferred s_u using SHANSEP method ($s_u = S(OCR)^m \sigma'_{v0}$) proposed by Ladd (1991). For sedimentary clays of low to moderate sensitivity, Ladd (1991) has adopted the relationships of S = 0.2+0.05PI and m = 0.88(1 -RR/CR) ± 0.06. For the clay and sandy clay encountered, S = 0.21 and m = 0.8. Note that the inferred s_u from piezocone has been assessed based on the corrected cone resistance (q_t) and using a cone factor (N_{kt}) of 15, which has been calibrated against the inferred s_u from in-situ vane shear, T-bar and dilatometer test results.

The observed relationship between field c_v and OCR from piezocone is presented in Fig. 3a. The results indicate a prominent linear trend between c_v and OCR in logarithmic space for each soil type. Adopting the power function of Equation (4), regression analyses for the piezocone data give a best fit line with $c_{v\,(NC)}$ = 10m^2/yr and Λ = 1.0 for clay and $c_{v\,(NC)}$ = 22m^2/yr and Λ = 3.38 for sandy clay. Also, sandy clay has a steeper increase of c_v with OCR and a higher Λ value than that of clay. Further discussion is provided in Section 2.4.

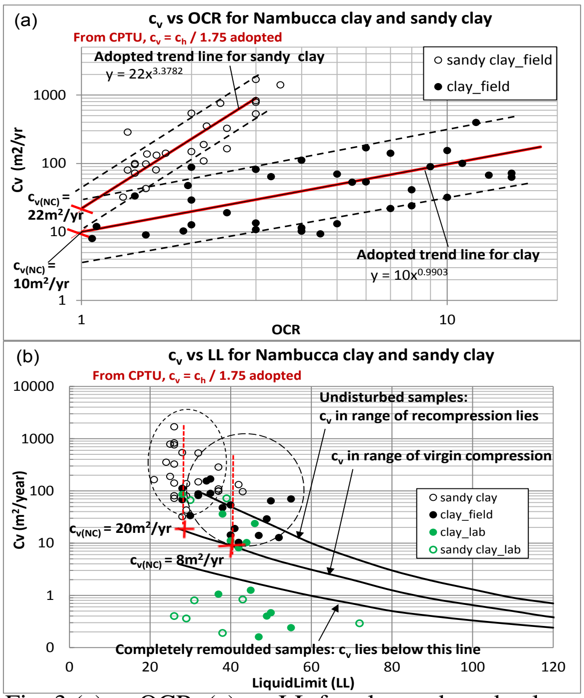

Fig. 3 (a) c_v-OCR, (a) c_v -LL for clay and sandy clay

NAVFAC (1986) has developed correlations of c_v for remoulded, normally and over-consolidated clay soils with their LL as shown in Fig. 3b. The field c_v for clay has a LL range of 35-50, which was determined from laboratory tested samples obtained from adjacent boreholes and at similar depths. These c_v data generally lie between the NAVFAC curves for NC and OC soils, indicating that the soils are lightly over-consolidated. By using a mean LL value of 42 and extrapolating down to intersect the NAVFAC curve for normal consolidation, it can be assessed that $c_{v\,(NC)}$ is about 8m^2/yr, which is consistent with that assessed in Fig. 3a. Similarly for sandy clay, the LL range of the field c_v is 25–40, the $c_{v\,(NC)}$ as determined from NAVFAC in Fig. 3b (20m^2/yr) is consistent with that from the c_v–OCR plot in Fig. 3a (22m^2/yr). The laboratory c_v values are lower than the piezocone inferred c_v due to sample disturbances, and lie below the NAVFAC curve for remoulded soil.

2.2 *Soft soil site 2 – Hastings River Floodplain*

Hastings River Floodplain is located at the middle reach of the river west of Port Macquarie and is near an existing river crossing of the Pacific Highway connecting between Sydney and Brisbane. The alluvium within the floodplain is up to 20 m deep and is composed of clays, silts and sands.

Using the approach outlined in Section 2.1, Fig. 4a presents a plot of c_v vs. OCR estimated from piezocone soundings. The field data have been separated into fine grained silt/clay soils and sand clay mixtures which generally range from sandy clay through to clayey sand. A similar linear trend is observed between c_v and OCR in logarithmic space for each soil type. Using the power function of Equation (4), the average trends from regression analyses of the field data indicate $c_{v\,(NC)}$ = 3.2 m^2/yr and Λ = 1.39 for silt/clay and $c_{v\,(NC)}$ = 12.5 m^2/yr and Λ = 2.16 for the sand clay mixtures. The LL ranges of the field c_v are 48 – 69 for silt/clay and 25 – 45 for the sand clay mixtures. Using the mean values from the respective LL ranges, the $c_{v\,(NC)}$ as determined from NAVFAC correlations are 3.5m^2/yr and 13m^2/yr (Fig. 4b), which are consistent with those from the c_v – OCR plot in Fig. 4a

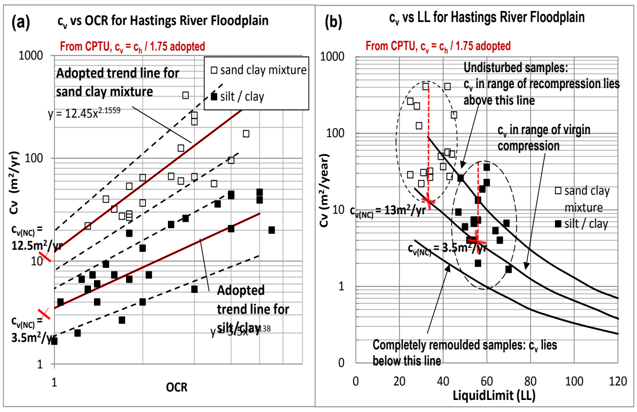

Fig. 4 (a) c_v - OCR, (a) c_v - LL for silt/clay and sand clay mixture (Hastings River Floodplain)

2.3 *Soft soil site 3 – Kooragang Island*

Kooragang Island lies near the mouth of the Hunter River, Newcastle (NSW) and is primarily a coal export port. Most of the coal terminals are situated on reclaimed swamp typically consisting of 'mud' deposit of very soft, dark grey clay with shells (Soil Type B) extending up to about 5 m depth, followed by soft sandy clays and loose sands (Soil Type A). The mud is highly plastic with average LL and PI values of 80 and 54 respectively. Conversely, the sandy clay is of low plasticity with average LL and PI of 25 and 9 respectively.

The oedometer and triaxial test results generally under-estimate c_v due to sample disturbance. This is demonstrated in Fig. 5b. From NAVFAC correlation, $c_{v\,(NC)}$ are likely to be at least 25 m^2/yr and 1.5 m^2/yr for Soil Types A and B, respectively. The dissipation tests from piezocone provide more realistic time rate behaviour. Regression analyses from the c_v – OCR plot in Fig. 5a indicate that the $c_{v\,(NC)}$ values are 28 m^2/yr and 2.2 m^2/yr for Soil

Types A and B, which are commensurate with NAVFAC for NC soils. The assessed Λ for Types A and B are 2.02 and 0.89 respectively.

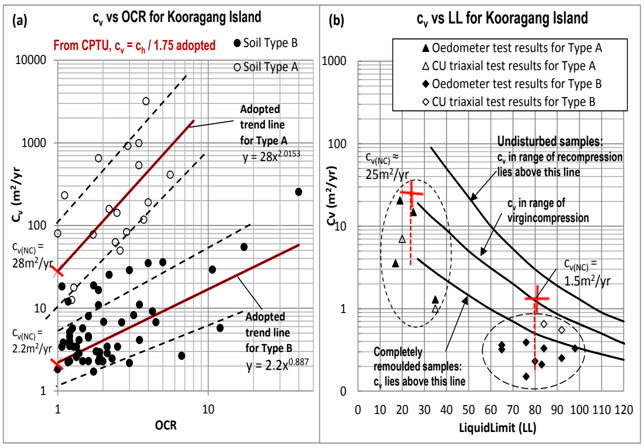

Fig. 5 (a) c_v - OCR, (b) c_v - LL for Soil Types A and B at Kooragang Island

2.4 *Discussion of c_v results and parameter Λ*

Understanding site geology and identifying soil stratigraphy are paramount for site characterisation and c_v assessment. The following design tasks shall be carried out: (i) Careful sorting and identifying the material types at which the piezocone dissipation tests were conducted, using the adjacent borehole information as well as the piezocone test data for the inferred material behaviour types; (ii) Identifying the corresponding LL of the field c_v based on Atterberg limit results from the tested samples obtained from adjacent boreholes; and (iii) Assessing the corresponding OCR of the field c_v using SHANSEP method (Ladd,1991) in conjunction with the piezocone inferred s_u.

Following the works of identifying material types and assessment of field c_v values and their corresponding LL and OCR, it can be shown from the illustrated soft soil sites that the c_v - OCR relationship inferred from piezocone test data for a particular material type follows a linear trend in the double logarithmic space. This is equivalent to the power function given by Equation (4). The y-intercept of this equation is the normally consolidated $c_{v\,(NC)}$, which has been shown to be consistent with that determined by NAVFAC correlation for $c_{v\,(NC)}$ with LL for normally consolidated soils.

It is observed that there is a steeper increase of c_v with OCR as the clay soil become less plastic with lower liquid limit (LL) value. Subsequently, the parameter 'Λ' in Equation (4) that controls the rate of change of c_v with OCR increases as LL reduces. Hence Λ and LL are inversely related. Fig. 6 presents a plot of Λ with the corresponding mean LL vales that were assessed from the illustrated soft soil sites. It can be seen that a correlation exists between Λ and LL, albeit with limited data sets. This correlation can be represented by:

$$\Lambda = 55 \times LL^{-0.96} \qquad (5)$$

It is envisaged that correlations of Λ with other soil index properties such as PI, clay content or shrinkage index may exist. The investigation of these correlations warrants further research.

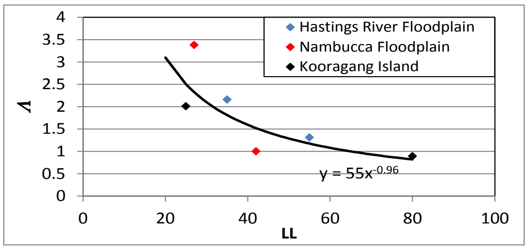

Fig. 6 Λ vs LL

3 CONCLUSIONS

In this paper an attempt has been made to investigate the variation of c_v with stress history (i.e. OCR) for soils with different soil index properties. The influences and conclusions drawn are based on c_v results obtained from piezocone dissipation tests and index properties determined from laboratory tested samples obtained from adjacent boreholes and at similar depths. Based on these results, a correlation equation in the format of power function has been proposed to predict c_v in terms of OCR:

$$c_{v(OC)} = c_{v(NC)} OCR^{\Lambda}$$

It has been shown that $c_{v\,(NC)}$ is consistent with NAVFAC correlation with LL for normally consolidated clay and Λ is inversely related with LL. It is envisaged that Λ could also be well correlated with other soil properties such as PI, clay content or shrinkage index, which merits further research.

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