

Discussion: Constant rate of displacement test on ultra-soft soil

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The authors have elucidated the underlying importance of using an appropriate strain rate (R) in order to obtain the true e - $\log \sigma'_v$ response and the non-linear steady-state C_v and k values (Equations 8 and 9) from the constant rate of displacement (CRD) consolidation test, and their proposed method, based on estimated compression index values, for selecting a suitable strain rate for large-strain CRD testing of slurry sediments is welcomed. In carrying out a series of CRD tests for R between 0.01%/min and 0.1%/min on high-plasticity clay (CH) slurry specimens, the authors rightly point out that the high measured pseudo-preconsolidation pressures, which clearly do not exist in reconstituted ultra-soft soil, are due to viscous effects during the test procedure.

The authors have used Gibson's coefficient for large-strain consolidation, C_F , in developing Equation 3, which is subsequently used to determine suitable strain rates for CRD testing of these ultra-soft sediments. However, we have had difficulty in reproducing the suggested strain rate values in Table 1, and although further guidance on the use of the compression indices (Equations 4–6) in implementing the proposed method would be most welcome, on further investigation we suspect that there may be an error in Equation 2. According to Gibson *et al.*,¹⁸ C_F is defined by

$$17 \quad C_F = \frac{(1 + e_i)C_v}{1 + e}$$

Using this expression, Equation 3 is rearranged as

$$18 \quad R = \frac{C_F(1 + e)C_c}{m^2 H_0(1 + e_1)^2} \left[\frac{u_b/\sigma_1}{1 - 0.7(u_b/\sigma_1)} \right]$$

Slower strain rates should be used for CRD test specimens with increasing liquid limit values (following recommendations based on liquid limit by ASTM D4186¹⁹), although, on the basis of Table 1, the authors state the contrary. It should also be noted that Burland²⁰ defined the intrinsic compression index (C_c^*) in relation to reconstituted clays with $w_L < w < 1.5w_L$ (where w_L is the liquid limit), although most of the

moisture content values reported in Table 1 fall outside this range.

The authors also state in Section 6.2 that test specimens with lower moisture content require a slower strain rate than those with higher moisture contents for the same type of ultra-soft soil, although the contrary would be expected, and is supported by a CRD study by Smith and Wahls¹ on high-moisture-content clay minerals. Indeed, the authors conclude by recommending the slowest strain rate used of 0.01%/min, or slower, for the CH slurry specimens tested in this study. ASTM D4186–06¹⁹ recommends an even slower rate of about 0.0017%/min in this case, which may have yielded excess pore pressure ratio values of less than 0.3, in accordance with the steady-state solution for the non-linear theory of Wissa *et al.*² (where steady-state conditions are assumed to occur when the dimensionless time factor T is less than 0.5). According to Figure 5, the measured excess pore pressure ratio did not fall below 0.3, and only for the slowest strain rate of 0.01%/min at the lower moisture content tested does the stabilised excess pore pressure ratio fall below 0.4. Since the shorter duration test period is one of the main advantages of both CRD and CRS tests over EOP step-loading consolidation tests (against which the e - $\log \sigma'_v$ response, C_v and k values derived from CRD/CRS tests are benchmarked), we appreciate that ultimately a balance must be struck; otherwise, CRD tests carried out at $R \leq 0.01\%/min$ and standard EOP tests would take comparable time periods to complete.

Finally, can the authors' conclusions regarding the strain rate used in CRD testing these ultra-soft seawater sediments be equally applied for alluvial and lacustrine sediments? Recent research by Yukselen-Aksoy *et al.*²¹ has suggested that saline pore water may have a significant effect on the load-compression and consolidation responses when the plasticity index value is greater than 70 ($I_p = 74$ in this study).

Authors' reply

The authors would like to thank the discussers for the positive comments on the proposed method for a suitable strain rate for large-strain CRD testing of ultra-soft soils.

Regarding Equation 3, Gibson *et al.*¹⁸ proposed the following equation for C_F

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$$C_F(e, e_0) = -\frac{k(e)}{\rho_f} \frac{(1 + e_0)^2}{1 + e} \frac{d\sigma'}{de}$$

However, Gibson *et al.*¹⁸ have stated that in most applications it is preferable to work in terms of the equation

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$$g(e) = -\frac{k(e)}{\rho_f} \frac{1}{1 + e} \frac{d\sigma'}{de}$$

Been and Sills²² therefore described the coefficient of large-strain consolidation for self-weight consolidation of soft soils as

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$$C_F(e) = -\frac{k(e)}{\rho_f} \frac{1}{1 + e} \frac{d\sigma'}{de}$$

Again, Gibson *et al.*²³ proposed the relation between g and C_v with the following equation as described in Equation 2 of our paper.

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$$g = C_F = \frac{C_v}{(1 + e)^2}$$

The strain rate equation given in Equation 3 in our paper therefore remains valid.

Although ASTM D4168¹⁹ suggested a slower strain rate for CH material than for CL material, it was not based on liquid limit; it was based on the hydraulic conductivity of the material, as stated in Note 16 of the standard.

In Equation 5 of our paper, Burland²⁰ described C_c^* as increasing with e_L . Therefore a higher liquid limit would yield a faster strain rate, based on Equation 3 of our paper.

Burland's²⁰ intrinsic compression index (C_c^*) is defined as void ratio change per log cycle, especially within the range of e_{10} and e_{1000} for reconstituted clays with $w_L < w < 1.5w_L$. It should be noted that when an ultra-soft soil is compressed to a void ratio lower than e_{10} , its water content will also fall within the same range.

The authors agree that further study is required to confirm whether specimens with lower moisture contents would require a slower strain rate than those with higher moisture contents

for the same type of ultra-soft soil, even though this observation was supported by Smith and Wahls.¹

Unlike tests on natural soil, the consolidation test on ultra-soft soil may take from several weeks to a few months to complete.²⁴ This is because of the large strain followed by low hydraulic conductivity and little or no dissipation of excess pore pressure in the early stage of consolidation, as reported by Bo *et al.*¹⁰ Therefore the strain rate of 0.01%/min is still much faster than the conventional test.

Finally, the strain rate suggested in our paper can still be applied for any ultra-soft soil, provided the liquid limit is known.

As described by Yuxselen-Aksoy *et al.*,²¹ the effect of salt water on consolidation is insignificant. Although there may have been a small effect on the rate of consolidation, owing to the slightly higher unit weight of pore water, the compression parameters are unlikely to be affected, provided the necessary salt corrections are made in the moisture content determination where required, as suggested by Bo²⁴ and Imai *et al.*²⁵

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