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Preconsolidation Pressure of Post-Glacial Soft Clay and Silt Deposits

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Abstract. Preconsolidation pressure, σ'_p, plays a major role in settlement analysis, in design of precompression and surcharging operations, and interpretation and evaluation of undrained shear strength. The original definition of preconsolidation pressure using the oedometer test began with Arthur Casagrande at a time when the role of aging on structure of soft clay and silt deposits was not fully recognized. It is now well established that all soft clay and silt deposits, independent of geological loading–unloading history, are expected to display a preconsolidation pressure with σ'_p/σ'_{vo} greater than unity. There are different alternatives, in addition to undisturbed sampling and incremental loading (IL) or constant rate of strain (CRS), oedometer testing to determine preconsolidation pressure. These include in situ vane shear and push cone penetration tests, together with well-established empirical correlations. Important uncertainties, however, still remain in connection to (a) magnitudes of σ'_p/σ'_{vo} to be expected for soft clay and silt deposits, (b) evaluation of preconsolidation pressure from end-of-primary or 24 hour void ratio-effective vertical stress relations from IL oedometer tests, (c) interpretation of preconsolidation pressure from CRS oedometer tests subjected to different imposed vertical strain rates, (d) determining preconsolidation pressure from in situ vane shear undrained shear strength, (e) interpretation of preconsolidation pressure from push cone penetration resistance, and (f) interpretation of preconsolidation pressure from field porewater pressure observations in soft clay and silt deposits subjected to embankment loading.

Keywords. Soft clay and silt deposits, preconsolidation pressure, oedometer tests, undrained shear strength.

1. Introduction

Preconsolidation pressure, σ'_p, defining the boundary between recompression and compression in an end-of-primary (EOP) void ratio versus logarithm of effective vertical stress relationship, is the most important characteristic of soft clay and silt deposits. Preconsolidation pressure is used by geotechnical engineers in settlement analyses, in design of precompression and surcharging programs, and in evaluating undrained shear strength from empirical correlations for stability analyses of soft clay and silt deposits [1].

Preconsolidation pressure is the yield stress in laterally constrained compression, and σ'_p is a point on the yield envelope of a soil. Therefore, σ'_p is the most appropriate consolidation pressure to normalize undrained shear strengths, such as $s_{uo}(TC)/\sigma'_p$, $s_{uo}(TE)/\sigma'_p$, $s_{uo}(DSS)/\sigma'_p$, and $s_{uo}(FV)/\sigma'_p$, as in Figure 1. One important application of σ'_p,

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is in an empirical equation for mobilized undrained shear strength for stability analyses of embankments, footings and excavations in inorganic soft clays [2, 3].

$$s_{uo}(mob) = 0.22\ \sigma_p^{'} \tag{1}$$

And for organic soft clays [4]

$$s_{uo}(mob) = 0.26\ \sigma_p^{'} \tag{2}$$

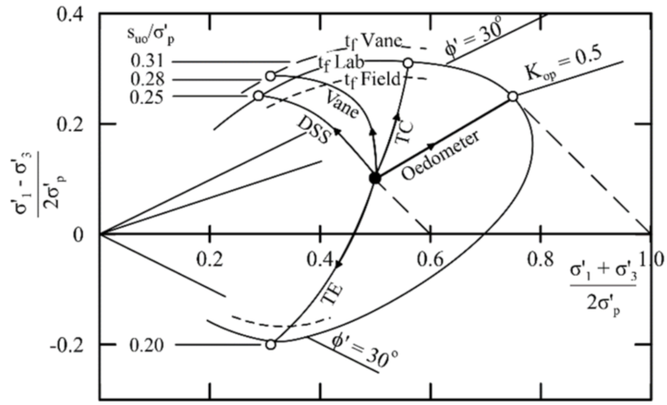

Figure 1. Preconsolidation pressure used to normalize yield surface.

In the recompression range of most soft clays, increases in effective vertical stress produce minor changes in soil structure. Therefore, the associated primary settlements are small, and the increases in undrained shear strength are insignificant. Precompression or surcharging programs intended to increase undrained shear strength or minimize post-construction secondary settlements, must produce during preloading or surcharging, effective vertical stresses in the soil exceeding the preconsolidation pressure. On the other hand, secondary settlement is expected to be significant for effective stresses in the recompression range with σ'_{vf}/σ'_p greater than 0.7, because duration of primary consolidation is short and secondary compression index, C_α, is expected to increase with time to C_α/C_c times the C_c just past the preconsolidation pressure.

2. Mechanisms responsible for preconsolidation

When preconsolidation pressure was first defined by Casagrande [5], it was assumed to represent the geologic maximum pressure to which the soil has been subjected in the past. The geologic preconsolidation pressure may result from an overburden sediment that has been eroded away, a snow or ice load that has melted, or a low groundwater level (or porewater pressure) that has returned to its higher present condition. However, it is now known that a preconsolidation pressure may also result from the aging of soils, such as secondary compression, thixotropic hardening, or even bonding of soil particles by carbonates or silicates. It is possible to predict magnitudes of σ'_p/σ'_{vo} resulting from geologic secondary compression or thixotropic hardening [6- 9],

$$\frac{\sigma'_p}{\sigma'_{vo}} = \left(\frac{t}{t_p}\right)^{\frac{C_\alpha/C_c}{1-C_r/C_c}+\beta} \tag{3}$$

where σ'_{vo} is the present effective overburden pressure, t_p is the geologic primary consolidation time of a sediment sublayer, t is the age of the deposit, C_α is the secondary compression index, C_c is the compression index, C_r is the recompression index, and β is the thixotropic hardening parameter (for values of C_α/C_c for all soils refer to Table 16.1. in [1]). Table 1 lists values of $(\sigma'_p/\sigma'_{vo})_S$ resulting from secondary compression and $(\sigma'_p/\sigma'_{vo})_{S+T}$ resulting from secondary compression plus thixotropic hardening, based on Eq. (3) together with $C_\alpha/C_c = 0.04$, $C_r/C_c = 0.1$, and $\beta = 0.02$.

Table 1. Computed values of σ'_p/σ'_{vo}.

t/t_p	$(\sigma'_p/\sigma'_{vo})_S$	$(\sigma'_p/\sigma'_{vo})_{S+T}$
100	1.23	1.35
1000	1.36	1.56
10000	1.51	1.81

A combination of soil aging, with possible preloading by a decrease in effective vertical stress, have produced magnitudes of σ'_p/σ'_{vo} in the range of 1.2 to 3.0, for soft clay and silt deposits (e.g. Table 1 in [10]). For soft clay and silt deposits, it has not been possible to confirm aging effects on σ'_p through a cement bonding of particles. For most soft clay and silt deposits, in the absence of preconsolidation resulting from a decrease in effective vertical stress, a minimum value of $\sigma'_p/\sigma'_{vo} = 1.4$ may be assumed.

3. Preconsolidation pressure from tests

3.1. Incremental loading oedometer

The most direct measurement of σ'_p has been from incremental loading (IL) oedometer tests on undisturbed, 20 mm thick specimens with a diameter to thickness ratio of 3. Undisturbed soft clay and silt specimens with SQD of A or B are required ([1], Table 12.1). The EOP e–log σ'_v relationship is used together with the Casagrande [5] construction to define σ'_p. In case the e–log σ'_v relation corresponds to the void ratio at elapsed time of 24 hours, then the correction factor in Table 2 should be used to obtain σ'_p corresponding to EOP consolidation.

Table 2. Correction factor to obtain σ'_p from $\sigma'_{p(24hrs)}$.

t_p/24hrs	$\sigma'_p/\sigma'_{p\,(24hrs)}$
0.02	1.17
0.04	1.14
0.08	1.11
0.17	1.07
0.33	1.05
0.67	1.02

For the IL test a pressure increment ratio of ½ is used between σ'_{vo} and $2\sigma'_p$, and pressure increment ratio of 1 in the remaining pressure range. For each pressure increment, the most precise definition of EOP compression is in terms of excess porewater pressure measurements (e.g. EOP compression at u' ≈ 1 to 2 kPa). However, in the absence of porewater pressure measurements, the Casagrande construction [11] is most suitable for defining EOP consolidation.

3.2. Constant rate of strain oedometer

Constant rate of strain oedometer test may be performed when reliable measurement of porewater pressure is possible [12]. In this oedometer test, drainage is allowed from the top of the 20 mm thick undisturbed specimen, and the porewater pressure is measured at the impermeable bottom. The main testing control is through imposed rate of vertical deformation. The EOP e-log σ'_v relationship corresponding to near zero excess porewater pressure at the bottom of the specimen is obtained using the following vertical strain rate [13].

$$\dot{\varepsilon}_p = \frac{k_{vo}}{2^{C_c/C_k} H^2} \frac{\sigma'_p}{\gamma_w} \frac{C_\alpha}{C_c} \tag{4}$$

where k_{vo} is the initial permeability of the specimen, C_k is the permeability change index, (C_k/C_c in the range of ½ to 2; $C_k = 0.5\ e_o$), H is the maximum drainage distance, and γ_w is the unit weight of water. The e-log σ'_v relation from a CRS oedometer test subjected to vertical strain rate near $\dot{\varepsilon}_p$ is compared in Figure 2a with EOP e-log σ'_v relation from an IL oedometer test. The preconsolidation pressure from CRS tests subjected to $\dot{\varepsilon}_p$ is compared in Figure 2b to σ'_p from EOP e-log σ'_v relation of IL oedometer tests. However, an imposed strain rate according to Eq. (4) results in a too long oedometer test duration, and the near zero excess porewater pressure at the impermeable bottom of the specimen does not allow computing soil permeability as a function of void ratio, using the porewater pressure measurements [12]. Therefore, it is suggested to use an imposed strain rate of

$$\dot{\varepsilon}_I = 10\ \dot{\varepsilon}_p \tag{5}$$

and correct the resulting e-log σ'_v relationship, with $\sigma'_v = \sigma_v - 2/3\ u'_b$, where u'_b is the excess porewater pressure measured at the bottom of the specimen, according to (see e.g. Figure 16.16 in [1])

$$\sigma'_p = [\sigma'_p]_{\dot{\varepsilon}_p} = 0.912\ [\sigma'_p]_{\dot{\varepsilon}_I} \tag{6}$$

The relationship between $[\sigma'_p]_{\dot{\varepsilon}_p}$ and $[\sigma'_p]_{\dot{\varepsilon}_I}$ is shown in Figure 2c for a series of CRS oedometer tests on undisturbed specimens of seven soft clay deposits.

3.3. In situ Vane shear

An empirical correlation between $s_{uo}(FV)/\sigma'_p$ and plasticity index, I_p, as shown in Figure 3a is available for inorganic soft clay and silt deposits, and can be used together with the measurements of $s_{uo}(FV)$ and I_p to determine σ'_p. Note that $s_{uo}(FV)/\sigma'_p$ of any soft clay deposit is a constant independent of σ'_p/σ'_{vo} as illustrated in Figure 3b ([1], Figs 20.10

and 20.11). An example of σ'_p (FV) computed using Figure 3a together with s_{uo}(FV) and I_p is shown in Figure 4a.

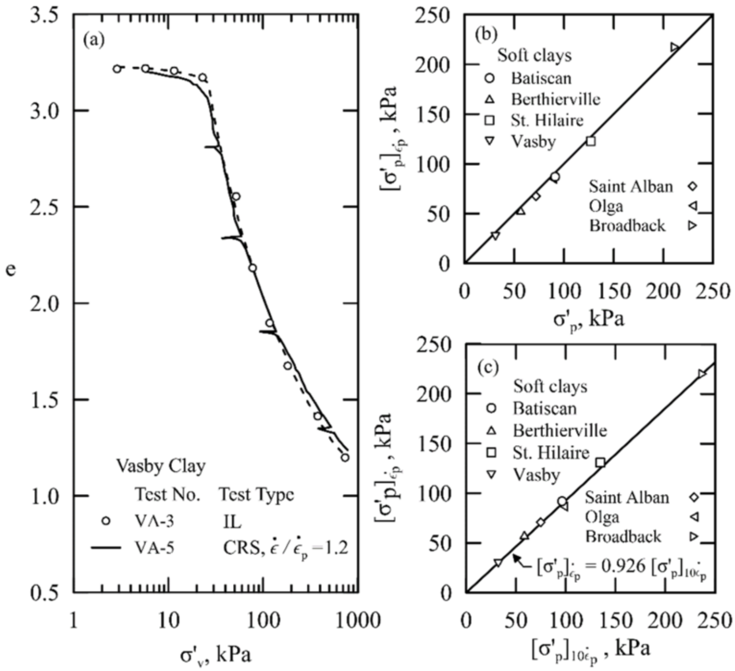

Figure 2. (a) The e-log σ'v relation from a CRS oedometer test subjected to imposed strain rate ò$_p$ compared with EOP e-log σ'_v from an IL oedometer test, (b) Preconsolidation pressure determined from the CRS oedometer test subjected to axial strain rate ò$_p$ compared to σ'_p determined from IL oedometer test; (c) Empirical correlation between σ'_p at ò$_p$ and σ'_p at 10 ò$_p$.

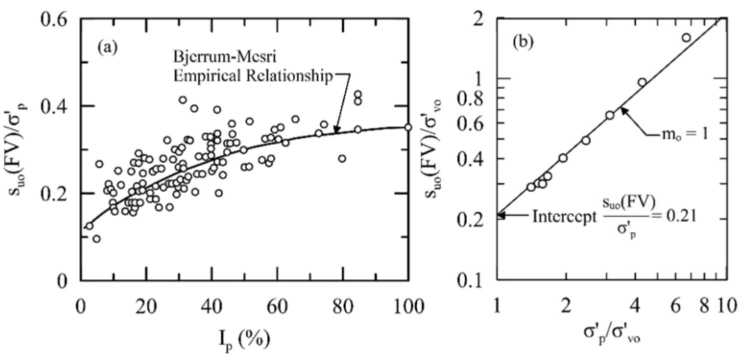

Figure 3. (a) Bjerrum-Mesri empirical relationship on $s_{uo}(FV)/\sigma'_p$ versus I_p together with additional data for a large number of soft clay and silt deposits [1, 2]; (b) undrained shear strength from in-situ vane tests for a soft clay in the Persian Gulf [14].

3.4. Push cone penetration

A number of empirical correlations between σ'_p and $(q_t - \sigma_{vo})$ are available, where q_t is the cone tip resistance, and σ_{vo} is the total vertical stress at the cone tip depth. One such empirical correlation [15] for inorganic soft clay and silt deposits is

$$\sigma'_p = 0.28\ (q_t - \sigma_{vo}) \tag{7}$$

and for organic soft clay and silt deposit is

$$\sigma'_p = 0.24\ (q_t - \sigma_{vo}) \tag{8}$$

An example of σ'$_p$ (cone) computed using Eq. (7) is shown in Figure 4b.

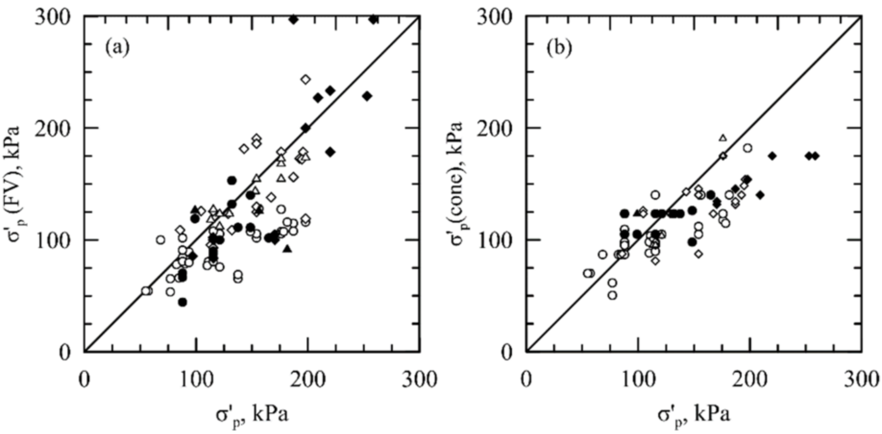

Figure 4. Preconsolidation pressure determined using, (a) s_{uo}(FV) and I_p together with Figure 3a; (b) q_t - σ_v together with Eq. (7), for the Beauharnois soft clays from Québec, Canada.

3.5. Laboratory shear

In some occasions, preconsolidation pressure may be determined from empirical correlations of undrained shear strength that have been normalized by σ'$_p$. As an example, s_{uo}(TC)/σ'$_p$ = 0.32 for inorganic soft clays and s_{uo}(TC)/σ'$_p$ = 0.38 for organic soft clays, are independent of plasticity index. Thus, for inorganic soft clays

$$\sigma'_p = 3.13\ s_{uo}(\mathrm{TC}) \tag{9}$$

and for organic soft clay and silt deposits is

$$\sigma'_p = 2.63\ s_{uo}(\mathrm{TC}) \tag{10}$$

4. Preconsolidation pressure from embankment loading

4.1. Porewater pressure response

Porewater pressure observations during embankment loading on soft clay and silt deposits can be used to compute preconsolidation pressure mobilized in the field [16, 17]. It has been observed, as shown in Figure 5, that the measured excess porewater pressure increment at any depth is less than the computed total vertical stress increment at that depth. However, at certain embankment load, the measured excess porewater pressure increment becomes equal to the total vertical stress increment. It has been reasoned that the transition instant in porewater pressure response, corresponds to the preconsolidation pressure, and σ'_p mobilized in the field is computed with σ'_{vo}, together with effective vertical stress increase. One explanation of porewater pressure response in Figure 5 is that in the recompression range, the coefficient of consolidation is large and part of the excess porewater pressure dissipates, whereas, in the compression range, the small coefficient of consolidation leads to fully undrained condition.

4.2. Porewater pressure dissipation

When an embankment load spans the preconsolidation pressure, then part of the excess porewater pressure corresponding to (σ'_p - σ'_{vo}) in recompression dissipates with time rapidly, and the remaining excess porewater pressure dissipates slowly in the compression range [7, 18]. A laboratory oedometer example of a pressure increment spanning the preconsolidation pressure is shown in Figure 6a, and a field example is shown in Figure 6b. From the observed value of $\mu_{mc} = u'_{mc}/\Delta\sigma_v$, and applied pressure increment expressed in terms of $\sigma'_{vf}/\sigma'_{vo}$, one can calculate preconsolidation pressure

$$\frac{\sigma'_p}{\sigma'_{vo}} = 1 + (1 - \mu_{mc})\ (\frac{\sigma'_{vf}}{\sigma'_{vo}} - 1) \qquad (11)$$

where u'_{mc} is the maximum excess porewater pressure remaining after the initial rapid dissipation $[\Delta\sigma_v - (\sigma'_p - \sigma'_{vo})]$. For the loading and porewater pressure dissipation data in Figs. 6a and 6b, the values of σ'_p/σ'_{vo} are computed using Eq. (11) and listed in Table 3.

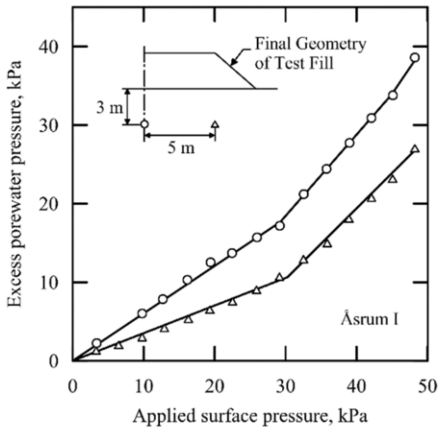

Figure 5. Excess porewater pressures observed during construction of Åsrum I test fill.

Table 3. Preconsolidation pressure computed using porewater pressure dissipation compared to the values from oedometer tests.

Porewater pressure Dissipation	$\sigma'_{vf}/\sigma'_{vo}$	μ_{mc}	σ'_p/σ'_{vo} (dissipation)	σ'_p/σ'_{vo} (oedometer)
Olga (Laboratory)	1.429	0.13	1.37	1.37
Gloucester (Field)	1.744	0.40	1.45	1.44

5. Preconsolidation pressure mobilized in the field

The EOP e-log σ'$_v$ relation, and therefore, σ'$_p$ is independent of the duration of primary consolidation [8, 19, 20]. In other words, the σ'$_p$ (Field) is equal to σ'$_p$ determined from EOP e-log σ'$_v$ relation of 20 mm thick undisturbed oedometer specimens, or to σ'$_p$ corresponding to ò$_p$ of the CRS tests. This is illustrated in Figure 7 using 75 different observations of porewater pressure response to embankment loading on 25 different soft clay and silt deposits.

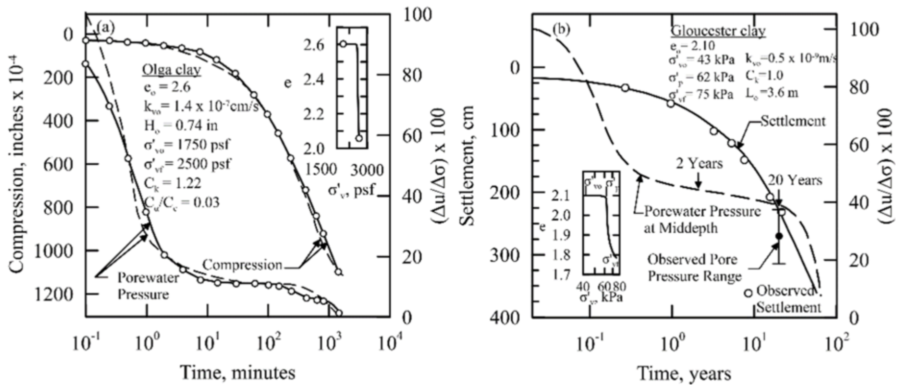

Figure 6. Consolidation behaviour for a pressure increment spanning the preconsolidation pressure (a) in the laboratory for the Olga clay; (b) the Field for the Gloucester clay in Canada.

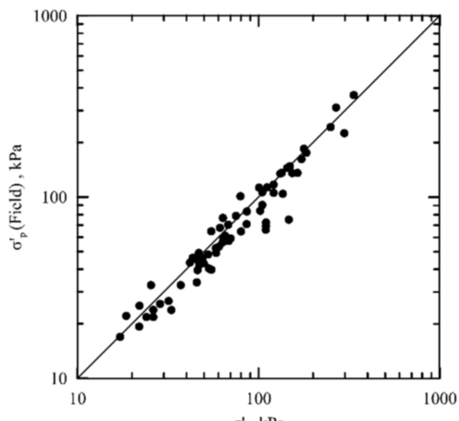

Figure 7. Preconsolidation pressure mobilized in the field compared with σ'$_p$ from EOP e- log σ'$_v$ curves of 20 mm thick oedometer specimens. Data from [21].

6. Conclusions

Preconsolidation pressure defines the boundary between recompression and compression, and is the most significant characteristic of soft clay and silt deposits, with σ'$_p$/σ'$_{vo}$ generally less than 3. Because preconsolidation pressure is a yield stress for laterally constrained compression on the yield envelope, it is the most appropriate consolidation pressure for normalizing undrained shear strength. The most common procedure for determining preconsolidation pressure is either IL or CRS oedometer tests on undisturbed SQD A or B specimens. However, σ'_p could also be determined from empirical correlation for s_{uo}(FV), (q_t - σ_v), and laboratory undrained shear strength, such as s_{uo}(TC). Preconsolidation pressure σ'_p is independent of the duration of primary consolidation, therefore, σ'_p corresponding to EOP consolidation of IL or corresponding to ò$_p$ of CRS oedometer tests, on 20 mm thick undisturbed specimens, can be used directly in settlement analyses, design of precompression programs and evaluation of undrained shear strength for stability analyses for field construction.

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