2 Estimating Consolidation Settlements of Shallow Foundations on Overconsolidated Clay

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STATEMENT OF PROBLEM

A shallow foundation is designed at a site underlain by a layer of saturated, overconsolidated clay. The maximum stress in the clay stratum due to overburden plus net increase in pressure due to the foundation is everywhere less than the maximum past (preconsolidation) pressure.

The clay layer is of sufficient thickness that the increase in stress due to loading may be attenuated with depth. The magnitudes of these stress increases are calculated from elasticity theory; if necessary (modular ratio > 5), a layered system is assumed.

The factor of safety of the foundation with respect to bearing capacity is 3 or more. Volume changes due to consolidation of the clay layer are assumed to be 1-dimensional. What procedures should be used to estimate the consolidation settlements assuming that "undisturbed" samples can be obtained either from hand-cut blocks or from thin-walled, fixed-piston samplers? If the clay neither swells an extraordinary amount when removed from the sampling tubes nor is especially sensitive to remolding, what magnitude of error in this estimate should be expected?

GENERAL CONSIDERATIONS

Inasmuch as volume changes are considered to be 1-dimensional, the apparent consolidation settlement S_i of each segment of the clay stratum, within which the initial void ratio e_o, the recompression index C_r, the initial effective vertical overburden pressure p_o', and the net change in vertical stress due to loading Δp do not vary greatly, may be computed from

$$S_i = \frac{C_r}{1 + e_o} H_i \log \frac{p_o' + \Delta p_i}{p_o'} \qquad (3)$$

The apparent total consolidation settlement S is

$$S = \sum_{i=1}^{i=n} S_i \qquad (4)$$

The first task is to identify the number and thickness of layers to be considered. This can be done with the help of a plot such as that shown in Figure 8. At least 2 consolidation tests should be performed on samples from each layer; if the layer is thicker than 20 ft (6 m), 1 test for each 10 ft (3 m) of thickness should be conducted. Data on water content and Atterberg limits should be available for every 5 ft (1.5 m) of depth.

In situ values of C_r are generally smaller than those measured in the laboratory principally because of

1. Disturbance during sampling, storage, and preparation of specimens;
2. Recompression of gas bubbles in the soil voids; and
3. Errors in test procedures and methods for interpreting test results, including difficulties in reapplying the initial state of stress that existed in situ.

The main objective of this chapter is to recommend procedures for estimating the consolidation settlements with a minimum of error, perhaps less than 50 percent: Without careful attention to all details the estimates can be too large by more than an order of magnitude. Values of C_r that lie outside the range 0.005 to 0.05 should be questioned (the lower values are for clays of low plasticity and low overconsolidation ratio); values between 0.015 and 0.035 are more typical.

It is assumed that "undisturbed" samples of high quality have been obtained and that the net change in pressure due to construction activities and structural loading and subsequent changes in loading have been appropriately considered.

RECOMMENDED PROCEDURE FOR DETERMINATION OF RECOMPRESSION INDEX C_r

The test equipment is described in chapter 1 . The recommended test procedure and presentation of test data in this chapter differ somewhat from those described in chapter 1 because the primary objectives treated are different.

It is good practice first to reapply p_o' and then to surround the sample with water and allow the dial reading to "equilibrate" (for at least 24 hours) before consolidation testing is commenced. The change in height should be recorded; if there is a swelling tendency, an additional stress increment should be applied.

The stress increments $\Delta\sigma$ in the consolidation test should be large enough so that the consolidation process can be identified from the settlement versus time readings (otherwise, pore water pressures must be measured to establish when the consolidation process has essentially ceased). In most soils this can be accomplished if the load increment ratio (LIR = $\Delta\sigma/\sigma'$) exceeds about 0.65. For lightly overconsolidated clays the minimum possible stress increment should be used; in any case, it is usually undesirable for the LIR to exceed 1. The measured data should be plotted to see whether a Terzaghi type of settlement versus time curve has been obtained (Figure 9). Only the increments in (R_{100} - R_o) should be used in plotting the curve of void ratio e versus effective vertical stress σ^1 to avoid cumulative additions of initial and secondary compressions. The duration of each load increment should be kept approximately constant, and long periods of secondary compression should be avoided. Ideally, the settlement beyond R_{100} should be less than 10 percent of the (R_{100} - R_o) value for the increment.

Figure 10 shows a typical curve of e versus σ' for 3 cycles of loading and unloading. The recompression index C_r depends on

Figure 8. Typical plot of soil properties versus depth.

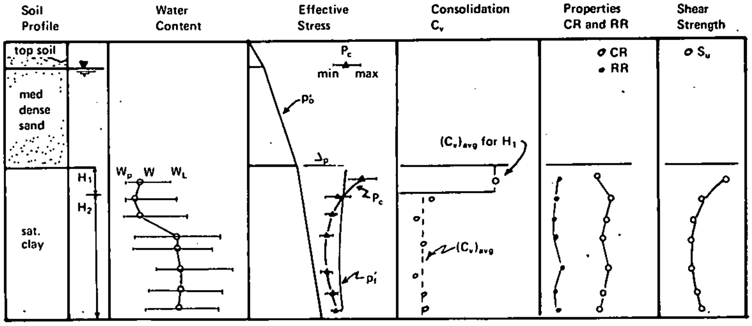


Figure 9. Typical curve of time versus settlement.

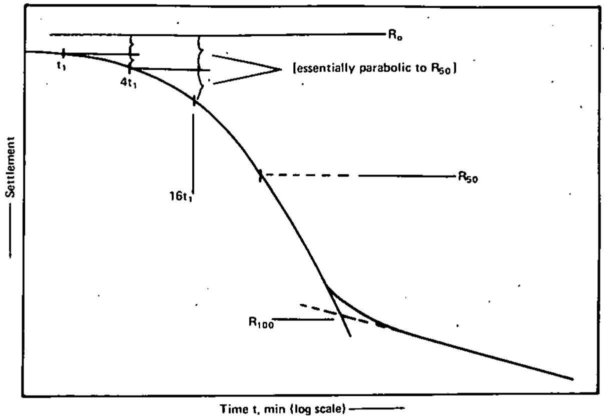


Figure 10. Typical curve of void ratio versus effective vertical stress.

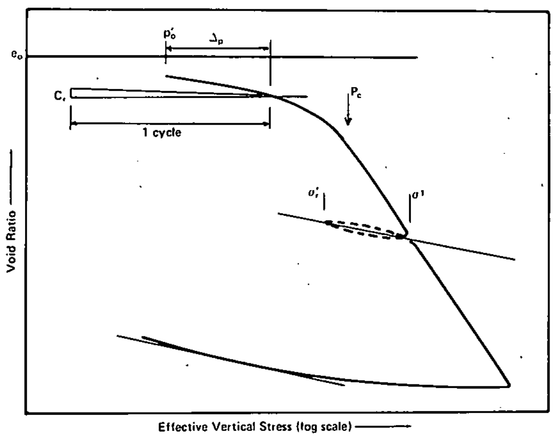
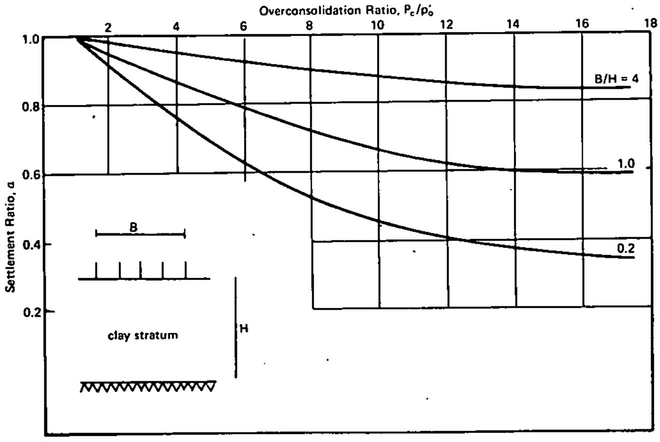


Figure 11. Relation between settlement ratio and over-consolidation ratio.



1. The magnitude of σ' at which unloading is begun, especially whether σ' is less than or exceeds the preconsolidation pressure P_c;
2. The overconsolidation ratio OCR to which rebounding (and reloading) is allowed (e.g., σ'/σ_r' in Figure 10); and
3. The degree to which gas bubbles are present in the sample because of the reduction in pore water pressure that resulted from sampling.

To reproduce as closely as possible the initial in situ state of stress, one should consolidate the sample to a stress slightly less than P_c and then allow it to rebound. Early in the testing program, before values of P_c have been established, the sample should initially be consolidated only to ($p_o' + \Delta p$): In either case, C_r should be evaluated over the range $p_o' + \Delta p$), as shown in Figure 10. Limited data indicate that C_r values obtained when a back pressure (to redissolve any gases in the soil voids) has been applied to the sample are less than those obtained when conventional apparatus is used. The use of consolidometers that permit application of a back pressure is recommended; alternately, the measured values of C_r may be appropriately reduced (about 25 to 50 percent).

CALCULATIONS OF CONSOLIDATION SETTLEMENTS

The values of C_r obtained as recommended in the previous section are used to calculate the apparent consolidation settlement S from equation 4. The consolidation settlement S_c is given by

$$S_c = \alpha S \qquad (5)$$

The coefficient α depends on the overconsolidation ratio (OCR = P_c/p_o') in the clay stratum and the effect of small departures from 1-dimensional compression on the initial excess pore pressures produced by Δ p. If the width of the loaded area exceeds 4 times the thickness of the clay stratum or if the depth to the top of the clay stratum exceeds twice the width of the loaded area, α may be assumed to be equal to 1. If loads are applied directly on the clay stratum, values of α may be interpreted from Figure 11, depending on the OCR and the ratio of the width of the loaded area B to the thickness H of the clay stratum. (Factors other than previous effective stresses can produce an overconsolidation effect in clays. These factors include long-term secondary compressions, changes in the ionic content of the pore water, weathering of clay minerals, and precipitation of cementations compounds. Such "bonded" clays are generally lightly overconsolidated, but their pore pressure response differs from that of clay deposits that are overconsolidated as a result of past changes in effective stress. Accordingly, Figure 11 is not applicable to bonded clays.) If α is less than about 0.7, the immediate settlements caused by shear strains may be significant compared to the consolidation settlements; accordingly, an estimate of the immediate settlements (based on elastic theory) would also be in order.