3 Estimating 1-Dimensional Consolidation, Including Secondary Compression, of Clay Loaded From Overconsolidated to Normally Consolidated State

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STATEMENT OF PROBLEM

A large shallow foundation is to be placed at a site underlain by saturated clay. The initial in situ stresses are less than the maximum past (preconsolidation) pressure P_c, i.e., in its initial state the soil behaves as an overconsolidated soil. (The past history of the soil that caused P_c is immaterial to the present discussion.) The final imposed stresses, due to the foundation loads and the overburden pressure, will exceed P_c. The geometry is such that a 1-dimensional analysis is valid. The problem is to estimate the rate and magnitude of the settlement that will occur, including recompression, virgin compression, and secondary compression.

PRIMARY CONSOLIDATION AND SECONDARY COMPRESSION

The solution outlined in this chapter assumes that primary and secondary effects can arbitrarily be separated.

1. Primary consolidation is the time-dependent volume change that takes place because and during the time when the excess pore pressure is dissipating and the effective stress is increasing.
2. Secondary compression is the time-dependent volume change that takes place at essentially constant effective stress and thus occurs after the completion of primary consolidation.

The above approach is the most commonly used approach although the above definitions are not universally accepted.

GENERAL CONSIDERATIONS

Inasmuch as volume changes are considered to be 1-dimensional, the settlement of each segment of the clay stratum, within which the soil properties and stresses do not vary greatly, may be computed from primary consolidation settlement S_p and secondary compression S_s by the following equations:

$$S_p = \sum \left\{ \frac{C_r}{1 + e_o} H_o \log \frac{P_c}{p_o'} + \frac{C_c}{1 + e_o} H_o \log \frac{p_f'}{P_c} \right\}_i \tag{6}$$

$$S_s = \sum \left\{ \frac{C_\alpha}{1 + e_o} H_o \right\}_i \log \frac{t_s}{t_p} \tag{7}$$

For instantaneous load applications, all times are measured from the instant at which load is applied. When the load is applied gradually over a finite time interval, engineering judgment must be used to select t_o, the initial time from which all time values are measured. For loads that increase approximately linearly with time, t_o may be estimated as the time at which one-half of the total load has been applied (28). This estimate also is satisfactory for irregular load applications when the total loading period is less than 20 percent of t_p. However, if the loading period is large compared to the time required for completion of primary consolidation, more complex methods, e.g., numerical analysis, are required for computing the rate of primary consolidation. Such cases are beyond the scope of this discussion.

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 consolidometer tests should be performed on samples from each layer and from each 10 ft (3 m) of thickness of a single layer. Data on water content and Atterberg limits should be available for every 5 ft (1.5 m) of depth.

WORKING HYPOTHESIS

As stated earlier, it is assumed that primary consolidation and secondary compression can be separated into 2 distinct processes. Primary consolidation can be predicted from Terzaghi's 1-dimensional consolidation theory or extensions of his theory (6, 21); therefore, this discussion will be restricted to secondary effects.

As a working hypothesis of secondary compression for engineering practice, Ladd (10) suggested the following assumptions for cases in which the load increment ratio is of sufficient magnitude to cause some primary consolidation:

1. C_α is independent of time, at least during the time span of interest.
2. C_α is independent of the thickness of the soil layer (of course, the thicker the layer is, the longer the time required for primary consolidation will be, but the strain, or Δe/log cycle of time, remains constant);
3. C_α is independent of load increment ratio as long as some primary consolidation occurs; and
4. $C_\alpha/(\Delta e/\Delta \log \sigma')$ at any given stress is constant (at least approximately), and for many normally consolidated clays over the normal range of engineering stresses, $(\Delta e/\Delta \log \sigma')_{max} = C_c$ = constant and thus C_α/C_c is constant for such a clay.

Behavior resulting from the working hypothesis is shown in Figure 12. The effects are shown of varying drainage distance, consolidation stress, and load increment ratio for a normally consolidated clay with a constant compression index.

The working hypothesis is admittedly an oversimplification of actual behavior. However, there are data to support, at least as a first approximation, the assumptions. Some of the references are listed below:

C_α Assumption	References
Independent of thickness	14, 19
Independent of load increment ratio	14, 19, 29
Independent of consolidation stress for constant compression index	8, 14, 16, 19, 23

TEST APPARATUS AND PROCEDURES

The test apparatus and procedures that are recommended for this application are the same as those recommended in chapter 1 for evaluation of P_c.

EVALUATION OF INDIVIDUAL TEST RESULTS

The dial gauge reading should be plotted against the logarithm of elapsed time since the addition of a new load for each load increment. This can best be accomplished on semilogarithmic paper. If an S-shaped curve results, the standard logarithmic (Casagrande) curve-fitting method may be used. If not, the methods suggested by Taylor (27) or Su (26) may be used and may be necessary for small load increment ratios. These methods are discussed below.

1. Semilogarithm method by Casagrande. The logarithm of time method is shown in Figure 13. It assumes that for the first 50 percent primary consolidation the graph is parabolic so that the settlement from $t = 0$ to $t = t_1$ equals the settlement from $t = t_1$ to $t = 4t_1$, provided the consolidation at $4t_1$ has not exceeded 50 percent primary compression. Thus, the 0 consolidation and seating correction should be the same as that obtained from the square root of time method. The 100 percent primary consolidation is obtained from drawing a tangent at the point of inflection of the S-shaped graph (i.e., the steepest slope) and an approximate straight line through the tail points of the graph.
2. Semilogarithmic method by Su. Su makes use of the maximum slope of the compression and logarithm of time plot. Using the Fourier series solution for Terzaghi consolidation theory, Su shows that

$$R_u = R_o + \frac{\text{max slope}}{0.688} U \tag{8}$$

This method is shown in Figure 14. A tangent to the steepest part of the settlement curve intersects a horizontal line through the corrected 0 consolidation point (as determined by the logarithm of time method) at point A. Point B is 1.5 times the distance of 1 log cycle along the horizontal line from A. From point B a vertical line intersects the tangent at C, which is the 100 percent primary consolidation point. The method may be applied to curves that do not exhibit the characteristic S shape; or, when secondary time effects are not of interest, the method may be applied before the straight-line tail is established, thus reducing the experimental test time required.

3. Square root of time method by Taylor. If dial readings are plotted versus the square root of time (Figure 15), a straight line can be fitted through the data points for the first 60 percent primary consolidation. This line can be extrapolated to $t = 0$ to obtain the theoretical 0 dial reading. A straight line then is constructed through the theoretical 0 point with a slope such that abscissas are 1.15 times the abscissas on the experimental curve for corresponding dial readings. This line will intersect the experimental curve at 90 percent consolidation. The 100 percent consolidation can be determined by taking (10/9) times the difference between the dial readings at theoretical

Figure 12. Illustration of 6 hypotheses for secondary compression.

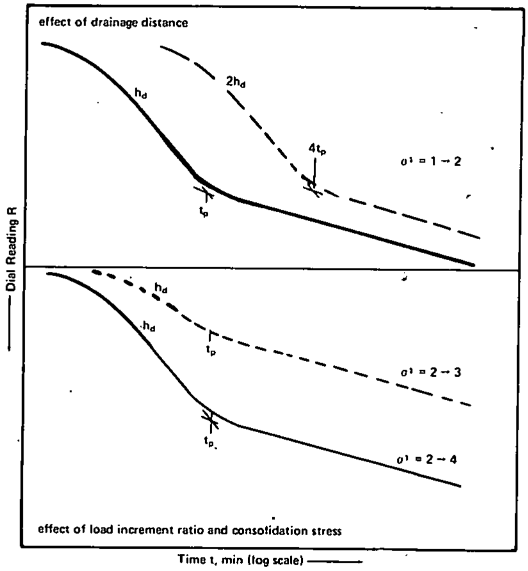


Figure 13. Casagrande curve-fitting method.

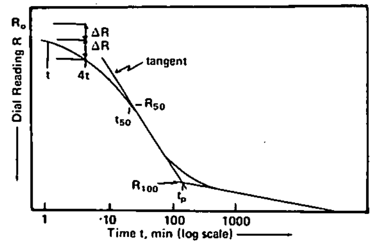


Figure 14. Su curve-fitting method.

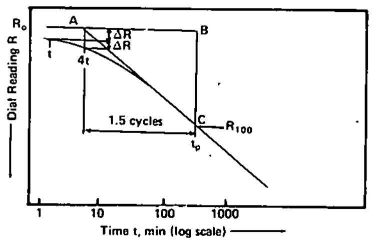


Figure 15. Taylor curve-fitting method.

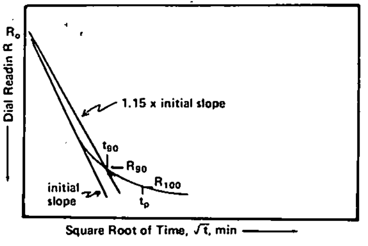
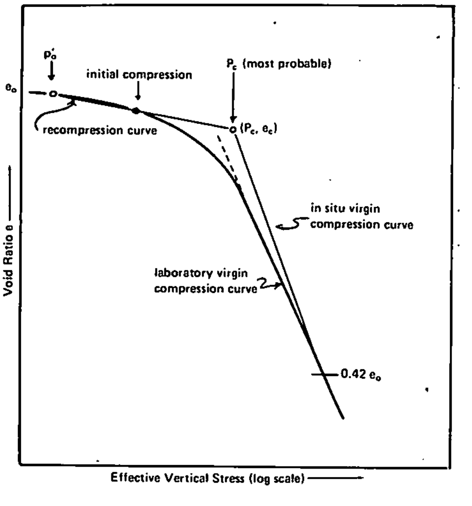


Figure 16. Schmertmann construction of in situ compression curve.



0 and 90 percent consolidation. The coefficient of consolidation C_v is computed as

$$C_v = T_{90}\left(\frac{h_d^2}{t_{90}}\right) \tag{9}$$

T_{90} is the theoretical time factor for 90 percent consolidation, $\simeq 0.85$, t_{90} is the laboratory time for 90 percent consolidation, and h_d is the drainage distance in the laboratory sample at t_{90}.

These methods will enable the values of the time to reach the end of primary consolidation, the amount of primary compression or strain, and the secondary compression coefficient C_α or secondary compression ratio SCR to be directly obtained for each load increment.

The dial gauge readings corresponding to the end of primary consolidation obtained from the above plots should now be plotted against the logarithm of the applied vertical stress. This again is best accomplished on semilogarithmic paper. This plot enables the laboratory virgin compression index C_c or virgin compression ratio CR and the minimum and probable P_c to be obtained as outlined in chapter 1. If the soil specimen is heavily overconsolidated, then the recompression index C_r or recompression ratio RR may also be obtained from a straight line through the dial gauge readings at the overburden pressure and at half the initially estimated value of P_c. If the soil is lightly overconsolidated, resulting in no initial expansion, the recompression ratio may be disregarded and made equal to 0.

The laboratory virgin compression index may be corrected for sample disturbance effects by the method suggested by Schmertmann (24).

In this method, the correction to the laboratory virgin compression line is obtained as follows (Figure 16):

1. The recompression curve is extended from the overburden stress p_o' to the most probable preconsolidation pressure (P_c, e_c); and
2. The in situ virgin compression line is constructed from (P_c', e_c) to intersect the laboratory virgin compression line at 0.42 e_o.

Experience indicates that for many soft to medium clays this correction increases the virgin compression index by approximately 10 to 20 percent.

For each specimen tested, the following results should be summarized for each pressure increment:

1. Final increment pressure,
2. Strain or void ratio at the end of primary consolidation,
3. Coefficient of consolidation, and
4. Coefficient of secondary compression or secondary compression ratio.

Similarly for each specimen tested, the following data should be recorded:

1. Depth,
2. Initial effective overburden stress,
3. Final effective vertical stress imposed by the overburden and engineering structure, if known,
4. Minimum P_c,
5. Probable P_c,
6. Maximum P_c,
7. Recompression index or ratio, and
8. Virgin compression index or ratio.

Plotting these data versus depth, as shown in Figure 8, is considered to be essential to better selecting the probable P_c with depth and possibly in interpreting the previous geological history of the deposit.

Amount of Primary Settlement

The depth-stress profile for the whole deposit should be plotted. From these results, one can select a depth-probable preconsolidation profile, bearing in mind any relevant details of known geological history and general soil behavior (i.e., known erosion from studies of other sites, induced preconsolidation due to cementation or secondary compression) and the fact that sample disturbance will lower P_c.

Once this profile has been established, the total primary settlement may be calculated from equation 6. If several tests represent 1 soil layer or increment of depth, these should be averaged, neglecting, of course, any results that are suspiciously incorrect.

Rate of Primary Settlement

The rate of primary consolidation is characterized by the coefficient of consolidation C_v, which is determined in the laboratory as

$$C_v = T_{50}\left(\frac{h_d^2}{t_{50}}\right) \tag{10}$$

T_{50} is the theoretical time factor for 50 percent consolidation, $\cong 0.2$, t_{50} is the laboratory time for 50 percent consolidation, and h_d is the drainage distance in the laboratory sample at t_{50}. Alternately, C_v may be computed at 90 percent consolidation by the Taylor method. Values computed by the Taylor method generally are larger than the corresponding values from equation 10.

In general, C_v will vary with stress level during a consolidation test. The variation may be determined by plotting C_v versus the final stress for each load increment. The value of C_v corresponding to the final in situ stress p_f' at the sample depth then should be selected. (Because of sample disturbance and load increment ratio effects, some adjustment may be required when $p_f' < 2P_c$. For such cases, it is suggested that C_v corresponding $\sigma' = 2P_c$ be used.)

Primary consolidation occurs much more rapidly in the overconsolidated range than in the normally consolidated range. For the conventional sizes of consolidation test specimens, sufficient time data for the evaluation of C_v may not be obtained in the overconsolidated ranges. In such circumstances, the value of $(C_v)_{oc}$ for the overconsolidated range may be estimated approximately as

$$(C_v)_{oc} = \frac{C_c}{C_r}(C_v)_{vc} \tag{11}$$

Other alternatives are to use larger specimens or dynamic recording instruments or to measure the permeability directly, but these alternatives are beyond the scope of this chapter.

Consider first the case of the entire soil layer loaded into the virgin compression range. The selected value of C_v from each test is plotted against sample depth, and an average value is estimated for the entire layer. The time t_u for any percentage of consolidation may then be estimated from

$$t_u = T_u \frac{h_d^2}{C_v} \tag{12}$$

h_d is the estimated in situ drainage distance for the entire layer and depends on the evaluation of drainage conditions at the layer boundaries. If the layer is assumed to drain at both top and bottom, h_d is one-half of the entire layer thickness. If the layer is assumed to drain at only 1 surface, h_d equals the entire layer thickness.

In the second case, a portion of the layer, either near the surface or deep in the deposit, may remain overconsolidated. In this case, one average C_v should be estimated over the depth that is loaded into the virgin compression range, and another average C_v should be selected over the depth that remains overconsolidated. The problem then is one of the consolidation of 2 contiguous layers with different values of C_v. The rate of consolidation may be approximated by replacing the thickness of overconsolidated soil by an equivalent thickness of soil in the virgin compression range. Let

$$H' = H_{oc} \sqrt{\frac{(C_v)_{vc}}{(C_v)_{oc}}} \tag{13}$$

The rate of consolidation can then be determined from equation 12 by using $C_v = (C_v)_{vc}$. The equivalent layer thickness H' plus the thickness of soil loaded into the virgin compression range is the effective layer thickness.

Rate of Secondary Compression

The rate of secondary compression of the soil should be characterized by the coefficient of secondary compression or the secondary compression ratio for the load increment whose final stress approximates the final in situ stress at the same depth. Tests at any one depth should first be averaged in a similar fashion to that described for primary settlement. The secondary compression can then be evaluated from equation 7.

t_p in equation 7 must be estimated from the in situ rate of primary consolidation. If the typical S-shaped curve is obtained on a semilogarithmic plot, t_p can be estimated as the time coordinate of the intersection of the tangent constructed at the inflection point and the extension of the linear secondary compression line (Figure 12). If an S-shaped curve is not obtained, t_p may be estimated as the time to complete 100 percent primary consolidation as determined by the Su or Taylor methods.

Combined Primary and Secondary Compression

The total compression of a layer is determined by combining equations 6 and 7. Thus,

$$S(t) = U(t)\, S_p \tag{14}$$

for $t \leq tp$, and

$$S(t) = S_p + S_\alpha(t) \tag{15}$$

for $t \geq tp$.

CONCLUDING REMARKS

Although this chaper has been restricted to the use of the incremental consolidometer tests, the reader should not infer that incremetal tests are superior to other types of tests such as the constant rate of strain or controlled gradient tests. Nevertheless, the incremental test is the most common test in present-day practice, and the standardization of its interpretation is highly desirable.