1 Estimating In Situ Maximum Past (Preconsolidation) Pressure of Saturated Clays From Results of Laboratory Consolidometer Tests

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A proper evaluation of the in situ stress history of a clay deposit is a necessary prerequisite to estimating compressibility and strength characteristics of the clay. The term stress history refers to the existing in situ vertical effective stress p_o' in relation to the maximum past pressure P_c of the clay deposit. (Other names that have been used in addition to maximum past pressure include preconsolidation pressure, amount of precompression, critical pressure, and maximum past vertical effective stress.) When the maximum past pressure equals the net overburden stress, i.e., $P_c = p_o'$, the clay is called normally consolidated, and volume change caused by loading of a normally consolidated clay deposit is referred to as virgin compression. If the existing in situ stress is less than the maximum past pressure, i.e., $p_o' < P_{c'}$, the clay is called overconsolidated, preconsolidated, or precompressed. The degree of overconsolidation is expressed by the overconsolidation ratio OCR.

$$OCR = P_c/p_o' \tag{1}$$

Various mechanisms can cause a clay deposit to be overconsolidated. In particular, removal of overburden stress during the geological history of the clay deposit is only one of several possible causes of P_c. Consequently, the term P_c denotes the stress at which a characteristic change in compressibility occurs rather than a certain value of maximum past vertical effective stress per se.

The concept of a maximum past pressure P_c based on changes in the compressibility of the clay is shown in Figure 1. Vertical strain ϵ_v is plotted versus consolidation stress σ' for 1-dimensional compression of a hypothetical clay with an in situ stress p_o' equal to 500 lb/ft^2 (23.9 kPa). On the natural scale, when σ' approaches a value of 2,000 lb/ft^2 (95.8 kPa), the compressibility increases and then decreases at larger stresses. On the log scale, the curvature of the compression curve in the vicinity of

P_c changes markedly and, at stresses greater than P_c, ϵ_v versus σ' is often closely approximated by a straight line with many natural clays.

In this chapter, the Casagrande method of estimating the in situ P_c from the results of laboratory consolidometer tests is presented first and then the various mechanisms that can cause a P_c are discussed. The principal factors influencing laboratory compression curves, recommended consolidometer test procedures, and specific recommendations for determining P_c are then presented. The discussion is restricted to the estimation of P_c from incremental consolidometer tests on undisturbed samples of medium to soft saturated clays obtained from below the water table.

CASAGRANDE METHOD FOR DETERMINATION OF P_c

Casagrande (5) presented the empirical method shown in Figure 2 for estimation of the value of P_c from the results of laboratory consolidometer tests on undisturbed samples of saturated clay. The estimated value of P_c is obtained as follows:

1. Determine the point T of minimum radius on the laboratory compression curve (ϵ_v or e versus log σ').
2. Draw 2 lines from point T, one horizontal and one tangent to the compression curve. The angle θ between the 2 lines is then bisected.
3. Extend the straight-line portion of the compression curve. The point of intersection C of the extension with the bisector line is the estimated value of P_c.
4. Round off the estimated value of P_c to 2 significant figures and report together with possible range of P_c. The lower limit of P_c is usually assumed to be the point of intersection of a horizontal line through point E and the extension of the straight-line portion of the compression curve. The maximum value is assumed to be the point (M in Figure 2) beyond which the compression curve can be approximated by a straight line.

The Casagrande method is widely used in practice and is generally considered to yield satisfactory results if samples are of high quality and consolidometer tests are properly conducted. Other methods for estimating P_c are given by Burmister (4), Janbu (7), and Schmertmann (24), who also presents a procedure for correcting the laboratory compression curve for the effects of sample disturbance.

POSSIBLE MECHANISMS CAUSING P_c

The concept of maximum past pressure is most easily visualized in terms of the maximum stress that has acted on the clay. At stresses less than this maximum value, the compressibility is low compared to the compressibility that is exhibited by the sharp change in slope of the compression curve as the stresses approach and then exceed P_c. This same type of behavior (increased compressibility and characteristic shape) can result from mechanisms other than a prior stress increase.

Table 1 (10) gives mechanisms by which a clay might acquire a P_c greater than the existing vertical effective stress. Change in total stress is the most obvious cause, and change in the pore pressure condition is the next most obvious. Desiccation is commonly recognized if associated with a clay crust. However, desiccation may also have been an important factor during deposition of many alluvial, backswamp, and tidal mud-flat deposits.

Clays may also exhibit an increased P_c without having had an increased effective stress. In Table 1, these mechanisms are referred to as change in soil structure (12), which denotes soil fabric (orientation and distribution of particles) and interparticle forces (types and relative magnitude). The relation between secondary compression and P_c is now well documented (1, 2, 15, 18), but the mechanism postulated by the authors for explaining the relation is different. Environmental changes and chemical alterations can also influence the in situ value of P_c.

When interpreting the results of consolidometer tests and when selecting values of P_c

Figure 1. Definition of P_c in relation to in situ compressibility.

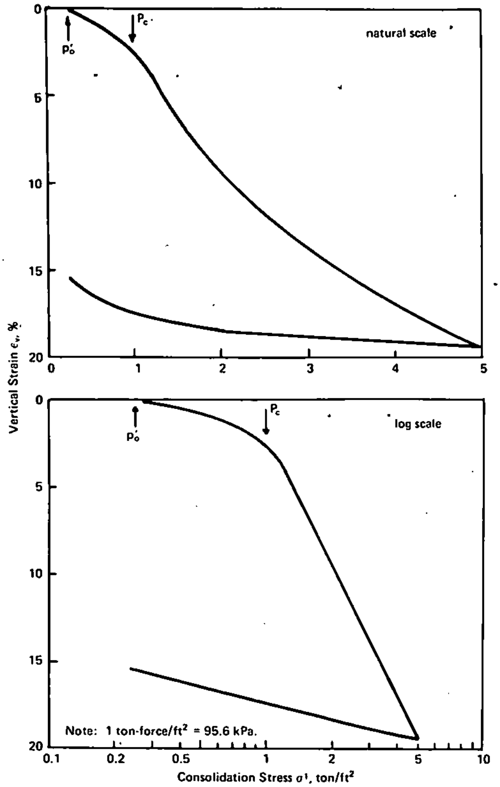


Figure 2. Casagrande method for estimating P_c.

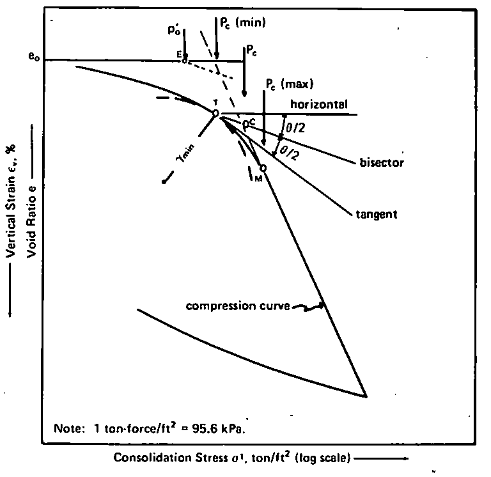


Table 1. Mechanisms causing P_c.

Mechanism	Remarks and References
Change in total stress due to	
Removal of overburden	
Past structures	
Glaciation	
Change in pore water pressure due to	
Change in water table elevation	Kenney (9) gives sea level changes
Artesian pressures	Common in glaciated areas
Deep pumping	Common in many cities
Desiccation due to drying	May have occurred during deposition
Desiccation due to plant life	May have occurred during deposition
Change in soil structure due to	
Secondary compression (aging)[a]	Raju (20) Leonards and Ramiah (13) Leonards and Altschaeffl (15) Bjerrum (1, 3)
Environmental changes such as pH, temperature, and salt concentration	Lambe (12)
Chemical alterations due to "weathering," precipitation cementing agents, ion exchange	Bjerrum (1)
Change of strain rate on loading	Lowe (18)[b]

[a]The magnitude of P_c/p_o' related to secondary compression for mature natural deposits of highly plastic clays may reach values as high as 1.9 or higher (15, 1, 2, 22).
[b]Further research is needed to determine whether this mechanism should take the place of secondary compression.

to use in design, one should always try to determine the mechanisms involved. This will help in deciding how the maximum past pressure should vary with depth and whether erratic values should be ascribed to sample disturbance, testing procedures, or natural occurrences.

PRINCIPAL FACTORS INFLUENCING THE DETERMINATION OF P_c FROM LABORATORY CONSOLIDOMETER TESTS

The 3 most important factors influencing the determination of P_c from laboratory consolidometer tests are sample disturbance, load increment ratio, and load increment duration. (A change in the electrolyte of the pore water during laboratory testing would also affect the compressibility of certain type clays, but its influence is not discussed here.)

Sample Disturbance

Figure 3 shows compression curves from consolidometer tests on high-quality and poor-quality samples of an overconsolidated clay in relation to the in situ compression curve. Increasing sample disturbance

1. Decreases the void ratio (or increases the strain) at any given value of consolidation stress;
2. Obscures and/or lowers the estimated value of P_c from the Casagrande construction if the disturbance is excessive, especially with sensitive clays and clays that have developed a P_c as a result of secondary compression;
3. Increases the compressibility at stresses less than P_c; and
4. Decreases the compressibility at stresses greater than P_c.

Load Increment Ratio

The load increment ratio LIR denotes the change in consolidation stress divided by the initial consolidation stress.

$$\text{LIR} = \frac{\sigma'\,\text{final} - \sigma'\,\text{initial}}{\sigma'\,\text{initial}} = \frac{\Delta\sigma}{\sigma'\,\text{initial}} \qquad (2)$$

Conventional consolidometer tests usually employ an LIR of unity; that is, the load (consolidation stress) is doubled for each successive increment. The influence of varying the LIR for consolidometer tests on a sensitive clay is shown in Figure 4. The use of the conventional procedure with LIR = 1 does not properly define the in situ compressibility and hence the P_c of clays, especially if the clay is strain sensitive.

Experience with sensitive soft clays that exhibit in situ compression characteristics typical of those shown in Figure 4 also shows that the clay is likely to undergo sudden collapse and may squeeze out of the consolidometer (between the ring and the porous stones) if the load is doubled in the vicinity of P_c. Consequently, the LIR must be reduced in the vicinity of P_c in order to measure, even approximately, the in situ compressibility and P_c.

Load Increment Duration

The load increment duration denotes the total time t_f allowed for consolidation prior to application of the next load increment. Standard consolidometer test procedures often use a duration of 1 day for each increment. Since the time for primary consolidation t_p for typical sample heights and values of the coefficient of consolidation for saturated medium to soft clays is only 5 to 100 min, appreciable secondary compression occurs during a 1-day duration. Consequently, the 1-day compression curve will fall below the compression curve corresponding to the end of primary consolidation. This, in turn, influences the value of P_c determined from the test.

The effect of load increment duration on the estimated value of P_c is shown in Figure 5. The dashed curve corresponds to the strain or void ratio measured at the end of each 1-day increment. The solid curve corresponds to the strain or void ratio measured (the curve is plotted on the assumption that 100 percent of the initial excess pore pressure is dissipated at $t_r = t_p$)

1. From a test in which the next load is applied as soon as primary consolidation is completed; or
2. From the 1-day test, but where the e or ϵ_v at the end of primary consolidation is plotted rather than the value at the end of the increment. [It has been assumed in the second procedure that the location of the compression curve with $t_r = t_p$ is unaffected by the secondary compression that occurred during the previous increment. This is a reasonable assumption if the amount of primary consolidation is a significant fraction (65 to 75 percent) of the total compression for the increment.]

The amount of the reduction in the estimated value of P_c from 1-day tests as opposed to that determined at the end of primary consolidation will obviously be most significant in clays that exhibit a high rate of secondary compression in the vicinity of P_c. For typical soft CL and CH clays, the amount of the reduction in P_c is likely to be on the order of 10 to 20 percent.

RECOMMENDED PROCEDURES FOR DETERMINATION OF P_c

Test Equipment

The equipment employed for incremental consolidometer tests should generally conform to the recommendations of ASTM D2435-70 and Lambe (11). The following are particularly important.

1. A diameter-to-height ratio of at least 2.5 but no more than 6 should be used; a ratio of 3 to 4 is preferable. Side friction is likely to affect the results if a ratio smaller than 2.5 is used, and bending stresses during handling are likely to disturb the soil structure when larger ratios are used.
2. The ring must be noncorrosive, be smooth to the touch, and have sufficient wall thickness to prevent ring distortion. In general, the harder the ring material is, the less the wall friction will be. A coating of silicone grease or molybdenum disulfide lubricant on the ring wall is recommended. Very thin teflon linings may be used, but they are subject to abrasion and increased wall friction with continued use.
3. Minimum specimen dimensions should generally be 2 in. (5 cm) in diameter and 0.75 in. (1.9 cm) in height. The larger the specimen size is, the better.
4. Porous stones, such as Norton P2120 mixture, should generally have a clearance of about 0.01 in. (0.025 cm), that is, have a diameter 0.02 in. (0.05 cm) smaller than that of the ring, and be replaced or cleaned periodically. Truncated, cone-shaped porous stones, if used, reduce the possibility of drag resulting from uneven compression.
5. The applied loads must be constant and accurately known, and vertical deformations must be measured with a sensitivity of 0.0001 in. (0.00025 cm).

Figure 3. Effect of sample disturbance on laboratory compression curves and estimated value of P_c.

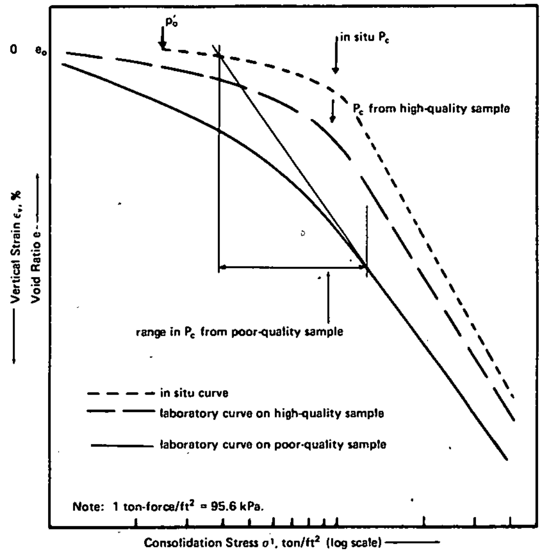


Figure 4. Influence of load increment ratio on laboratory compression curve for sensitive clay.

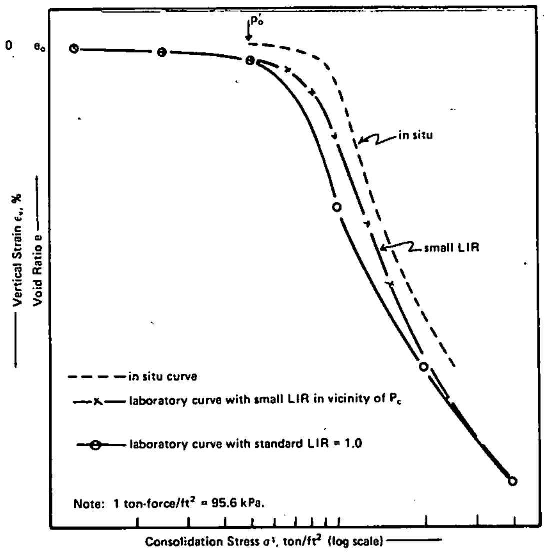
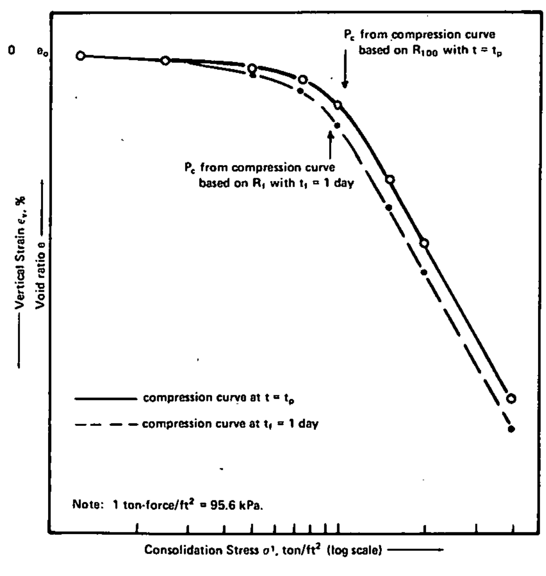


Figure 5. Effect of load increment duration on laboratory compression curve and estimated value of P_c.



Test Procedures

The test procedures employed for incremental consolidometer tests should generally conform to the recommendations of ASTM D2435-70 and Lambe (11). Modifications and items of importance are noted below.

1. The initial total, the final total, and final dry weights of the entire specimen should be obtained. As an independent measurement of the sample thickness, the dial gauge should be set to 0 by the use of a metal spacer of known thickness and the porous stones to be used in the test.
2. Before water is added, an initial "seating" load of 0.3 to 0.7 lb/in.^{2} (2 to 5 kPa) should generally be applied to the sample while an initial dial reading corresponding to the initial height of the sample is quickly obtained. Water should then be added while the dial reading is watched. If the sample wants to swell, the load should be increased to prevent swelling and to obtain an initial equilibrium consolidation stress.
3. A load increment ratio equal to unity, i.e., doubling of the load, may satisfactorily define the compression curve for many medium to soft saturated clays. However, if the clay has compression characteristics that vary with LIR and the amount of secondary compression under the previous increment (which is typical of very sensitive clays and of soft plastic clays with a high liquidity index), the load increment ratio should be reduced in the vicinity of the estimated P_c. (σ' values of 0.5 P_c, 0.7 P_c, 0.85 P_c, 1.0 P_c, 1.3 P_c, and 1.5 P_c will often be adequate to define P_c and/or to prevent squeezing of clay from the consolidometer ring.)
4. The compression curve in the recompression region is defined by unloading the sample, after it is initially loaded to a stress close to P_c, to the effective overburden pressure and then reloading it. For best definition of the recompression index the specimen should be unloaded when $0.5\ P_c \le \sigma' < 1.0\ P_c$. To define the virgin compression slope requires that loading of the test specimen be continued to a sufficiently high level to establish the straight-line portion of the compression curve beyond P_c. Normally, loading must be continued to a stress level equal to 8 times P_c. For excellent quality samples of soft clays, the maximum applied stress may be less than 8 times P_c; for moderately to highly overconsolidated clays the maximum stress may have to be more than 8 times P_c.
5. The load increment duration t_f should be maintained approximately constant for each increment. However, if the total test time is critical, shorter increment duration times may be used in the overconsolidated region without sacrificing accuracy. It is important that sufficient dial gauge readings be obtained to define both the end of primary consolidation and the slope of the approximately linear secondary compression curve on the plot of dial reading versus log time.
6. Temperature fluctuations of more than a few degrees, approximately ±7 F (±4 C), should be prevented. Since temperature fluctuations significantly influence the rate of secondary compression, accurate estimates of secondary compression necessitate closer temperature control, approximately ±1.8 F (±1 C).

Presentation and Interpretation of Test Data

The objective is to obtain the P_c of a compression curve that corresponds, at least approximately, to the end of primary consolidation (the solid curve t_p in Figure 5). Since it is generally impractical to apply a new load each time the sample reaches the end of primary consolidation, the procedure shown in Figure 6 is recommended. Figure 6 shows a hypothetical set of dial readings versus time from a consolidometer test with a variable LIR and 1-day increments on a sample of clay having a value of P_c between 14.2 and 21.3 lb/in.^{2} (1.0 to 1.5 kg/cm^2). The dial reading R_{100} at the end of primary consolidation ($t = t_p$), not the final dial reading R_f, is used to compute the compression curve. When the LIR is unity, a typical Terzaghi type of consolidation curve is generally obtained, and R_{100} is easily evaluated by the intersection of the straight lines as shown for the top and bottom curves in Figure 6. When the LIR is sufficiently small, such as shown for the middle curve in Figure 6, the clay generally does not follow the Terzaghi consolidation theory, and t_p must be established. [Leonards and Altschaeffl (15) and Lowe (18) give a more complete discussion of this phenomenon.] In this case t_p depends on LIR and on the amount of secondary compression under the previous increment. One can reasonably assume, however, a value of t_p that falls between the values measured in the previous and subsequent increments.

If a Terzaghi consolidation curve is not obtained for the increments within the recompression region, one can determine an average value of t_p obtained from increments in the normally consolidated range and use this approximate value of time to select the appropriate dial readings for all of the increments.

The next step is plotting the compression curve based on R_{100} dial readings to a suitable scale in order to use the Casagrande method of construction (or perhaps one of the other methods referenced here) to estimate P_c. [The next chapter states that the summation of (R_{100} - R_o) values should be used in the plotting of the compression curve. For saturated clay and for $t_f \approx t_p$, the methods proposed in chapter 2 and in this chapter will result in essentially identical curves. If t_f > tp, the curve should be plotted on the basis of R_{100} dial readings.] Figure 7 shows 2 suggested scales of vertical strain versus consolidation stress for use with soft clays of medium to high compressibility [vertical strain = $\Delta h/h_o = \Delta e/(1 + e_o)$]. The use of average strain rather than void ratio is recommended because

1. Strains are easier to compute than void ratios;
2. Differences in initial void ratio may cause samples to exhibit quite different plots of void ratio versus stress but almost identical plots of strain versus stress;
3. Settlements are directly proportional to strain, but use of Δ e data also requires a knowledge of $(1 + e_o)$, which introduces 2 variables, Δ e and $(1 + e_o)$; and
4. Strain plots are easier to standardize than void ratio plots.

CONCLUDING REMARKS

Although this chapter has been restricted to use of incremental consolidometer tests for estimation of P_c, readers should not infer that incremental tests are superior to tests in which the sample is continuously loaded, such as in the controlled gradient test (17) and in the constant rate of strain tests (25, 30). In fact, such tests have several important advantages:

1. A continuous compression curve is obtained;
2. The measured compression curves generally correspond to the end of primary compression, and thus the need to make plots of dial reading versus time in order to obtain R_{100} is eliminated;
3. The problem of loss of soil due to squeezing is minimized or eliminated; and
4. The total time required to perform the primary compression portion of the test is greatly reduced.

However, continuously loaded consolidation tests generally require more sophisticated equipment, including a data acquisition system. Information on secondary compression can be obtained with the equipment used for controlled gradient test, but not with all types of equipment used for constant rate of strain tests. Finally, it should be emphasized that

1. Proper evaluation of the in situ P_c is an art that requires considerable judgment and, above all, an appreciation of the various geological and testing factors that control and influence values of P_c;
2. Evaluation of the in situ P_c from laboratory tests requires that the profile of test values be superimposed on the profile of the effective overburden stress; and
3. It is the exception rather than the rule to encounter normally consolidated cohesive deposits, i.e., with $P_c = p_o'$, except for the case of underwater sediments now being formed or soil deposits that have recently been subject to load.

Figure 6. Determination of compression curve corresponding to end of primary consolidation.

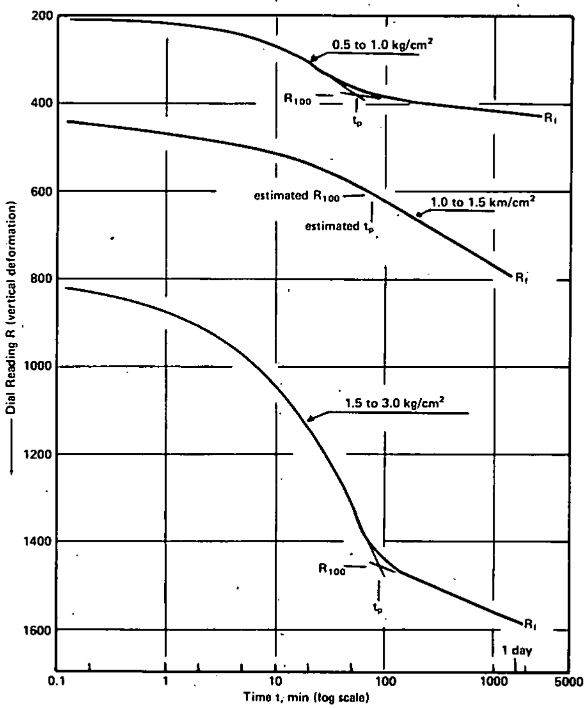


Figure 7. Suggested scales for presentation of compression curves.