The consolidation test: Interpretation and sample disturbance

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ABSTRACT
Casagrande's method of determining the preconsolidation load on clays was presented in the form of a relatively brief note at the 1st International Conference on Soil Mechanics and Foundation Engineering in 1936. His four-page note was in reply to questions addressed to him from members of the conference. It was based on Terzaghi's early investigations of the relationship between void ratio and applied pressure and on the existence of a discontinuity in the present relationship in the form of void ratio versus pressure or void ratio versus log pressure. However, it is cautioned in the present paper that even a completely linear relationship between void ratio and pressure will display - purely for mathematical rather than geotechnical reasons - a minimum radius of curvature in the corresponding void ratio versus log pressure plot. The pressure at which this occurs can be - and often is – misinterpreted to be the preconsolidation load. With respect to sample disturbance it is suggested here that a decrease in void ratio corresponding to a vertical strain exceeding one or two percent is in all probability an indication of unacceptable disturbance.

RÉSUMÉ
Casagrande méthode de détermination de la charge de préconsolidation des argiles a été présenté sous la forme d'une note relativement brève à la 1ère Conférence internationale sur la mécanique des sols et d'ingénierie des fondations en 1936. Sa note de quatre pages a été en réponse aux questions qui lui sont adressées par les membres de la conférence et a été fondée sur des enquêtes au début de Terzaghi de la relation entre le taux de porosité et la pression appliquée et sur l'existence d'une discontinuité dans cette relation sous la forme d'indice des vides fonction de la pression ou le taux de vide par rapport à la pression du journal. Toutefois, il est prié de noter dans ce document que même une relation linéaire entre complètement indice des vides et la pression d'affichage - purement mathématique plutôt que des raisons géotechniques - un rayon de courbure minimal dans le rapport de vide correspondant par tranche de pression journal. La pression à laquelle cela se produit peut être - et est souvent - interprété à tort comme la charge de préconsolidation. En ce qui concerne les perturbations échantillon, il est suggéré dans le document que la diminution du rapport des vides correspondant à une déformation verticale supérieure à un ou deux pour cent est selon toute probabilité, une indication de perturbation inacceptable.

1. INTRODUCTION

According to Janbu (Flaate and Senneset 2001), Terzaghi stated in 1925 – on the basis of tests he had carried out on "dry powder" during the period 1916-1920 – that both strength (τ_f) and modulus (E) of dry powder were basic concepts, both being linearly dependent on the intergranular pressure. He referred to this idea as being of "fundamental importance". However, according to Janbu, "Terzaghi unluckily did not pursue and further develop this basic concept. Instead, unfortunately the e-log p concept was introduced - in the early 1930's. This disastrous event hindered a rational development of a settlement analysis based on simple and intelligible mechanical-physical principles".

According to Casagrande (1936), Terzaghi's early investigations on the mechanics of consolidation of fine-grained soils had also led him to the conclusion that the relationship between void ratio and pressure for the primary or virgin branch of the compression curve could be expressed by a logarithmic curve and that such a logarithmic relationship for clay would hold true at least up to 2000 kPa. Any important deviation from this virgin compression curve for an undisturbed sample seemed to be caused by variations in loading during the geological history of the soil and on its removal from the ground. Casagrande went on to present a graphical method of determining the load under which the soil was consolidated in the ground, the so-called pre-consolidation load, from "a properly conducted consolidation test". The method is based, as is well known, on determining the position of the straight-line virgin compression line in the void ratio versus log pressure plot and on locating the minimum radius of curvature (also referred to as the maximum curvature) of the compression curve.

Casagrande (ibid.) presented his method as a relatively brief note "in reply to numerous questions on this subject which were addressed to the writer [Dr. Casagrande] from members of the conference" [the 1st International Conference on Soil Mechanics and Foundation Engineering, held at Harvard University].

In his note, Casagrande discusses in considerable detail the possible effects of sample disturbance on the determination of the pre-consolidation load. He states that "undisturbed samples obtained from drill holes often display relatively steep initial re-compression curves which approach the virgin line more gradually.

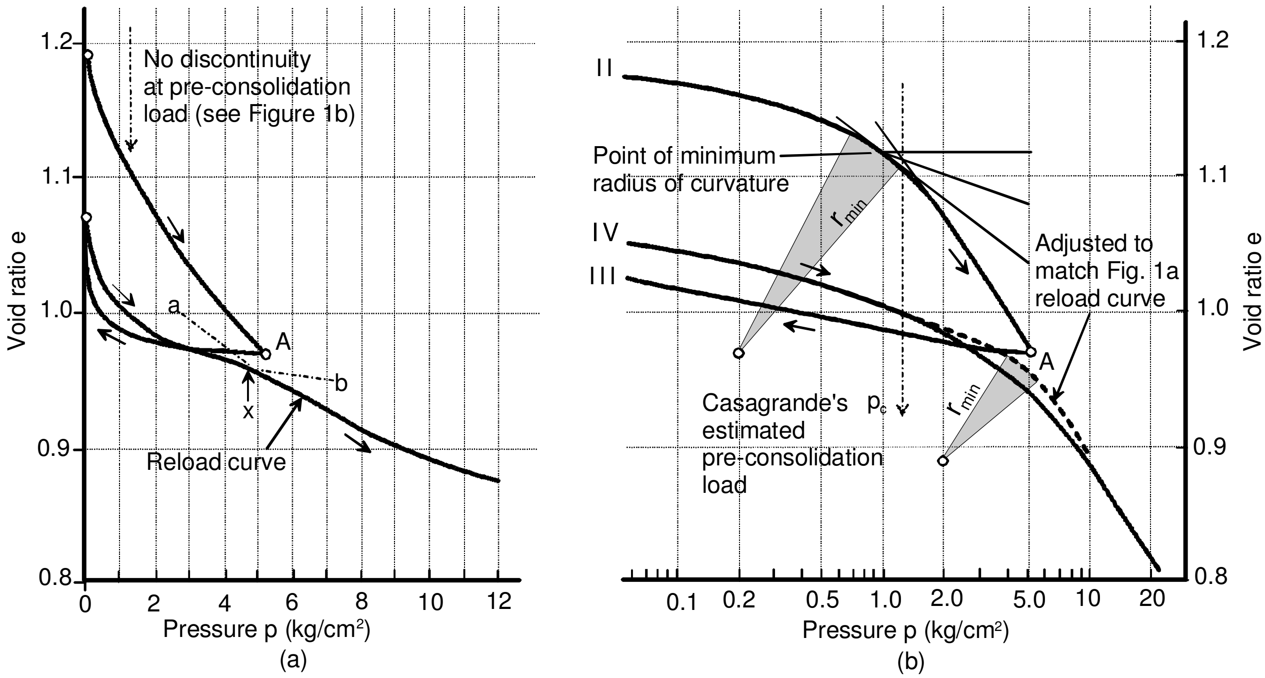

Figure 1. Casagrande's (1936 Fig. 1) plots of void ratio versus applied pressure: (a) natural scale (b) log scale

To what extent this is caused by partial disturbance of the internal structure of the clay and to what extent by swelling, cannot at present be decided from the shape of the curve". He concluded however, that "the slope of the virgin compression curve seems to be very little affected by swelling and minor disturbances due to the sampling and testing operations. For such cases the entire increase in load should be considered to take place along the virgin compression curve and the shape of the approach to the virgin curve can be disregarded".

2. CASAGRANDE'S, TAYLOR'S AND CRAIG'S COMPRESSION CURVES

On comparing Casagrande's plots of void ratio versus pressure (e vs p', Fig. 1a of this paper) and void ratio versus log pressure (e vs log p', Fig. 1b of this paper), it will be seen that no discontinuity exists in his e vs p' curve at the point of the estimated pre-consolidation load ($p'_o \approx 1.3$ kg/cm^2). It can, however, be shown (graphically) that the e vs log p' curve does display – although not very distinctly - a minimum radius of curvature and that this occurs around p' = 1.0 kg/ cm^2. The reload curve does show a discontinuity, appearing in the form of an inflection point. The exact location of this point is not well defined, but the double curvature of the reload curve suggests that it may be near point A, for example at point x (Fig. 1a) at the assumed intersection of curve extensions ax for pressures lower than x and xb for pressures higher than x. Surprisingly, the reload curve shown in Casagrande's e vs log p' curve (curve IV, Fig. 1b) does not share the same co-ordinates as those of the reload curve shown in Fig. 1a. The corrected co-ordinates, i.e. those corresponding to Fig. 1a, are those shown by the thick dashed curve in Fig. 1b, and this curve does show a distinct minimum radius at the pressure near A.

Figure 2a is Casagrande's plot, based on "a large number of tests on different types of soils" and used by him to determine the pre-consolidation load "with a satisfactory degree of accuracy". This curve displays a definite minimum radius at point T, yielding a pre-consolidation load of 1.6 kg/cm^2 at point C. However, if replotted in a diagram of e vs p' (Fig. 2b), no discontinuity is seen at this (or any other) pressure.

Is should be noted that the Casagrande plot in Fig. 2a of this paper does not show any ordinate (void ratio) values. The reason for this is clearly that this plot is included for demonstration purposes only, i.e. for demonstrating the Casagrande graphical method of determining the preconsolidation load. For this purpose the fact that no discontinuity exists in the e vs p' plot is of no significance. But it is unfortunate that his choice of diagram for the demonstration of the new method may have led to its use for tests on soils sufficiently disturbed to yield plots such as that shown in Fig. 2a.

Taylor's plots of void ratio versus pressure (e vs p, Fig. 3a) and void ratio versus log pressure (Fig. 3b) are those shown in Taylor's (1948) Figs. 10.5a and b for a Boston blue clay. Taylor does not refer to Casagrande's method of determining the pre-consolidation load (although Casagrande's 1936 paper was included in the list of references), but he states that "the curvature of the initial line (Fig. 3b) at pressures smaller than 4 kg/cm^2 resembles the curvature of the recompression branch at pressures smaller than 10 kg/cm^2". He concludes that the curved

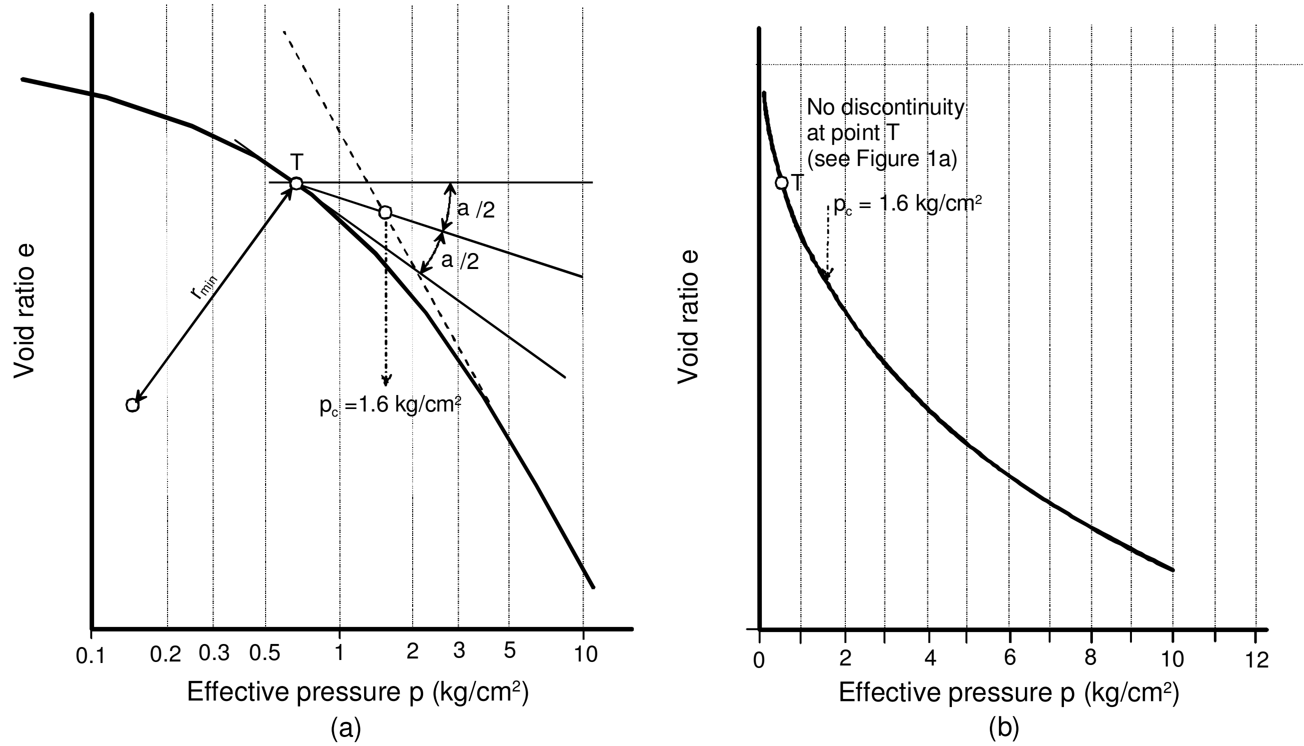

Figure 2. (a) Casagrande's (1936, Fig.2) plot of void ratio versus applied pressure (log scale), (b) same relationship plotted here as void ratio versus applied pressure (natural scale). No ordinates indicated.

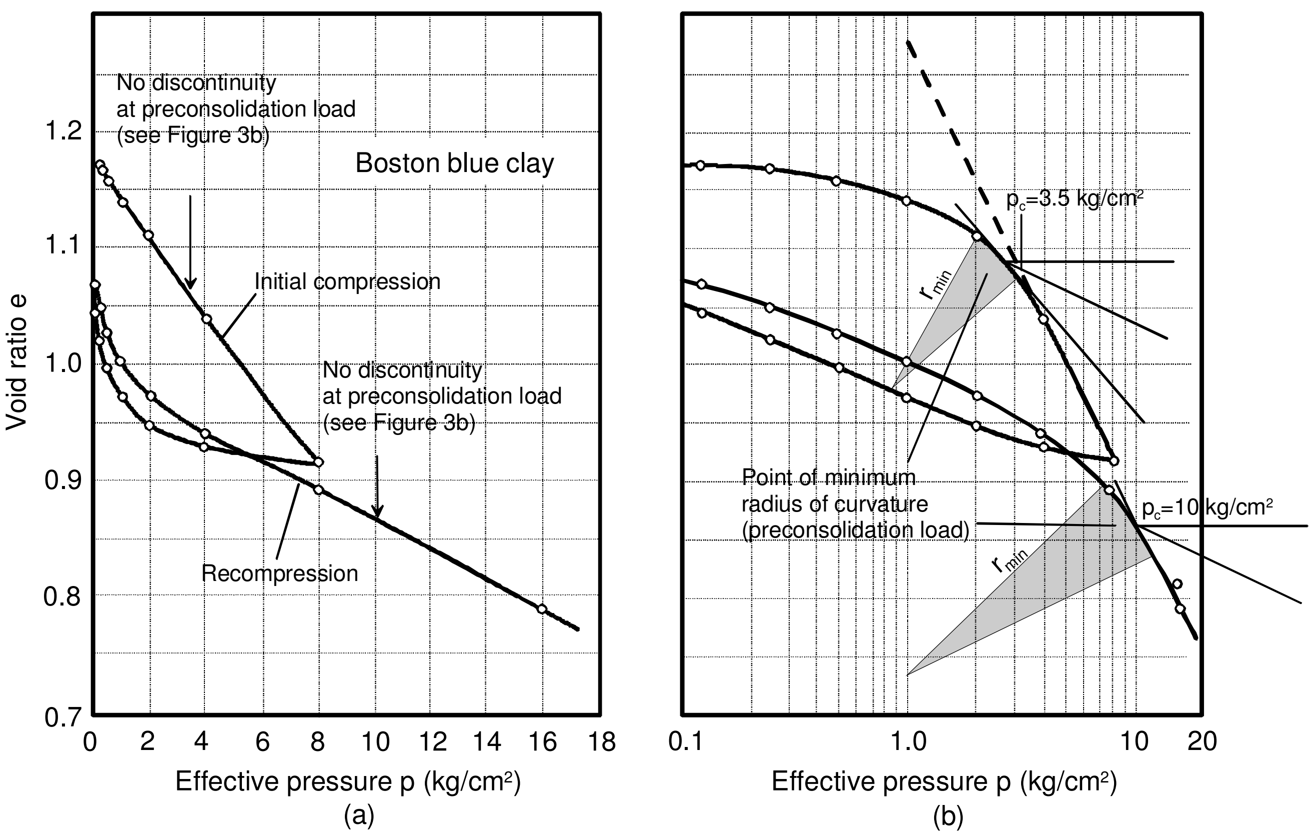

Figure 3. Taylor's (1948, Figs 10.5a and 10.5b) plots of void ratio versus pressure (natural and log scales).

portion of the initial line is a recompression curve and that a "convex curvature on this type of semi-logarithmic plot always indicates recompression". The minimum radius of curvature of the initial line in Fig. 3b is between 2 and 3 kg/cm^2 and that of the recompression curve is between 9 and 11 kg/cm^2, as determined graphically. Thus in this particular case the two methods give reasonably similar results. However, it is again noted that no distinct discontinuities exist in the e vs p' plots, whether initial or recompression. Indications are therefore that the points of maximum curvature may be the result of a mathematical rather than a geotechnical behaviour.

Craig (2004), in his Fig. 7.6 plot, shows an e vs log p' plot (Fig. 4a) which has a very gradual increase of gradient, so much so that a point of maximum curvature is not well defined. When plotted in an e vs p' diagram (Fig. 4b), no discontinuity of any kind can be discerned.

3. HOLTZ AND KOVACS' INTERPRETATION OF THE CASAGRANDE CONSTRUCTION

Holtz and Kovacs (1981) use their Fig. 8.6, shown as Fig. 5a of this paper, to illustrate the Casagrande procedure for determining the pre-consolidation load pc'. Their e vs log p' compression curve shows an unusually distinct minimum radius, i.e. an unusually sharp change of gradient, so much so that they suggest that its location may be chosen by eye. Since no numbers along the axes were shown in the original Fig. 8.6, it would appear that the curve does not represent an actual consolidation test. The numbers along the ordinate axes are based on Holtz and Kovacs' Fig. 8.7. The Casagrande ("most probable") preconsolidation load is about 120 kPa. For comparison, the void ratio was plotted against pressure directly in Fig. 5b. This plot shows a distinct discontinuity around p' = 110 kPa. The important point here is that the e vs p' plot does display a distinct discontinuity at p_c'. However, if the Fig. 5a curve is not real, but rather made up for the purpose of demonstrating the Casagrande construction, any conclusions based on a comparison of Figs. 5a and 5b would not be relevant.

Holtz and Kovac's Fig. 8.7, shown as Fig. 6a of this paper, shows the stress-strain history of a sedimentary clay soil during deposition, sampling and finally reloading in the laboratory. The consolidation stress at point C is between 80 and 90 kPa. At this stress, according to Holtz and Kovacs, "the soil structure starts to break down, and if loading continues, the laboratory virgin compression curve CD is obtained". However, if curve C is shown in an e vs p' plot (Fig. 6b), no discontinuity is found at any stress level, which suggests to these authors that there is no structural breakdown.

The vertical strain Δε the sample undergoes from its original void ratio e_o to the void ratio e_{rc} after recompression can be determined from:

$$\Delta\varepsilon = \frac{e_o - e_{rc}}{1 + e_o}$$

For curve BCD, Δε ≈ 0.03 (i.e. 3%), and since there is no discontinuity in the e vs p' plot, this provides a first indication that a recompression of 0.03 is excessive, suggesting disturbance of the sample. Curve C'' in Fig. 6a (not shown in Holtz and Kovacs' Fig. 8.7) is intermediate between the field virgin curve and curve BCD (closer to the former) and based on a vertical strain of Δε = 0.01. This curve, if replotted to a natural scale of pressure (Fig. 6b) does show a definite discontinuity, suggesting that the upper limit for disturbance could be in the vicinity of Δε = 0.02. This would be in agreement with the limits proposed by Lunne et al. (1997); they suggest an upper limit of Δε = 0.02 for "very good to excellent samples of normally consolidated soft low-plastic clay".

4. e VS LOGp' PLOT WHEN THE e VS p' RELATIONSHIP IS LINEAR

Figure 7a shows a hypothetical relationship between void ratio and the logarithm of the effective stress. As shown in this figure, the curve displays a definite maximum curvature (minimum radius) somewhere between 170 and 270 kPa, probably around 215 kPa. Using the Casagrande method, this corresponds to a preconsolidation stress of 340 kPa, as shown. The e vs log p' is replotted as an e vs p' curve in Fig. 7b. It is seen that not only is there no discontinuity, but the e vs p' "curve" is in fact a straight line!

The observation that a definite point of maximum curvature occurs in the semi-logarithmic plot e vs log p' where the actual e vs p' relationship is linear suggests that in many cases such a point may be a mathematical rather than a geotechnical feature.

5. CLOSURE

A review of a large number of published consolidation tests has shown that in many cases the e vs log p' plots display only a gradual increase of gradient rather than a distinct maximum curvature (minimum radius of curvature). In many cases the point showing the existing effective overburden pressure p'_o and the corresponding void ratio e_o are not included in the diagrams, despite the great significance of such a point which in most cases can be determined with great accuracy. Perhaps the most significant use of this point is that its position relative to the void ratio e reached after reloading to p'_o will be a reliable indicator of the degree of disturbance. For example, if the vertical strain of samples of normally consolidated clay after reloading to the overburden pressure exceeds one or at the most two percent, indications are that the

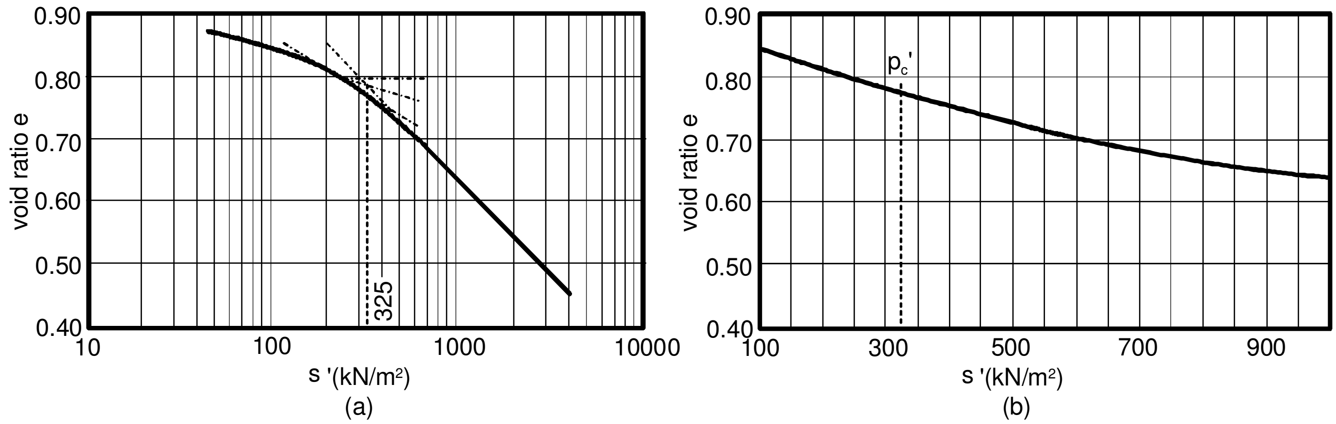

Figure 4. Craig's (2004, Fig. 7.6) plot of void ratio versus applied pressure (log scale), (b) same relationship replotted here as void ratio versus applied pressure (natural scale).

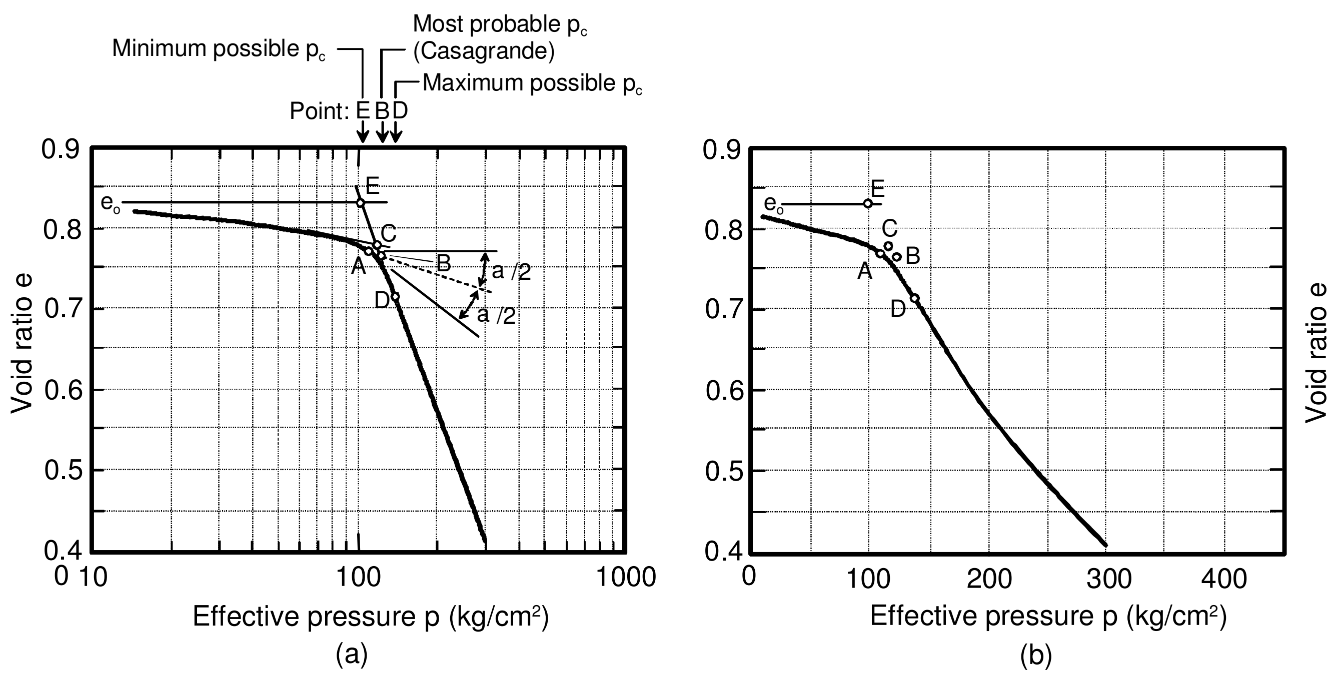

Figure 5. (a) Holtz and Kovacs' (1981, Fig. 8.6) diagram of void ratio versus applied pressure (log scale), (b) same relationship replotted here as void ratio versus applied pressure (natural scale).

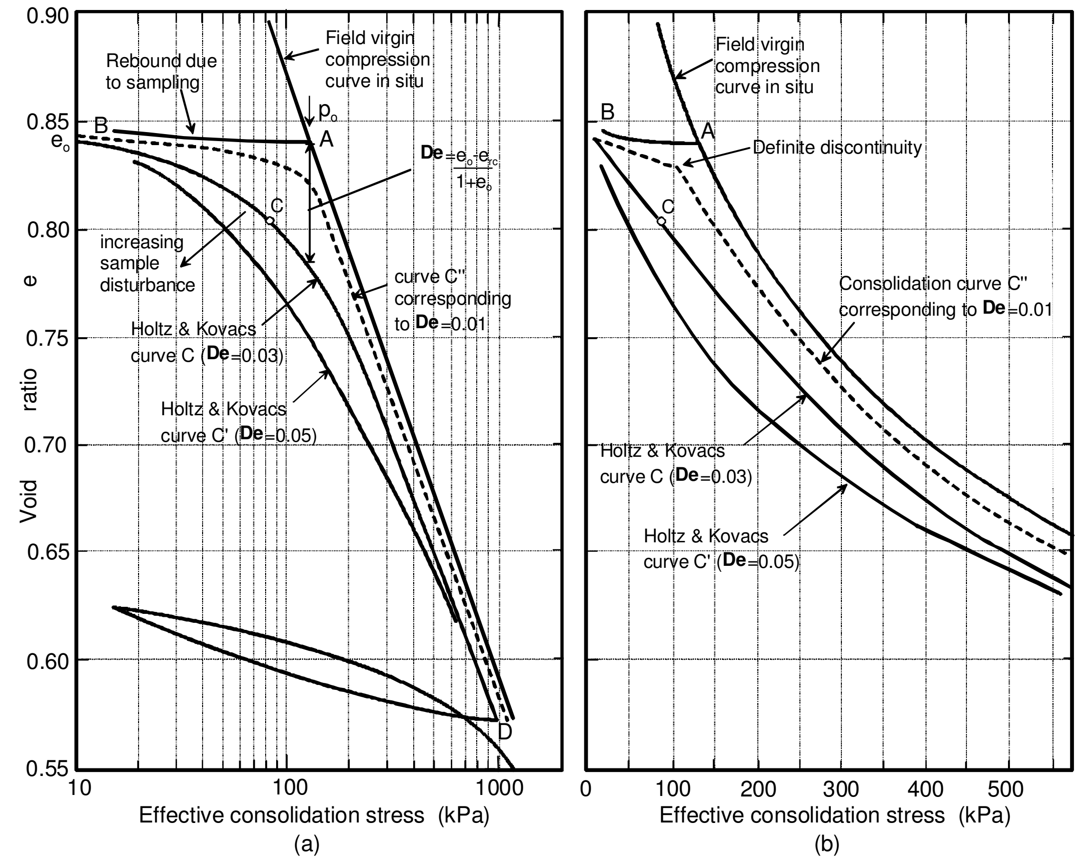

Figure 6. (a) Holtz and Kovacs' (1981, Fig. 8.7) diagram of void ratio versus applied pressure (log scale), (b) same relationship replotted here as void ratio versus applied pressure (natural scale).

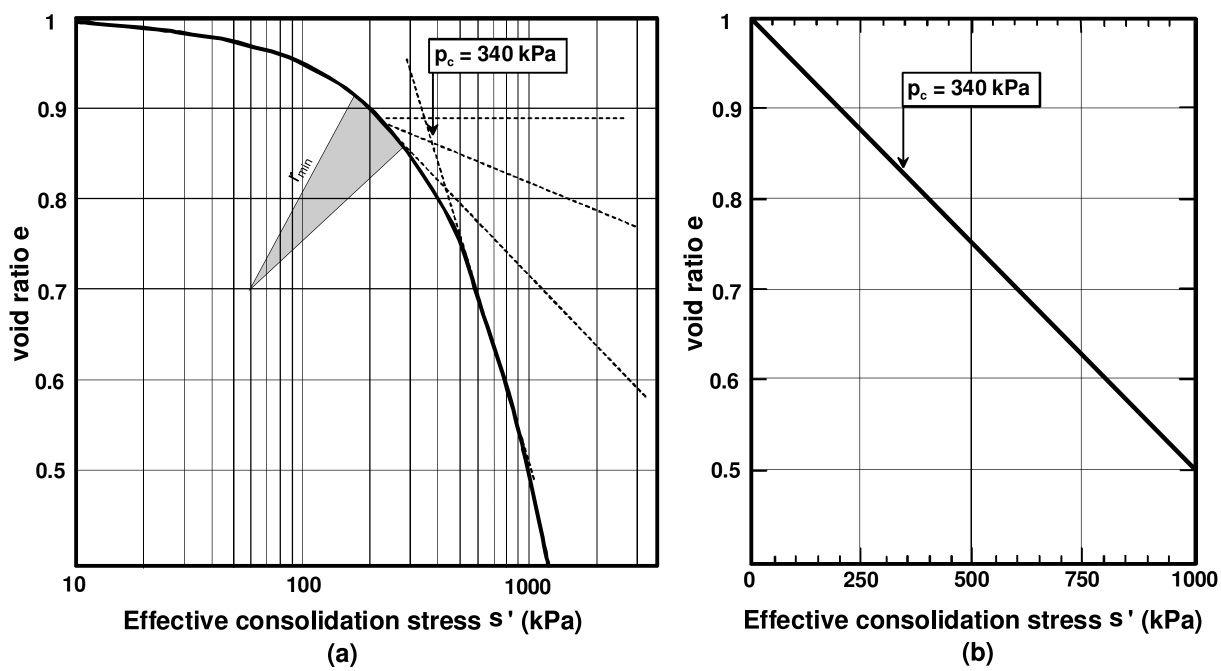

Figure 7. Plots of void ratio versus (a) log pressure and (b) pressure for the case of a linear relationship between void ratio and pressure.

sample is disturbed and the calculated settlement may not therefore be realistic.

Another important conclusion that can be drawn from this study is that e vs log p’ plots should always be supplemented with e vs p’ plots. If the e vs p’ diagram does not display any discontinuity, it is probable that any indication of a maximum curvature in the corresponding e vs p’ diagram is a mathematical rather than a geotechnical phenomenon. In such a case the pressure at the point of maximum curvature would not be indicative of a preconsolidation load.

6. REFERENCES

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