Soil stiffness measured in oedometer tests

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Keywords: foundation stiffness, oedometer test, linear stress scale, log stress scale.

ABSTRACT

The manner in which the results of oedometer tests are normally presented and used for determining stiffness parameters is examined. The basis for using a logarithmic scale for pressure is examined and shown to be of limited relevance to many soils. It is suggested that a linear pressure scale often gives a much improved picture of soil stiffness, and that oedometer test results should always be presented using both log and linear scales.

1 INTRODUCTION

The soil structure interaction situation most commonly encountered by engineers is presumably that of a framed structure on spread footings on clay, as illustrated in Figure 1. Loads on internal foundations (B and C) are normally substantially higher than those on outside foundations (A and D) leading to differential settlement and distortion of the building. This will be "resisted" by the stiffness of the building, so that some load will be transferred from internal foundations to external foundations. This situation is handled in a very simplistic manner, as we are all well aware. The settlement at each foundation is calculated, and the differential settlement is then compared with some empirical limits. This means that the "interaction" is all one way. The influence of the soil stiffness on the structure is considered, (but only with respect to deformations) but the influence of the structure stiffness on foundation loads is ignored.

Methods are available to take account of the stiffness of the structure, although this is seldom done. It could be done iteratively, or by finite element analysis. It is not the purpose of this paper to describe the above methods. Rather, it is to look at the way in which the stiffness of the soil is measured in oedometer tests. Results are routinely presented as graphs of void ratio versus (log) pressure (e-log σ' graphs), from which soil compressibility parameters are determined. These are most commonly the log parameters, C_c and C_s but could be the linear (arithmetic) parameter m_v. Apart from foundation settlement estimates, C_c or C_s are rarely used in soil-structure interaction studies. Soil-structure interaction analysis normally makes use of stiffness parameters expressed in modulus form, giving a direct relationship between stress and strain. There is a case therefore for presenting the results of oedometer tests as simple graphs of

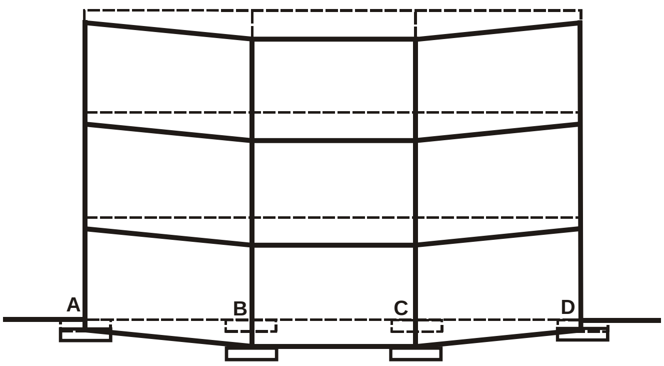


Figure 1: A framed structure on a compressible foundation.

stress versus strain, rather than as conventional e-log σ′ graphs. Janbu has promoted this for many years (Janbu, 1963, also Janbu and Senesset, 1979), not only because of the modulus issue, but also because the log scale for pressure gives a distorted picture of the soil compressibility and is routinely misinterpreted. Deficiencies in the e-log σ′ plot, and the advantages of a linear plot are described in the following sections.

2 BASIS OF THE CONVENTIONAL E-LOG σ′ GRAPH

The origin of the e-log σ′ plot lies in the way sedimentary soils behave when initially consolidated. This is illustrated in Figure 2, which shows the result of an oedometer test on a slurry sample, plotted using a log scale. Two unloading and re-loading cycles are part of the test.

The attraction of the log scale is immediately apparent, because a tidy pattern of behaviour emerges. The virgin consolidation line is linear and the unloading and reloading graphs also approximate to linear. In contrast there is little evidence of any linear behaviour if a linear pressure scale is used (not shown here). For these reasons, the log plot was adopted in the early days of soil mechanics and has been in use ever since. However, the picture in Figure 2 has limited or no relevance to many natural soils, especially residual soils, and in recent years, other voices, including the authors (eg Wesley, 1983, Pender et al, 2000), have been added to that of Janbu, expressing reservations about the log scale for pressure and suggesting more use of linear scales.

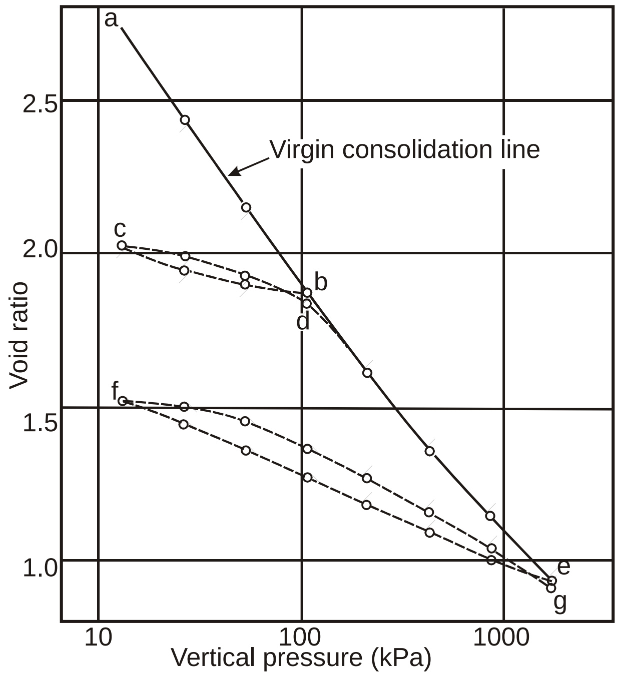


Figure 2: Oedometer test on a slurry clay sample.

3 ARGUMENTS FOR AND AGAINST LOG AND LINEAR PLOTS

3.1 Formation process and the stress history concept

The behaviour shown in Figure 2 is clearly directly related to the past stresses that have acted on the soil, in other words to the stress history of the soil. The assumption that this is also the case with natural sedimentary soils has been seriously questioned in recent years, because after deposition, sedimentary soils undergo “ageing” or hardening effects, or leaching, so that their properties are no longer directly related only to stress history. Most so-called normally consolidated soils show a pre-consolidation pressure significantly greater then their overburden pressure. In other words they behave as lightly over-consolidated clays. Also, genuinely over-consolidated soils seldom show a clear pre-consolidation pressure. This is evident in Figure 2; on reloading to Point g, the slope of the re-loading line is almost the same as that of the virgin consolidation line.

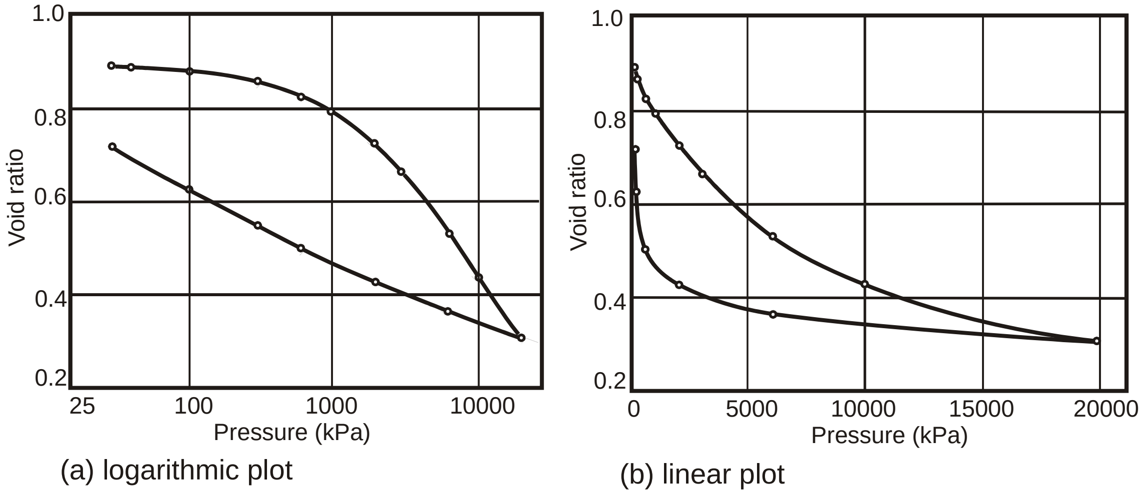


Figure 3: Oedometer test result from a heavily over-consolidated clay

The absence of a clear pre-consolidation pressure is also illustrated in Figure 3, which shows the results of an oedometer test on a heavily over-consolidated clay, presented using both log and linear plots. It could easily be inferred from the log plot that there is a pre-consolidation pressure of about 1000kPa, corresponding to a significant change of slope. However, when re-plotted using a linear scale, there is no evidence of such a change, and the impression of a pre-consolidation pressure is thus an illusion created by the way the data is plotted. The loading curve in Figure 3(a) is similar in shape to the curve f-e in Figure 2, so that the true pre-consolidation pressure could be at least 20,000kPa.

3.2 Residual soil behaviour

With residual soils, there is no logical reason at all to use a log plot. Their formation does not involve a sedimentation process, and the expectation of a virgin consolidation line is without foundation. Similarly, there is no logic in looking for a pre-consolidation pressure, or seeking to identify whether a residual soil is normally consolidated or over-consolidated. This does not mean that residual soils may not display behaviour that is similar to some sedimentary soils, as we shall see shortly, but it is not related to stress history.

Figure 4 shows the results of oedometer tests on four residual soils of varying origins. Figure 4(a) is the normal e-log σ' plot. Because one of the samples has very high void ratios, different scales for void ratio are used in order to bring the graphs together in one drawing. The impression gained from the log plot is that the compression behaviour is rather similar, with three of the samples showing apparent pre-consolidation pressures. In Figure 4(b) the data is re-plotted as linear stress strain (percent compression) graphs, limited to the stress range likely to be of relevance to design situations. This shows quite a different picture. Only one sample (4) displays an apparent pre-consolidation pressure. Two samples (1 and 3) show almost linear behaviour, and the last sample (2) shows steadily increasing stiffness with increasing pressure.

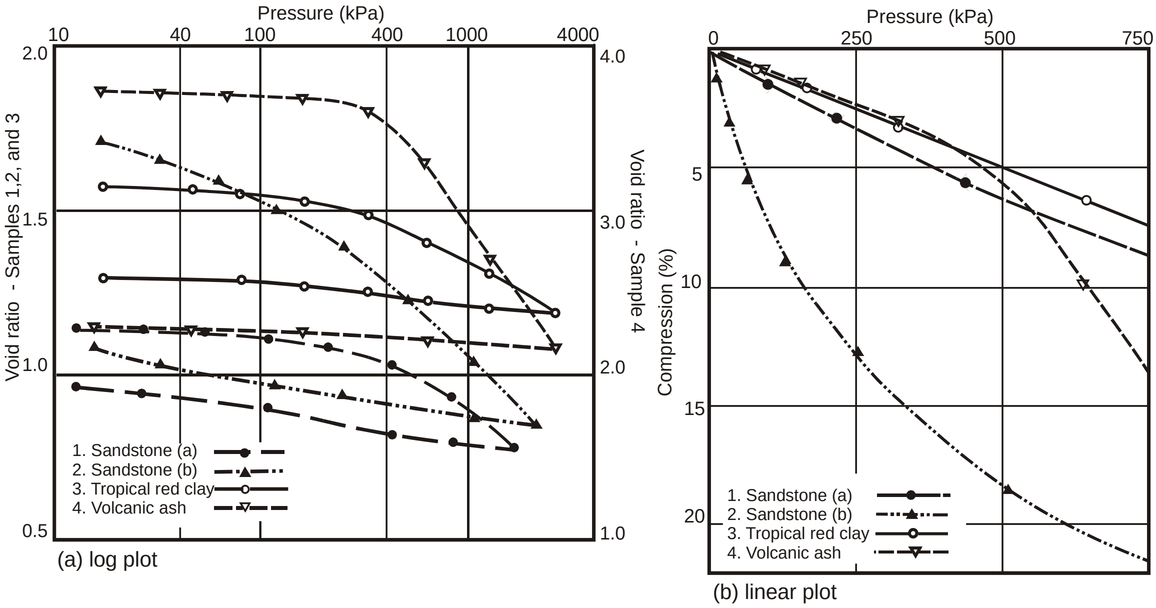


Figure 4: Oedometer test results from four residual soils

Figure 4 shows very clearly the advantages of plotting oedometer tests using linear plots. We can summarise the deficiencies of the log plot as follows:

(a) It suggests that the compression behaviour of all soils is similar.
(b) It has led to a widespread, but faulty belief, that the compression behaviour of all soils can be represented by two straight lines on a log graph.
(c) It is routinely misinterpreted, with “pre-consolidation” pressures being identified when in fact they are only an illusion resulting from the log scale.
(d) It does not allow comparisons of compressibility between different soils to be made.

These shortcomings are largely overcome by using a linear plot. It should be recognised that the range of behaviour illustrated in Figure 4(b) is typical of all soils, not just residual soils. Some “strain harden” with stress increase, some “strain soften” and some have approximately constant stiffness. We should note also that the term “vertical yield pressure” is a much better term to designate the pressure at which the soil “softens” rather than pre-consolidation pressure, because it is applicable to all soils, and covers all the factors that my contribute to the yield pressure (not just stress history).

3.3 Relative complexity of settlement estimates

Settlement estimation using the logarithmic plot requires values for C_c, C_s, the preconsolidation pressure, the in situ effective vertical stress prior to the load application, and the increase in vertical stress in the layer under consideration. Determination of C_c and C_s is often an artificial procedure because the plot consists of a smooth curve rather than two linear sections. Using a linear stress plot to estimate settlement requires the value of m_v, the in situ effective vertical stress prior to the load application and the increase in vertical stress in the layer causing the settlement. In principle, m_v is not constant so it has to be calculated by taking the slope between the two relevant stresses on the oedometer curve.

Clearly, the amount of information required is less using m_v, so proponents of the e – log σ' method are not able to appeal to simplicity as a line of defence. In this regard, Janbu (1998) makes good reading.

4 FURTHER EXAMPLES

4.1 General

We think that the point being made in this paper is important enough to warrant presenting two more examples to emphasise that the linear stress plot is a very satisfactory way of presenting and interpreting oedometer data.

4.2 Volcanic soil

Figure 5 from Wesley (2003) gives oedometer plots for tests on volcanic ash. It is very clear from the natural stress scale plot in Figure 5(b) that all but two of the soils do not exhibit yielding. On the other hand, from the logarithmic plot on Figure 5(a) one would conclude that all the specimens exhibit yield.

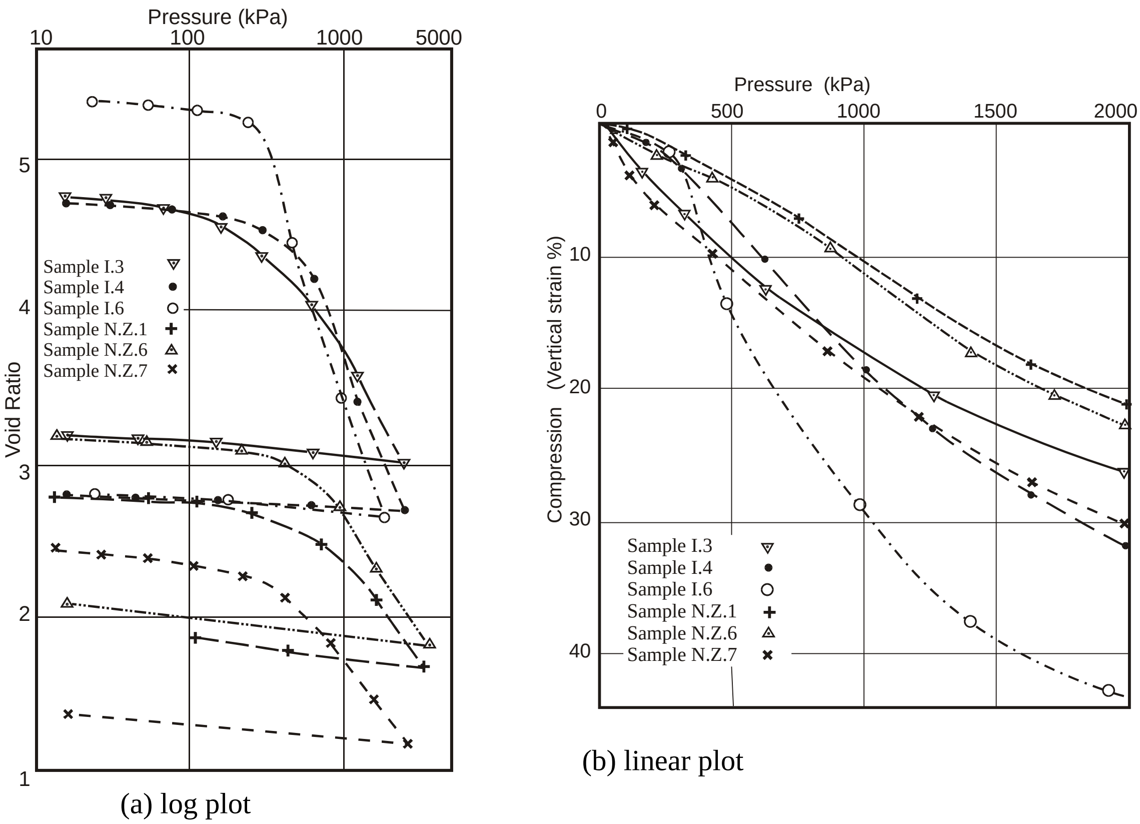


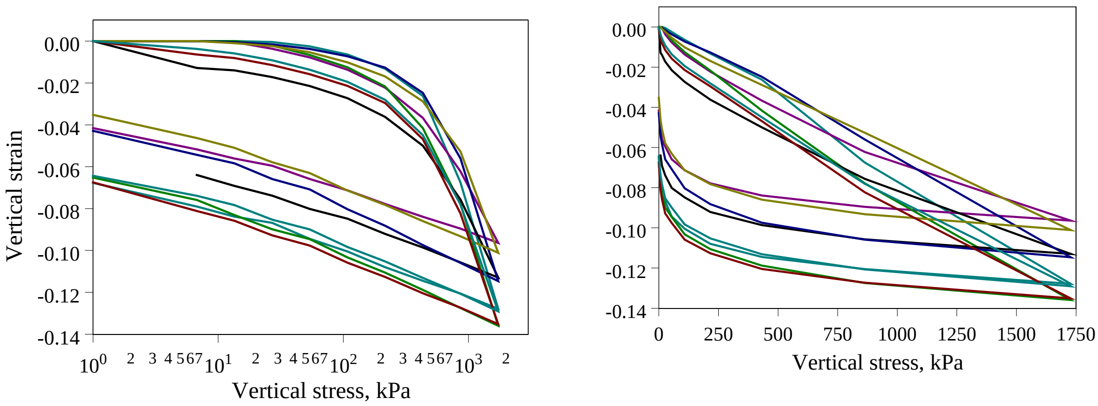
Figure 5 Oedmeter data on volcanic ash (from Wesley, 2003).

4.3 Auckland residual clay

Figure 6 presents oedometer data on Auckland residual clay from Pender et al (2000). The linear plot in Figure 6(b) shows compression graphs that are almost straight lines, so the apparent preconsolidation pressures in Figure 6(a) are quite misleading.

5 OTHER COMMENTS

Having cast aside the e – log σ′ framework many other possibilities come to light. The first realisation is that m_v is simply the inverse of the constrained modulus, which in turn is a relative of Young's modulus.



(a) log plot

(b) linear plot

Figure 6 Oedometer tests on Auckland residual clay (from Pender et al, 2000).

So any test method that enables Young's modulus to be determined for soil can be used to get parameter values for settlement estimates. The obvious candidate is a triaxial test. With careful preparation of specimen ends the triaxial test will give soil stiffness values less affected by bedding errors than the conventional oedometer.

6 CONCLUSIONS

Our point in writing this paper is to emphasize that we think geotechnical practice in New Zealand would be enhanced if the slavish following of the e – log σ′ method of settlement prediction was abandoned in favour of the m_v method based on an e - σ′ curve.

A positive contribution to this process would be for geotechnical testing laboratories to present the results of oedometer tests in both linear and log plots. The examples presented here emphasise how the natural stress scale gives much more reliable insight into soil compressibility behaviour than the log scale.

It should be a matter of professional embarrassment to find that materials that for so long have been interpreted in the e – log σ′ curve framework as exhibiting yielding compression behaviour often have nearly linear compression curves when looked at in the e - σ′ framework.

REFERENCES

Janbu, N. (1963) Soil compressibility as determined by oedometer and traixial tests. *Proc. 4th European Conference on Soil Mechanics and Foundation Engineering*, Wiesbaden.

Janbu, N and Senneset, K (1979) "Interpretation procedures for obtaining soil deformation parameters", *Proc. VII European Conference on Soil Mechanics and Foundation Engineering*, Brighton, pp. 185-188.

Janbu, N (1998) "Sediment deformations", Bulletin No. 35, Institutt for Geoteknikk, Norwegian University of Science and Technology, Trondheim.

Pender, M.J., Wesley, L.D., Twose, G., Duske, G.C. and Pranjoto, S. (2000) Compressibility of Auckland residual soils. *Proceedings GeoEng 2000*, Melbourne.

Wesley, L.D. (1983) Interpretation and evaluation of test results. *Proceedings Key Issues in Foundation Engineering*, Institute for International Research, Kuala Lumpur.

Wesley, L. D (2003) "Geotechnical properties of two volcanic soils". *NZGS Symposium NZ Geotechnical Society Symposium* Tauranga, pp. 225-244.