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Rethinking aspects of theory and tradition in soil mechanics teaching

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ABSTRACT: Some basic aspects of theory and tradition in soil mechanics teaching are examined and shown to be deficient. The first is the absence of material on residual soils despite the fact that at least half the world's surface consists of residual soils. The second aspect is the continued use of the e-log(p) plot for representing soil compressibility. This plot leads to routine misinterpretation of the compressibility of both sedimentary and residual soils. The third aspect is the water table and the seepage state above and below it. The water table is not a boundary below which seepage occurs and above which there is no seepage or pore pressure. The fourth aspect is the critical height of vertical cuts in clay. Equations for critical height are presented as though they can be used in practice. This is quite wrong, and a serious matter involving life and death.

1 INTRODUCTION

By way of introduction the following comments are made on university teaching, before moving on to the specific issues addressed in this paper:

(a) There is too much emphasis on methods and too little on concepts and principles. Graduates generally have a fairly good grasp on methods, but a weak understanding of the concepts and assumptions behind these methods This reflects both the natural inclinations of engineers, and the fact that much engineering teaching, especially with large classes, is more akin to "production line knowledge transfer" than true education. This issue has been addressed elsewhere, for example Streveler et al. (2008).
(b) The order in which material is presented in soil mechanics courses is often unsatisfactory. The first lecture should be on the principle of effective stress to stimulate the thinking and interest of students, followed by worked examples using the principle. Clay mineralogy, phase relationships, or classification tests, can be slotted in later in the course.
(c) Universities need to be clear on what they aim to achieve in their courses. "Geotechnical Engineering" and "Soil Mechanics" should not be confused. Soil mechanics is a theoretical discipline, while geotechnical engineering is a practical undertaking, more akin to a profession; it involves many components, including soil mechanics, geology, observation, experience, and a large measure of judgement. The role of universities should be to teach soil mechanics, and to be sure that what they teach is relevant to geotechnical engineering.

The issues addressed in this paper are those the author considers important and which space allows. Others that are of significance include:

(1) determination of the coefficient of consolidation from standard oedometer tests on residual soils. In these soils the rate of pore pressure dissipation is often too rapid for sensible time versus deformation data to be obtained.
(2) the rate of consolidation of small surface foundations on clay. Consolidation in this case is certainly not two dimensional, yet text books or courses seldom address this issue. Graduates tend to apply one dimensional theory to this situation and continue the practice throughout their careers.
(3) the Laplace equation, the Terzaghi consolidation equation, and the general transient seepage equation used in groundwater studies should all be linked, or derived together, to show their common basis and their connections.
(4) the stability situations, namely soil bearing capacity, earth pressure, and slope stability, should also be linked together to bring out their common basis, as well as their differences, especially with respect to the way the safety factor is applied.

2 RESIDUAL SOIL COVERAGE

Half the world's surface consists of residual soils, and yet soil mechanics text books and courses rarely even mention these soils, let alone give adequate coverage of their properties. There was some excuse for this in the past, since soil mechanics grew up in northern Europe and America where sedimentary soils predominate, but surely the time has come when the properties

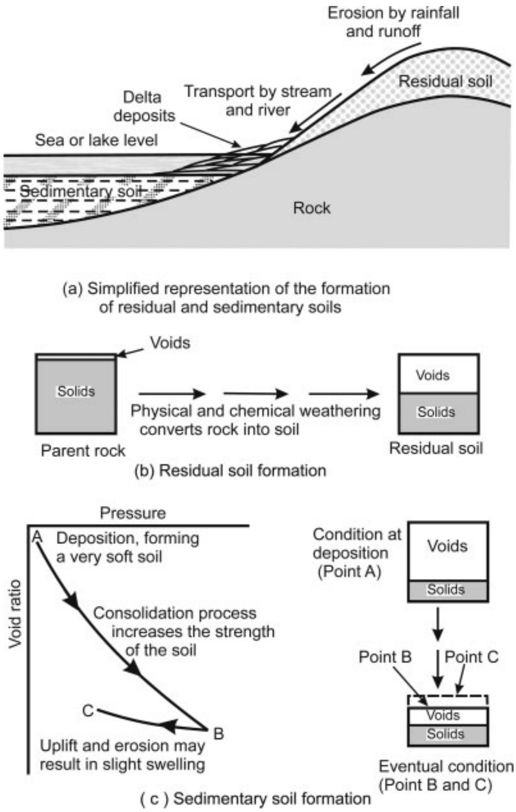

Figure 1. Sedimentary and residual soil formation.

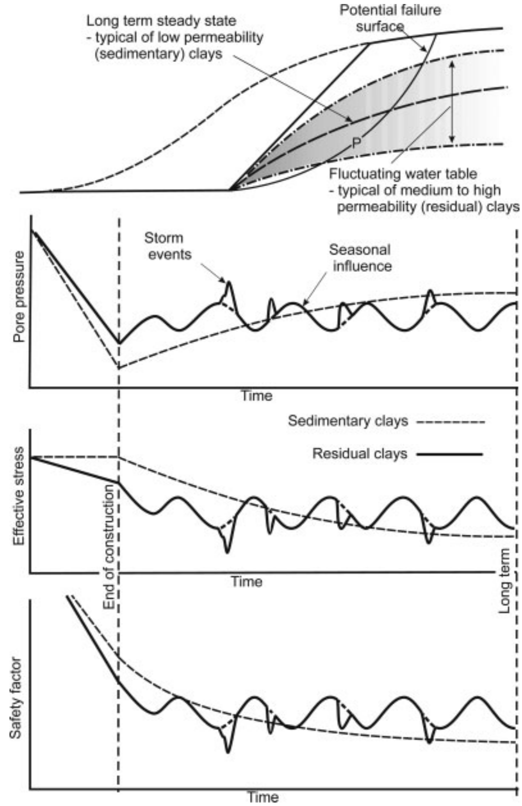

Figure 2. Short and long term stability of cut slopes.

of residual soils should be just as much a part of main stream soil mechanics as sedimentary soils.

In today's globalised world, geotechnical engineers can expect to encounter residual soils sometime during their working life, especially since the most rapidly developing countries today are those in which residual soils predominate. It is surely a cause for concern that in many such countries, soil mechanics courses do not cover residual soils at all, even though the universities in which these courses are taught are surrounded by residual soils on all sides, as far as the eye can see.

Figure 1 illustrates the very minimum that students should be made aware of, namely that the processes forming residual soils are very different to those forming sedimentary soils. Important factors follow from this:

(a) The transport and sedimentation processes of sedimentary soils give them a degree of uniformity and predictability that is missing from residual soils
(b) Stress history and concepts of normal and overconsolidation are irrelevant to residual soils, and there is no such thing as a virgin consolidation line for a residual soil.

Various other important differences follow from their formation method, one of which is that the permeability of residual soils is generally much higher than that of sedimentary soils. This has implications for various aspects of their behaviour, such as the short term and long term stability of excavated cuts.

Figure 2 shows the likely behaviour of residual soils compared with the well known representation for sedimentary soils. It is unlikely that residual soil behaviour will be undrained during construction, as water will flow towards the excavation as it deepens. In addition, there will not be a long term steady state situation, only a transient state reflecting seasonal and storm events. Thus, the challenge for the geotechnical engineer in assessing the long term stability of cuts in clay is very different for the two soils. With sedimentary soils, the challenge is to estimate the long term steady state seepage pattern, while with residual soils it is to estimate the worst possible pore pressure state resulting from a combination of seasonal and storm influences.

3 THE e-log(p) PLOT

The e-log(p) plot is a source of routine misinterpretation of compression behaviour, and it is extraordinary that it is still in (almost) universal use. If there is one "foundation" of soil mechanics that needs shaking virtually to destruction this is it. The author has promoted the use of a linear plot for many years based on experience with residual soils, only to discover relatively recently that Professor Janbu of Norway has

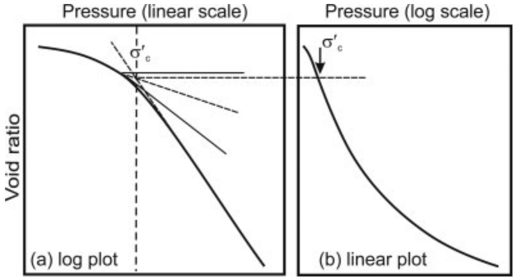

Figure 3. Conventional (log) representation of soil compression behaviour and a linear plot of the same curve.

been doing the same for considerably longer based on his experience with sedimentary soils.

> *"It is very surprising, to say the least, to observe all the efforts still made internationally in studying remoulded clays. If the aim of such research is practical application, it is obviously a total waste of money".*
>
> "*— it remains a mystery why the international profession still uses the awkward e-log p plots, and the incomplete and useless coefficient C_c which is not even determined from the measured data, but from a constructed line outside the measurements —*" Janbu (1998)

Figure 3 shows the standard representation of the compressibility of clay and the method for determining the pre-consolidation pressure, and the same graph re-drawn using a linear scale.

It is immediately apparent that the linear graph shows no evidence of a pre-consolidation pressure; the value inferred from the log plot is purely a result of the way the data are presented. As far as the author is aware, all presentations in text books illustrating pre-consolidation pressures suffer from the same defect as Figure 3.

There are countless examples in the literature of oedometer test graphs from which pre-consolidation or yield pressures have been determined that are completely absent when the data are re-plotted on linear scales. Examples are given in Figures 4 and 5. Figure 4 shows an example from a residual soil found in the southern part of the USA, known as Piedmont soil. Values of pre-consolidation pressure and over-consolidation ratios (OCRs) determined from the log plot are shown in the figure. The data have been re-plotted using a linear scale for pressure; these linear plots show no evidence of yield or pre-consolidation pressures.

For the plot in Figure 4 (and in some subsequent figures), using a linear scale, the compression is shown as strain in percent, rather than void ratio. This is done as it gives an immediate indication of compressibility and enables valid comparisons to be made between the compressibility of different samples or soils. A direct comparison of this sort is not possible using void ratio.

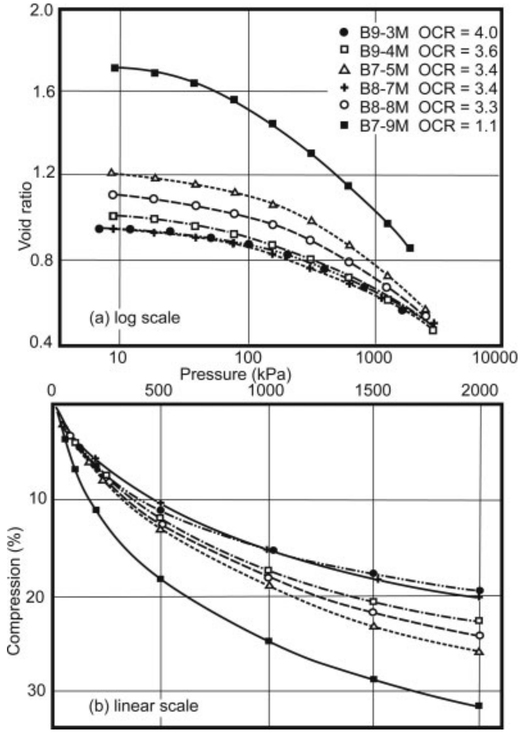

Figure 4. Compressibility of Piedmont residual soil (after Wesley 2000).

From what was said earlier, it is quite inappropriate to be seeking pre-consolidation pressures in residual soils, since their formation does not involve a consolidation process. If residual soils indicate a decrease in stiffness at a particular stress level, this should be termed a yield pressure. Many residual soils do not show a yield pressure at all, but there are plenty that do. Some residual soils derived from the same parent material can even show both types of behaviour, as is illustrated in Figure 5.

The compression curves in Figure 5 are from three samples of volcanic ash clay, again plotted using both scales. This figure also illustrates clearly another defect of the log plot, namely that it conveys the impression that the compression behaviour of all soils is similar. On the log plot the behaviour of the three samples looks similar, with each giving some evidence of a yield pressure. However, the linear plot shows that their behaviour is quite different. Only Sample A shows a clear yield pressure. Sample B shows linear behaviour, and Sample C shows steadily increasing stiffness.

Because of the defects of the e-log(p) graph, as illustrated in the above figures, a more realistic portrayal of soil behaviour is that shown in Figure 6.

This portrayal is intended for the stress range of interest in geotechnical engineering and is appropriate for both sedimentary and residual soils. In both groups, some soils show clear yield pressures, some

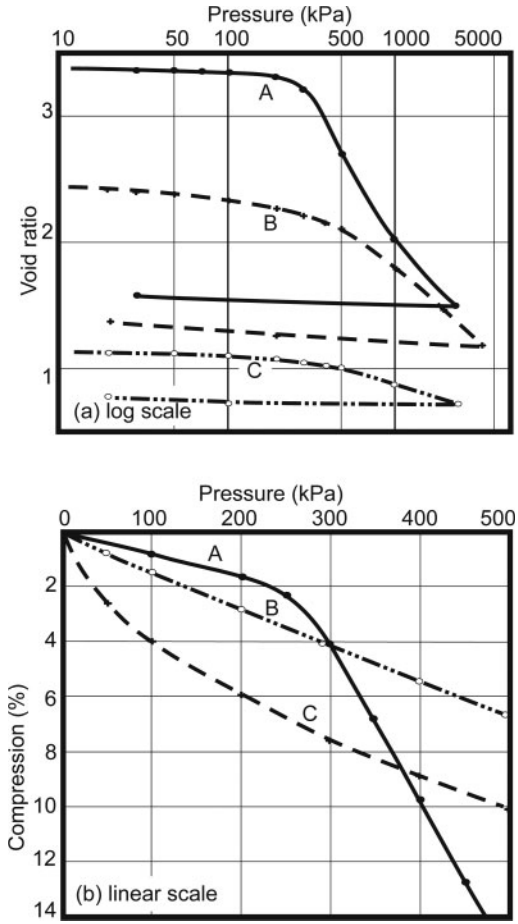

Figure 5. Oedometer tests on three samples of volcanic ash clay (after Wesley 2009).

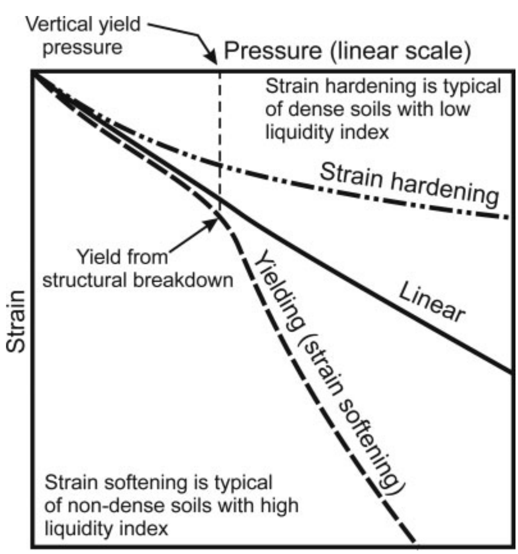

Figure 6. A realistic portrayal of soil compressibility (after Wesley 2010).

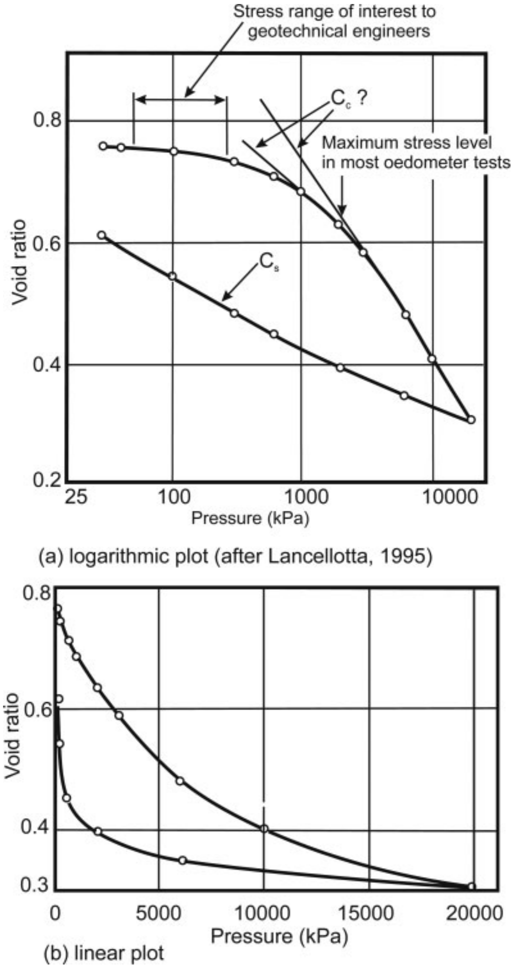

Figure 7. An oedometer test on an over-consolidated clay.

show approximately linear behaviour, and some show strain hardening.

To explain the above behaviour it is important to recognise that compression (or compaction) of a soil has two distinct effects, as follows:

1. Densification: Compression “densifies” the soil by pressing the particles closer together. This generally means a greater number of contact points between particles and a consequent decrease in compressibility.
2. Structure Destruction: Compression also tends to destroy any natural structure found in the undisturbed soil, which weakens and softens the soil.

The resulting compression curve will reflect the relative importance of these two effects. If the influence of densification is stronger than destruction of structure the soil will show strain hardening and vice versa.

Figure 7 illustrates a further defect of the log plot, namely the uncertainty and irrelevance of the parameters associated with it. The figure shows an oedometer test on an over-consolidated clay taken to a high stress level. The log plot seems to suggest a pre-consolidation pressure a little greater than 1000 kPa, but the linear plot shows no evidence of this. The graph suggests a linear section at higher stress levels, and the slope of this section should presumably represent the compression index C_c. However, most oedometer tests are only taken to a stress level between 1000 kPa and 2000 kPa.

A tangent to the curve at these stress levels would produce quite different values of C_c. Except for soft normally consolidated clay, the compression index is both of uncertain value and irrelevant to engineering situations. The meaning of C_c for a residual soil has not been seriously addressed. As originally conceived C_c was the slope of the virgin consolidation line. No such line exists for a residual soil, and C_c seems to be taken as the slope of the tangent to the end of an e-log(p) graph. As such it is of arbitrary value and of no practical use.

The value of the swell index is equally problematic, since the original loading line is clearly not parallel to the final unloading line. The slope of the initial loading line is much flatter than the rebound line. Neither of the conventional log parameters, C_c and C_s determined in the traditional manner has any relevance to a settlement estimate for a building foundation. The part of the curve relevant to such an estimate is likely to be between about 25 kPa and 300 kPa.

4 THE WATER TABLE AND SEEPAGE STATE

Much of the action of interest to geotechnical engineers actually takes place above the water table, especially in residual soils, and yet surprisingly little attention is paid to this regime in university courses, or in text books. Students should be made aware of the very different situation with clay to that with sand. The static situation is illustrated in Figure 8. The important point is that in wet or temperate climates clay remains fully saturated for many metres or tens of metres above the water table, and that it only becomes unsaturated as the result of evaporation at the ground surface, and not because water drains out of the soil under gravity forces.

With coarse grained materials, the situation is very different. In this case, water drains out of the voids under simple gravity forces. As drainage takes place air enters the void space formerly occupied by water, and the soil becomes unsaturated or partially saturated.

The water table (or phreatic surface) is not a boundary separating zones where seepage and pore pressures exist from those where they don't exist; it is simply a line of zero pore pressure.

The conventional portrayal of the seepage pattern in a clay slope may be valid for some slopes, but certainly not all. This point is illustrated in Figure 9, which shows two possible seepage conditions for the same measured water table. The upper graph shows the conventional portrayal, which implies that seepage into

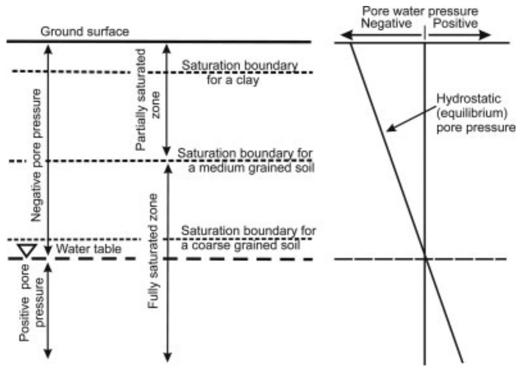

Figure 8. Water table and pore pressure state in the ground.

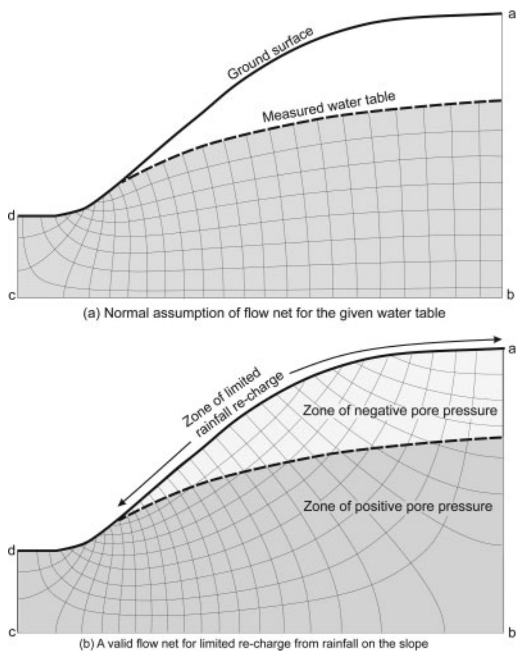

Figure 9. Possible seepage states for the same water table.

the slope only comes from an adjacent catchment. This is somewhat odd, as the rainfall most likely to affect the seepage state in the slope is rain falling directly on the slope itself.

The lower figure illustrates the situation for a symmetrical, double sided hill. In this situation the only source of water to the slope is from direct rainfall, and the seepage pattern is then quite different. The flow net in the lower figure has been obtained using the programme SEEP/W. To obtain a phreatic surface below the ground surface the boundary condition at the surface can either be a negative pore pressure (not realistic in practice) or a rainfall intensity less than the maximum capacity that the ground can accept.

5 STABILITY OF TRENCHES AND VERTICAL CLAY BANKS

Terzaghi once warned against over-reliance on theory with the following statement:

> "*However, as soon as we pass from steel and concrete to earth, the omnipotence of theory ceases to exist. In the first place, the earth in its natural state is never uniform. Second, its properties are too complicated for rigorous theoretical treatment. Finally, even an approximate mathematical solution of some of the most common problems is extremely difficult*" (Terzaghi 1936).

An example of over-reliance on theory is the way in which the maximum height of vertical banks or cuts in clay is described in soil mechanics courses or text books. The formulae normally presented, without warning about their practical relevance, are:

In terms or effective stress:

$$H_c = \frac{4c'}{\gamma\sqrt{K_a}} \tag{1}$$

where K_a is the active pressure coefficient.

For undrained conditions:

$$H_c = \frac{(3.8\,to\,4)S_u}{\gamma} \tag{2}$$

where S_u is the undrained shear strength.In the author's experience, the following parameters are typical of many residual clays;

Unit weight – $16\,\text{kN/m}^3$, $c' = 15\,\text{kPa}$, $\phi' = 35°$ Undrained shear strength $= 100\,\text{kPa}$.

Using the formula above the depths obtained are illustrated in Figure 10. Undrained analysis gives $H_c = 24$ or 25 m. This is a nonsensical estimate, as it is quite impossible to imagine a clay bank of this height remaining stable even for a few seconds. Using the formula in terms of effective stress gives $H_c = 7.2$ m, which is still unrealistic. The values using a safety factor of 3 are also shown, and are still hardly realistic.

There is probably no issue in soil mechanics where theory is less useful than this question of vertical bank stability. Many lives have been tragically lost because of the collapse of vertical banks, especially those forming the sides of trenches in which workers are laying pipes or cables. Such collapses have occurred in situations where the above formula would suggest the banks would be stable. Teachers of soil mechanics should make it clear to students that the formulae above are of theoretical interest only. Statements found in text books such as "*for vertical cuts the best solution, and the one that is commonly used in design*" *is*: $H_c = 3.8S_u/\gamma$, are a recipe for tragedies.

Fortunately, agencies that regulate work-place safety have a better understanding of the behaviour of vertical cuts in clay than many authors of text books, and indeed of many geotechnical engineers.

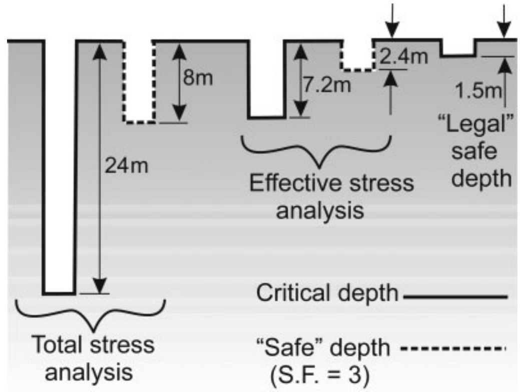

Figure 10. Heights or depths of vertical cuts in clay.

Such agencies normally place a limit of 1.5 m (some use 1.2 m) on the height of vertical banks or depth of trenches where workmen are employed.

This issue of the stability of vertical banks in clay appears to be a prime example of theory being given an omnipotence that is totally unwarranted. It is an interesting and somewhat worrying example, as the problem appears to lie as much with the theory itself as with the vagaries of nature. The author does not have a satisfactory explanation for the divergence between theory and observed behaviour in this case. One possible explanation is the complete absence in the above equations of pore water pressure. There is no doubt that some collapses of vertical clay banks are triggered by rainfall, but it is equally true that even without rainfall, clay banks do not remain vertical for long.

The issue is perhaps also an example of the failure of geotechnical engineers, or text book writers, to observe the behaviour of soils in practice. It is very difficult to find a vertical clay bank anywhere, even with a height of only a few metres. However, high banks of 60° to 75° are not difficult to find, so there seems to be a significant change in the behaviour of steep banks as their inclination is reduced from vertical to about 70°. It may be that a zone of horizontal tension is created in the upper part of steep slopes and this leads to the development of vertical cracks that play a role in initiating the failures.

6 CONCLUSION

Several "foundations" of conventional soil mechanics teaching have been examined, including the e-log(p) graph, the seepage pattern commonly assumed to apply in natural hill slopes, and the formulae for the critical height of vertical clay banks. Quite gentle shaking shows that these are not nearly as technically sound as they are commonly assumed to be.

These examples will hopefully encourage those teaching soil mechanics to address not only the questions of curriculum content and techniques for teaching the content, but also whether various commonly accepted components of the curriculum are in fact based on firm foundations.

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