Unconfined seepage behaviour in coarse and fine grained soils

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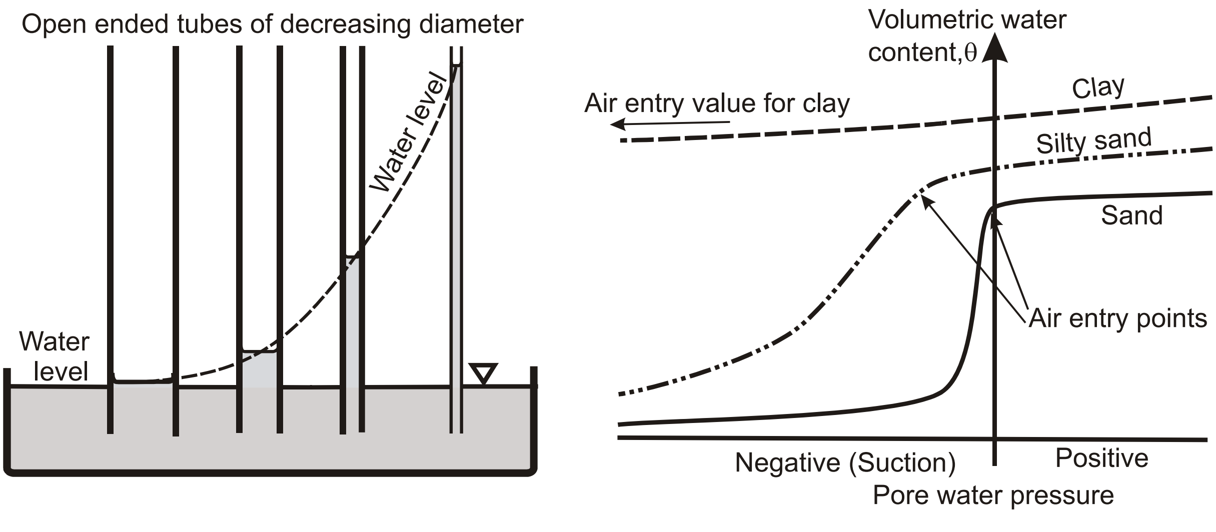
ABSTRACT

Human activity is increasingly impacting on the natural seepage state in the ground, both in terms of its pattern and the quality of the seeping water. This paper addresses a widespread misconception regarding seepage behaviour, namely that unconfined seepage in fine grained and coarse grained soils is the same. For example, flow nets through homogeneous earth dams are routinely presented as though they are applicable to all soils. Natural seepage in hillsides is portrayed as though there is no seepage above the water table. Both portrayals are true of coarse grained materials, but are not true for clays. This issue is examined by first looking at the physical reasons for the differences and then at practical situations where failure to understand the difference can lead to serious misconceptions regarding the seepage state. These situations include the influence of rainfall on the pore water pressure state, flow into dewatered excavations, and the estimation of slope stability.

Keywords: unconfined seepage, water table, Dupuit, Laplace, drawdown.

1 INTRODUCTION

A great deal of time and energy in recent years had been put into developing sophisticated models of soil behaviour. Constitutive modelling appears to be a dominant feature of research in many universities. However, not a lot of attention has been paid to the environment in which the soil exists in the ground, especially the seepage and pore water pressure state. Some simplifying assumptions adopted in the early years of soil mechanics have now become so entrenched that they are rarely questioned, despite the fact that they may be unsound. The assumption challenged here is that unconfined seepage in a fine grained soil is the same as that in a coarse grained soil.



(a) Capillary rise in open ended glass tubes

(b) Air entry values in coarse and fine grained soils

Figure 1. Capillary rise and air entry values in soils.

The difference in behaviour arises from the physical laws illustrated in Figure 1. Figure 1 (a) shows the simple phenomenon of capillary rise - the finer the tube, the higher the water will rise in the tube. Figure 1 (b) shows graphs of volumetric water content plotted against pore water pressure. It is seen that with sand, the curve drops sharply as soon as the pore water pressure becomes negative. Water drains out of the material to be replaced by air. With finer soils the air entry value increases, and with clays it is extremely high, possibly equivalent to many tens of metres of water. This means that clay can remain fully saturated for tens of metres above the water table. Near the ground surface the clay may become partially saturated due to evaporation, although in wet and temperate climates this will be a shallow zone of only one or two metres. The water table is thus the upper boundary of the seepage zone only in coarse materials. In clays it is simply a line, or surface of zero (atmospheric) pore water pressure. Seepage occurs above and below this surface according to identical laws and the water table is not a discontinuity in the flow pattern. The following sections describe the seepage state in the two materials in some practical situations. The terms coarse grained and fine grained here are intended to mean free draining materials such as clean sands and gravels, and clays of moderate to high plasticity respectively

2 EMBANKMENT SEEPAGE AND HILLSIDE SEEPAGE

Examples of the difference in bahaviour between coarse and fine soils are given in the following two figures. Figure 2 shows the flow nets applicable to an embankment dam made of coarse and fine grained soil. The upper figure shows the conventional pattern found in soil mechanics text books since the early days of the subject. The phreatic surface is assumed to be the upper boundary of the seepage zone. This can only be physically possible if the embankment is made of coarse grained soil, which is extremely unlikely to be the case. Such an embankment would not be stable and the seepage rate through it would be huge.

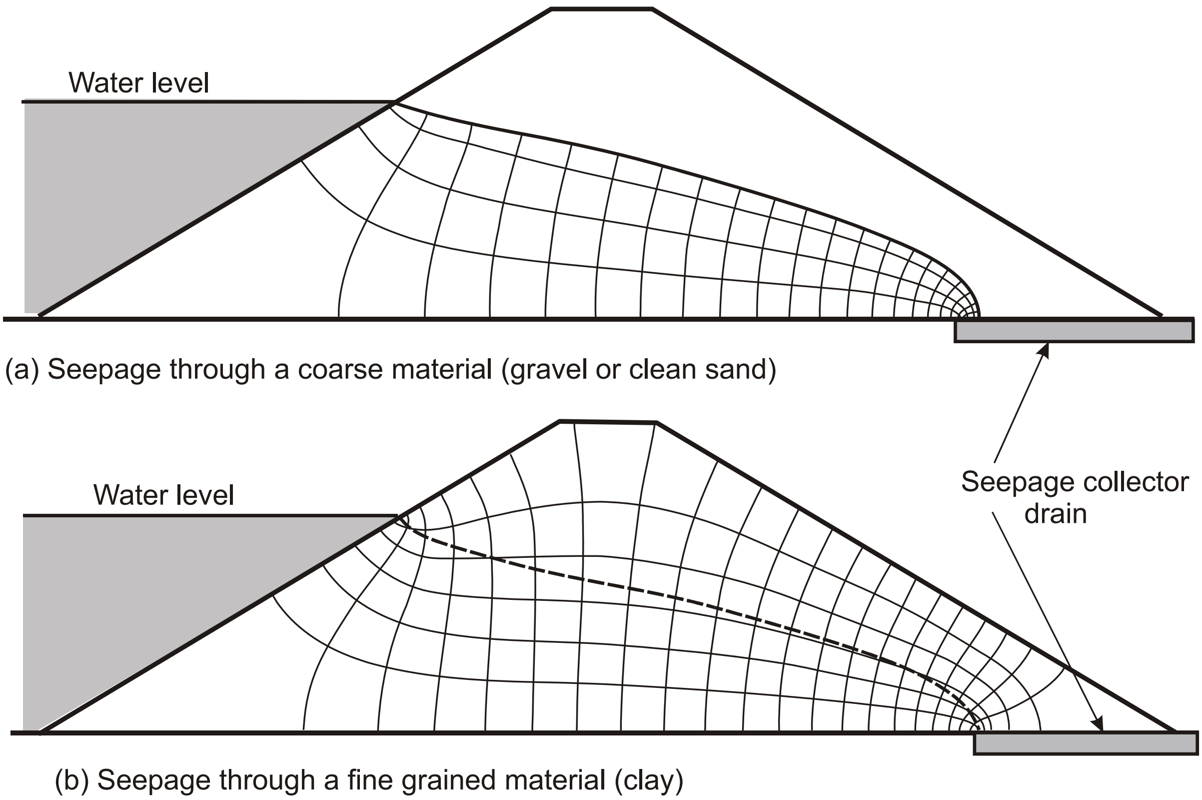


Figure 2. Flow nets in homogeneous embankments built of coarse and fine grained soils.

The lower figure shows a realistic flow net when the embankment is made of clay. In this case the upper surface of the embankment is the upper boundary of the seepage zone. In practice this flow net may well be distorted by weather effects. During rainfall some water will enter the embankment from the surface, and in hot dry weather some water will be lost through evaporation at the surface. One of the reasons the seepage pattern in Figure 2(a) became firmly established in the early days of soil mechanics appears to be because seepage studies undertaken at that time involved models made of sand in glass sided tanks. By using dye tracers these studies give a very good picture of the seepage pattern, and are still valuable as a teaching tool. Their weakness, however, is that they are strictly applicable only to coarse grained materials and tend to reinforce the idea that the phreatic surface is the upper boundary of the seepage zone. The above flow nets and all other flow nets in this paper have been determined using the computer programme Seep/W.

Figure 3 illustrates two possible seepage patterns compatible with one specific water table. Figure 3(a) shows the flow net normally assumed to be compatible with such a water table. This would be true of a hillside consisting of coarse grained free draining soil. However, this flow pattern is rather odd, as it implies that seepage is being recharged from a catchment on the right side of the drawing. It implies that no rain falls on the slope itself. Alternatively, it could imply that rainfall does occur at the surface and water trickles downward and enters the flow net at the water table. This would only be possible if the soil was coarse grained.

Figure 3(b) shows a second flow net compatible with the same water table, but for a clay soil. This flow net is based on a limited supply of water from rainfall at the ground surface. The capacity of the soil to accept surface rainfall is greater than the rate of supply, so that the actual pore pressure remains negative in the upper part of the slope.

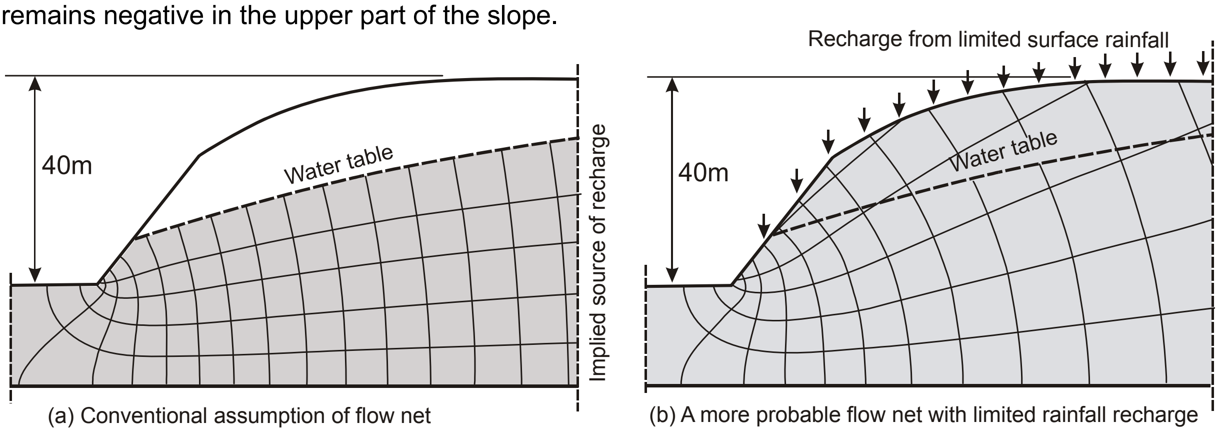


Figure 3. Flow nets compatible with a given water table.

These two examples illustrate that in clays the seepage pattern may well be quite different to that in a coarse grained soil. In particular, the water table (or phreatic surface) is not the upper boundary of the seepage zone. In clays, the upper boundary is in fact the soil surface and strictly speaking the seepage state is no longer unconfined. For geotechnical engineers the most significant point is that knowing the position of the water table alone is not sufficient to give an adequate picture of the actual seepage state. We shall see in later section of this paper that relying solely on the water table for estimating pore water pressures in slope stability assessments can lead to serious errors.

3 GROUNDWATER MECHANICS AND DUPUIT'S ASSUMPTION

Groundwater mechanics appears to have developed independently of soil mechanics and with different objectives. It is concerned primarily with natural seepage and the use of groundwater as a resource. Its focus is on relatively flat ground with coarse grained water bearing layers and gentle gradients. Books on groundwater mechanics, such as Freeze and Cherry (1979) and Strack (1989), contain many analytical solutions to various groundwater seepage situations, such as unconfined flow towards a well or open drain. These solutions are based on Dupuit’s assumption that the equipotential lines are essentially vertical and the hydraulic gradient is the same as the slope of the phreatic surface, which is assumed to be the upper boundary of the seepage zone. The solutions therefore are strictly applicable only to coarse grained soils.

Figure 4 illustrates the flow nets valid for seepage in fine and coarse grained materials towards a dewatered excavation. The recharge source in Figure 4 is a line source some distance from the excavation. In the clay, the seepage occupies the full depth of the layer, while in the sand the seepage occurs only below the phreatic surface

Figure 5 shows the transient changes to the seepage state and ground level that result from an excavation extending below the water table. The mechanism of dewatering is different in each material. In coarse material volume change is normally very small and water drains from the void space to be replaced by air. The volume of water that drains from the soil is therefore primarily dependent on the volume of the void space from which the pore water drains, and to a minor extent on its compressibility

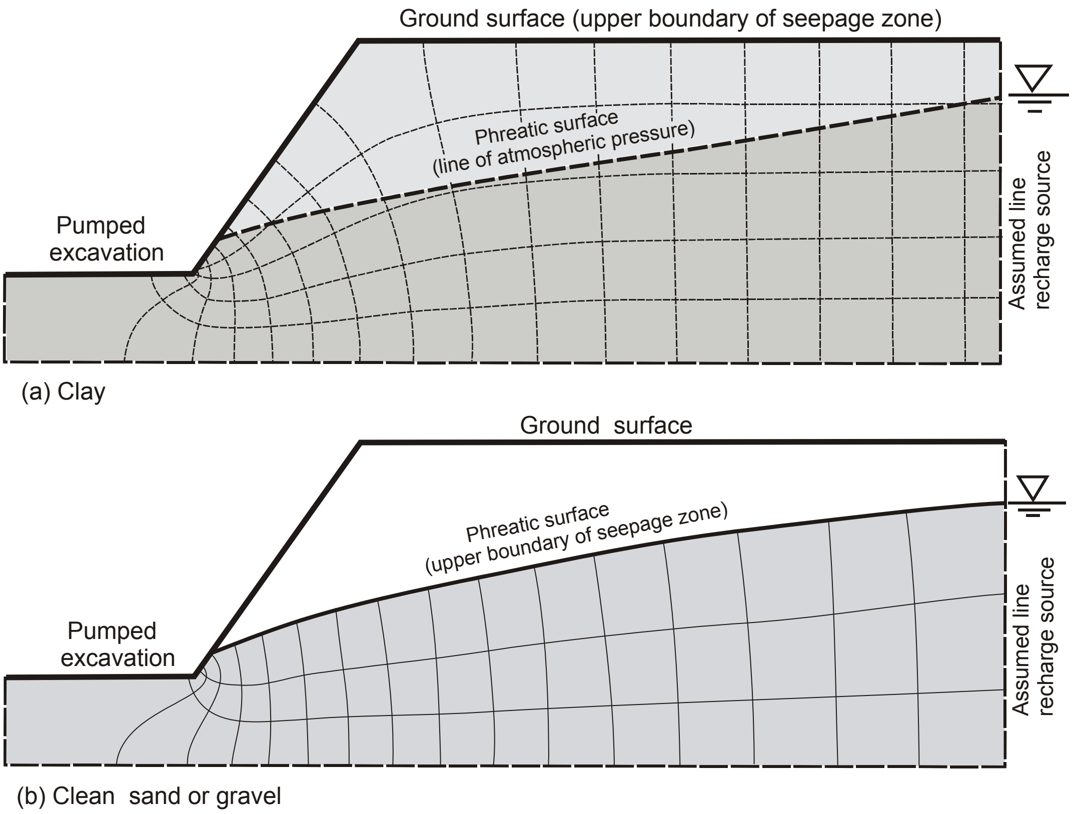


Figure 4. Seepage toward a pumped excavation in clay and in sand or gravel.

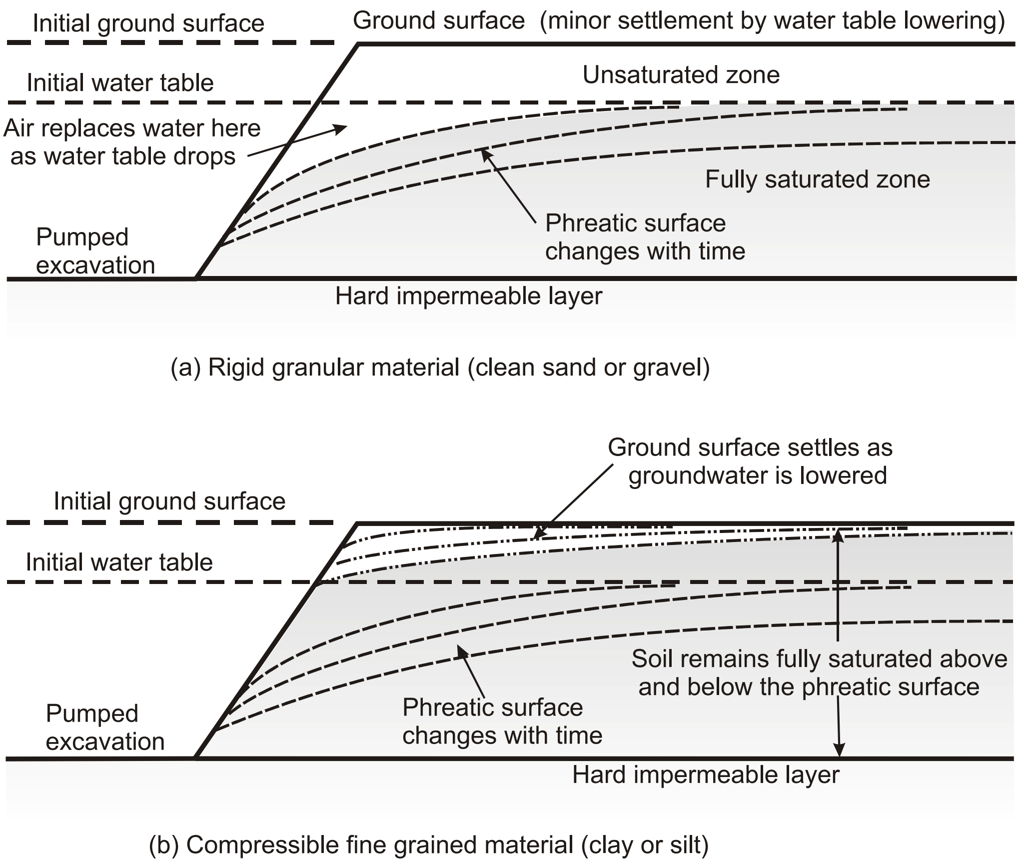


Figure 5. Response of seepage pattern and ground level to dewatering in coarse and fine soil.

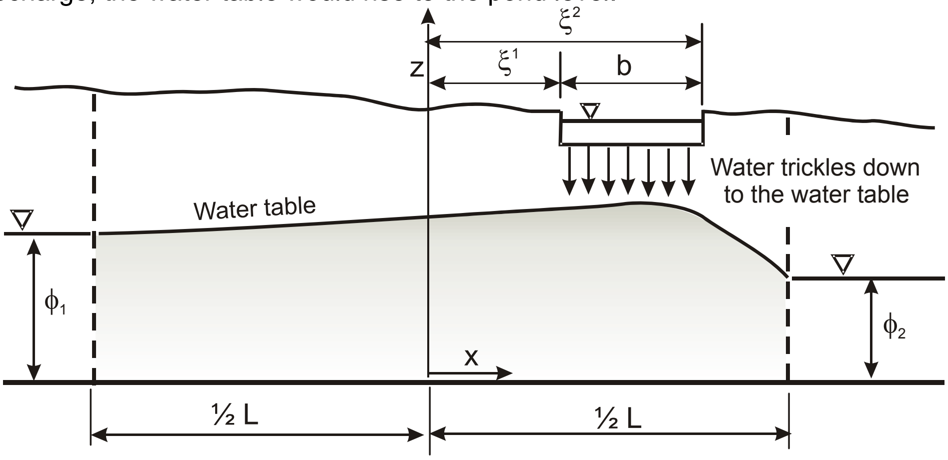
The governing soil parameters are therefore the permeability, k, and the porosity, n, of the material, and to a minor extent on its constrained modulus, M. During dewatering, the soil below the phreatic surface is still governed by the Laplace equation, and the significant transient changes are occurring at the phreatic surface. In clay, the soil remains fully saturated and consolidation occurs, resulting in a volume decrease and settlement of the ground surface. The governing soil parameters are therefore the permeability and the compressibility of the material, that is k and m_v or their combined form c_v the coefficient of consolidation. Analytical solutions (Edelman, 1972, also Nguyen and Raudkivi, 1982) are available for the rate of drawdown in the coarse material but not for clay.

It is worth noting in passing that for a fully saturated soil there is a direct relationship between the soil mechanics compressibility parameter m_v and the groundwater mechanics storativity parameters S_s and S. This is to be expected since in the volume of water to flow out of a soil due to a change in pore pressure is governed directly by its compressibility. It can readily be shown that this relationship is:

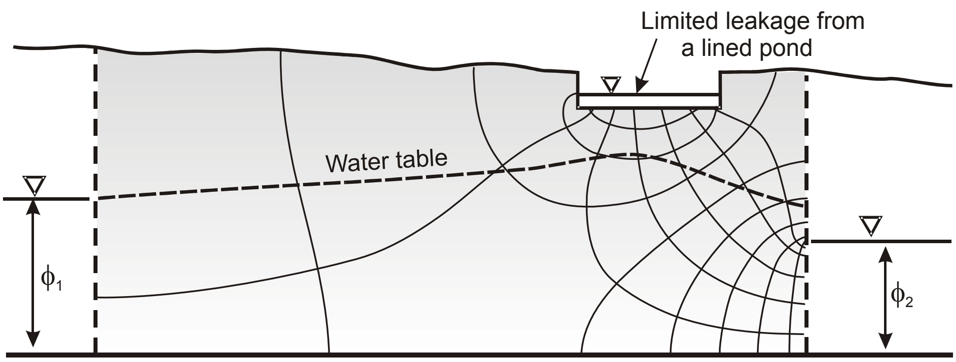
$$m_v = \frac{S_s}{\gamma_w} = \frac{S}{b\gamma_w}$$

where m_v = coefficient of compressibility of the soil.
Ss = the specific storage = volume of water released per unit volume of soil per unit change in head
S = storativity = volume of water released per unit area per unit change in head
= S_s b where b = depth of the seepage zone.

Figure 6 illustrates seepage from a leaky pond or landfill. The upper diagram from Strack (1989) shows the way such leakage is normally portrayed in groundwater mechanics texts. Water trickles down through the ground to meet the water table and induces a “hump” in the water table. This is valid for free draining materials but not for clays. In this case the soil is fully saturated, but with limited leakage from the pond a zone of negative pore pressure remains above the water table. With unlimited recharge, the water table would rise to the pond level.



(a) Seepage from a pond, after Strack (1989), for a coarse material



(b) Limited seepage from a lined pond, through clay.

Figure 6. Seepage patterns beneath a leaking pond.

4. INFLUENCE OF RAINFALL

The influence of rainfall on the pore water pressure state and the water table is very different in coarse and fine soils, as illustrated in Figure 7. In coarse materials water trickles down through the unsaturated zone to meet the water table which rises in response. In clay the water causes the soil to swell, starting at the surface and penetrating deeper with time. There is a limit to the depth affected and the water table may not change at all.

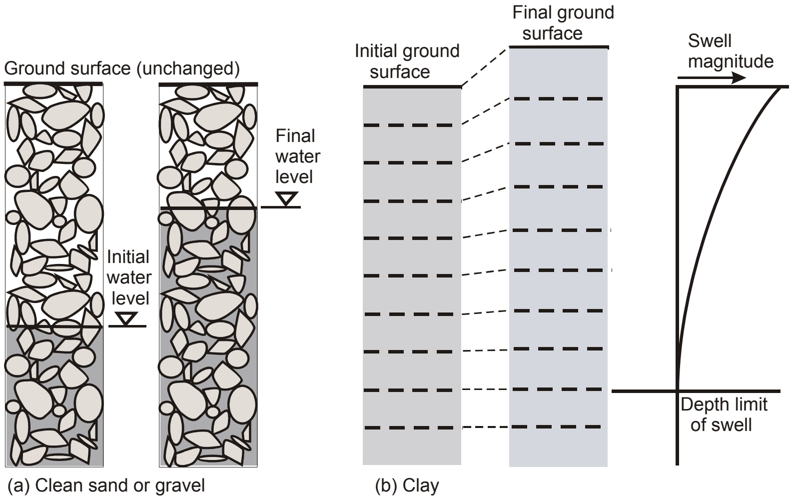


Figure 7. Influence of rainfall on coarse and fine grained soils.

5 INFLUENCE OF SEEPAGE ASSUMPTIONS ON THE STABILITY ESTIMATES

In attempting to estimate the long term stability of cut slopes in residual soils, an assumption can be made that the worst case will occur when prolonged rainfall causes the water table to reach the ground surface. Using a computer programme the water table can be put in at the ground surface and the safety factor determined. Most computer programmes determine the pore water pressure from the vertical intercept between the water table (the ground surface in this case) and the slip surface. This approach is acceptable for gentle slopes but can result in significant errors with steep slopes, because the equipotential lines cannot be even approximately vertical and the pore water pressure estimates may be much higher than the true values.

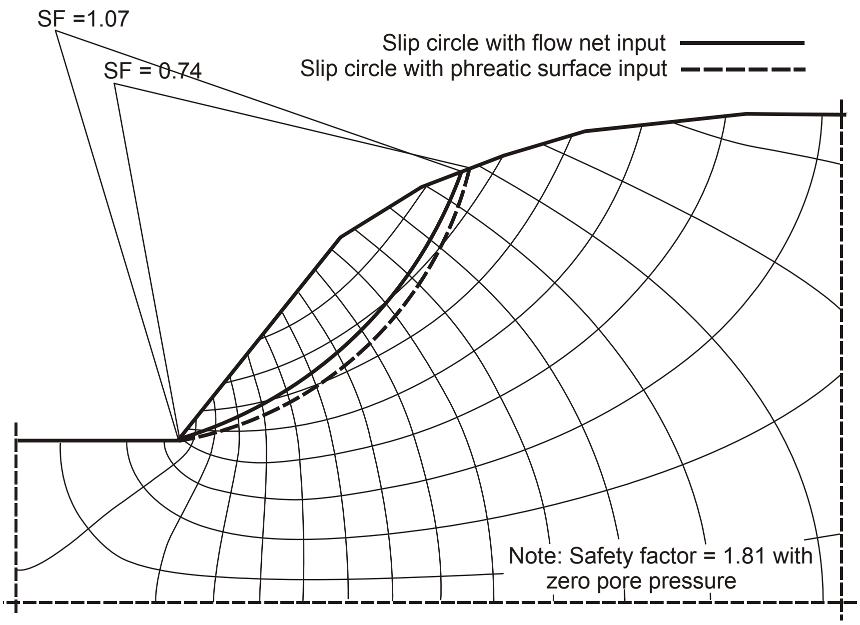


Figure 8. Influence of water table assumption on factor or safety.

A much more realistic approach is to establish a flow net compatible with the water table at the ground surface, and use this as the basis for the stability estimate. This is very easily done using the computer programmes SeepW and SlopeW. In this case the ground surface is given a boundary condition of zero pore pressure. Figure 8 illustrates the results from these two methods. When the phreatic surface is drawn at the ground surface, the resulting safety factor is 0.74, but with the flow net the value becomes 1.07. To save space and to focus on the area of interest, the flow net shown in Figure 8 is only a section of the complete flow net which was obtained by analysing a much longer catchment extending horizontally a considerable distance to the right of the section shown in the figure.

CONCLUSIONS

(a) Unconfined seepage flow is not the same in fine grained soils as in coarse soils. Strictly speaking, unconfined flow does not occur in saturated clays as the ground surface is the upper boundary of the seepage zone.

(b) In clays, the water table (or phreatic surface) is not a boundary or a discontinuity in the seepage pattern, and knowledge of the water table alone is not adequate to establish the seepage state.

(c) Transient behaviour in coarse and fine grained materials is very different. In coarse grained materials water can drain into or out of the void space, while clays remain fully saturated.

(d) Caution is needed in using computer programmes for stability estimates of steep slopes as a common assumption regarding the pore pressures can lead to large errors in the safety factor.

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