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The effect of climate on the degradation of overconsolidated clay slopes

Les effets du climat sur la dégradation des pentes argileuses surconsolidées

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ABSTRACT: Natural slopes in overconsolidated clays experience progressive slope failures to some limiting angle governed by soil strength and pore water pressure within the slope. Under current wet temperate climatic conditions pore pressures can not generally rise above that governed by a hydrostatic distribution, where groundwater is at surface. Slopes, at angles lower than this, do exist in north west Europe and contain relict slip surfaces. The development of these lower slopes requires a periglacial climate. This controls the development of pore pressure and its distribution in a fundamentally different way to that under temperate conditions. The processes of slope degradation under the two environments are therefore different. The resulting morphology of the slope form and the character of the soils, even on slopes of similar angles, reflects the differing processes. An understanding of the processes that have influenced such slopes is crucial to safe and adequate engineering design on or close to them.

RÉSUMÉ: Les pentes naturelles en argile surconsolidée se dégradent jusqu'à atteindre un certain angle. Cet angle est fonction de la solidité du sol et des conditions de la pression interstitielle dans la pente. Sous climat humide tempéré, la pression dans les pores ne peut normalement pas s'accroître au dessus d'un niveau gouverné par la distribution hydrostatique, quand l'eau souterraine atteint la surface. Il y a des inclinaisons plus faibles au nord-ouest de l'Europe qui contiennent des restes de glissements de terrain. Les conditions qui permettent le développement de tels pentes nécessitent un climat périglaciaire. Ces éléments contrôlent le développement et la distribution de la pression interstitielle dans les argiles d'une façon fondamentalement différente de celle du climat tempéré. Les processus de dégradation des pentes dans ces deux climats sont donc différents. La forme morphologique de la pente résultante, et le caractère des sols, même dans le cas de pentes identiques, reflètent les différents processus. Leur compréhension est crucial pour des ouvrages de génie civil sur ou proches de ces pentes.

1. INTRODUCTION

The Quaternary is characterized by the episodic development of continental ice in northwest Europe and other parts of the world. The associated alternation between wet temperate and periglacial climatic conditions is one of the most significant factors to have affected the character of the slope processes involved in the process of degradation.

Areas which are underlain by geological formations which can be described as 'overconsolidated clay' have slopes which are at angles which can be shown to be naturally stable under present climatic conditions. However, such slopes also contain slickensided surfaces indicating that movement has previously occurred on them. Clearly for these slopes to have experienced failure, then either the factors influencing their development must have been different to those acting today, or some other process than mass movement was involved.

The soil mechanics of slope failure in overconsolidated clays have been firmly established and described in the literature. In practice, the association of these principles and the implication of the long geological history of most natural slopes is often not taken into account when engineering situations are under consideration. This paper discusses the relevent soil mechanics of low angled slopes and demonstrates how the climatic situation has influenced the development of the failure mechanism. It shows that periglacial conditions can provide certain overriding controls to the depth at which low angled slope movements will develop. In order to provide a suitable approach to engineering projects which interact with such slopes an appreciation of the geological as well as mechanical controls on slope development is necessary.

2 THE LIMITING FACTORS TO SLOPE DEGRADATION

If the toe of an overconsolidated clay slope is steadily removed it will undergo failure. If the erosion subsequently ceases the slope will continue to degrade by a natural series of processes which have been described by various workers (Chandler, 1970a; Hutchinson, 1967, 1975; Savigear, 1952; Skempton and Hutchinson, 1969). During this subsequent degradation the slope angle will reduce to some minimum, or ultimate angle of stability.

Hutchinson (1967) showed that as the slope angle reduces then the mode of failure shows a gradation from rotational to a predominantly translational character. Movement of the slope ceases as the ultimate angle of stability is reached.

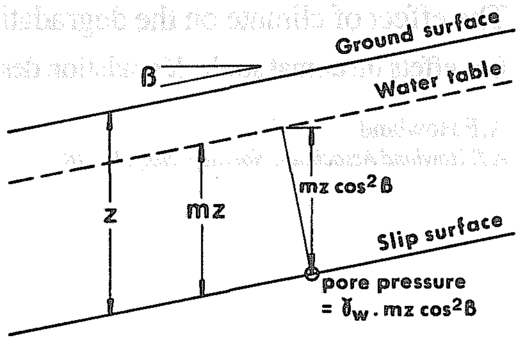

Figure 1. The infinite slope analysis

The actual slope angle in any situation is affected by a variety of factors but for the relatively uniform character of the overconsolidated clays Skempton and Delory (1957) showed that the strength of the material, and in particular its angle of internal friction dictate the potential ultimate angle of stability. They showed that the dominance of translational movement on low angled slopes means that a typical element could be assessed in isolation as representative of the slope as a whole. Termed the infinite slope analysis, the soil properties and pore pressure at any given depth on the slope are assumed to be constant and the failure surface is taken as planar and parallel to the slope (Fig. 1). The general form of this is:-

$$Yz\sin\beta\cos\beta = c' + (Y - mY_W)z\cos^2\beta\tan\varnothing' \quad (1)$$

The degradation history of a low angled slope requires that it has progressively failed from some steeper condition and will therefore have residual shear surfaces within its mass. This together with the general weathering which occurs following stress relief of overconsolidated clays (Skempton, 1948; Skempton et al 1969) means that the strength parameters approach the residual condition. The effective residual cohesion, c_r' tends towards zero and the effective residual friction angle, $\varnothing_r'$ to some limiting value associated with the mineralogy of the clay. Equation 1 can then be written to show that:-

$$\tan\beta = \left(\frac{1 - Y_W mz}{Yz} \right) \tan\varnothing_r' \quad (2)$$

When the groundwater table rises to the ground surface, Figure 1 shows that m becomes unity and since the unit weight of water is approximately half that of the soil ($Y_W \triangleq 0.5Y$) equation 2 can be re-written as:-

$$\tan\beta \triangleq 0.5\tan\emptyset_r' \qquad (3)$$

This shows that the slope angle in any given material is sensitive to the pore pressure acting, or which has acted, on the slip surface. It can be seen that the limiting condition will occur when the groundwater table is at ground surface when the angle of ultimate stability will equal $\emptyset_r'/2$. Therefore, in order to produce failures on slopes with angles flatter than this it would be necessary to generate pore pressures on the failure surface which are in excess of the hydrostatic condition with groundwater at surface.

The pore pressure on a slip surface can also be considered in terms of the pore pressure ratio, r_u. If the pore pressure, u on the slip surface is given by $Y_w mz$ and the pore pressure ratio by u/Yz, equation 2 may be also written as:-

$$\tan\beta = (1 - r_u)\tan\emptyset_r' \qquad (4)$$

When the groundwater is at the ground surface, r_u approximates to 0.5 so that equation 4 compares to equation 3. Figure 2 shows the relationship of the angle of stability to pore pressure ratio developed from equation 4. The angle of stability is also influenced by any residual cohesion. If equation 1 is rewritten,

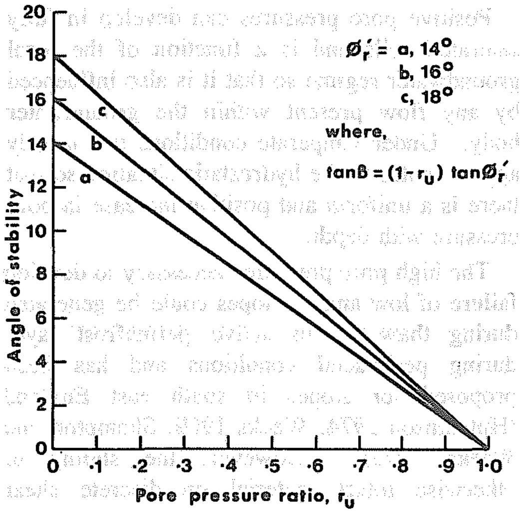

Figure 2. Variation in the stable slope angle against the pore pressure ratio for differing residual angles of friction

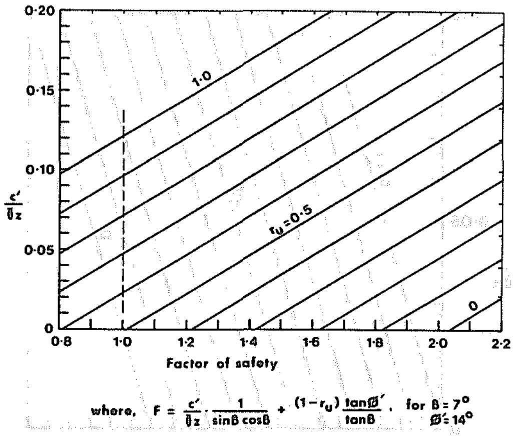

Figure 3. Variation in factor of safety with the factor c'/Yz for varying pore pressure ratios in a slope of 7° and an internal friction angle of 14°

$$F = \frac{c'}{Yz} \cdot \frac{1}{\sin\beta\cos\beta} + (1 - r_u)\frac{\tan\emptyset_r'}{\tan\beta} \qquad (5)$$

Figure 3 shows a graphical plot of the stability number c'/Yz against the factor of safety F, for a 7° slope in a soil with a residual angle of friction of 14°. Use of the stability number eliminates the need to define the geometry of the failure surface in the same way that the pore pressure ratio eliminates the geometry of the groundwater table. The effect of cohesion can be further seen in the increase of the ultimate angle of stability for differing pore pressure ratios through the equation;-

$$\tan\beta = \frac{c'}{Yz} \cdot \frac{1}{\cos^2\beta} + (1 - r_u)\tan\emptyset_r' \qquad (6)$$

This is shown graphically on Figure 4 for a material with a residual angle of friction of 14°.

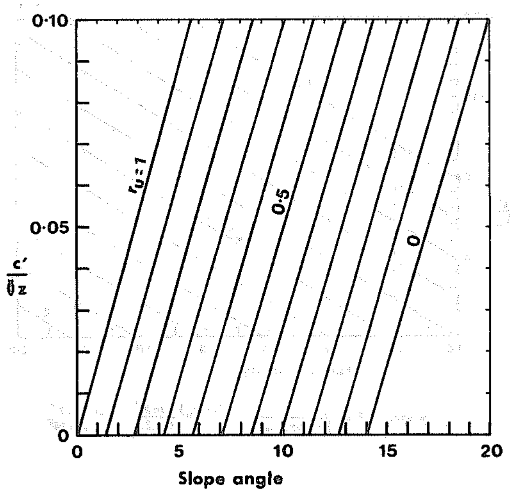

Figure 4. The effect of small amounts of residual cohesion on the ultimate angle of stability for varying pore pressure ratios and a residual friction angle of 14°

3 CLIMATIC INFLUENCES

Chandler (1972), Harris (1977) and McRoberts et al (1978) have shown in the field that artesian pore pressures can be associated with hillslope processes in modern periglacial environments. The development of pore pressures above the hydrostatic condition results in a pore pressure ratio (equation 4) greater than 0.5. This could be taken to suggest that as long as the pore pressures can be generated there must be no lower limit to the angle at which a slope can experience movement. This prompts the conclusion that slope processes under periglacial climates are only a special condition of those active under temperate conditions. However, Figure 3 shows that the ultimate angle of stability should reduce as the depth to the slip surface increases.

If the proposal is correct that the process of slope degradation forms a continuum which is independent of climate, then slip surfaces should develop more readily at increasing depths for any slope form. The infinite slope analysis of Skempton and Delory does not then have general application, but must be related only to specific known slip surfaces, otherwise any slope can be assessed to be unstable and analysis would suggest probable relict slip surfaces at increased depths. The fundamental limitations of the infinite slope analysis are therefore twofold. Firstly, slopes are not infinite and the boundary effects of the failing mass will become increasingly important as the depth of any analysed slip surface is increased. Secondly, the assumption that uniform soil properties exist with depth is also largely incorrect. Figure 4 shows that as the shear strength increases then so does the ultimate angle of stability, or alternatively, the factor of safety of any given slope angle.

Nonetheless, the usual approach to the analysis of low angled slopes is to assume that the residual strength conditions prevail. However, this is strictly only true of discrete shear surfaces within the mass. These can not develop below a certain limiting angle without the control of excess pore pressures. Under temperate conditions localized situations could develop excess pore pressure, for example due to the loading from other failed material. However, the widespread occurrence of low angled slopes with evidence of past failure indicates that the pore pressures would need to be caused by an event with a regional rather than a localised effect.

Positive pore pressures can develop in fully saturated soils and is a function of the local groundwater regime so that it is also influenced by any flow present within the groundwater body. Under temperate conditions this largely approximates to the hydrostatic situation so that there is a uniform and positive increase in pore pressure with depth.

The high pore pressures necessary to develop failure of low angled slopes could be generated during thaw of an active permafrost layer during periglacial conditions and has been proposed for slopes in south east England (Hutchinson 1974, Weeks 1969, Skempton and Weeks 1976). However, the sliding of otherwise intact material on discrete shear surfaces, which has been postulated in these instances, does not resemble the process of saturated soil flow which is usually reported from modern periglacial environments (Harris

1981). Similarly overconsolidated clays are not typical of the soils undergoing present solifluction activity, which usually classify as clays or silts of low plasticity (Harris 1987).

The process whereby excess pore pressures are developed under periglacial conditions may be attributed to the process of thaw consolidation proposed by Morgenstern and Nixon (1971). This combines Terzaghi's one dimensional consolidation theory with the Neuman equation for thaw penetration through frozen ground. The amount of excess pore pressure, which develops as the contained ice lenses melt, is indicated to be dependent on the relative rate of thawing balanced against the rate at which the soil consolidates by drainage of the released water. These are combined in the thaw consolidation ratio R,

$$R = 0.5 \left(\frac{\alpha}{\sqrt{c_v}} \right) \qquad (7)$$

where c_v is the coefficient of consolidation and α is the thaw parameter from the Neuman equation,

$$X_t = \alpha\sqrt{t} \qquad (8)$$

in which X_t is the depth of thaw at time t.

Skempton and Weeks (1976) argued that thaw consolidation within an active permafrost layer was the cause of the high pore pressures needed to generate solifluction lobes on slopes of the Lower Greensand Escarpment, in south east England. However, the evidence from modern environments suggests that significant amounts of water are not available within the active permafrost layer of fine grained plastic soils during thaw. Mackay (1981) has shown that these develop a reticulated ice network when frozen. Although thin partings of ice develop within the soil mass, pore water in the contained blocks of soil may remain unfrozen at temperatures below 0^oC and can in fact experience significant desiccation. Mackay showed that the limited ice growth above the base of the active layer results in only negligible thaw consolidation and that movement does not occur until the thaw reaches the ice rich basal zone. Harris (1987) cites this and the work of Washburn (1967) to suggest that distinct basal shear planes carrying otherwise undeformed soil masses are more likely to develop than the mechanism of saturated flow in the plastic soils typical of overconsolidated clays.

Slope processes active under periglacial conditions on low angled slopes are therefore intimately related to the presence of permafrost, or seasonally frozen ground. It is this unique factor which means that they are fundamentally different to those operating under temperate conditions, even where the slope angles are the same.

In general, the slope processes operating under periglacial conditions may be separated into two categories. The first relates to soils which are predominantly fine sands or where the matrix comprises silts or clays of low plasticity. These are frost susceptible and will readily allow the development of ice lenses during ground freezing. These lenses can grow by the absorption of more water and can develop equivalent moisture contents above the normal saturated moisture content of the host soil. On subsequent thawing the meltwater may become trapped allowing the development of excess pore pressure. sufficient to cause local failure, or it will allow the soil to flow if the resulting moisture contents are sufficiently high to reduce the undrained shear strength. The thawing front develops from surface and occurs on a cyclic basis. As the frequency of thaw will decrease with depth the amount of movement which results from the thaw will also have a tendency to decrease with depth.

The second category applies to those soils with high clay contents which are less frost susceptible. Freezing causes these to develop a brecciated structure which produces a fine ice network throughout the mass. However, more significant ice lenses will develop at the base of the active layer at the top of the permanently frozen ground. This means that only limited free water will become available during thaw. Also it is likely that the secondary permeability due to the ice brecciated discontinuities will allow rapid dissipation of pore pressures as the thaw develops. Thawing will have very little effect on the material until it reaches the base of the active layer. If at that time the brecciated structure in the upper layers has closed as the clay swells the release of substantial water from the basal ice rich zone will produce pore pressures that will cause a distinct basal shear surface to develop. In this way the shear surfaces recorded in the otherwise intact material, as well as those below the more clayey head deposits could be readily developed.

Pore pressure development can be further aggravated during the periglacial conditions. Snow drifts will develop along the crest lines of escarpments. Their presence, possibly aggravated by slumping could readily cause a further surcharge loading able to induce high pore pressures in saturated ground. This is consistent with localized solifluction lobes being found more commonly along the higher slopes below the Lower Greensand cap reported by Skempton and Weeks (1976). Further influences would arise with intense frosts during periods of thaw. These could produce an impermeable cover to a thawing soil mass. If the frost table is present below, and water becomes trapped between the two freezing fronts, it is feasible that this would also cause the development of excess pore pressure over extensive areas.

4 CONCLUSIONS

The process of degradation of overconsolidated clay slopes under temperate climatic conditions will not allow slope angles to develop which are equivalent in value to about half of the residual effective angle of friction of the soil making up that slope. Failure of the slope to some lower angle requires the development of pore pressures in excess of the hydrostatic condition. This can occur in periglacial environments where there is the presence of permafrost with an upper active layer.

Low angled clay slopes which have been subjected to former periglacial conditions may show no present evidence of instability. Within a geological timescale these slopes are a product of past slope processes. The residual effects of such earlier movement will still exist within the slopes, often in the form of relict shear surfaces and these can impart a major control on the potential for subsequent movements in the slope. The development of these relict shears is not random but controlled pore pressure development under the former climatic situation active during the slope formation.

Any engineering development that involves these slopes will require some form of analysis and this can be improved by an adequate understanding of the natural controls which have acted on the slope and, if appropriate, led to the formation of the relict shears. This understanding allows a more realistic modelling of the slope condition. It ensures that appropriate engineering parameters are used during the analysis and provides an insight to the geometry of the potential failure. In contrast, analyses carried out without this understanding may lead to conclusions which are grossly in error.

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