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Predicting Landslips Caused by Rainstorms in Residual/Colluvial Soils of Nigerian Hillside Slopes

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Abstract. Soil slips, some turning into debris flows, have become common in Nigerian hillside slopes. They have already caused losses of millions of dollars in agricultural land and products and have become a source of fear for the people living near the sites of occurrence. During the year 1987, no less than four were recorded in a period of six weeks; all occurred during the rainy season and were caused by rainstorms.

Stability analyses have been carried out and stability charts developed to help in predicting these slips. Prediction depends on knowledge of the slope inclination, the rise of the water table with respect to the thickness of the soil mantle that is subject to sliping, the saturated unit weight of the soil mantle and the effective angle of shearing resistance of the soil.

Key words. Prediction, landslips, hillside-slopes.

1. Introduction

Landslides are common in hilly terrains of many parts of the world. Some involve rocks and may occur as rockfalls, rock slides or topples; others involve soil mantles (residual or colluvial) and may occur as slumps or translational slips.

In most instances, these landslides are triggered by heavy rainstorms. In Nigeria, for example, no less than four landslides involving residual/colluvial soils were recorded from hillside slopes within a period interval of six weeks during the rainy season (April–October) of 1987. In each of the occasions it rained for at least three consecutive days before the final triggering rainstorm. Although all the sites do not have complete records, the two sites that have records show that no less than 7.5 mm per-hour of rainfall preceded the landslides. Most of them occurred in the form of landslips (Figure 1) which turned into debris flows as the initial sliding movement caused reconstitution of the apparently saturated sliding soil masses into flowing, viscous, debris-laden mud down existing depressions/drainage courses. The results in all cases were devastating economically as fertile farm lands at the footslopes of the hills became covered by sterile stony debris that became deposited following the flows.

This paper focuses on these landslips. It discusses the conditions that lead to their occurrence and attempts a sensitivity analysis of the variables involved in the hope of utilizing the analysis in some kind of prediction of occurrence.

Fig. 1. Photograph showing a soil slip at one of the landslip sites in Nigeria.

2. Conditions Leading to Slip of Colluvial/Residual Soil Cover on Steep Hillsides

Experience (Campbell, 1974a; Rice and Foggin, 1971; Nwajide *et al.*, 1988) has shown that soil slips on steep hillsides occur after the colluvial/residual soil cover has reached field capacity (i.e. the moisture at which under gravity water flows out of the soil zone as fast as it flows in), followed by rainfall intense enough to exceed the infiltration rate of the parent (bedrock) material underlying the soil mantle. Under this condition (i.e. as the rainfall intensity exceeds the infiltration rate of the bedrock), a perched water table would begin to form inside the slope mantle. The configuration of such water tables has been observed (Serizwa, 1981; Matsukura and Yanaka, 1983) to be parallel to the slope (see Figure 2). The longer the heavy rain continues, the higher the piezometric head may rise and the greater will be the increase in pore pressure near the base of the mantle. Failure occurs when pore pressure exceeds some critical value.

Also, the cohesion resulting from intergranular air-water surface tension is reduced as water replaces air in the soil interstices. The soil is on the verge of slipping when the shearing stress becomes equal to the shearing resistance of the soil, i.e. when the factor of safety (FS) becomes numerically 1.0.

Field observations show that these soil regoliths slip along the soil/bedrock interface and, as already mentioned, the perched water table is parallel to the slope. Thus slippage occurs as shown in Figure 3 at uniform inclination and depth. Considering this

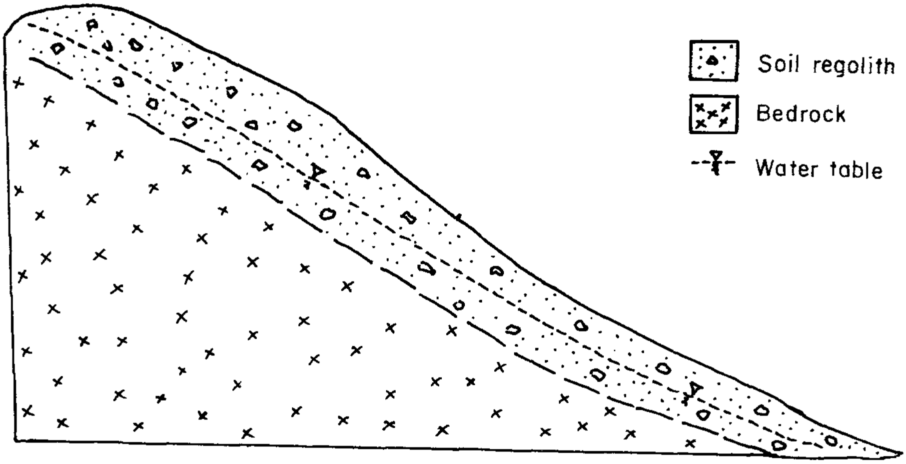

Fig. 2. Slope with soil regolith showing perched water table. Note that the water table more or less parallels the slope.

figure, the mantle of soil is on the state of limiting equilibrium when

$$\mathrm{FS} = 1 = \frac{(c' + \rho - m\rho_w)z\cos^2\beta}{\rho z\sin\beta\cos\beta}, \tag{1}$$

where FS is the factor of safety, z is the vertical depth of the soil to the slip surface, β is the slope angle, ρ is the saturated density of the soil, ρ_w is the density of water, m is the

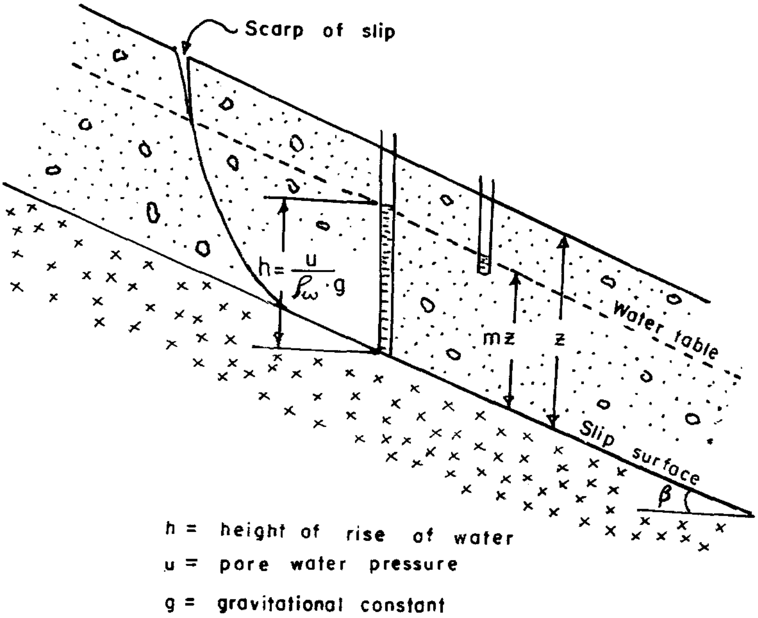

Fig. 3. Slip of soil regolith along soil-bedrock interface. Note that slippage occurs at uniform inclination and depth.

fraction of z such that mz is the vertical height of the groundwater table above the slip surface, c' is the effective cohesion and ϕ' is the effective angle of shearing resistance of the soil.

Assuming $c' = 0$ then at failure (i.e. FS = 1)

$$\tan\beta = \left(1 - \frac{m\rho_w}{\rho}\right)\tan\phi' \tag{2}$$

3. Geological and Geotechnical Conditions for the Affected Hillsides in Nigeria

Some of the hillsides affected by the recent soil slips in Nigeria include the Olusoye ridge near Ile-Ife (Jeje, 1979), the Umomi and Ugwulawo hill ranges near Idah (Akor, 1987), the Akovolwo hill ranges near Jato Aka (Nwajide *et al.*, 1988) and the Bambariko hill ranges in the Ikom area (Abu, 1987). Topographic studies by the author showed that the hillsides, excepting the ridge near Ile-Ife, vary in slope between 45° (1:1) and 18° (1:3.1). Jeje (1979) reported that the Olusoye ridge slopes at angles varying between 26 and 16°. Also the soils affected are generally granular perhaps due to their parent rock origin and mode of weathering. The soils arise mostly from Pre-Cambrian basement rocks (gneisses, schists and migmatites) and Jurassic granites excepting the soils of Umomi and Ugwulawo hills which originate from the lateritic sandstones of the Ajali/Nsukka formations. The rocks weather into clayey sand littered with pebbles and cobbles of all sizes in varying stages of chemical decay. They are also well drained.

Rainfall data in one of the landslips (the Akovolwo hill slip-debris flow, erroneously called a slump-debris flow, Nwajide *et al.*, 1988) suggest that a 348 mm antecedent rainfall was probably required to bring the residual/colluvial soils of the area to field capacity. From the intensity of the triggering rainstorm (7.5 mm per-hour of rainfall) it would appear that the soils involved have a maximum infiltration rate of 2.08×10^{-2} cm/s. Beyond that rate, surface infiltration exceeds subsurface drainage so that pore pressures are raised in a zone above the less permeable parent materials.

No extensive laboratory testing of the materials have been done due to the lack of appropriate sampling equipments. Undisturbed samples would be required for correct geotechnical characterisation of these soils. A few tests carried out on the Umomi site samples gave an average density value of 2000 kg/m^3 and a shear resistance angle of 35°. In the absence of extensive tests, however, it is clear from knowledge of geotechnical properties of most natural soils that such soils would seldom have saturated densities and effective angles of shearing resistance lying outside the ranges 1400–2200 kg/m^3 (87.4–137.3 lb/ft^3) and 25–45°, respectively (see Campbell, 1974b). This wide range of geotechnical values would cover most, if not all soils of this nature, hence stability analyses have been done with these extreme values as controls.

4. Influence of Variables on Stability

Figures 4*a* through *d* show stability charts developed from Equation (2) for critical state conditions (i.e. FS = 1.0) for slopes with varying saturated densities. Each of the figures can be used to predict the critical height of the perched water table with respect to the thickness of the soil regolith required for a slip. In using any of the charts, the soil's effective angle of shearing resistance and the hillside slope angle need to be known. For example, a hillside of 30° slope having a soil saturated density of 1400 kg/m^3 (Figure 4*a*) and an effective shearing resistance angle of 35°, requires a fractional rise of water table of 0.24 of the soil thickness for a slip to occur whereas a hillside of same inclination and shear strength but with a saturated density of 2200 kg/m^3 (Figure 4*d*) would require a fractional rise of water table of 0.39 for a slip to occur.

With respect to variations in soil shearing resistance angles, a hillside of slope 30° having a saturated density of 1400 kg/m^3 (Figure 4*a*) and effective shearing resistance angle of 35° requires a fractional critical water table rise of 0.24 of the soil thickness whereas the critical fractional rise would be 0.59 if the soil angle of shearing resistance was 45°. Similarly, the critical fractional water table rise would change from 0.39 to 0.93 of the soil thickness if the shearing resistance angle changed from 35 to 45° for a similar hillside slope (30°) but with soil density 2200 kg/m^3 (Figure 4*d*). Thus, with these charts, it is possible to predict when a soil slip is likely to occur provided that the following facts are known: (i) the water table rise in any well drilled in the slope that is known to slip during the rainy season, (ii) the hillslope angle (which is readily measured either using existing contour maps or Abney hand levels/altimeters in the field), (iii) the soil density (readily measured on weight-volume ratio basis) and (iv) the soil's angle of shearing resistance (measured by drained testing in the laboratory). A step by step illustration of further example situations is given below.

Example Situation I

Hillside slope angle, $\beta = 25°$,
thickness of the soil mantle above the bedrock, $z = 3$ m,
saturated density of the soil, $\rho = 1800\,kg/m^3$,
effective angle of shearing resistance of soil, $\phi' = 40°$.

Use of Chart

Chart to be used = Figure 4*b*.

A horizontal line is drawn through $\beta = 25°$ on the ordinate line to meet the curve $\phi' = 40°$. A line is projected vertically (up or down) from the point of intersection to meet the abscissa line at m = 0.8.

This means that for a slip to occur on this hillside, the water table must rise $0.8 \times 3 = 2.4$ m from the base of the soil i.e. 0.6 m to the ground surface.

Example situation II

Hillside slope angle, $\beta = 40°$,
thickness of the soil mantle above the bedrock, $z = 3$ m,
saturated density of the soil, $\rho = 1800\,kg/m^3$,
effective angle of shearing resistance of soil, $\phi' = 35°$.

Use of Chart

Chart to be used = Figure 4*b*.

A horizontal line drawn through $\beta = 40°$ on the ordinate line does not meet the curve $\phi' = 35°$ on the positive axis but rather on the negative, if so attempted.

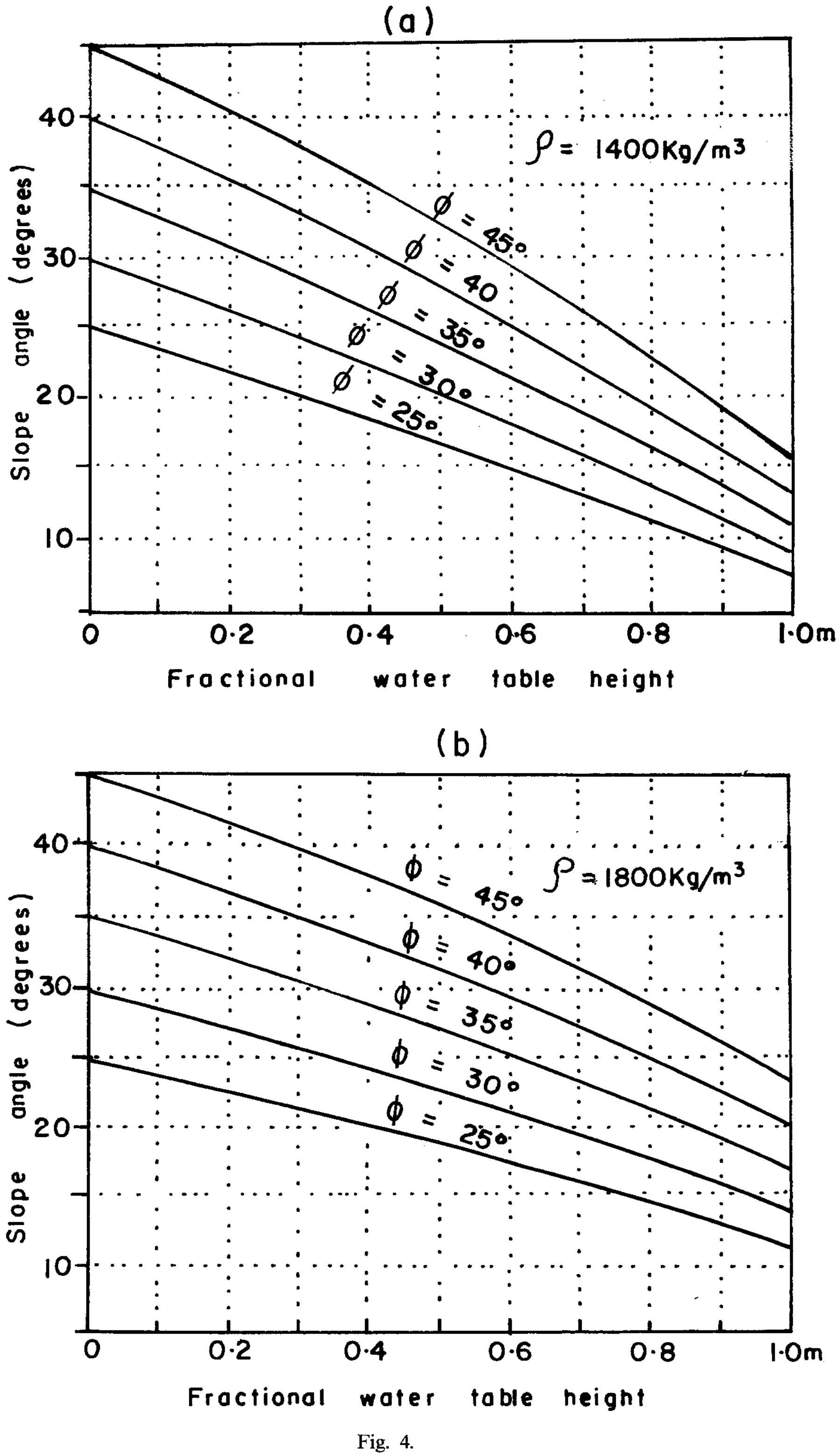
(a)
ρ = 1400Kg/m³
φ = 45°
φ = 40
φ = 35°
φ = 30°
φ = 25°
Slope angle (degrees)
10
20
30
40
0
0·2
0·4
0·6
0·8
1·0m
Fractional water table height
(b)
ρ = 1800Kg/m³
φ = 45°
φ = 40°
φ = 35°
φ = 30°
φ = 25°
Slope angle (degrees)
10
20
30
40
0
0·2
0·4
0·6
0·8
1·0m
Fractional water table height

Fig. 4.

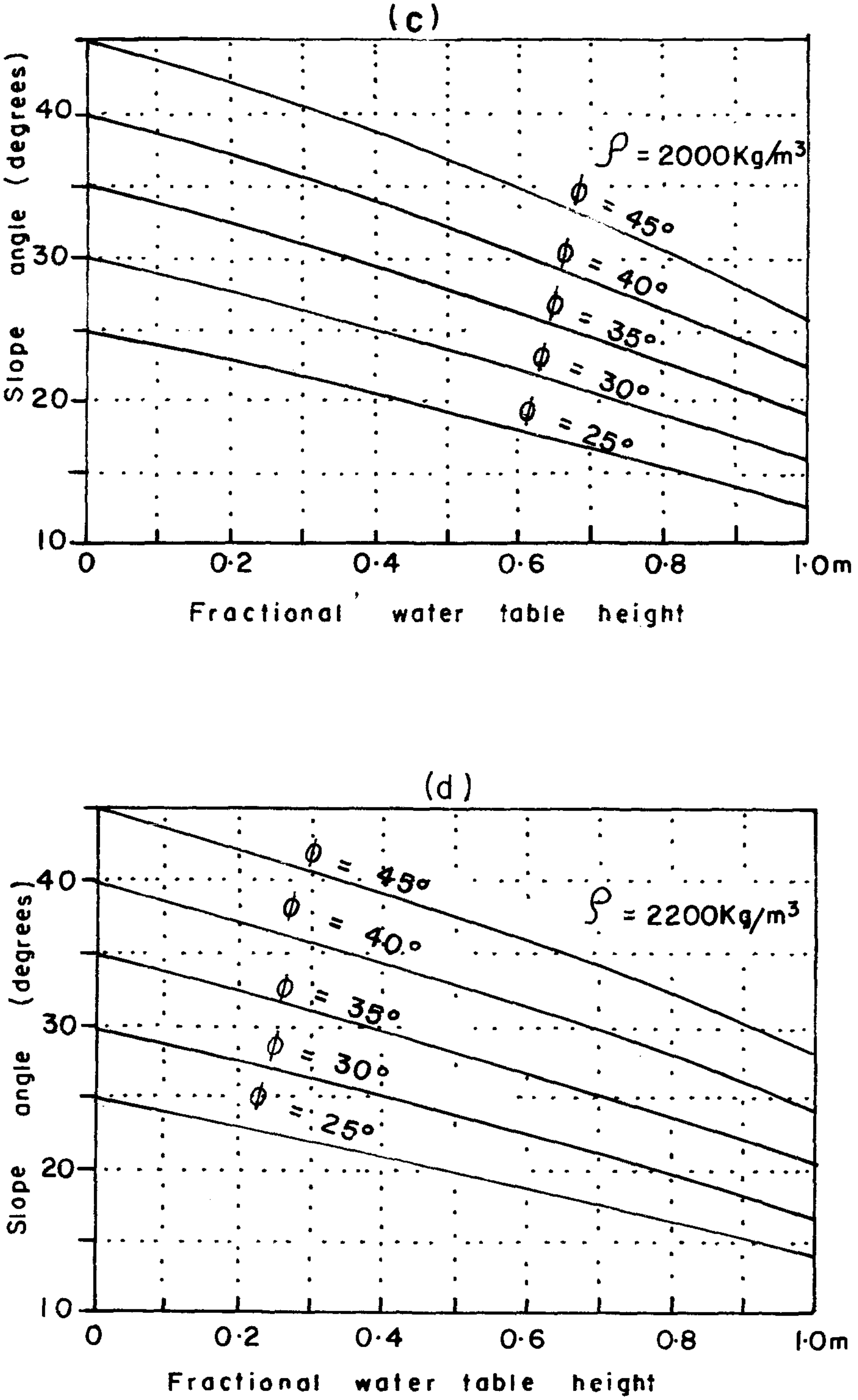

Fig. 4. Relation of failure to groundwater rise and slope angle for (a) Slope with soil mantle of density 1400 kg/m³, (b) Slope with soil mantle of density 1800 kg/m³, (c) Slope with soil mantle of density 22000 kg/m³, (d) Slope with soil mantle of density 2200 kg/m³.

The interpretation for such and similar situations is that the soil needs only to reach field capacity for a slip to occur. In other words, no perched water table or rise therefrom is necessary for a soil slip. Such will be the situation for all cases where $m \leqslant 0$. In general, however, hillside slopes whose angles are greater than the mantling soil shear resistance angles may not be that common. They would not be expected for soil mantles that are purely cohesionless.

5. Discussion and Conclusions

A look at the charts shows that they have not been designed for slopes steeper than 1:1, i.e. steeper than 45°. The obvious reason is that to cover these slopes would require analyses for soils having angles of shearing resistance greater than 45° (see Equation (2)), a situation that is seldom found in nature. Perhaps more important is the fact that slopes steeper than 45° generally do not have a continuous mantle of residual/colluvial soils; most commonly they are bare bedrocks such that the type of soil slips discussed in this paper is seldom encountered in them.

The soil slips which the charts deal with are those that seem to have in common several characteristics and associations with rain storms that set them apart from other classes of landslides, such as rotational slumps. While the latter, for example are commonly deep, depend more on deep percolation of groundwater, and may not respond to the effects of heavy rainfall until long after a storm, in contrast, the shallow soil slips occur during, and only during, heavy rainfall. They also appear to occur only on steep slopes ($>15°$), as contrasted with the low slopes which may fail by other classes of landslides. Most of these soil slips tend to degenerate into debris flows when the initial movement of the soil slabs causes a reconstitution of the saturated sliding masses into viscous, debris-laden mud, which then flows down available drainage courses. Most of the Nigerian examples have turned out this way.

The soil mantle covering the Nigerian hillsides under consideration are no more than 2–4 m thick (see Nwajide *et al.*, 1988); some may be less than 2 m (see Jeje, 1979). It is, therefore, relatively easy to make shallow boreholes through which rise of water table measurements can be made. Once the thickness of the soil regolith has been established, the critical rise of water table can be established (using the chart) and used to predict stability.

The charts developed in this paper are not limited to use for only Nigerian hillside slopes, but can be used to predict stability in any part of the world where similar soil slips as described in this paper occur.

So far, due to financial constraints, no monitoring boreholes have been installed in any of the Nigerian hillside slopes to utilise the developed charts.

Acknowledgement

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