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Stability analysis and simulated hydrologic response of some vulnerable slopes in Nigeria implications for rainfall-induced landslides

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Abstract: *Hillslope geometry, material properties, and hydraulic heterogeneities complicate slope stability models. To reduce uncertainties in the determination of Factor of Safety, parameters obtained at in-situ stress levels using ASTM standards were used in two slope stability models to identify and classify some vulnerable slopes in northern and southern parts of Nigeria.Steady-state and peak strength parameters were applied separately in an infinite slope analysis simulating the variation of slope attributes with degree of saturation. The application yielded FS that were consistent with instability, and accurately predicted the characteristics of slopes in which failure was likely. While rainfall was a common trigger, the probability of failure was higher on slopes > 38^o in the northern part of the country underlain by igneous and metamorphic rocks. Contrastingly, slopes with angles > 25^o were predicted to be at risk in the southern part underlain by semi-consolidated sandstones. These predictions are in good agreement with field and reported cases of mass movements in the two regions. Using another stability method based on Bishop Model to correlate and validate the findings, the research observed that the slopes were sensitive to moisture with considerable drop in FS as saturation gradually increased. The study discovered that about 80 % saturation was enough to induce instability and that beyond this threshold failure occurred when the slopes became marginally stable (FS ≤ 1). This threshold value and the decline in FS with rise in saturation have important implications for rainfall-induced landslides on the hilly areas of Nigeria.*
Keywords: *slope stability, saturation level, rainfall, shear strength, failures*

I. Introduction

Slope failures have a wide range of causative and triggering factors, which may be geological, hydrological or structural (Selby 1993; Cruden and Varnes 1996; Wieczorek 1996; Takahashi 2001; Dai et al. 2002; Fell et al. 2008). Critical rainfall events are known to initiate movements (Guzzetti et al. 2008; Tsai and Chen 2010; Tsai and Wang 2011) with most mass movements in Nigeria occurring during or after heavy rainfall. Yet concerns remain regarding the impact of inherent heterogeneities on the accuracy of landslide forecasting.The non-homogeneity of the geological, hydrological and structural components can constitute a major source of error in predicting factors of safety. To achieve high accuracy, an improved methodology taking advantage of new advances in landslide research is a necessity. While some of these factors (geologic and stratigraphic settings) can be accounted for indirectly by using normal and shear stresses calculated from exact field conditions during laboratory testing of slope-materials, other factors can be used directly as simulation variables. Shear strength parameters obtained from such tests, which form the core input values in the stability models, can yield reliable FS for accurate designs and management.

Experimental, numerical and stability studies have aided the analysis of slopes subjected to rainfall infiltration (Griffiths and Marquez 2007; Igwe et al. 2012; Sarkar et al. 2012; Ma et al. 2013; Singh et al. 2013; Alemdag et al. 2014; Kalatehjari et al. 2014). Laboratory testing of samples collected at sediment-disaster sites yields parameters such as the critical stress ratio, peak and steady-state strength that are invaluable in stability and numerical analyses. Wang et al. (2002) and Wang et al (2003) used ring shear testing to study rainfall-induced landslides in Fukushima and Hiroshima Japan respectively. Similarly, Stark et al. (2005) employed shear strength parameters in landslide evaluation. Iverson et al. (2010) also studied the effect of soil aggregates on the mobilization of debris flow using ring shear tests.

Water-infiltration weakens slopes by reducing suction and strength (Crosta and Frattini 2008; Igwe and Fukuoka 2014; Igwe 2014), and may eventually induce failure when the shear stress on the slope becomes greater than the mobilized shear resistance (i.e. when the Factor of Safety drops considerably). Therefore studying the spatial variation of FS with saturation and the factors that affect stability are crucial to predicting and managing landslides. Such study has yet to be undertaken on the Nigerian terrain. The specific objectives of this research are to: (1) apply two slope stability models using input values obtained from field and a systematic laboratory evaluation of material strengths under the different stratigraphic and structural conditions commonly present in the field, (2) analyze the variation of factor of safety with moisture and other slope characteristics with a view to understanding their implications for rainfall-induced landslides in Nigeria.

II. Method

Field survey and aerial photographs were used in the mapping and identification of landslides (using Crozier 1984, 1986 as standard)in several locations covering the northern and southern parts of Nigeria (Fig. 1). The geologic and stratigraphic setting of the study locations are discussed in detail in Caby (1989), Ephraim (2012), Igwe et al. (2013) and Igwe (2014). On the basis of their location, size, age, freshness, morphology and materials displaced, some landslides were selected for detailed mapping and documentation. Structural conditions of the slopes, nature of the old and new landslides, possible failure mechanisms and processes were studied. Failures that are typical to different areas were identified and classified using Cruden and Varnes (1996), and Hungr et al. (2001).

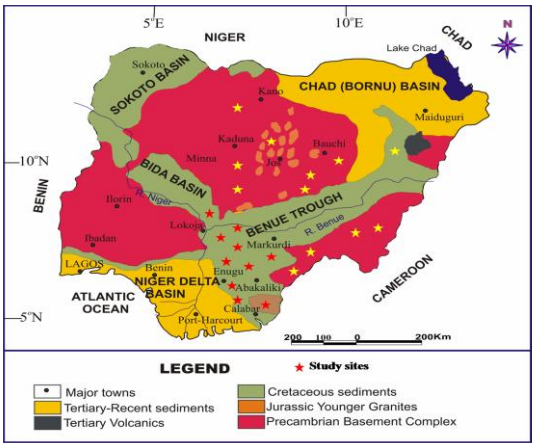


Figure 1: Study sites underlain by the different geologic units

Geotechnical and hydrologic analysis of samples collected at the headscarp were undertaken to determine appropriate input parameters for the slope stability models. Silica sands were used as control. Aside the conventional geotechnical tests (grain size distribution, specific gravity, unit weight and consistency limit) triaxial and direct shear tests were conducted following ASTM standards to obtain shear strength parameters cohesion c and angle of internal friction . Some specimens were sheared (up to 10 m) to steady-states of deformation in the ring shear apparatus to obtain values applicable in the prediction of landslide mobility. To account for the field conditions of slopes, normal stress and shear stresses were calculated from relevant equations using slope information.

To study the effect of increased groundwater table on FS, changing water level was analyzed using the infinite slope model and results validated by slope stability analysis incorporating Bishop Method with SLOPE/W program developed by Geo-slope International Limited. The boundary conditions were chosen in accordance with Chugh (2003) and Huat et al. (2006). The analysis employed varying B_D values (saturation degree, Sassa 1998; Igwe and Fukuoka 2014) to determine critical input parameters. B_D value was varied from 0.51 to 0.95. Slope height H and inclination , cohesion c, angle of internal friction and unit weight were also used in the rigorous analysis, of which averages were later applied in the interpretations.

The infinite stability analysis followed steps outlined by Duc (2013), which relied on three specific assumptions: (1) that the slope is infinite (2) that the slip or failure surfaces are long compared to their depth (3) that the driving force at the upper end and the resisting force at the lower end of the sliding mass can be ignored. The approach is consistent with Griffiths and Lane (1999) and Tsai and Chiang (2013). The factor of safety (Fs) was first determined from the equation:

$$Fs = A(\tan \phi' / \tan \alpha) + B(c'/\gamma/H) \quad \text{..(1)}$$

Where H is the depth of soil measured vertically to the sliding surface, ϕ' and c' are effective strength parameters, α is the slope angle, γ is soil density. Parameters A and B in (1) which account for the pore pressure acting normal to the sliding surface and the shear resistance along the sliding surface respectively were determined from the equations:

$$A = 1 - (r_u/\cos^2 \alpha) \quad \text{..(2)}$$

$$B = 1/(\sin \alpha . \cos \alpha) \quad \text{..(3)}$$

Where r_u is the pore pressure ratio and is given as:

$r_u = m \cdot (\gamma_w/\gamma)(\cos^2 \alpha)$..(4)

Where m is the saturated fraction of the residual soil, γ_w is the density of water, and γ is the density of soil. The saturated fraction of the residual soil was then determined by:

$m = (X/T)$..(5)

Where X is the thickness of the residual soil that is saturated and T is the total thickness of the residual soil. A wide range of m values of 0.1 to 1.0 was considered in the analysis.

III. Results and discussion

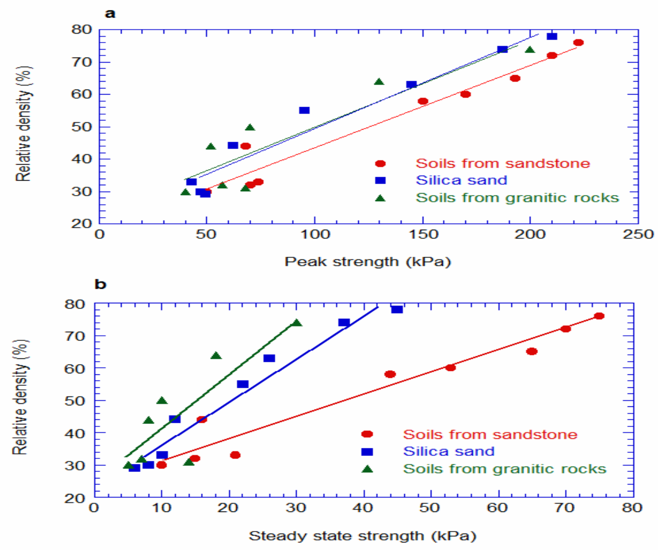
182 landslides and scars were identified by field survey and aerial photographs out of which 36 were selected for detailed mapping and documentation. Most landslides occurred on slopes > 40^o in the north and > 30^o in the south. The landslides in the north were predominantly shallow translational slides (> 300 m in length on average) which failure did not appear to significantly alter the steepness of the hard rock terrains (Fig. 2). Curiously, the steepness of the slopes adjacent to some of the failures tended to be inversely proportional to the runout length. On the contrary, some mass movements in the south tended to make the local slope steeper because of the nature of failure (shallow movements < 10 m on average) on the loose sandstone terrains that often defy remedial measures (Fig. 3). Landslide inventory of the study areas showed that landslides in the north consisted of mainly falls, debris flow and occasional debris avalanche. In the south the landslides were mainly slumps, short runout slides and occasional debris flow.

Figure 2: A translational slide on one of the slopes on the Benue mountain range in the North (photo by Igwe)

Figure 3: A slope near Nsukka Southeast Nigeria revealing failure on a remediated portion (photo by Fukuoka)

The frequency of events also showed that landslides were relatively less frequent in the north. Owing to these differences in frequency and failure mode, landslide volume in the north tended to be greater (averaging 615, 000 m^3) than those in the south (with an average of 5021 m^3).

The average value of the geotechnical and hydraulic properties of the samples are shown in Table 1, while the variation of factor of safety with B_D value is summarized in Table 2. The strength characteristics of the materials are presented in Fig. 4.



Figures 4a and b: The peak and steady state strength characteristics of the different slope soils

Table 1 Summary of the soils' geotechnical and hydraulic properties

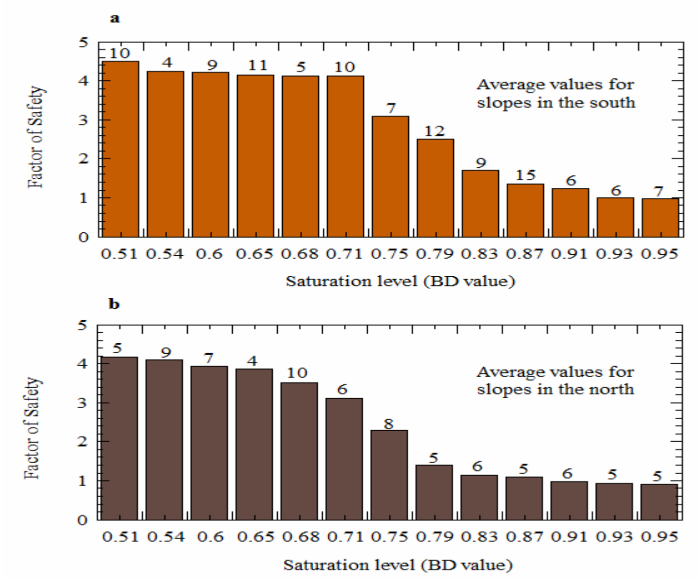
Soil property	Soils derived from granitic rocks	Soils derived from sandstone	Silica sand
Classification based on USCS	Average values	Average values	Average values
Sand fraction (%)	69	75	62
Silt fraction (%)	17	16	16
Clay fraction (%)	14	9	22
Uniformity coefficient C_u	8.3	2.8	3.3
Coefficient of curvature C_c	0.30	0.89	0.83
Bulk density (kg/m^3)	1787-1854	1762-1804	1624 - 1697
Hydraulic conductivity K (m/s)	10^{-8}–10^{-4}	10^{-7}–10^{-5}	10^{-8}–10^{-5}
Cohesion (kPa)	11	5	9
Angle of internal friction (deg.)	21	25	22

Table 2 Variation of FS (average values) with changing saturation level

Soils of granitic origin		Soils of sandstone origin	
B_D value	FS	B_D value	FS
0.51000	4.1800	0.51000	4.5000
0.54000	4.0900	0.54000	4.2500
0.60000	3.9300	0.60000	4.2100
0.65000	3.8600	0.65000	4.1500
0.68000	3.5200	0.68000	4.1300
0.71000	3.1200	0.71000	4.1100
0.75000	2.3000	0.75000	3.0900
0.79000	1.4000	0.79000	2.5000
0.83000	1.1500	0.83000	1.7100
0.87000	1.1000	0.87000	1.3600
0.91000	0.98000	0.91000	1.2400
0.93000	0.94000	0.93000	1.0000
0.95000	0.92000	0.95000	0.98000

At all density, the peak and steady-state strength of the specimens from the sedimentary terrain are higher than those from the hard rock region. The peak strength of the silica sands used as control is almost the same with those of specimens from hard rock terrains. The compressibility characteristics of materials affect their shearing resistance (Igwe 2014). Highly compressible soils experience more severe reduction in sample height and permeability (Fortin et al 2007) which results in higher excess pore pressure and lower strength. It is remarkable that the steady-state strength of the silica sands is noticeably different from that of the hard rock locality (Fig. 4b). This appears to confirm the validity and reliability of the use of the steady-state parameters in the stability models. At steady-state, all particle rearrangement and restructuring cease and pore pressure, effective stress and shear resistance remain constant (Poulos 1981). The most remarkable find however, is that whereas the gradient of the peak and steady-state strength of the soils derived from sandstones are nearly the same, the gradient of the steady-state strength of silica sand and soils derived from granitic rocks tend to be steeper than their peak strength (Fig. 4a,b). The result shows that at large shear displacements, the steady-state strength of more compressible materials are not significantly affected by changes in density, which may be a reason for the longer travel distances of landslides involving such soils.

In the stability model, the factor of safety varied from 4.5 to 0.98 for soils from the sedimentary locations (Fig. 5a).



Figures 5a and b: The variation of factor of safety with changing saturation level

For soils from the igneous and metamorphic terrain, FS varied from 4.1 to 0.94 (Fig. 5b). In both cases, the onset of instability began at B_D value < 0.80. In the infinite slope model, similar results were obtained as the factor of safety decreased with increasing moisture content m and slope angle □ for all the slopes (Figs. 6 and 7).

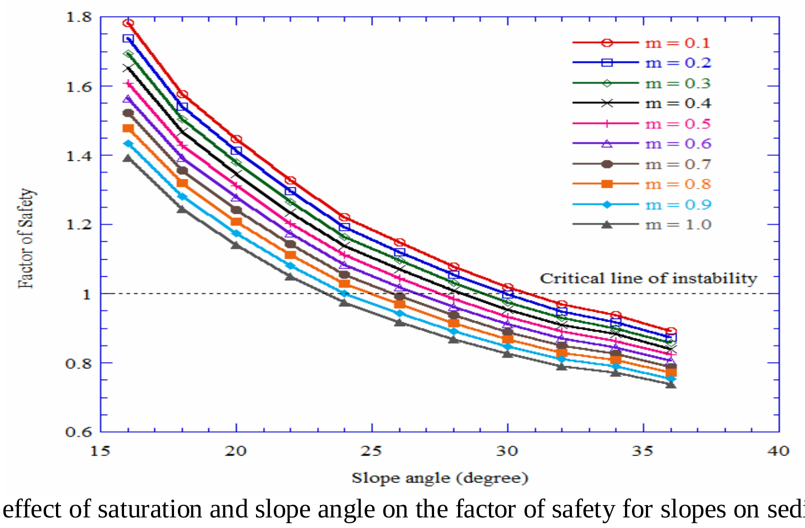


Figure 6: The effect of saturation and slope angle on the factor of safety for slopes on sedimentary rocks

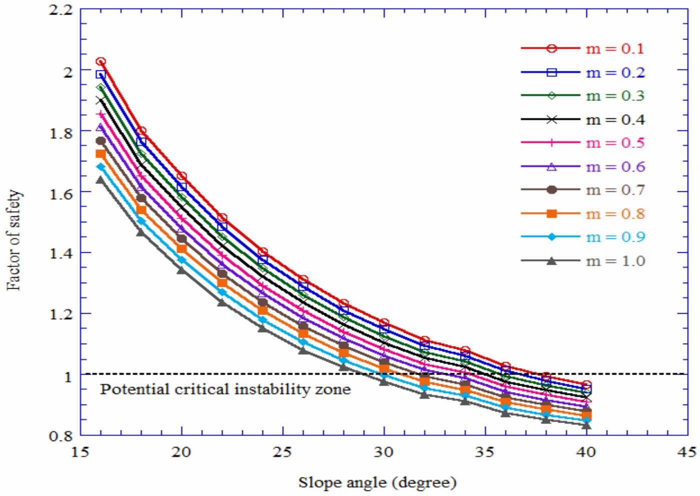
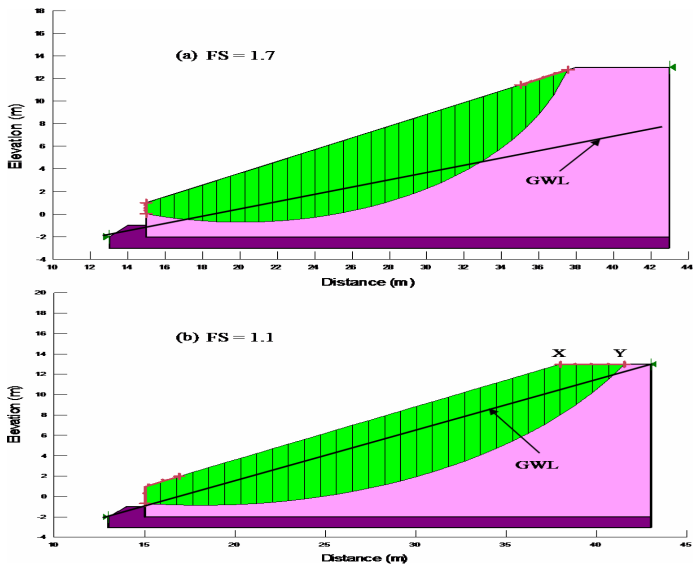


Figure 7: The relationship between factor of safety and slope angle for slopes on igneous and metamorphic rocks

Parameters such as the shear strength (c□ , tan□ □), the unit weight(□)and pore pressure(u) were assumed to be distributed over the depth of the slope (Griffiths and Lane 1999; Tsai and Chiang 2013). Because the factor of safety appeared to drop to unrealistic level when slope angles were higher than 40°, only results from 15° to 40° are presented. Although the decline was general, results for slopes sitting on sedimentary rocks indicated that failures are unlikely in the slopes having low saturation and with angle less than 25°. At all saturation level, slopes less than 25° scarcely experienced instability. However, most slopes above 25° fell under the critical line of instability (Fig. 6). For slopes on the hard rock areas, stability was maintained in slopes < 30° with slope being more prone to failure as the slope angle increased further (Fig. 7). At slope angle of 30° the critical line of instability (CLI) passed only through slope at 0.9 and 1.0 levels of saturation; slopes at lower saturation levels were probably safe. However, at 38°, the CLI passed through the slopes having even the minimum level of saturation (Fig. 7). These impacts on stability are consistent with reported behaviors of slopes in Eid et al. (2006), Eid (2010), Hungr and Amann (2011). By means of these analyses, the zones of potential instability could be predicted for the whole area under study. These values agreed closely with field measurements of documented failures in the region. Field investigations have reported landslides on slopes < than 30° in south-east Nigeria (Igwe and Fukuoka 2014).

Investigation using actual groundwater levels of the two regions showed that at deeper groundwater level in the South FS was 1.7 Fig. 8a, but became 1.1 at shallower groundwater table in the North Fig. 8b, showing there was significant drop in FS with increasing saturation. The extension XY (Fig. 8b) may indicate additional instability on the landscape. Similar responses of residual soils to changes in hydrologic conditions have been reported by Reid et al. (1988), Onda et al. (2004) and Rahardjo et al. (2005). It also shows that where appropriate drainage is undertaken, there would be drastic improvement of FS.



Figures 8a and b: Stability analysis using actual ground water levels of the study area

The reduction of FS with saturation and slope angle, and the finding that less than full saturation can trigger failure have important implications for rainfall-induced landslides. Water-infiltration substantially weakened the materials (both the regolith and the underlying units) with a corresponding drop in the factor of safety. Rainfall-induced failures (debris flow and avalanche) in residual soils initiate by a reduction of confining stress and shear resistance due to elevation of pore-water pressure during heavy or prolonged rainfall (Reid et al. 1988; Rahardjo et al. 2005; Crosta and Frattini 2008). But this research has shown that light rains can also induce failures on the slopes, which seems to explain the mechanism of many landslides that have occurred in southern part of Nigeria during light showers especially a moderate rain-induced debris slide on a 36^{o}hillslope at an agricultural town of Ugwueme (6^o 00'N – 6^o 03'N and 7^o 24'E – 7^o 28'E; elevation 366 m) Awgu Local Government Area in October 2008 which marks the tail end of rains. Analysis of the mechanics of the failure showed that the depth and inclination of sliding surface was 2 m and 32^o respectively, while the slip surface was composed of black shale. The gap-graded sandy materials from the headscarp had cohesion 5 kPa, peak strength 45 kPa, steady-state strength 10 kPa and maximum pore pressure of 115 kPa, which were good conditions that may cause the soil mantle to become unstable with little precipitation. Calculated factors of safety for the thin residual soils were similar to Sidle and Swanston (1982), Simon et al. (2002) and consistent with predictions of this research using steady-state strength parameters. Early warning strategies and landslide prevention measures that take this finding into consideration may be more effective in protecting the society.

Slope failures are caused by a combination of factors (Moser and Hohensinn 1983) but some factors can be major or minor depending on the site. Although Rahimi et al. (2011), Lee et al. (2012) and Mahmood et al (2013) have reported the significant effect of antecedent rainfall on slope stability, this research has demonstrated clearly that the amount of rainfall (as represented by m and B_D saturation values) in addition to contributing factors such as geological and soil-mechanical properties, slope inclination and slope morphology may be more important than antecedent rainfall, land use, slope aspect and vegetation in determining the type, mode and severity of slope movements in the study sites.

The prediction of slope stability in Nigeria can be complicated by the highly variable nature of residual soils, hydrological parameters, and the inherent heterogeneity of local geology. Contrast in hydraulic conductivity affects groundwater seepage forces, effective stresses, which in turn influences slope failure potentials (Crosta and Negro 2003; Onda et al. 2004). Such contrasts exist on heterogeneous slopes and can be characterized by quantitative stability analysis. Results of similar analysis (Ali et al. 2014) provided a reliable platform for the prediction of rainfall induced landslides. The varying hydrological and geological attributes can be indirectly accounted for by utilizing input parameters that adequately represent the actual field conditions of slopes in slope stability models. Fs arising from the models can accurately predict vulnerable slopes and highlight potential for failure initiation over an area. Field survey can be used to ground-truth the findings.

IV. Conclusions

Processes inducing instability are multi-faceted, and require a multi-method approach for effective hazard assessment. This paper combined field, geotechnical, experimental and slope stability analysis to determine reliable Factors of Safety that corresponded to actual field cases of instability. A stability analytical method taking into account water infiltration in which the shear strength parameters were considered as a function of saturation degree was applied. The method permitted clear understanding of the dominant factors affecting the stability of slopes and their implication for rainfall-induced landslides in the study areas. The important parameters used in the stability models were obtained at in-situ stress levels simulating near-field slope conditions.

It is remarkable that whereas the gradient of the peak and steady-state strength of the soils derived from sandstones (which were less compressible) were nearly equal, the gradient of the steady-state strength of silica sand and soils derived from granitic rocks tended to be steeper than their peak strength. The result appeared to demonstrate that at large shear displacements, the steady-state strength of the more compressible materials were not significantly affected by changes in density, which may be a reason for the long travel distances of landslides involving such soils.

Results of stability analysis showed that slope stability were significantly influenced by material properties, slope angle and saturation level. Factors of safety obtained from the stability analysis showed good agreement with those of the infinite slope model. The results also showed that the method of infinite analysis could precisely predict the slopes that are more at risk, differential land use practices notwithstanding. Most areas with FS > 2.0 corresponded with stable areas observed in the field. Similarly all elements within areas having FS < 1.5 were in locations of documented past failures. Within the unstable areas, the critical failure factors were quantitatively ascertained.

Slope failures are common in Nigeria during periods of intense rain. But failures that differ in mode and severity, and thickness of failed mass, timing and mobility can also occur under light rain conditions. Relatively small failures predominate in the south while larger ones are more common in the north. By applying stability analysis, vulnerable slopes in the two regions have been predicted and classified. The stability results showed that slopes higher than 38^o are vulnerable in the north underlain by granitic and gneissic rocks, while slopes with angles > 25^o are predicted to be at risk in the south. These predictions are in good agreement with field and reported cases of failures in the two geologically different localities.

Following rainfall, infiltration reduces suction and shear strength that may lead to instability when the intensity and duration of rainfall exceed a certain threshold. But such unstable slopes may only fail if they fall within the critical failure line that heavily depends on slope angle. Intense rainfall, soils' hydrologic response to saturation and terrains at unsustainable slope angles are considered the major causes of the failures. The apparent loss of suction and increased pore-water pressure lead to sharp drop in FS and failure at shallow depths. Therefore, the scale of a failure event will depend more on the intensity (and probably duration) of the triggering rainstorm and the topography of the location; and less on other potential factors.

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