Igwe *Geoenvironmental Disasters*
DOI 10.1186/s40677-014-0008-z

Geoenvironmental Disasters
a SpringerOpen Journal

RESEARCH ARTICLE Open Access

The geotechnical characteristics of landslides on the sedimentary and metamorphic terrains of South-East Nigeria, West Africa

Ogbonnaya Igwe

Abstract

Background: Landslides in Nigeria occur in various forms and vary in mode, scale and frequency. The variations appear to be significantly controlled by geologic setting, hence the need to study in detail the distinctive features that differentiate landslides in sedimentary environments from those on metamorphic localities. The aim is to understand the actual features impacted on the landslides by geology, from which future predictions of occurrence and identification of instability could be based. The recognition of features that are characteristic of certain geologic setting may be a major step in early warning development in Nigeria. To achieve the objectives detailed mapping of the study area was carried out using topographic maps, aerial photographs and multiple field surveys.

Results: The landslides on the sedimentary terrain were mainly shallow, low-volume movements, material slumps and short runout slides some of which activated on slopes that followed the dip of strata, along wavy shear surfaces controlled by impermeable bedding planes. Runoff-triggered movements caused by erosion of channel bed and banks and failures caused by sediment bulking of runoff with material eroded from headwater slopes are also common on the sedimentary terrain.

Conclusions: In comparison, the landslides on the metamorphic terrain were complex translational and rotational movements and mudslides on steep slopes sometimes involving a combination of slide and flow with curved headscarps and slickensided shear surfaces. The looseness of slope materials and their relatively low strength parameters account for the dominance of landslides on the sedimentary zone.

Keywords: Landslides; Sedimentary rocks; Metamorphic terrain; Strength parameters; Stability

Background

Landslides are a major hazard in Africa where resources worth several millions of dollars are lost annually during seasons of heavy and also light rains. The mechanisms of rainfall-induced landslides have been extensively studied and some of the conclusions assert that the amount of rain, nature of slope-material, discontinuities and weathering are the major factors predisposing a slope to failure (Iverson 2000; Msilimba and Holmes 2010; Wang et al. 2002; Sassa et al. 2004; Guzzetti et al. 2008). Water-infiltration is a significant triggering factor for slope failures around the world. Prolonged and/or intense rainfall can trigger landslides, floods and secondary floods (stagnancy of rain on low permeability surfaces) that could result in damage and fatalities (Petrucci and Polemio 2009). In West Africa, landslides are caused primarily by rainfall. Depending on meteorological and geomorphologic conditions, individual rainfall events can trigger small or large slope failures. Liao et al. (2012) defined the relationship between factor of safety and rainfall on an infinite slope by means of a physical model known as SLope-Infiltration-Distributed Equilibrium (SLIDE) which took into account the effect of water infiltration on the stability of slopes. Landslides induced by high-intensity or prolonged rainfalls constitute a major risk factor in Nigeria especially because they have generally been poorly defined in the past. The landslides have the potential to damage human settlements, industrial development, cattle ranch, forestry, and agricultural activities. For instance in October 2008 at 3:30 a.m. local time, a mudflow occurred 200 km east of Enugu metropolis, south-east Nigeria. During a rain

Correspondence: igwejames@hotmail.com
Department of Geology, University of Nigeria, Nsukka, Nigeria

storm, a portion of an unstable hill (< 500 m) collapsed, sending mud and debris across the rural neighborhood killing 2, damaging agricultural farms and covering an area of approximately 1.3 km^2. Recognition, identification and mechanisms of such landslides has received intense study (Wei et al. 1993; Sassa 1998; Aleotti 2004; Wang et al. 2005, 2009; Sassa et al. 2004; Wang and Sassa 2010), however a few studies have attempted a systemic evaluation and grouping of landslides according to their geologic origin. While landslide susceptibility maps attempt to delineate areas with potential for future failures, they appear silent on the distinctive features locality can impact on slope movements. A comprehensive landslide risk assessment should therefore not only include investigation of landslide processes and formulation of procedures for hazard reduction, but also the identification of imprints of geologic setting on the shape, size (morphology) and mobility of landslide. To understand morphology and mobility, detailed analysis of the source, location, severity, recurrence interval, triggering and displacement mechanisms are important areas of consideration.

Two localities (Calabar and Enugu, Figure 1) that differ in geology and land use were studied. While landslides are common and frequent in the hilly parts of Enugu because of its unique geology, long-time residents report that the recent landslides at the international tourist town of Obudu in Calabar (Figure 2) are the first known slope failures despite the much higher elevation and steepness of slopes in the area. These differences in scale and frequency were the major motivating factors for the research. Although the landslides vary in scale and frequency in the two areas, they are all shallow, rainfall-induced landslides. Wieczorek and Glade (2005) and Gabet and Mudd (2006) reported that debris flows can be mobilized from shallow landslides. The landslide debris frequently creates inconveniences by destroying communication and hydraulic facilities, or by blocking roads and communication routes. Sometimes death also

Figure 2 The International tourist area of Obudu, Calabar (photo by Igwe).

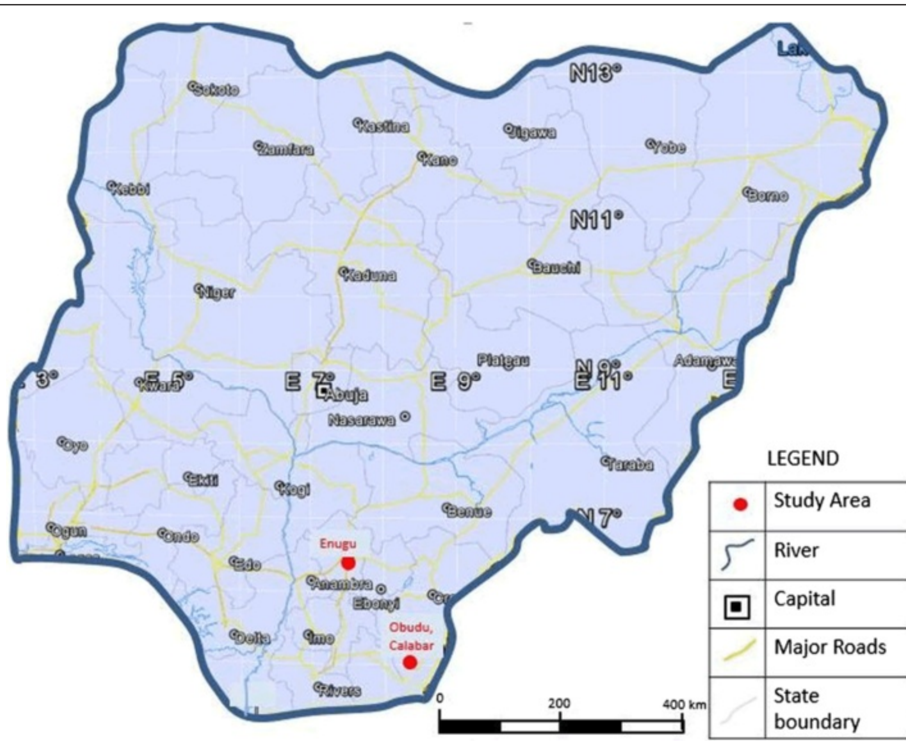

Figure 1 Location of the study areas.

Figure 3 **Shallow slides at the sedimentary terrain in Enugu (photo by Igwe).**

Figure 5 **Some of the casualties of the Obudu landslide were the occupants of a car that tumbled when a slope near the road failed (photo by Igwe).**

occurs when displaced landslide masses crash on buildings or into people. The prolonged rainfall of October 2013 triggered 28 new shallow landslides in Enugu (some of which are shown in Figure 3) and four pronounced landslides at Obudu area of Calabar (one of such is shown in Figure 4). Some of the landslides brought untold hardship to international tourist who had flocked to Obudu to catch a glimpse of the beauty of the fading sun on the Obudu Hills during the months that demarcate the wet and dry seasons. These landslide events caused casualties (one such casualty from the ditched vehicle in Figure 5) and severe economic losses and illustrated the need for the risk assessment through proper understanding of the geotechnical and hydrological characteristics of the slopes. Knowledge of the mechanisms of precipitation-induced slope failures is of great importance in the management of landslide hazards, especially because there is no systematic monitoring of slopes in Nigeria. Marchi et al. (2002) reported the usefulness of slope monitoring in hazard and risk assessment.

Figure 4 **A landslide on the metamorphic terrain in Obudu Calabar (photo by Igwe).**

The objective of this study is two-fold: (1) to carry out a medium to large-scale assessment of landslides in two vulnerable localities in south-east Nigeria that lie on two different geology – sedimentary and metamorphic, (2) to understand their geotechnical properties and attempt to develop a size-predictive model that may contribute to future preventive and management measures.

Methods

General procedure

Detailed mapping of the study area was carried out using topographic maps in the scale of 1: 50,000, aerial photographs and multiple field surveys, The major goal of the study was to identify areas frequently affected by landslide episodes and compare their hydro-geological and geotechnical characteristics. By comparing these characteristics in areas prone to the hazard, susceptible zones and initiation mechanisms could be properly understood. Several documents that provided historical data on past landslides were reviewed and chronologically sorted to determine cases that had been the most damaging to lives and property. The landslide types were classified in accordance with Cruden and Varnes (1996). Landslide locations in the study area were identified from interpretations of aerial photographs and field surveys. During the mapping, aerial photographs (taken in the 1970s and 80s) and topographic maps at a scale of 1:50,000 were evaluated. Validation of the aerial photos was later done by carrying out multiple field surveys of the study site. Measurements essential to the preparation of an adequate geologic map were taken at various locations within the study area. Such study has not been carried out on the Nigerian landscape.

Landslide bodies were mapped from crown to toe of rupture. Similar method was reported by Aleotti and Chowdhury (1999). Note was taken of the slope height, slope length, slope gradient, lithology, and dip direction of slope, the thickness and slope of the sliding surface. Original geometry of slope, position of water table and shear strength parameters were also analyzed. Depths were estimated from trial pits and boreholes. Geological cross-sections were then made to study the morphology of the slides. The soils' cohesion intercept (c) and angle of shearing resistance (ϕ) were comprehensively determined with a series of consolidated, undrained, and saturated triaxial tests. Using the geological and geotechnical data, interpretations were made and conclusions drawn.

Precipitation record was obtained from metrological stations near the landslides. Data obtained included the mean annual precipitation, the average number of rainy days, the precise or approximate location of the area affected by the landslides, the precise or approximate time, date, or period of the failures, the rainfall conditions that resulted in slope failures and the number of landslides triggered by rain. Such information has not been reliably or sufficiently documented. Analysis was then made of the geographical distribution of the rainfall and landslide events. An apparent limitation in the use of the rainfall information was the unavailability of many rain gauges in the study areas. This prevented decisions on the reliability of a rain gauge based on the geographical distance

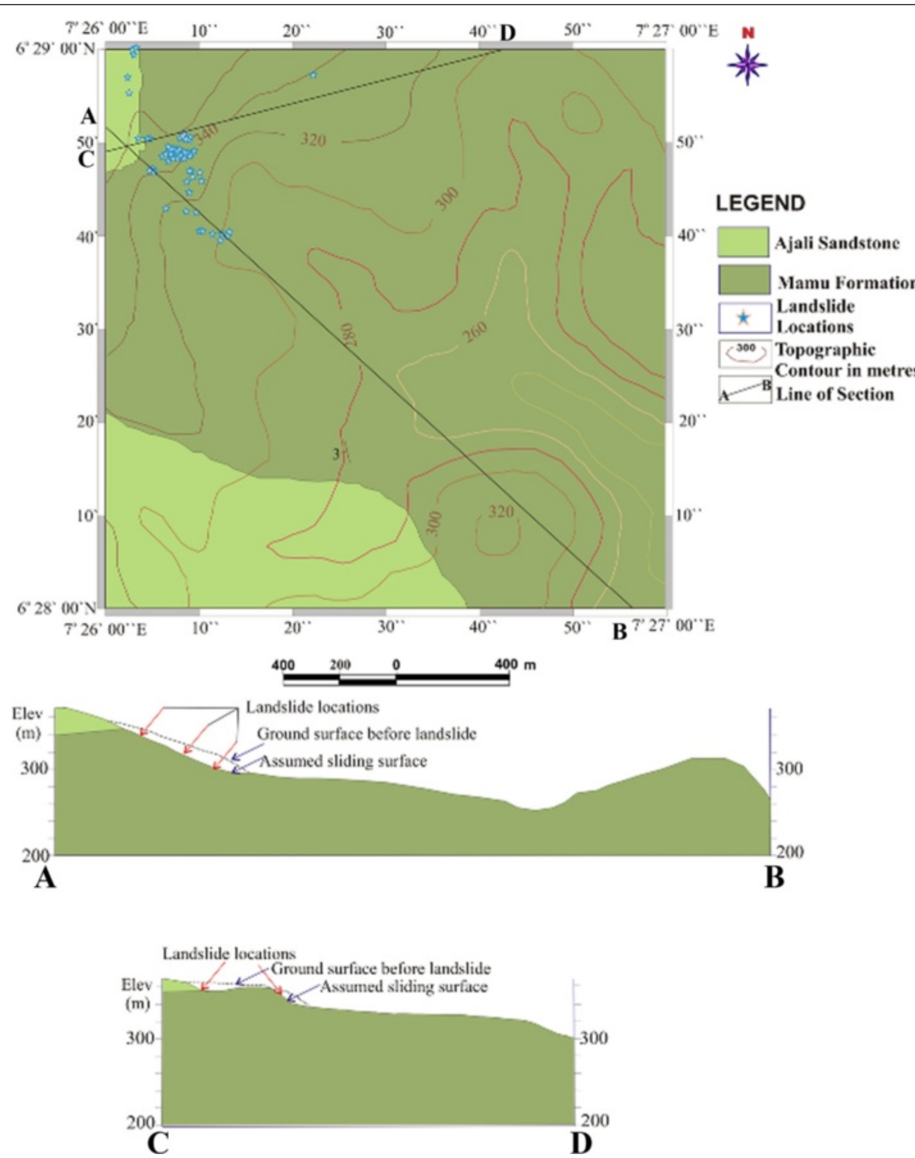

Figure 6 Local Geology of Enugu study site with cross sections.

to the landslide (or landslide area), the elevation of the rain gauge compared to the elevation of the landslide, and the location of a rain gauge with respect to the local topographical and morphological setting. Generally, the study used the information from any available rain gauge closest to the landslide area.

Site characteristics

Geology

The dominant rock types in Enugu area are sandstone siltstone and shale (Figure 6) that range from the Campanian to the Eocene in age and were deposited in environments that pass from continental in the proximal parts through paralic to shallow marine in the distal parts (Kogbe, 1989; Oboh et al. 2005). The oldest deposits with the Anambra basin belong to the Campanian Nkporo Group composed of the diachronous Enugu Shale formation, Nkporo shale formation and the Owelli Sandstone formation. Rocks of the Mamu Formation outcrop in the study area and consist of bluish dark grey shales containing abundant carbonaceous matter with thin siltsone and sandstone layers. The Mamu Formation was deposited after the Enugu

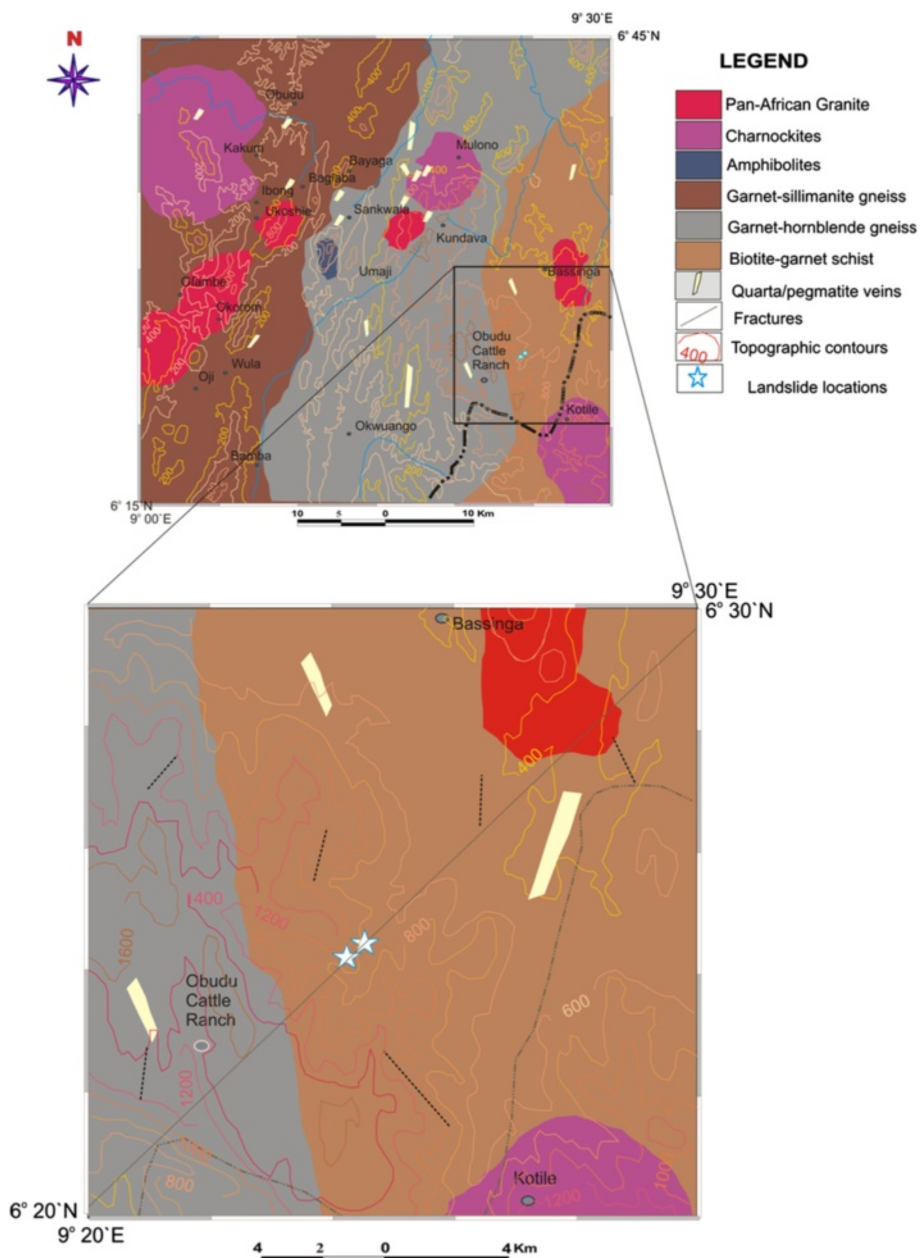

Figure 7 Geology at the metamorphic locality.

Table 1 Select geotechnical characteristics of the slope materials

Specimen No.	Terrain type	Average frictional resistance (°)	Average cohesion (kPa)	Average coefficient of permeability (cm/sec)
Enugu Group 1	sedimentary	25	11	3×10^{-2}
Enugu Group 2	sedimentary	13	10	1×10^{-4}
Enugu Group 3	sedimentary	15	10	1×10^{-3}
Enugu Group 4	sedimentary	25	16	2×10^{-4}
Calabar Group 1	Metamorphic	18	20	4×10^{-4}
Calabar Group 2	Metamorphic	16	25	3×10^{-4}
Calabar Group 3	Metamorphic	18	25	1×10^{-5}
Calabar Group 4	Metamorphic	18	40	2×10^{-5}
Calabar Group 5	Metamorphic	18	40	3×10^{-4}

shale and consists of heteroliths of siltstone, shale and fine grained sands with coal seams. The Maastrichian Ajali Sandstone Formation lies conformably on the Mamu Formation. It consists of characteristically friable, cross-bedded sandstones with a virtual absence of clay. The Ajali sandstone which is about 406 m thick in the area is overlain by lateritic/red earth deposits.

The dominant rock types in Obudu, Calabar are gneisses, migmatites, amphibolites, quartzites, schists, granites and pegmatites (Ekwueme 1991). According to Ukaegbu and Oti (2004) and Ukaegbu and Beka (2007) the basement rocks of the Obudu plateau have undergone amphibolite to granulite facies metamorphism and consist dominantly of the aforementioned rocks (Figure 7). Additionally, polyphase deformation has caused folding, refolding, faulting, foliation and shearing of the metamorphic rocks with mainly N-S to NE-SW trends in conformity with trends in other parts of the reactivated Basement Complex of Nigeria. They reported that the tectonic imprints are reflected as remnant Pre-Pan-African (E-W to NW-SE) to dominant Pan-African (N-S to NE-SW) structural features. The area is considered the terminal end of the western prolongation of the Cameroon Massif (Edet et al. 1994; Ejimofor et al. 1996; Ekwueme, 1998; Toteu et al. 2004).

For geotechnical investigations, the entire road stretch was divided into 16 uniform slope sections based on slope angle and rock types following the method espoused in Dai et al. (2002), Chen and Wang (2007) and Das et al. (2010).

Climatic features

Calabar and Enugu have similar tropical climate, with dry summers (monthly minimum or zero rainfall in from November to March) and wet season (widespread monthly high rainfall from April to October). The mean annual temperature at Obudu varies from 14°C to 28°C and mean annual rainfall of approximately 2000 mm to 3000 mm (Ekwueme 1991; Ejimofor et al. 1996). The mean monthly temperatures in Enugu vary from 22°C to 28°C in the wet season and between 28°C and 32°C in the dry season. Intense and short duration rainfalls characterize the outset of rainy season in the area. Annual rainfall (based on 2012 precipitation amount) ranges between 1500 mm to 2100 mm (Igwe et al. 2013). The areas lie between the tropical rainforests which dominate nearly half of southern Nigeria and is characterized by luxuriant vegetation and abundant plant species. It is bounded by fresh water swamp forest in the south and Guinea Savanna in the North. The vegetation is marked by continuous growth of trees, shrubs and climbing plants.

Due to the movement of meteorological perturbations and the heat/moist exchange with the sea the rainiest areas are the southern parts. Nevertheless, the northern parts are sometimes hit by very intense storms because of enhancement due to the relief. During such periods, daily rainfall could increase to 20–30% of mean annual rainfall in the area.

Results and discussion

The Obudu tourist area landslide

This research is the first work distinguishing landslide features on two different terrains in Nigeria. Obudu hills

Figure 8 Some of the landslides in Obudu cut power supply by damaging or deforming the electric lines (photo by Igwe).

are located in the Obanliku Local Government Area of Cross River State, southeastern Nigeria. They lie between latitudes 6°20’ and 6°30’ N and longitudes 9°20’ and 9°30’ E (Figure 7). The area is about 104 m^2 and stand at a height of about 1576 m above sea level (Ekwueme, 2003). The geotechnical properties of the slope materials are summarized in Table 1.

On October 14th 2013, after many days of heavy rain with cumulative precipitation of over 600 mm, several debris slides were triggered in the mountain of Obudu. Some of the landslides blocked the only access route to the sightseeing area, while others cut power supply (Figure 8). The water table varied from 0.9 to 4 m. The undulating topography, and non-homogeneous or anisotropy of the slope materials, make assessment of water table depths and ground-water flow patterns difficult. To validate the results from the hand-dug wells, geophysical method – vertical electrical sounding – was utilized. The results agree with the observation wells’ data.

Field observations showed that the landslides on the metamorphic terrain have discrete, slickensided shear surfaces on which analyses were possible. This was a major difference between mass movements on the metamorphic and sedimentary landscape. There were rupture surfaces from which movements began as slides and continued for long distances as mudflow/slides. The materials involved were typically poorly-sorted sandy colluviums supported by about 43% clay matrix produced

Figure 9 The landslide debris initially covered the road before being cleared in (A) and damaged power cables prompting the erection of a new power line in (B) (photo by Igwe).

from the weathering of the rocks. The consistency of such materials is usually closer to the plastic rather than the liquid limit (Hutchinson 1988). The characteristics the clay matrix probably contributed to the rapid movement witnessed on the metamorphic terrain. For long distance travel, motion down the slope may be facilitated by undrained loading (Hutchinson and Bhandari 1971; Wang et al. 2000, 2002). One of the landslides involved mass movement of 19,000 m^3 materials downslope for 7 m (from the head scarp to the toe) covering the section of the road and completely blocked access to the hills or the city centre and destroyed some power cables (Figure 9A, B). The thickness of the regolith varied from 0.2 m to 0.7 m in some places. The slope elevation and inclination were 790 m and 62° respectively. The access road was promptly cleared of debris by the Municipal government authorities to restore confidence in the foreign visitors. Direct field observation and photographs taken appear to show the presence of discontinuities and lines of weakness. Field observation and slope stability analysis revealed that sliding of the top block (failed block, Figure 9B) was likely. Dip slope failure of the regolith directly above the fine materials is possible.

The recent landslides in the area are the first known landslides in the hills, indicating high stability. There had been no previous landslide experience on the slopes although the slopes are quite steep and stand at high elevations. The area is hilly with some peaks reaching 1000 m. Access roads (which obviously decreased stability) were constructed to improve scenery and attract tourist. But during or after the road construction, no slope stabilization technique was put in place to check sliding. It is therefore not a coincidence that all the dangerous landslides occurred along the roads axes. Excluding gravelly materials in the failed masses, the average sand, silt and clay content of the samples is 52%, 34% and 14% respectively. The average range of coefficient of permeability was $4 \times 10^{-4} - 2 \times 10^{-5}$ cm/sec. At one of the exposed sections of a landslide on the slope, three layers of varying thickness and permeability were observed (Figure 9A). The calculated average vertical permeability kv of the three-layered profile visible at the landslide site was about 0.84 × 10–3 cm/sec. While the average range of the angle of internal resistance and cohesion were (16° – 18°) and (25 kPa – 40 kPa) respectively.

The Enugu landslides

Slumps and short runout debris slides of limited volume are frequent and many at this location in spite of the areas relatively low elevation and slope angle. The slow to rapid of the mostly unsaturated movements usually initiate within the sandy body or on clayey/shale interlayer, but are typically on non-discrete, matrix-poor shear surfaces. The movements were mainly non-confined and without established channel. The slope material is dominantly unconsolidated, friable sands that easily give way during intense rain. The average content of sand, silt and clay is 75% sand, 16% silt and 9% clay with uniformity coefficient of 2.8. The average range of coefficient of permeability was $3 \times 10^{-2} - 2 \times 10^{-4}$ cm/sec. The slope is dominantly a two-layered profile with a calculated vertical permeability, kv of 1.6×10^{-2} cm/sec. The average range of the angle of internal resistance and cohesion were (13° – 25°) and (10 kPa – 16 kPa) respectively.

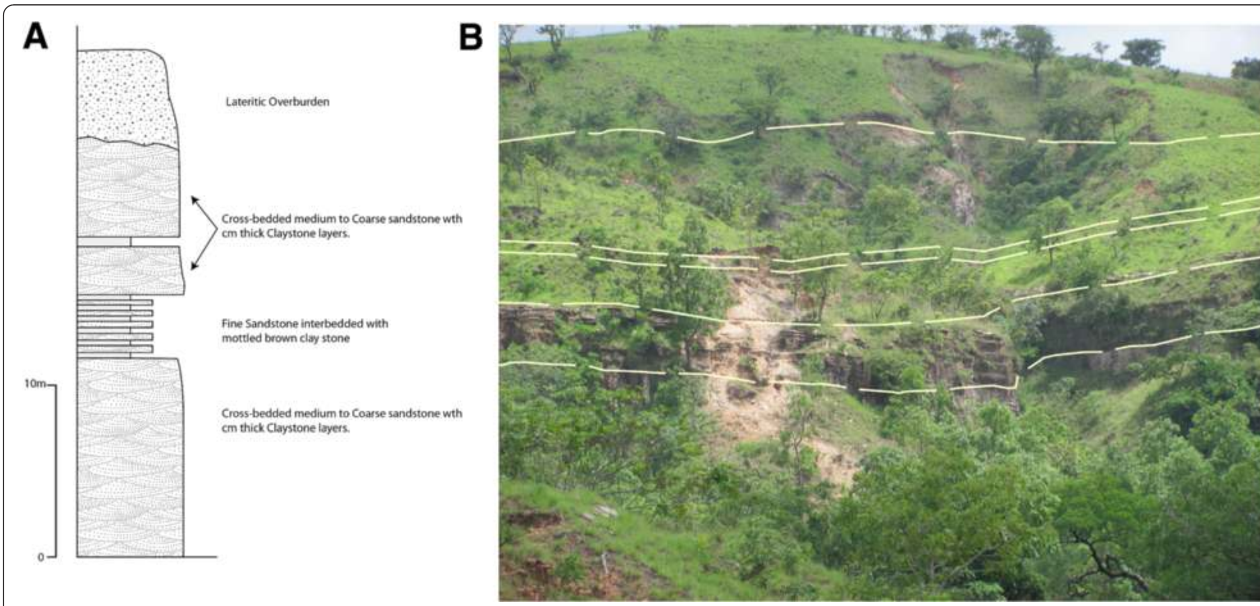

Figure 10 Enugu landslide and its lithologic description (photo by Igwe).

Table 2 Summary of field measurements from the sedimentary terrain

Longitude (E)	Latitude (N)	Length (m)	Width (m)	Slope angle (°)	Elevation (m)	Depth to slip surface (m)
007 °26'13.4"	06°28'40.6"	6	3.2	20	309	0.5
007 °26'22.3"	06°28'57.7"	9.4	3.5	14	307	0.3
007 °26'12.2"	06°28'40.3"	6.08	2.9	18	314	0.6
007 °26'12.5"	06°28'40.1"	4.6	2.8	16	315	0.35
007 °26'12.0"	06°28'40.8"	4	4.5	31	311	0.9
007 °26'10.0"	06°28'46.1"	15	7.73	32	337	3
007 °26'09.0"	06°28'45.6"	8	6	10	349	1
007 °26'08.7"	06°28'46.0"	12	8	29	353	3
007 °26'09.1"	06°28'46.1"	8	5	32	350	1
007 °26'10.1"	06°28'46.4"	20	10	20	354	1.5
007 °26'09.0"	06°28'46.6"	15	9	55	358	1
007 °26'08.8"	06°28'46.7"	13	8	40	354	1
007 °26'05.9"	06°28'48.8"	18	12	35	368	2
007 °26'06.1"	06°28'49.0"	10	5	32	370	1.5
007 °26'06.3"	06°28'49.0"	9	5	45	370	1
007 °26'06.4"	06°28'48.8"	6	3	35	366	2
007 °26'06.2"	06°28'48.6"	10	4	33	364	1
007 °26'06.4"	06°28'48.6"	6	3	34	365	1
007 °26'06.4"	06°28'48.6"	1.5	0.5	35	368	0.2
007 °26'06.8"	06°28'49.3"	25	10	40	375	2
007 °26'06.9"	06°28'48.6"	9	4	30	366	0.5
007 °26'07.5"	06°28'49.4"	15	9	40	374	1
007 °26'07.9"	06°28'48.7"	7	3	60	363	3.5
007 °26'08.2"	06°28'48.6"	8	4	35	364	2
007 °26'08.2"	06°28'48.9"	6	4	30	363	2
007 °26'08.4"	06°28'48.8"	2	0.5	32	359	0.3
007 °26'08.6"	06°28'48.9"	4	0.5	30	357	1
007 °26'08.6"	06°28'48.7"	5	3	30	353	1.5
007 °26'08.6"	06°28'49.1"	20	10	28	359	4
007 °26'08.6"	06°28'49.3"	3	1	46	361	1.5
007 °26'09.2"	06°28'48.9"	1	0.7	20	351	0.45
007 °26'09.7"	06°28'49.1"	12	4	40	357	1
007 °26'09.0"	06°28'49.4"	1.5	0.7	35	351	0.7
007 °26'08.9"	06°28'49.3"	2	0.5	30	352	0.7
007 °26'08.8"	06°28'49.3"	1	0.25	28	353	0.5
007 °26'08.7"	06°28'49.6"	5	3	33	359	1.5
007 °26'08.5"	06°28'49.7"	5	2.5	35	361	2
007 °26'08.2"	06°28'49.6"	2.5	1	32	363	1.5
007 °26'08.2"	06°28'49.4"	3	1	35	365	0.7
007 °26'08.1"	06°28'50.4"	12	4	31	377	1.5
007 °26'08.4"	06°28'50.8"	9	5	24	375	2
007 °26'08.7"	06°28'50.7"	5	6	28	373	1.5
007 °26'08.9"	06°28'50.4"	5	3	22	371	1
007 °26'09.0"	06°28'50.3"	2.5	2	25	370	1

Table 2 Summary of field measurements from the sedimentary terrain *(Continued)*

007 °26'08.9"	06°28'50.1"	7	2.5	29	367	2
007 °26'08.6"	06°28'49.1"	1.5	0.5	60	352	1
007 °26'03.4"	06°28'59.4"	7	3	20	404	1
007 °26'03.3"	06°29'01.1"	3	1.5	30	406	2
007 °26'03.3"	06°29'01.3"	5	2.5	35	407	1.5
007 °26'02.3"	06°28'57.4"	6	2.5	35	394	1
007 °26'02.6"	06°28'55.9"	3	1.5	25	388	0.5
007 °26'04.7"	06°28'50.6"	4	0.5	20	370	0.5
007 °26'04.6"	06°28'50.5"	5	2.5	25	374	1
007 °26'03.5"	06°28'50.4"	10	4	30	380	2.5
007 °26'05.3"	06°28'47.6"	5	2.5	28	360	1.6
007 °26'05.1"	06°28'47.6"	5	2	20	358	1
007 °26'05.2"	06°28'47.4"	2	0.15	24	355	0.3
007 °26'05.3"	06°28'47.3"	4	1.5	22	355	1
007 °26'06.9"	06°28'43.1"	10	5	22	348	2
007 °26'08.8"	06°28'41.7"	4	11	20	339	3
007 °26'10.1"	06°28'40.5"	4	1.5	20	330	0.3
007 °26'10.2"	06°28'40.6"	1.5	0.5	18	331	0.3
007 °26'11.7"	06°28'40.2"	1.3	0.6	15	322	0.2

Although liquefaction may be an associated mechanism of movement, the non-discrete nature of the shear zones and the short travel distances of majority of the slides make such conclusion uncertain. Sassa (1998) and Wang et al. (2002) noted that liquefaction may develop on similar materials but not at source but as motion progresses and modification and entrainment of materials occur. One of the landslides with its lithologic sequence is shown in Figure 10. The slide involved the sequence of coarse to medium friable sand units overlying fine to medium sand body inter-bedded with thin, impermeable claystone layers. Field observations indicated the existence of interlayer of claystone/shale in the debris directly below the displaced materials. The slope height and inclination were 67 m and 42° respectively. The slopes are characterized by well-defined undulating surfaces and landslide scarps. In rainy season, the slopes are covered by shrubs and grass. During the six months of dry season, partial stripping of the slopes occurs, decreasing the resistance of the slopes to erosion or landsliding. The return of rains subjects the area to intense gulling and surface failures. The water table varied from 7 to 15 m. Table 2 displays the results of field investigation on the sedimentary terrain where landslides are ubiquitous. Analysis of the 63 shows that most of the landslides have width < 7 m and length < 15 m (the slides are constrained to a particular narrow dimension), and that there is a particular trend of landslide occurrence in the area. The slides also occur more frequently on slopes which angles are between 30° and 35° (Figures 11 and 12). The trend appears to show that most of the landslides with bigger width also have larger length, and occur more on slopes with angles greater than 30° but less than 40°, which may be related to the triggering mechanism. It can be predicted therefore that the Enugu area is more prone to smaller slides than those with bigger dimensions. At every landslide width, the length could be determined, and vice versa. The prediction of potential landslide displacement and size should be a critical component of an early

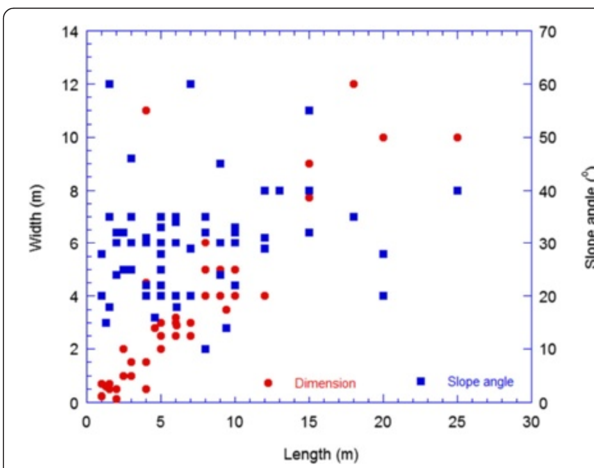

Figure 11 The relationship among landslide dimensions and slope angle.

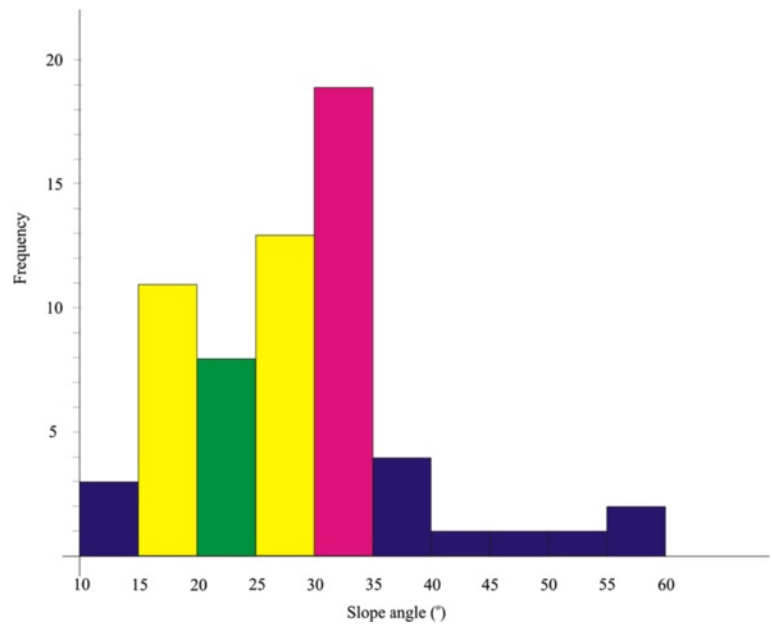

Figure 12 **Correlation between frequency of landslide and slope angle indicating that landslides occur more on slopes with angles greater than 30 degree but less than 40 degree.**

warning systems aimed at preventing property damage and loss of human lives.

The shallow sliding that result after a rainfall event involves the movement of debris, rock fragments, coarse to fine medium sands and the vegetation skin of the slope. Many landslides exhibit a combination of two or more types of movements, resulting in a complex type (Varnes 1984) and may be triggered by a number of external factors, such as intense rainfall, water level change, storm waves, rapid stream erosion etc. (Dai et al. 2002).

Landslides are typical geomorphologic phenomena associated with the normal erosion cycle in tropical climates in hilly areas. They are frequent in some parts of Nigeria, and become disastrous when they affect populated areas or man-made structures. From the analyses, the materials from the Obudu, Calabar landslide are likely to be less porous than the materials from the Enugu landslide; and also have higher cohesion (Figure 13). Porosity, particle size, particle size distribution particle shape and orientation, and stress history have significant effect on permeability (Selby 1993) which in turn exerts strong influence on the shear behavior of slope materials. These factors may have influenced the different mechanisms of failure in the two areas of interest. In addition, the landslides at the metamorphic terrain have deeper depth to sliding surface than those of the sedimentary landscape.

Landsides in Iva Valley, Enugu are mainly triggered during the intense rains that mark the outset of wet season in April or May, while those in Obudu, Calabar occur mainly during the heavy rains that precede the end of rainy season in October and early November. Landslides are frequent and widespread geomorphological phenomena the world over (Guzzetti, 1999; Dai et al. 2002; Das et al. 2010). Several people were killed and many more trapped when landslides were triggered by a heavy downpour in October 14th 2013 in the tourist town of Obudu that hosts thousands of foreign visitors annually. Helicopters rescued foreign and local people who were stranded inside this popular amusement and strategic arena. While early rains at the beginning of the wet season are usually the cause of most landslides in some parts of southeastern Nigeria, heavy rains during the peak season induced mass movements on the mountains of Obudu. There had been no sign of rain on the fateful day as tourist scanned the scenery. The sudden rain induced many landslides simultaneously and prompted a rescue effort from the Municipal Government.

Using Cruden and Varnes (1996) the landslides in both localities were characterized according to their types of movements, the materials involved and the states or activities of failed slopes. It was found that the two areas were dominated by debris slides. Montgomery and Dietrich (1994) have highlighted the importance of topographic control on shallow landslides. In the metamorphic terrain, the sliding material is dominated by finer fraction (71.5%) of micaceous silty sand and coarser fraction of gravel to boulder size. Saturation of the residual soil, weak bedrock and high slope angle are the primary factors in the slide-trigger. At the sedimentary area, the sliding mass is mainly loose, friable sands of high permeability. Saturation at the sand-shale interface

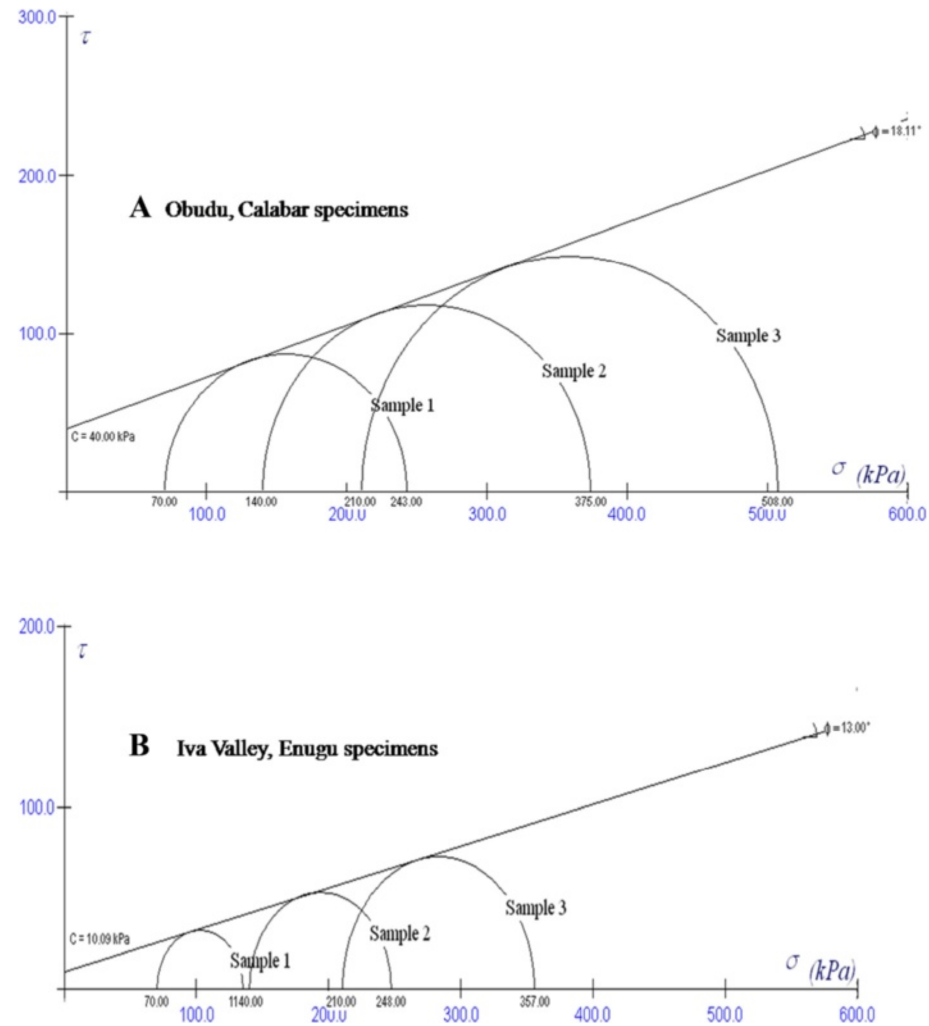

Figure 13 The shear strength parameters of Obudu and Iva Valley specimens.

facilitates the formation of slip surface and eventual failure of the masses, which are quite consistent with Wu and Sidle (1995), Wilson and Wieczorek (1995) and Jakob et al. (2003). The research developed a potential prediction model for the size of landslide (Figure 11). The prediction of potential landslide displacement and size should be a critical component of an early warning systems aimed at preventing property damage and loss of human lives.

It is noted that extensive human interference in hill slope areas for construction of roads along the hill slopes, deforestation, and change in land use have contribute to instability in the Obudu area. Communication with policy makers and planners can avert disaster. Correct development planning is necessary to avoid irreparable mistakes especially where risks are high and safety of lives and property are the key issues.

The social and economic costs of landslides are not well documented because of the dearth of scientific and inventory data. It is hoped that our study will stimulate interest in the cost of landslide damage and thereby bring about heightened awareness on the need for improved strategies for safety.

Conclusions

Field observations showed that the landslides on the steep metamorphic terrain have discrete, slickensided shear surfaces. There were rupture surfaces from which movements began as slides and continued for long distances as mudflow/slides. The materials involved were typically poorly-sorted sandy colluviums supported by about 43% clay matrix produced from the weathering of the rocks. The characteristics the clay matrix probably contributed to the rapid movement and longer travel distance witnessed on the metamorphic terrain. On the sedimentary terrain, slumps and short runout debris slides of limited volume dominate the medium steep landscape. The slow to rapid mostly unsaturated movements usually initiate within the sandy body or on clayey/shale interlayer, but are typically on non-discrete, matrix-poor shear surfaces. The movements are mainly non-confined and without established channel. Generally, the size of the shallow landslides appeared to depend on soil thickness and saturation. The landslides occurred when soil thickness accumulating at sufficient depth was saturated by rain infiltration.

The sedimentary zone was more susceptible to landsliding than the areas that lay within the metamorphic locality. Evidently, there were more landslides on the sedimentary terrain despite a relatively low elevation range of 300 – 450 m. The climatic condition, deforestation, and erosion at the study area accelerate weathering and influence landslide occurrence. During the peak of rains in October, landslides are common in the international tourist area of Obudu and their mechanism depends upon the thickness of the loose residual soil.

Two failure mechanisms are proposed for the two terrains. For the metamorphic terrain with lower permeability but higher cohesion, stagnancy of rain on the material akin to prolonged rain infiltration produced a rise in pore pressure that initiated failure. The initial displacement following the failure probably weakened or destroyed the cohesion along a relatively deeper failure plane. Further rainfall during the same period triggered the sudden and rapid movement of debris downslope with movement only stopping because debris had crossed the road and hit the base of the opposite slope. For the slopes on the sedimentary terrain with little cohesion, the high permeability of the materials ensured significant pore pressure was developed at the sand-shale interface. Additional stress from rain and self-weight readily initiates much shallower failures that may move a few meters because of the absence of satisfactory conditions that could result in a transformation to flow. The occurrence of landslides in Iva Valley Enugu can be correlated to slope gradient and vegetation cover. Most failures on the sandy slopes, which were < 1 m deep, occurred on slopes with gradients between 30 and 35.

Consent

Written informed consent was obtained from the (persons whose images are present in Figures 1 and 8) for the publication of this report and any accompanying images.

Competing interests

The author declares that he has no competing interests.

Acknowledgement

The research was carried under the auspices of the Engineering and Environmental Geology Group of the University of Nigeria, Nsukka and was supported by the President of the University of Nigeria who encouraged research as the major development platform in the institution. I am indebted to all staff and students of the Department of Geology, University of Nigeria, Nsukka for the useful aid they offered during the field, laboratory and analytical stages of this work.

Received: 3 May 2014 Accepted: 21 October 2014
Published online: 17 January 2015

References

Aleotti P (2004) A warning system for rainfall-induced shallow failures. Eng Geol 73:247–265

Aleotti P, Chowdhury R (1999) Landslide hazard assessment: summary review and new perspectives. Bull Eng Geol Environ 58:21–44

Chen Z, Wang J (2007) Landslide hazard mapping using logistic regression model in Mackenzie valley, Canada. Nat Hazards 42:75–89

Cruden D, Varnes DJ (1996) Landslide Types and Processes. In: Turner AK, Schuster RL (eds) Landslides Investigation and Mitigation. Special report 247. Transportation Research Board. National Academy of Sciences, Washington, DC, pp 36–75

Dai FC, Lee CF, Ngai YY (2002) Landslide risk assessment and management: an overview. Eng Geol 64(1):65–87

Das I, Sahoo S, Van Westen CJ, Stein A, Hack R (2010) Landslide susceptibility assessment using logistic regression and its comparison with a rock mass classification system, along a road section in the northern Himalayas (India). Geomorphology 114:627–637

Edet AE, Teme SC, Okereke CS, Esu EO (1994) Lineament analysis for groundwater exploration in Precambrian Oban massif and obudu plateau, SE Nigeria. J Min Geol 30(1):87–95

Ejimofor OC, Umeji AC, Turaki UM (1996) Petrology and major element geochemistry of the basement rocks of northern Obudu area, eastern Nigeria. J Min Geol 32:1–9

Ekweume BN (2003) The Precambrian Geology and Evolution of the South Eastern Nigeria Basement Complex. University of Calabar Press, Calabar

Ekwueme BN (1991) The geology of the area around obudu cattle ranch, southeastern Nigeria. J Min Geol 1:129–134

Ekwueme BN (1998) Geochemistry of Precambrian gneisses of obudu plateau, southeastern Nigeria. Global J Pure Appl Sci 4(3):277–282

Gabet E, Mudd S (2006) The mobilization of debris flows from shallow landslides. Geomorphology 74(1–4):207–218

Guzzetti F, Carrara A, Cardinali M, Reichenbach P (1999) Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31:181-216

Hutchinson JN (1988) General report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. In: Bonnard C (ed) Proceedings Fifth International Symposium on Landslides, vol 1. Balkema, Rotterdam, pp 3–36

Hutchinson JN, Bhandari RK (1971) Undrained loading: a fundamental mechanism of mudflows and other mass movements. Geotechnique 21:353–358

Igwe O, Mode W, Nnebedum O, Okonkwo I, Oha I (2013) The analysis of rainfall-induced slope failures at Iva Valley area of Enugu State, Nigeria. Environ Earth Sci doi:10.1007/s12665-013-2647-x

Iverson RM (2000) Landslide triggering by rain infiltration. Water Resour Res 36(7):1897–1910

Jakob M, Weatherly H (2003) A hydroclimatic threshold for landslide initiation on the North Shore Mountains of Vancouver, British Columbia. Geomorphology 54:137–156

Kogbe CA (1989) Palaeogeographic History of Nigeria from Albian times. In: Kogbe CA (ed) Geology of Nigeria. Elizabethan Publ.Co, Lagos, pp 257–275

Liao ZH, Hong Y, Kirschbaum D, Liu C (2012) Assessment of shallow landslides from Hurricane Mitch in central America using a physically based model. Environ Earth Sci 66(6):1697–1705

Marchi L, Arattano M, Deganutti AM (2002) Ten years of debrisflow monitoring in the moscardo torrent (Italian alps). Geomorphology 46:1–17

Montgomery DR, Dietrich WE (1994) A physically based model for the topographic control of shallow landsliding. Water Resour Res 30(4):1153–1171

Msilimba G, Holmes P (2010) Landslides in the rumphi district of northern Malawi: characteristics and mechanisms of generation. Nat Hazards 54(3):657–677

Oboh-Ikuenobe FE, Obi GC, Jamarillo CA (2005) Lithofacies, palynofacies and sequence stratigraphy of paleogene strata in Southeastern Nigeria. J Afr Earth Sci 41:79–101

Petrucci O, Polemio M (2009) The role of meteorological and climatic conditions in the occurrence of damaging hydro-geologic events in Southern Italy. Nat Hazards Earth Syst Sci 9:105–118

Sassa K (1998) Mechanisms of landslide triggered debris flows. Environ Forest Sci 54:499–518

Sassa K, Wang G, Fukuoka H, Wang FW, Ochiai T, Sugiyama ST (2004) Landslide risk evaluation and hazard mapping for rapid and long-travel landslides in urban development areas. Landslides 1(3):221–235

Selby MJ (1993) Hillslope Materials and Processes, 2nd edn. Oxford University Press, New York, p 451

Toteu SF, Penaye J, Djomani YP (2004) Geodynamic evolution of the Pan-African belt in central Africa with special reference to Cameroon. Can J Earth Sci 41:73–75

Ukaegbu VU, Beka FT (2007) Petrochemistry and geotectonic significance of enderbite-charnockite association in the Pan-African Obudu plateau, southeastern Nigeria. J Min Geol 43(1):1–14

Ukaegbu VU, Oti MN (2004) Geology of the Pan-African metamorphic rocks of southern obudu plateau, bamenda massif, southeastern Nigeria. Scientia Africana 3(2):8–18

Varnes DJ (1984) Landslide Hazard Zonation: a Review of Principles and Practice. Review report. UNESCO, Daramtiere, Paris, p 61

Wang FW, Sassa K (2010) Landslide simulation by a geotechnical model combined with a model for apparent friction change. Phys Chem Earth 35(3–5):149–161

Wang FW, Sassa K, Fukuoka H (2000) Geotechnical simulation test for the Nikawa landslide induced by January 17, 1995 Hyogoken-Nambu earthquake. Soils Found 40(1):35–46

Wang FW, Sassa K, Wang G (2002) Mechanism of a long-runout landslide triggered by the August 1998 heavy rainfall in Fukushima prefecture, Japan. Eng Geol 63(1–2):169–185

Wang FW, Matsumoto T, Tanaka Y (2005) Two recent flowslides in Yamashina area, Kanazawa city, Japan. Landslides 2(3):229–234

Wang FW, Cheng Q, Highland L, Wang H, Yan C (2009) Preliminary investigation of some large landslides triggered by the 2008 Wenchuan earthquake, Sichuan Province, China. Landslides 6(1):47–54

Wei NP, Nutalaya P, Aung Z, Zhibin T (1993) Catastrophic landslides and debris flows in Thailand. Bull Int Assoc Eng Geol 48(1):93–100

Wieczorek GF, Glade T (2005) Climatic Factors Influencing Occurrence of Debris Flows. In: Jakob M, Hungr O (eds) Debris Flow Hazards and Related Phenomena. Springer, Berlin Heidelberg, pp 325–362

Wilson RC, Wieczorek GF (1995) Rainfall thresholds for the initiation of debris flow at La Honda, California, Environ. Eng Geosci 1(1):11–27

Wu W, Sidle RC (1995) A distributed slope stability model for steep forested basins. Water Resour Res 31:2097–2110