Mechanical And Structural Analysis Of Rock Slide In Ado Ekiti, Ekiti State Nigeria

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***Abstract*—Rock fall is a process which involves the travelling of boulders through distances on slopes and vertical heights. It can be in form of projectile and sliding. It has posted great dangers to the dwellers in mountainous zones, motorists that pass through highways constructed within high and rocky area. Generally, it is initiated by some events which may include pore pressure increases due to rainfall infiltration, erosion of surrounding material during heavy rain falls, weathering of the rock and root growth which exert pressure on rock to break off from the main rock mass. The purpose of this research work was to analyze the events related to rockfall and rock slide in Ado-Ekiti metropolis, Nigeria. Geological and structural data were obtained from four major locations through field observation and direct measurement with the aid of compass clinometers and Global Positioning System (GPS). Samples of rocks were taken to the laboratory for the determination of some of the physical and mechanical properties. It was discovered that the estimated weight of lump of rocks that are dangerously hanging on the slopes of locations 1(N7°36'56" E5°20'02" ELEV.416 m) and 4 (N7°37'02" E5°13'01" ELEV:456 m) ranges from 0.57 - 23.9 tons and 25.35-28.44 tons respectively. Also, at locations 2 (N7°37'02" E5°20'42" ELEV. 430 m) and 3 (N7°35'02" E5°13'03" ELEV: 421.5m) there occurred rock sliding during a season of heavy down pour which hauled boulders of estimated weights of 0.0316-8.16 tons and 15.26 - 37.93 tons correspondingly.**

Keywords—Rockfall, Boulders, Sliding, Slope

INTRODUCTION

Rock fall is a frequent occurring event in mountainous areas and relatively, it's a small landslide which leads to the removal of rocks from a cliff face. But the large-scale movement of rock material is defined as rockslides (Selby, 1982; Abele, 1994; Cruden and Varnes, 1996). The inability to predict the rate and degree of rock fall, will highly risk human lives and properties. (Bunce *et al*., 1991; Badger and Lowell, 1992), and this require a practical study of the rock fall activities in mountainous settled and mining zones. Essentially, rolling, sliding, bouncing and free fall are four types of motion which rock fall activity undergoes.

Rock falls as geological hazards regularly occur along highways and within hilly terrains and causes enormous loss to lives, properties and considerable inconvenience to commuters. (Fookes & Sweeney 1976). Rock pieces get separated from the slope face and fall down under the influence of gravity and follow a projectile path. Rock fall dynamics depends on various parameters such as: rock block geometry, slope geometry, slope morphology and the coefficient of restitution which is frequently determined by back analysis, laboratory and field tests (Crosta et al. 2015).

MECHANICS OF ROCK FALL

Bedrock slopes are affected by weathering in various degrees which do lead to fracturing, opening of joints and therefore to the proliferation of rock fall. The level of its increase depends on the bedrock type and the environmental factors that cause physical and chemical weathering (Day, 1997). The factors that determine whether a rock could fall or not are the morphology of slope and the surrounding potential falling rock (McCarrol *et al*., 1998; Matsuoka and Sakai, 1999). Vidrih *et al*. (2001) studied the relationship between rock fall and seismic activity and concluded that rockfall was activated by seismic activity. Wieczorek *et al*. (2000) reported that rockfalls in the Yosemite Valley were caused by earthquakes, rain storms, rapid snow melt, freeze–thaw cycles of water in joints, root penetration and wedging, or stress relief following deglaciation. Also, human and animal actions have led to the reduction in stability of hill slopes in hard rock are of great importance locally, for instance undercutting of slopes during quarrying or excavations for infrastructure (Selby,1992). All of the evidence showed that the combination of topographical, geological, climatological factors and time determine whether rock fall occurs.

Modes of Motion of Falling Rocks

Once the rock piece separates from the rock mass, it begins to move and descends the slope in different modes of motion, which sturdily depend on the mean slope gradient. The three most important modes of motion are freefall through the air, bouncing on the slope surface and rolling over the slope surface. Freefall of rocks occurs on very steep slopes, where translation of the centre of rock and rotation of the block around its centre take place. After the rock rotates in air, it can jump onto a different direction and collision with other falling rocks on their fall tracks can occur; but these effects are difficult to evaluate (Azzoni *et al*., 1995).

Furthermore, air friction insignificantly affects the velocity of a freefalling rock and as the mean slope gradient decreases in the down-slope section, a bouncing effect occurs due to rock impact on the slope surface after free falling. If the mean slope gradient is less than approximately 45°, a bouncing rock progressively transforms its motion to rolling as it gathers rotational momentum. During the switch between bouncing and rolling, the rock rotates very fast and only the edges with the longest radius maintain contact with the slope. So, the centre of gravity moves, almost in straight path, which is an efficient mode of motion with respect to energy loss. Sliding being another form of movement over the slope surface, it generally, occurs in the initial and final stages of a rock fall. If the mean slope gradient increases, a sliding rock starts falling, bouncing or rolling. If the mean slope gradient does not change while sliding, the rock usually stops because of energy loss due to friction (Bozzolo and Pamini, 1996).

Investigations have revealed that the velocity of a falling rock depends on the mean slope gradient, the size of the rock and on the material covering the slope such as soil scree and vegetation. Small rocks retard more easily than larger rocks because during a rockfall the total kinetic energy of small rocks is lower than that of bigger rocks, and also, large obstacles such as trees can easily stop small rocks, and finally, small rocks retard more easily on talus slopes than larger rocks. Stopping occurs because energy is lost through collisions and friction forces that act on the rock during transport over slope surfaces. The friction force of a moving rock is not only dependent on the rock shape, but also on the surface characteristics of the slope (Statham and Francis, 1996).

Due to the fact that the slope surface characteristics vary a lot within short distances, the friction force between a rock and the slope surface can best be characterized by a dynamic angle of friction, which is the variation in height perpendicular to the slope within a certain slope distance (Kirkby and Statham, 1975; Chang, 1998; Pfeiffer and Bowen, 1999). Dynamic angle of friction for a falling rock can be determined by the following expression:

$\tan f_{ud} = \tan f_o + {kd}/{2R}$. eq. 1 (1) (Kirkby and Statham, 1975)

where, $f_{\mu d}$ - dynamic angle of friction (°);

f_0 - angle of internal friction (°) (between 20.3° and 33.8°);

k - constant (between 0.17 and 0.26);

d - mean diameter of scree on the slope surface (m);

R - radius of the rock (m).

Jahn (1998) and Hétu and Gray (2000) made research into one of the few quantitative studies on the effect of forest cover on rockfall and concluded that three to ten times as many falling rocks were stopped on forested slopes compared with similar slopes without a forest cover. Research studies have shown forests cannot stop the destructive effect of large magnitude rockfall events, but for low magnitude to high frequency rockfall events, forest can provide effective protection. The above described rock fall events in some part of the world has led to the investigation into the analysis of the structural and mechanical phenomenon of rock slide in the metropolis of Ado-Ekiti, Ekiti State, Nigeria.

METHODOLOGY

This study considered four locations within Ado-Ekiti metropolis, Nigeria with the following GPS reading: first location (Olokemeji street) N 7°36'56" E 5°20'02", second location (Ayunbo street) N7°37'23" E5°20'42", third location (Moferere street) N7°35'02" E5°13'03" and fourth location (Okeyinmi) N7°37'02" E5°13"01".

GEOLOGY OF ADO EKITI

The study area is located in the basement complex of southwestern Nigeria and is Archean to early Proterozoic in age as described by Talabi (2013). Moreso, investigations made by Oversby (1975) and Olanrewaju (1981) revealed that the study area is composed of migmatite-gneiss-quartzite complex with little supra-crustal rock relics. The basement complex of Nigeria is zoned in the western part of the Pan-African shield as described by McMurry (1976) and Ball (1980), occurring in the mobile zone of the Pan-African reactivation area between the West-African craton to the west and the Congo craton to the southeast. The lithologies of the study area is shown in the geologic map (Fig. 1) and they include quartzite, migmatite, schist with pegmatite intrusion, biotite rich granites, charnokitic rocks, and quartz veins.

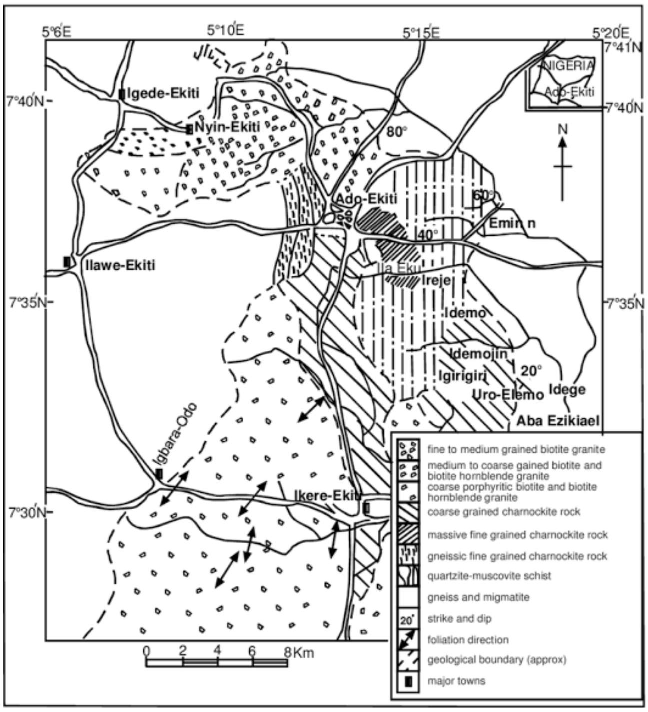


Fig. 1. *Geological map of Ado Ekiti; Source: www.researchgate.net.*

Rainfall chart of Ado-Ekiti

Ado-Ekiti experiences extreme seasonal variation in monthly rainfall. Averagely, the rainy period of the year lasts for 9.2 months, from February to November, with a sliding 31-day rainfall of at least 1.27 cm. The most rain falls around September, with an average accumulation of 21.59 cm. The rainless period of the year lasts for 2.8 months, from November to February. The least rain falls around December, with an average total accumulation of 0.51 cm.

Fig. 2. Average monthly rainfall, Source: NASA's MERRA-2 satellite-era reanalysis

DETERMINATION OF THE PHYSICAL AND MECHANICAL PROPERTIES OF THE INTACT ROCK

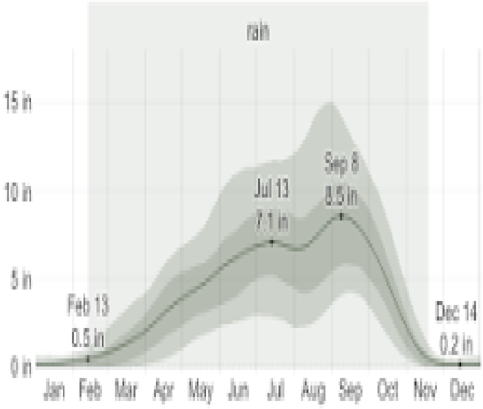
The following tests were carried out at the Mineral and Petroleum Resources Engineering Technology laboratory, Federal Polytechnic, Ado-Ekiti:

Determination of Point Load Strength Index and estimation of Uniaxial Compressive Strength

According to the American Society for Testing and Materials (ASTM D5731-08) procedure whereby ten regular block rock samples were prepared. The ratio of sample length to thickness was 2:1 and was placed between two platens during the test. The load was applied to the specimen such that failure occur within 10-60 sec. and the failure load (P) was recorded. The point load strength index (Is) was determined by the following expression:

$I_s = \frac{P}{D^2} .eq. 2$

Where



I_s = Point load strength index (Pa)

P – Load (N)

D = Dimension (m).

According to ISRM (1985), Uniaxial Compressive Strength (UCS) was obtained from the following expression:

$UCS = 23I_{s_{23}}$ ---------------------- eq. 3

The intact rock strength evaluation was carried out with table

Table 1. Classification of Point Load Test and Compressive Strength Test (Source: Broch and Franklin, 1972)

Term	Point Load Strength Index (Mpa)	Equivalent Uniaxial Compressive Strength (Mpa)
Extremely High Strength	Over 10	Over 160
Very High Strength	3 - 10	50 - 160
High Strength	1 - 3	15 - 60
Medium Strength	0.3 - 1	5 - 16
Low Strength	0.1 – 0.3	1.6 - 5
Very Low Strength	0.03 – 0.1	0.5 – 1.6
Extremely Low Strength	Less than 0.03	Less than 0.5

Density of the Intact Rock

Samples were taken from three locations using sledge hammer and weighed in a Balance and the mass was recorded in gram (g). Measuring cylinder was filled to a point with water to obtain initial volume (V_1) and the sample was gently immersed into the cylinder to get volume (V_2). The volume of water displayed represents the volume (V_s) of the rock sample. This was calculated by the following equation:

$V_s = V_2 - V_1$ eq. 4

Finally, the density was determined by the following formula:

$$Density(\gamma) = \frac{mass(g)}{Volume\ (cm^3)}\ .eq.5$$

Estimation of the Weight of the Lump of Rock

The volumes of the irregular shaped lumps and blocks of rocks that slid or hanging on the surface of the mountains of the studied locations were estimated by modeling them into mathematical regular shapes, such as triangle, trapezoid and polygon. This was done by measuring with tape-measure the distances between the most protruded points of the lumps, the proper height was measured and fitted into the right shape to obtain the volumes. Then, the weights of the lumps were estimated separately by multiplying the volume obtained by the density of the rock which was determined according to ISRM standard (ISRM, 2007) in the laboratory.

Measurement of Structural Properties of the Rock Mass

In each of the location investigated, dip angle and dip direction were measured with the aid of clinometers and measuring tape. The joint spacing, persistence and aperture of the rock mass were also measured and recorded.

Sliding of the Lumps of Rocks

In this study, due to the weight and the nature of the rock, sliding of rock through slope was considered. There were three possible situations that could be perceived in the down slope slide observation:

(i) When the slope angle (θ) is equal to friction angle (φ) of the rock, the gravity being the driving force and the resisting force (friction), the rock will slide off the down slope end of the segment, with a velocity equal to the initial velocity.

(ii) The case in which the slope angle (θ) is greater than the friction angle (φ), the driving force is greater than the resisting force and the rock will slide off the down-slope endpoint with an increased velocity. The exit velocity (V_{exit}) at the end of slope segment is the following expression:

$$V_{exit} = \sqrt{V_o^2 - 2sgk}\ .eq.6$$

Where:

V_0 - the initial velocity of the rock, tangential to the segment

s - the distance from the initial location to the endpoint of the segment

g - the acceleration due to gravity (-9.81m/s^2)

k is ± sin(θ) - cos(θ) tan(φ) (positive (+), if the initial velocity of the rock is down slope or zero and, Negative (-), if the initial velocity of the rock is upslope)

(iii) The case where, θ<φ, the resisting force is greater than the driving force and the rock will decrease in speed and consequently comes to a stop on the segment; this will depend on the length of the segment and the initial velocity of the rock.

RESULTS AND DISCUSSIONS

Results obtained from the field and the laboratory is presented in Table 2 and Plates 1 to 4. The UCS results that range from 66.59 to 94.53 Mpa showed that the boulders are of very high strength. This implies that when collided with any object along its path during consequential sliding, its negative effect is possible to be high. Also, the structural conditions as shown in fig. 3 and Table 2, where discontinuities and bedding plane crossed each other, could be the reason why there appeared boulders of different sizes and weights in the locations studied.

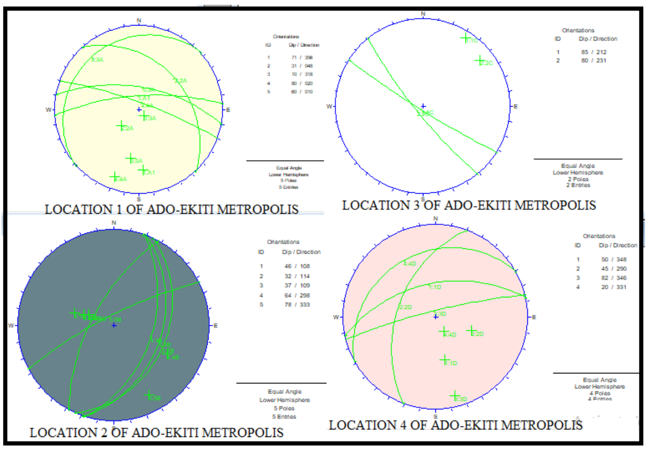


Fig. 3. Stereonet of discontinuity planes of Locations 1 to 4 of Ado-Ekiti Metropolis

Table 2. Structural and physic-mechanical properties of the rocks

LOCATIONS	GPS READINGS	Average UCS (Mpa)	I_s (Point Load Strength, Mpa)	Dip /Dip direction	Estimated rock lump weight (tons)	Average Joint Spacings (m)	Persistence (m)	Aperture (mm)	Remark
1	N7°36'56" E5°20'02" ELEV.416 m	66.59	3.03	71°/356° 31°/048° 10°/318° 80°/020° 60°/010°	0.57 - 23.9	0.85	1.75-4.5	5-180	No fill
2	N7°37'02" ,E5°20'42" ELEV.from 338 to 430m	94.53	4.53	46°/108° 32°/114° 37°/109° 64°/298° 78°/333°	0.0316 - 8.16	0.95	1.3-15	15	No fill
3	N7°35'02" E5°13'03" ELEV: 421.5m	67.01	2.91	85°/212° 80°/231°	15.26 - 37.93	-			No fill
4	N7°37'02" E5°13'01" ELEV:456m	67.01	2.91	50°/348° 45°/290° 82°/346° 20°/331°	25.35 - 28.44	-	1.0-1.5	20-25	Sand fill

The rocky outcrop in the Location 1 reveals porpheritic granite lithology with several intrusion of quartzite, xenoliths of charnockite quartz vein and is highly weathered through long influence of rainfall which lead to gradual wear of the rock, the high tropical temperature of the day and the drastic cooling of the night that produces cracks which occurs due to contraction and expansion of the same, and later harbor the growth of trees whose roots causes the cracks to expand and later peel off parts of the formation. This later form the boulders that are found on the top of the mountain as it can be seen on Plate no. 1. The size of the block of rocks ranges from 0.57 to 23.9 tons. The slope angle of the upper section of the rock is about 35^0 with slope length of 36 m and the boulders were hanging on different point of the slope. However, the lower part has a slope angle of 82^o and slope length of 9 m. Rock sliding, in this location, was initiated by climatic and biological conditions as trees and grasses were also found grown on the mountain. The events created by these conditions may include increase in pore pressure due to rainfall infiltration, erosion of surrounding material during heavy rain storms, chemical degradation or weathering of the rock, root growth or leverage by roots that caused part of the rock to break off (Day, 1997; Hoek,2000).

PLATE No. 1

In location 2, the outcropped surface revealed extensive weathering activities with the creation holes within the rock mass ,the lithology shows migmatite with various intrusion, the various resistance of the different consistency intrusion created quartz vein, dissolution holes, charnockite, biotite granite and quartz veins. During heavy rainfall in the zone, the weathered rock mingled with soil turned to liquid soil which runs down the slope angle of about 71^o and rock blocks of weights between 0.03 ton and 8.16 tons were partly rolled and partly slid down the slope. The path of the slid rock can be seen in Plate No. 2a and through a slope length of 55 m. Some of the hauled rock got stopped by the talus present on the slope path. This was due to the fact that the resisting force of the slope surface was greater than the driving force on the rock which made the rock to decreased in speed and consequently came to a stop on the slope segment; a mechanism in which the slope angle $(\theta) < \text{friction } (\varphi)$. The other boulders were stopped by the building at the base of the mountain thereby damaging it as a result of the rock impact (Plate No. 2B), but there was no life lost.

The lithology of location 3 (Plate No. 3 A) revealed granitic rock outcrop with considerable superficial deposit of residual soil made of lateritic clay with brownish red colour showing intensive effect of weathering activities. After long period of continuous heavy rainfall in Ado-Ekiti, Nigeria, the lateritic got dissolved and set in motion down slope, conveying two blocks of rocks of weights 15.26 tons and 37.93 tons, firstly, through a distance of 15 m along 65^o slope angle and then through a path of 56 m long on a slope angle of 45^o. The movement was consequently stalled by the shrubs and trees on their path (Plate 3 B). The devastating effect of the rock slide would have been enormous if the plot where the incident happened had been developed into habitation. The climatic condition that initiated the boulder's movement was the accumulated heavy rainfall that liquefied the weathered lateritic rock.

Finally, Plate 4 A and B were outcrops that revealed granitic lithology with intense disintegration of the rock mass, reflecting a high degree of physical weathering activity in the terrain, in addition to many boulders of the formation. The hanging rocks are about 25.35 ton (plate No 4 A) and 28.44 ton (plate No. 4 B) which have been there for quite a long time. Road and building for habitation were constructed near the rock site. They were supported underneath by a small contact of rock. The stability observed in this position is due to the principle of centre of gravity which hold it in place, or else, it would have fallen off and cause great havoc to the dweller or possibly motorist. Notwithstanding, further weathering of the rocks or any consequent occurrence of blast that produces seismic wave may likely cause rock fall.

CONCLUSIONS

In this research work, the rock slopes in the locations studied, were of discontinuities with randomly oriented joints that created a three-dimensional pattern. Also, boulders of very high strength and weights that range from 0.03 to 28.44 tons were found suspended at different points of some of the mountain slope. Rock slide events were observed in locations 2 and 3 where minor damage was done to the building situated at the foot of the mountain and the other locations 1 and 4 have grand potential for rock-fall and rock- slide respectively.

RECOMMENDATION

According to the observation noted in this research work, it is recommended that the resident presently living in the houses built at the foot of the mountains should be relocated and their residential permit in those locations be revoked.

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