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Numerical Investigation of the Influence of Rockfall near Structures in Selected Southwestern States, Nigeria

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Abstract: *Influence of rock fall in rocky and hilly area located near structures within Southwestern Nigeria was investigated. In this study, seven highly susceptible rock fall prone locations near structures were selected, RocFall 8.0 (RocScience software) was used for numerical simulation model and landslide intensity hazard level values/zones to predict the influence of rock fall. Rock fall movement trajectory and bounce height were modeled with their corresponding translational velocity and kinetic energy for predicting the influence of rock fall. Location 6 has the maximum bouncing height of 26.3 m and location 4 has the minimum bouncing height of 1.9 m as compared to other locations. The results of the rock fall impact simulation model predict that the study location 1, 2, 3, 5, 6 and 7 has respectively, total kinetic energy of approximately 61.2 kJ, 81.3 kJ, 42.1 kJ, 92.1 kJ, 92.6 kJ and 65,9 kJ which pose risk of medium intensity hazard level zone, while study location 4 which has total kinetic energy of 27.9 kJ pose risk of low intensity hazard level zone. In conclusion the research was able to predict the influence/magnitude of damage of rock fall near structure base on rock fall landslide intensity hazard classification. It is recommended that further research should be done in all parts of the country to establish rock fall hazard map for Nigeria. The residents of this study area should be cautious of rock fall occurrence capable of causing mortality and damaging structures, hence, barriers with capacity > 300 kJ are required to prevent rock fall vulnerability/consequence in the study area.*

1. INTRODUCTION

Lee and Elliot (1998), defined that a rock fall is the down slope movement of boulders (in case of natural slopes) or rock blocks (in cut slopes) which has the potential to destroy or damage the structures along its path or create an obstacle to public transportation networks, if not properly strained (i.e when inadequately managed, rock falls present a major hazard to any surrounding structures).

Rockfall is a widespread phenomenon in mountain environments where it threatens human beings and poses significant challenges to infrastructure, industry and housing (Volkwein *et al.*, 2011). Despite the fact that the process itself usually involves rather limited volumes, rockfall phenomena can nevertheless result in economic losses due to service interruptions and equipment damage, as well as to injury or death of users and operators of these facilities. As a consequence, rockfall protection via both structural and land use planning actions is an important issue for administrators and stakeholders in areas affected by rockfall (Agliardi *et al.*, 2009).

However, predicting the rockfall runout distance and propagation areas, i.e., the areas potentially threatened by rockfall, is still a challenge (Jaboyed off and Labiouse, 2011).

Landslides, rockfalls, and rock avalanches are associated with almost instantaneous collapse and spreading (Legros, 2002; DeBlasio and Crosta, 2015), due to their high mobility, threatening populated areas located even far away from the slope source (Crosta *et al*., 2005; Zhou and Cheng 2013). its occurrence had been attributed with loss of life and huge monetary loss (Ansari *et al*., 2018).The recent occurrence of rock falls and the alarming rate of change in land use as a result of the rapid growth in population and development with the needs of siting residential buildings and other structures in rocky/hilly areas prone to rockfall calls for research of this kind in Nigeria. Good knowledge and better understanding of rock fall phenomenon is important in order to adequately investigate the influence of rock fall near structures because rockfall disasters/hazard have been a subject of intensive research due to their significant destructive power.

Major causes of rockfall are rainfall, frost, discontinuities, differential erosion, animal dens etc. whereas minor causes are tree roots, springs, vehicle vibrations and rock weathering (Ahmad *et al*., 2012).

As stated by Jaboyed off *et al.* (2005), the design of protection measures and rockfall hazard zoning require data on three basic characteristics of rockfalls, namely the number of passing rocks per time unit, impact energy, and impact height. That is, information is required on the mass and velocity of the fall to determine the energy capacity and on the location of impact points, trajectory paths, and runout distances so as to determine danger zonation or the optimum location and dimensioning of defense structures (e.g., barriers or fences).

The performance of a rockfall protection barrier is usually expressed in terms of the maximum energy capacity they are able to absorb. Since the dissipation of energy is accomplished through the accumulation of permanent deformations of the system, the rating of the barrier can be defined also in terms of its deformability. The greater the barrier capacity, the higher its plastic compliance

Bourrier and Hungr (2013), established three different typologies of barrier physical behavior to stop falling rock, the first one consists of static barriers, which are composed by rigid elements that employ their high inertia to stop the rock (e.g, walls of concrete or gabions, formed by metal profiles and earth ridges), the second type corresponds to dymac barriers of static deformation, having a reduced capacity of energy absorption (below 150-200 kJ), which are mainly used as energy dissipators elements in docks with shock absorbers, while the third can be found as dynamic barriers of plastic deformation characterized by current absorption capacity of 8.000 kJ, using special elements that deform and tear for dissipating this high energy, so that they must be replaced after an impact. Of these three typologies, the latter is the most often used nowadays.

Depending on the initiation of the detached rock block and the geomorphic conditions of the slope, a rockfall trajectory is the combination of three main processes, namely: sliding or rolling, free falling and impact. These processes are controlled by well-known physical laws and can be described by simple equations and hence easily simulated if these processes are free of fragmentation. However, if fragmentation occurs during the rock falling, the process will be much more complicated to simulate.

Generally, there are two approaches to evaluate rock fall dynamics, which are experimental methods and numerical analyses (Agliardi and Crosta 2003; An and Tannant 2007; Bozzolo and Pamini 1986; Crosta and Agliardi 2003; Dorren 2003; Giacomini et al. 2009; Giani et al. 2004; Mougin *et al.*, 2005; Nocilla *et al.*, 2008). Experimental methods include field tests and empirical studies. Usually, field tests are carried out to determine rockfall trajectories and runout distances, and sometimes to evaluate the efficiency of protective measures.

Field test is undoubtedly effective, but it is expensive and time consuming. It is also impossible to test many scenarios such as, initial conditions (velocity, mass, location), natural and design topography and ground properties. Therefore, field tests are typically used to calibrate numerical models. By using the calibrated numerical models, statistical and parametric analyses may be performed to improve the understanding of rock fall events.

Numerical analysis mainly focuses on the evaluation of the trajectories of detached blocks for different morphological and geologic conditions. It becomes increasingly popular and powerful because of the development of computer technology and relevant information technology.

Several computer programs either in 2D and 3D have been developed and tested for rock fall analysis (Guzzetti et al. 2002). Most of the programs implement either a lumped mass or a rigid body approach.

Raetzo*et al.* (2002) developed a chart of the extent of danger in order to establish a similar and uniform means of assessing the various kinds of natural hazards affecting Switzerland. In the study, intensity and frequency/return period (probability) were the major parameters used to define the three degrees of dangers which are: i. High intensity, ii. Medium intensity, iii. Low intensity. The magnitude of damage that could be induced by an event is based on the classification of threshold values for degrees of dangers.

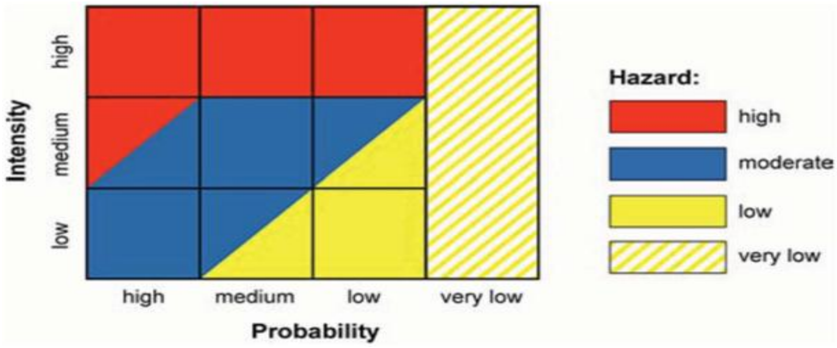


Figure1: *Diagram of hazard levels as a function of probability and intensity Lateltin et al. (2005).*

Lo *et al.* (2018), in their study further group landslide intensity values using different criteria to predict the magnitude of damage that could be induced based on the classification of threshold values for degrees of dangers.

Table1: *Criteria for landslide intensity values (Lo et al., 2018)*

Process	Intensity			
	Very low	Low	Medium	High
Rock falls Kinetic energy	<3 kJ	3–30 kJ	30–300 kJ	>300 kJ
Slides Mean annual velocity Displacement	– –	<2 cm/year –	2–10 cm/year –	>0.1 m/day >1 m/event
Debris flow Debris front thickness Debris front Depth of soil material (potential debris flow)	– – 0.5 m	– – 1 m	<2 m <5 m/s 1–2 m	>2 m >5 m/s >2 m

This study predicts the influence of rockfall based on the magnitude of damage to near structures using landslide intensity hazard level values. Seven locations in Ekiti, Ogun and Ondo States which lies in South-Western region in Nigeria were used as the study area, the study locations lie between latitude and longitude: 7º 16' 31.74" N and 5º 14' 37.10[11] E, 7º 06' 57.73" N and 5 º 06' 35.92" E, 7º 29' 56.85" N and 5º 13' 54.80" E, 7º 37' 53.77" N and 5º 13' 23.25" E, 7º 10' 45.97" N and 3º 21' 35.87" E, 7º 11' 9.10" N and 3º 20' 35.21" E, 7º 9' 37.08" N and 3º 21' 4.65" E (NGSA) (Figure 34).

2. MATERIALS AND METHOD

Materials used for field data acquisition are; Global Positioning System (GPS), measuring tape, stop watch, objects of different shape, a field book. Rocscience software (RocFall 8.0) was used for the Result analysis.

2.1. Method

The research methodology involves, rock fall distance and time taking to cover the distance measurement, elevation and coordinate measurement, other physical measurements and observations in the study areas. The data from the field were then analyzed.

2.2. Field Work Procedure

Outcrop near structural buildings that is characterizes with hanging rocks were selected across the whole location for this study. Distance between the outcrop and the nearest building was obtained using the measuring tape. The Global Positioning System was used to obtain the coordinates and the elevation. Stop watch was used to measure the time taking for the objects to move from the top of the slope to the end location of the slope. All data obtained were recorded in the field book.

2.3. Data Analysis

Parameters for rock fall simulation were determined by rigorous field study and laboratory experiments. Rock fall modeling was carried out using RocFall program 8.0. Lumped mass-modeling program was selected as it considered rock block to be a simple point with rock mass concentrated at the center of gravity. The assumed point mass is then released down the observation slope. As soon as the rock block collides with the slope surfaces, normal and tangential velocities to the slope are reduced to normal coefficient of restitution (Rn) and tangential coefficient of restitution (Rt). These coefficients of restitution depend upon rock type and slope morphology. Along with the coefficient of restitution, RocFall 8.0 program considers the angular velocity of the rock block and surface roughness. The RocFall program also help in determining remedial measures by computing kinetic energy and location of impact on a barrier at the same time determine the capacity, size and location of barriers. Incompatibility of the results file was avoided by exporting all results obtained from the rock fall model in JPEG image format.

3. Results and Discussion

3.1. Rock Fall Modelling

For each of the seven locations selected for this study, a computer simulation has been run using the program Rocfall 8.0 (RocScience, 2018). The natural variability of site conditions that includes irregularly shaped blocks of rock, and slope roughness were taking into account for the modelling of the rock falls. The material types used in the analysis was rock for the entire slope, it is assumed that all rock falls originated higher on the top of the slope, so the seeder velocities have values that generate trajectories that are consistent with observed field conditions. The model was performed with a typical seven rock falls. These analyses demonstrate the operation and results of the program.

Figure 2 to 5 show the rock fall modeling results of study location 1

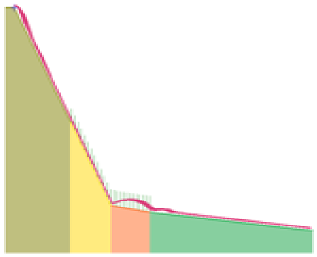


Figure2: *Simulation of seven rock fall model*

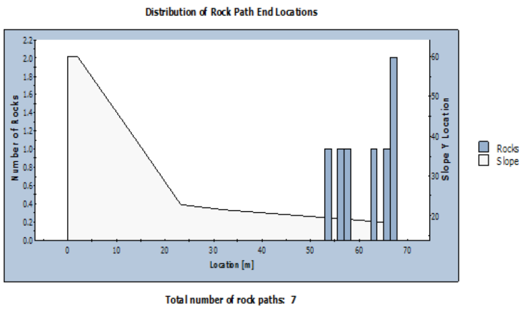


Figure3: *Rock fall end location from RocFall 8.0 simulated results*

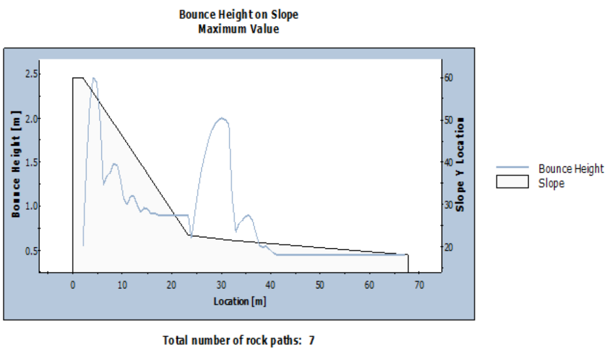


Figure4: *Trajectory height envelope from RocFall 8.0 simulated results*

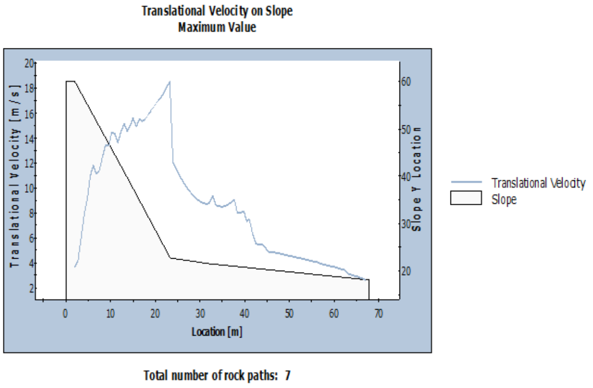


Figure5: *Trajectory translational velocity envelope from RocFall 8.0 simulated results*

Figure 6 to 9 show the rock fall modeling results of study location 2.

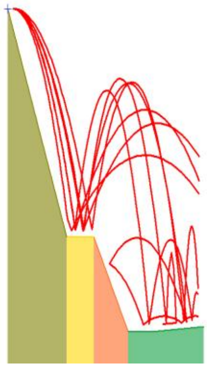


Figure6: *Simulation of seven rock fall model*

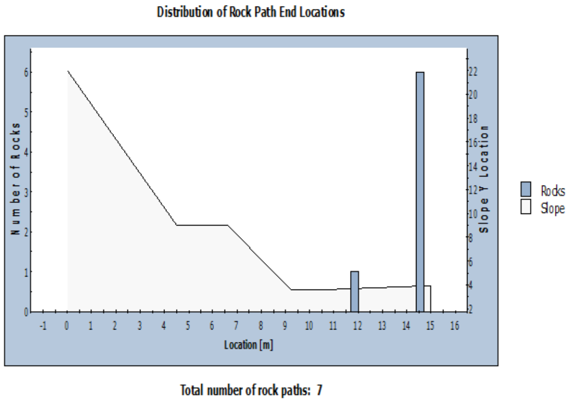


Figure7: *Rock fall end location from RocFall 8.0 simulated results*

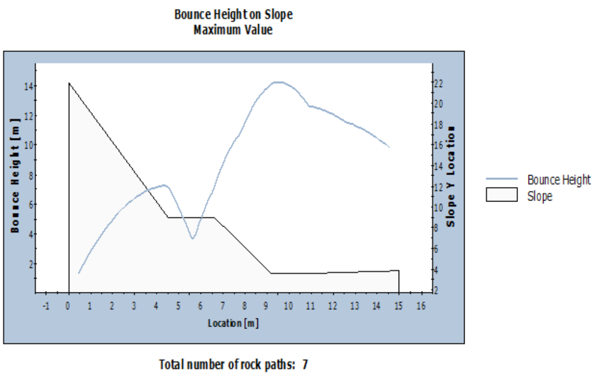


Figure8: *Trajectory height envelope from RocFall 8.0 simulated results*

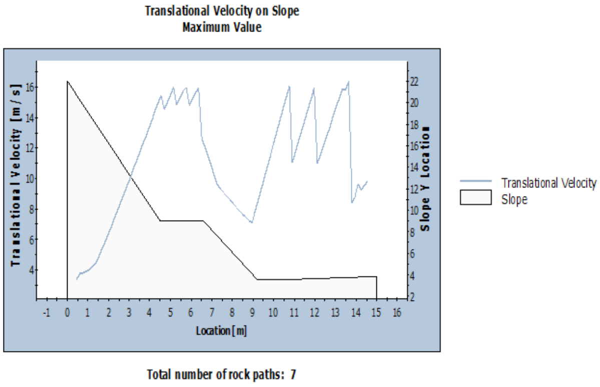


Figure9: *Trajectory translational velocity envelope from RocFall 8.0 simulated results*

Figure 10 to 13 show the rock fall modeling results of study location 3.

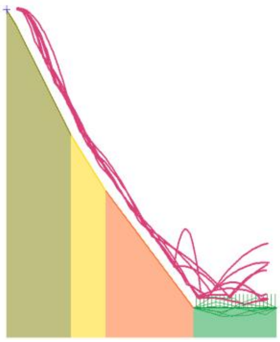


Figure10: *Simulation of seven rock fall model*

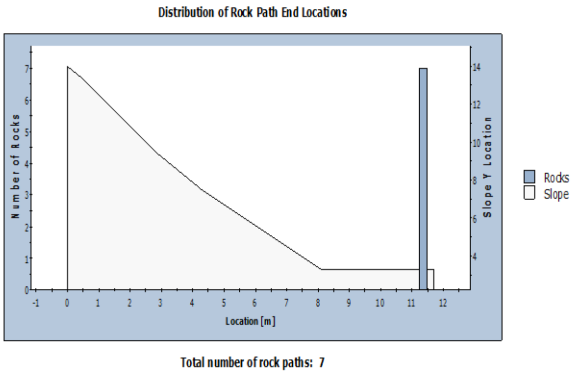


Figure11: *Rock fall end location from RocFall 8.0 simulated results*

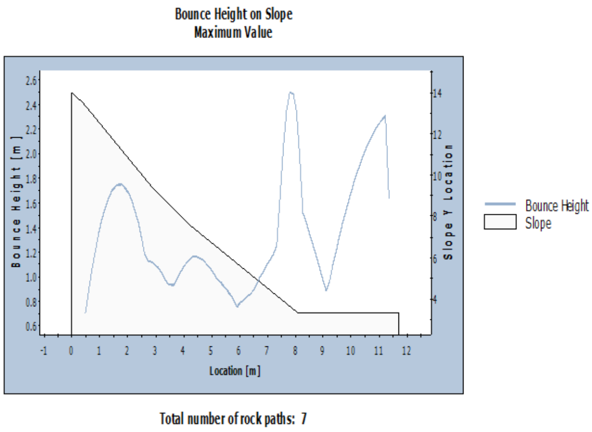


Figure12: *Trajectory height envelope from RocFall 8.0 simulated results*

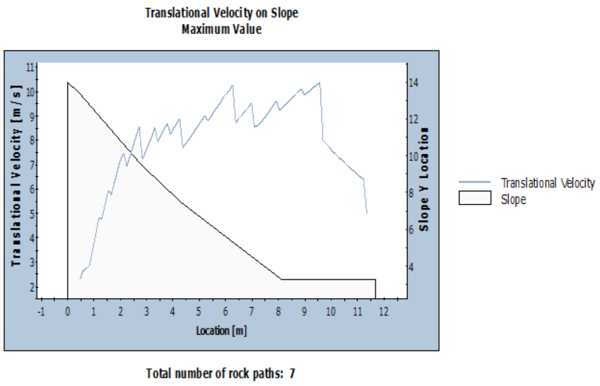


Figure13: *Trajectory translational velocity envelope from RocFall 8.0 simulated results*

Figure 14 to 17 show the rock fall modeling results of study location 4.

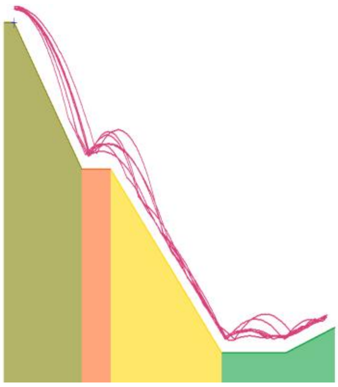


Figure14: *Simulation of seven rock fall model simulated*

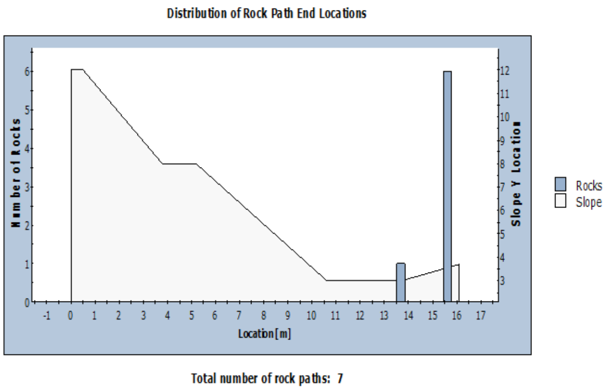


Figure15: *Rock fall end location from RocFall 8.0 results*

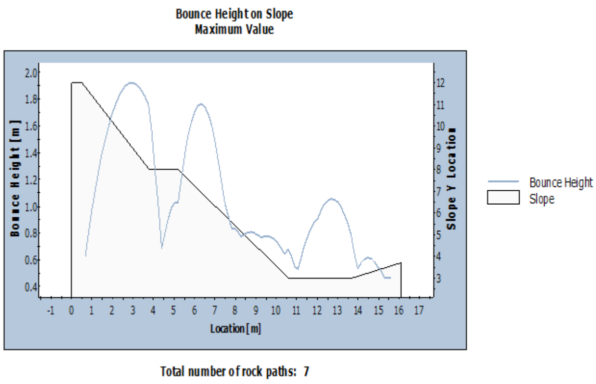


Figure16: *Trajectory height envelope from RocFall 8.0 simulated results*

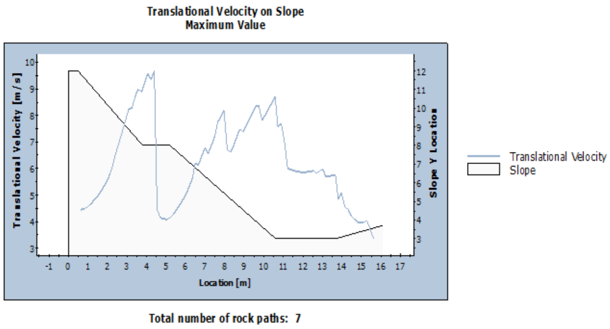


Figure17: *Trajectory translational velocity envelope from RocFall 8.0 simulated results*

Figure 18 to 21 show the rock fall modeling results of study location 5.

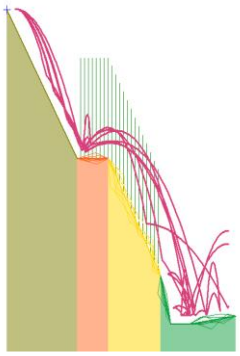


Figure18: *Simulation of seven rock fall model*

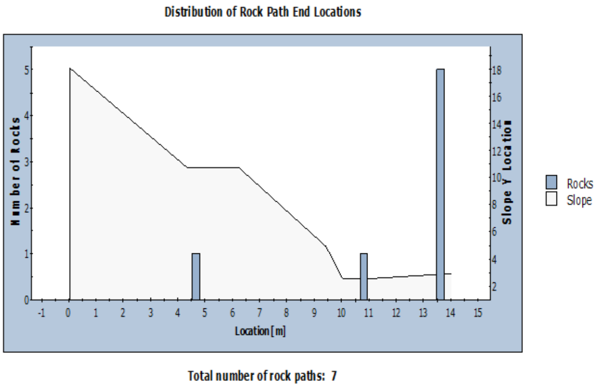


Figure19: *Rock fall end location from RocFall 8.0 simulated results*

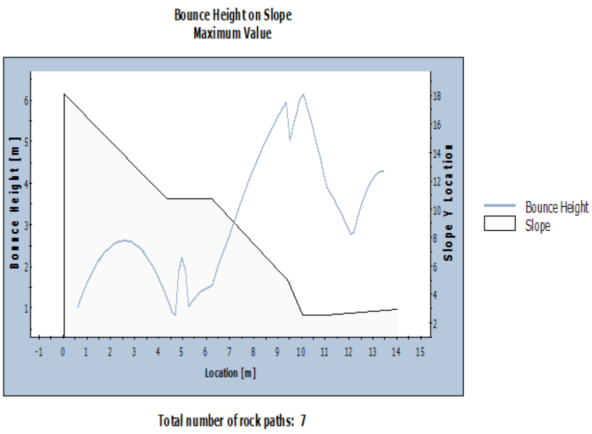


Figure20: *Trajectory height envelope from RocFall 8.0 simulated results*

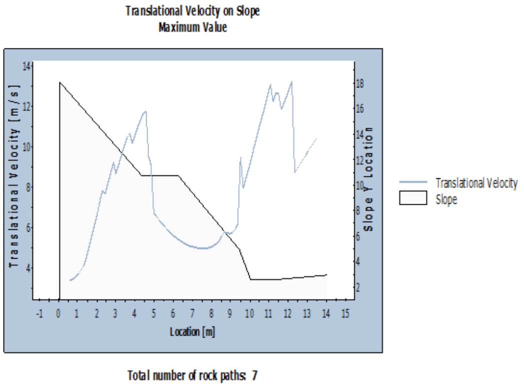


Figure21: *Trajectory translational velocity envelope from RocFall 8.0 simulated results*

Figure 22 to 25 show the rock fall modeling results of study location 6.

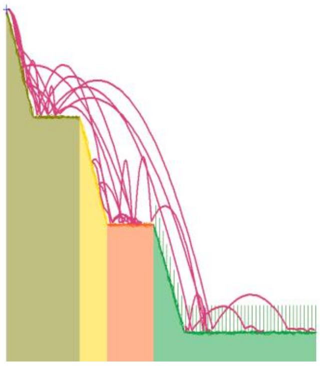


Figure22: *Simulation of seven rock fall model*

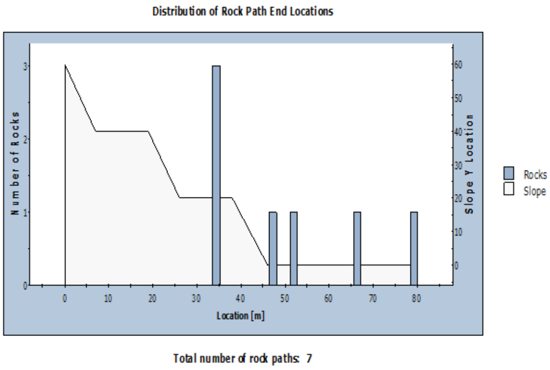


Figure23: *Rock fall end location from RocFall 8.0 simulated results*

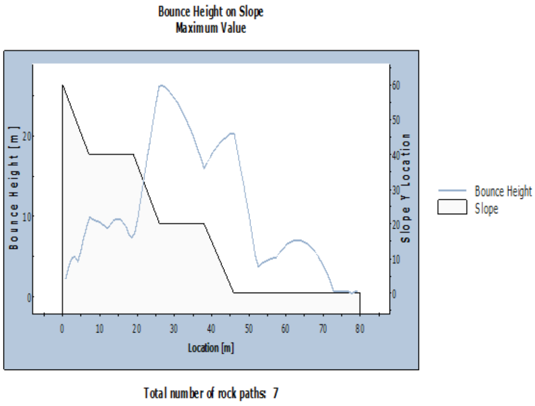


Figure24: *Trajectory height envelope envelope from RocFall 8.0 simulated results*

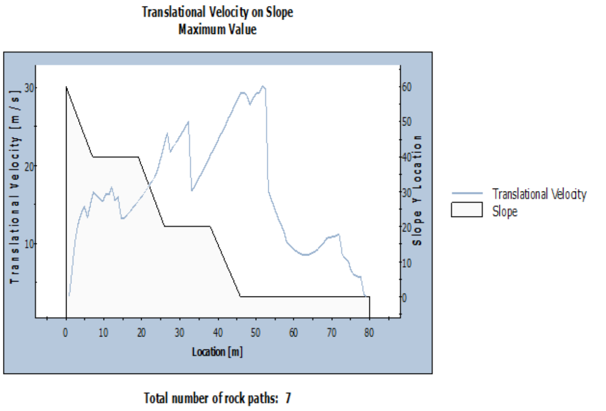


Figure25: *Trajectory translational velocity from RocFall 8.0 simulated results*

Figure 26 to 29 show the rock fall modeling results of study location 7.

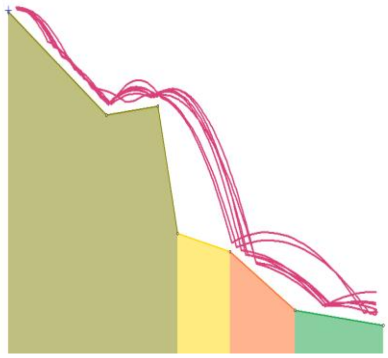


Figure26: *Simulation of seven rockfall model*

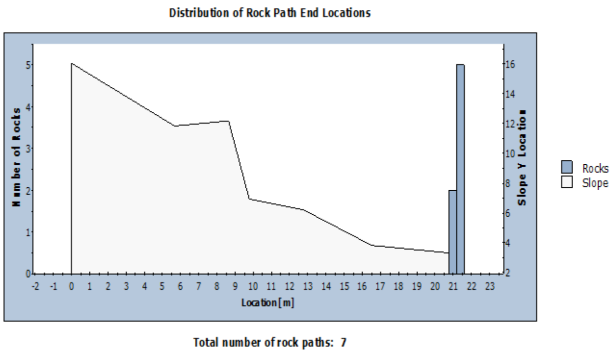


Figure27: *Rock fall end location from RocFall 8.0 simulated results*

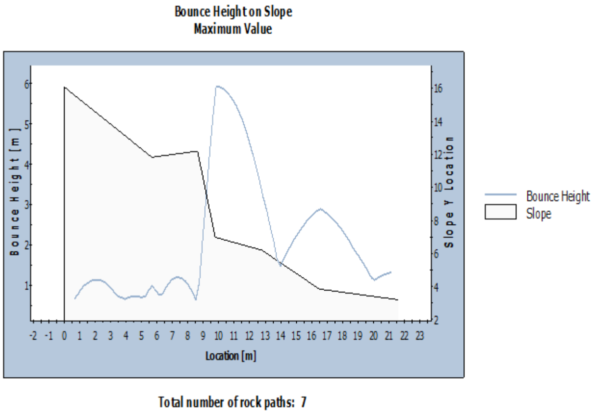


Figure28: *Trajectory height envelope from RocFall 8.0 simulated results*

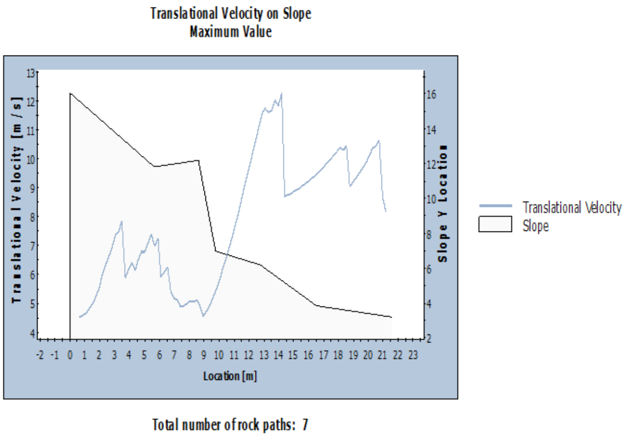


Figure29: *Trajectory translational velocity envelope from RocFall 8.0 simulated results*

Table2: *Results of RocFall Program Simulation of the Study Area*

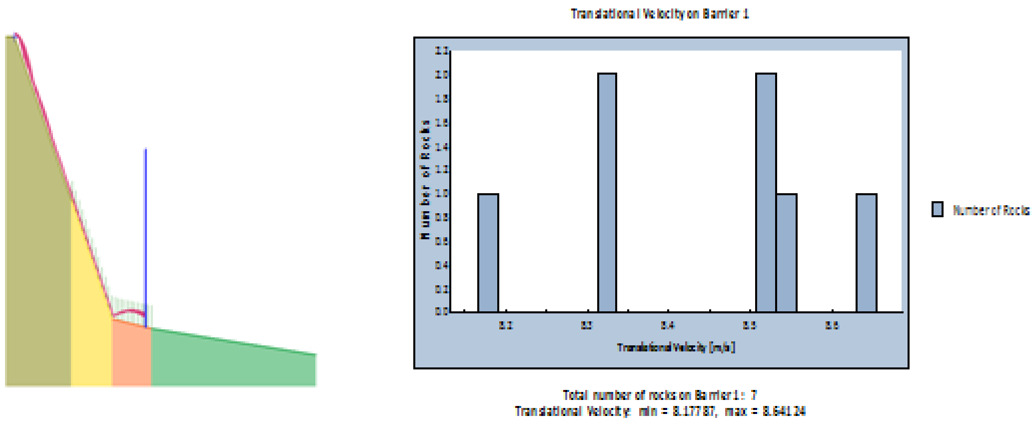
Study Location	1	2	3	4	5	6	7
End Point (m)	54.0-68.0	11.9-14.6	11.3	13.7-15.6	4.7-13.6	35.0-80.0	21.5
Max Bounce Height (m)	2.5	14.2	2.5	1.9	5.6	26.3	5.6
Max Trans velocity (m/s)	19.0	16.4	10.4	9.7	12.9	30.1	12.3

The results of RocFall program of seven locations analyzed and interpreted in terms of trajectory, motion, runout distance, bounce heights with translation velocity. The falling trajectories and their endpoints, bounce heights with translation velocity are shown in Figures 2 – 29. Their trajectories are decided by the characteristics of the slope. Additional slope characteristics determine the end point of the falling rocks some stop along the slope while some travel farther downslope to reach the base of the slope. The simulation results summarize in Table 2 showed the end points of falls at each location and also showed that location 6 attained the highest maximum bouncing height with 26.3 m while, Location 4 attained the lowest maximum bouncing height with 1.9 m as compared to other locations.

3.2. Rock Fall Impact on Barrier Modelling

Observations of rock fall impacts on the barrier provided reliable information on the impact velocity and energy. In this model, all the rock falls that reached the barrier location in each study location were contained by the barrier so it was not possible to use the back analysis feature in *RocFall 8.0*.

Figures 30 and 31 show the rock fall impact in study location 1.



(a)

Figure30: *Trajectory of falls that impacted the barrier.*

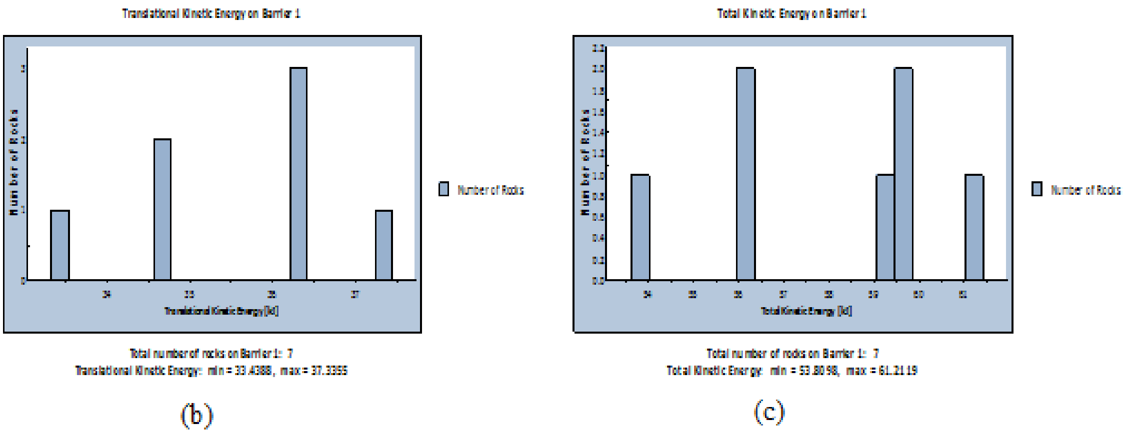


Figure31: *Analysis falls on barrier at location 1 (a) translational velocity distribution; (b) translational kinetic energy distribution; (c) total energy distribution.*

Figures 32 and 33 show the rock fall impact in study location 2.

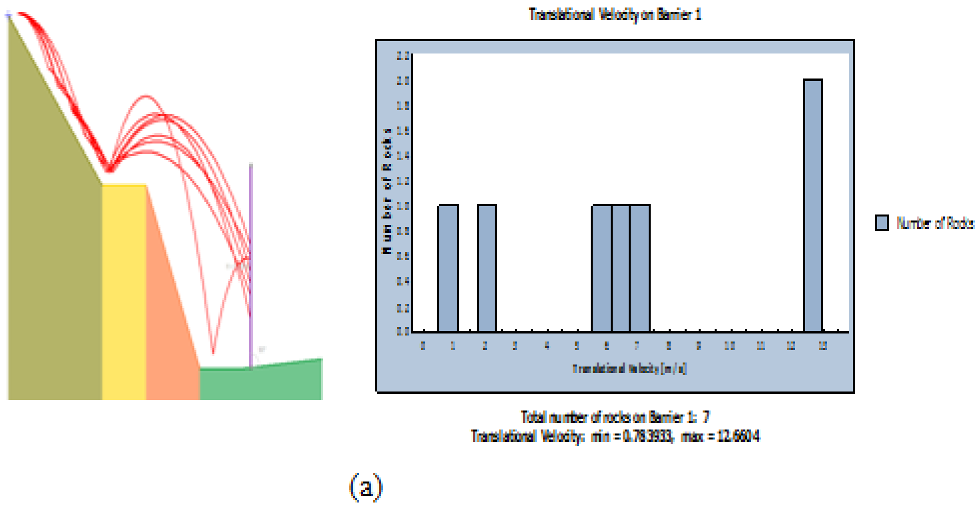


Figure32: *trajectory of falls that impacted the barrier.*

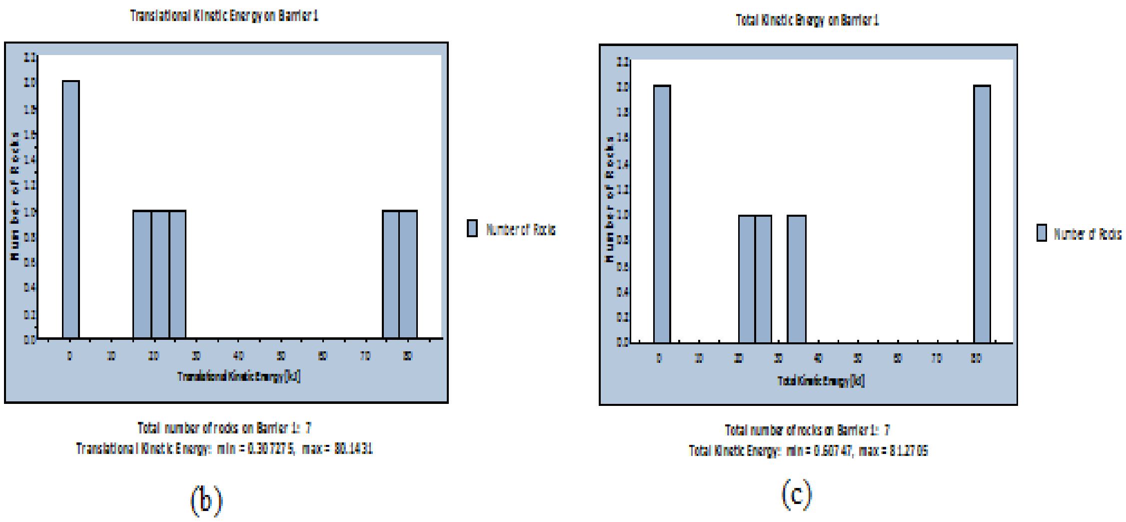
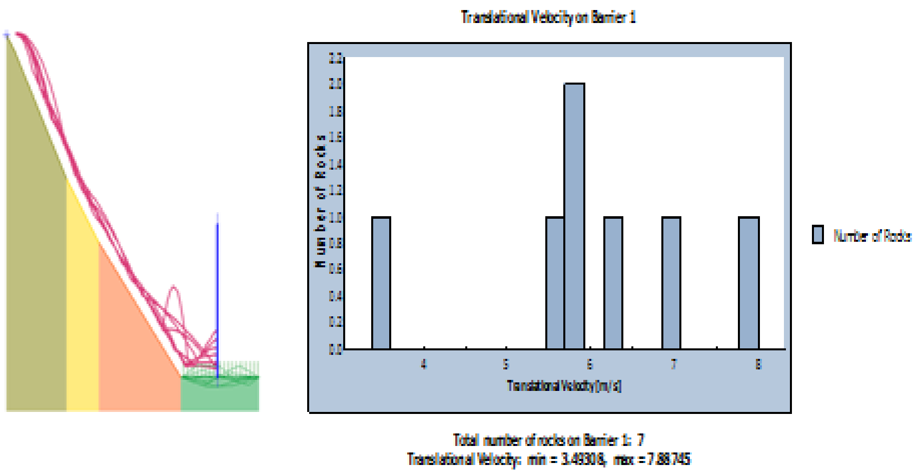


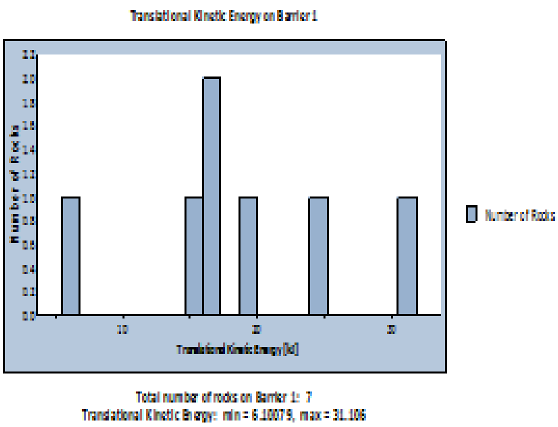
Figure33: *Analysis of falls on barrier at location 2 (a) translational velocity distribution; (b) translational kinetic energy distribution; (c) total energy distribution.*

Figures 34 and35 show the rock fall impact in study location 3.

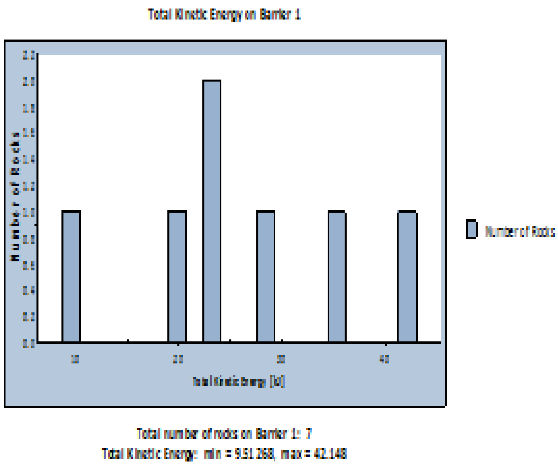


(a)

Figure34: *trajectory of falls that impacted the barrier.*



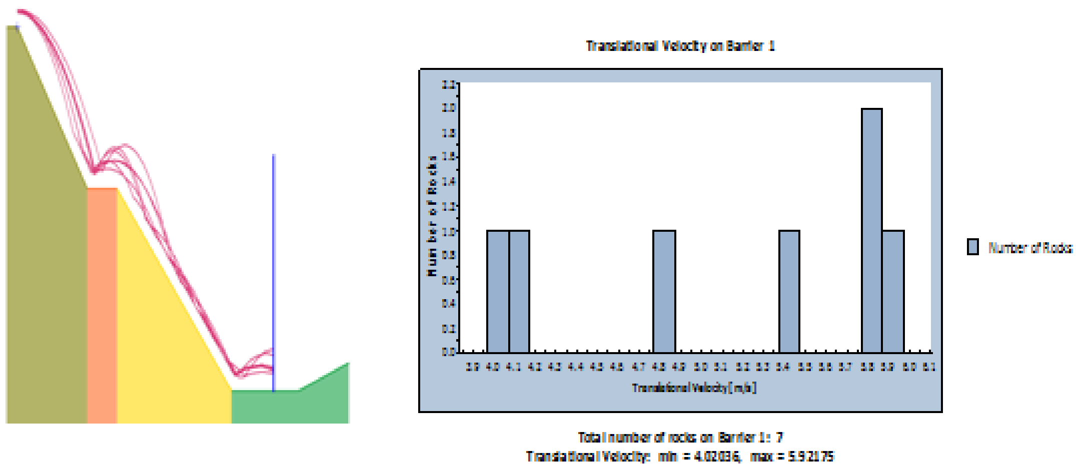
(b)



(c)

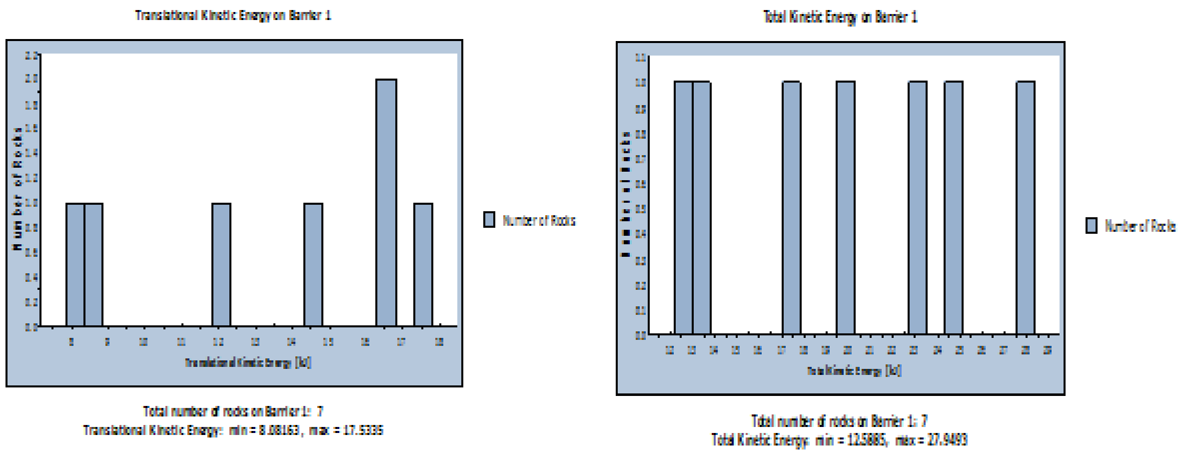
Figure35: *Analysis of falls on barrier at location 3 (a) translational velocity distribution; (b) translational kinetic energy distribution; (c) total energy distribution.*

Figures 36 and 37 show the rock fall impact in study location 4.



(a)

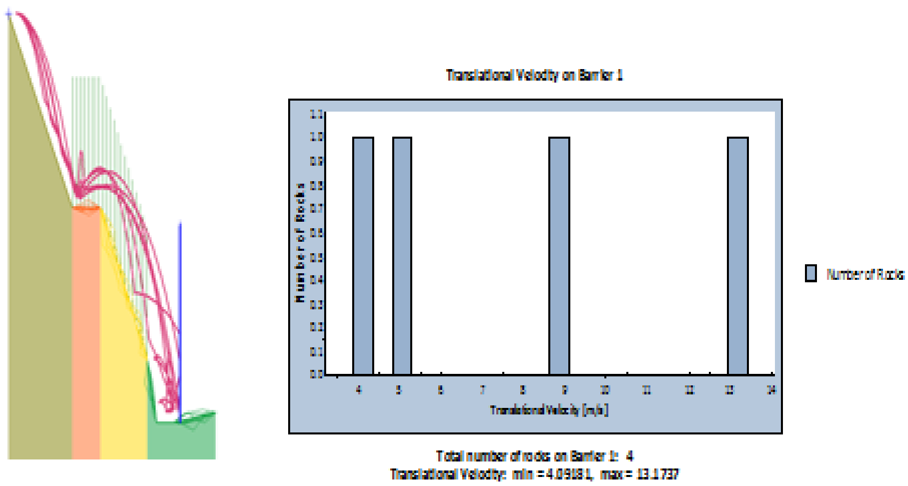
Figure36: *Accumulation of falls that impacted the barrier.*



(b) (c)

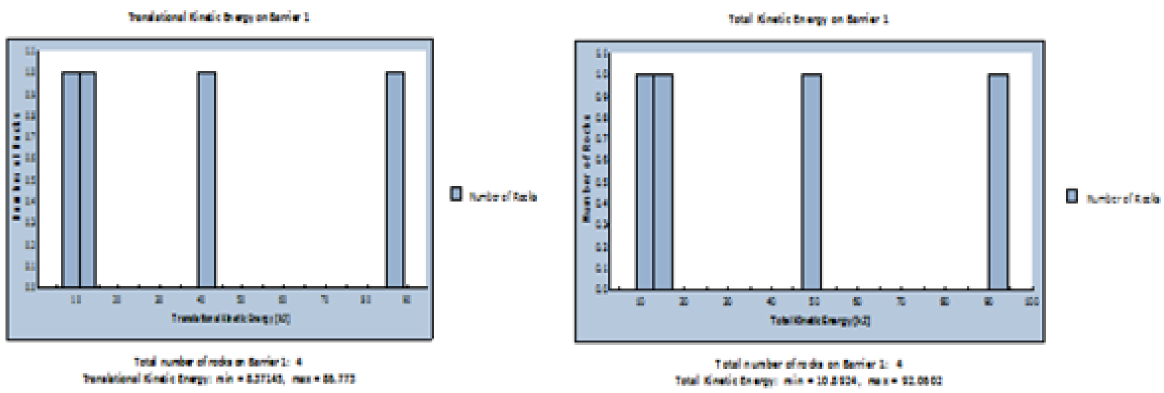
Figure37: *Analysis of falls on barrier at location 4 (a) translational velocity distribution; (b) translational kinetic energy distribution; (c) total energy distribution.*

Figures 38 and 39 show the rock fall impact in study location 5.



(a)

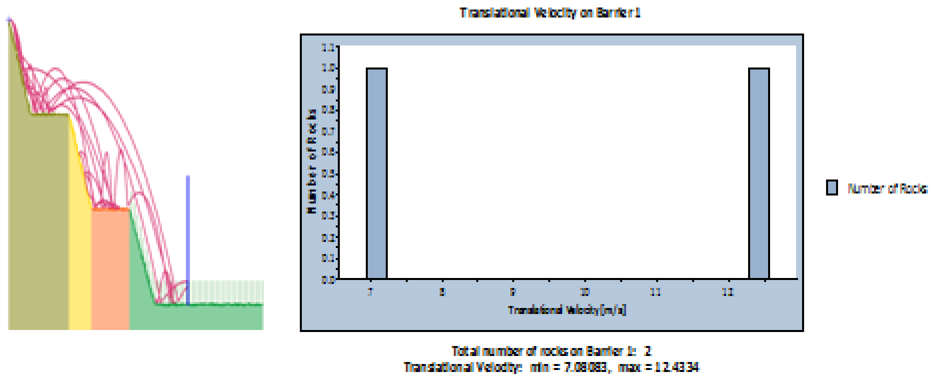
Figure38: *Accumulation of falls that impacted the barrier.*



(b) (c)

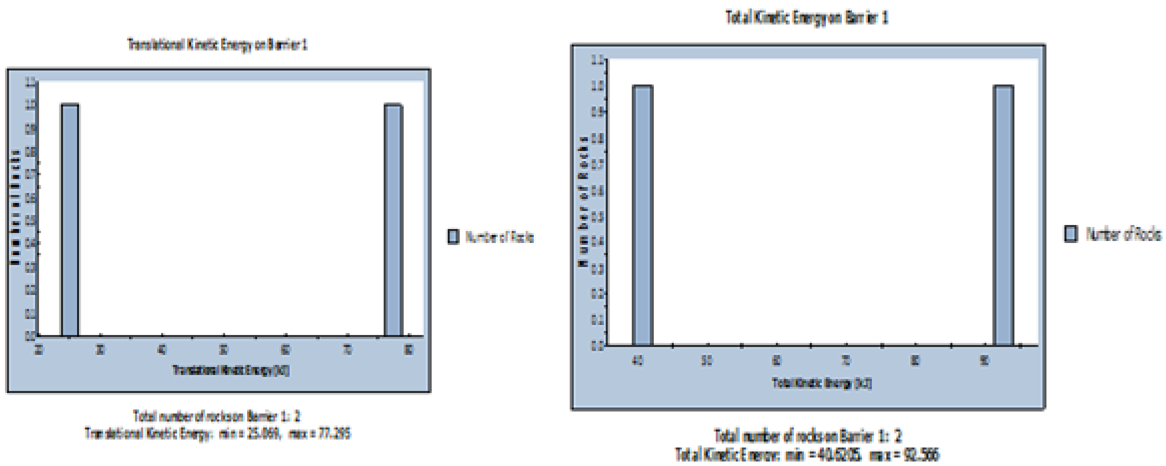
Figure39: *Analysis of falls on barrier at location 5 (a) translational velocity distribution; (b) translational kinetic energy distribution; (c) total energy distribution.*

Figures 30 and 31 show the rock fall impact in study location 6.



(a)

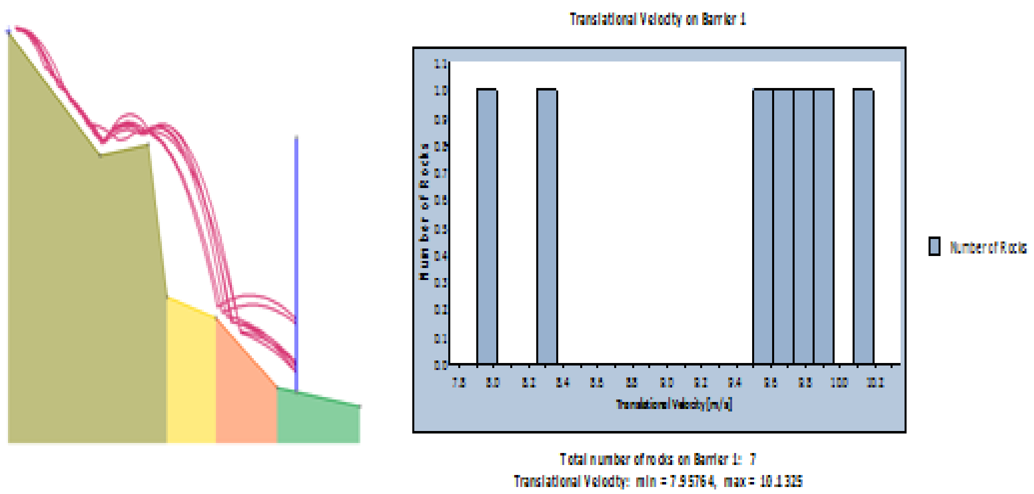
Figure31: *Accumulation of falls that impacted the barrier.*



(b) (c)

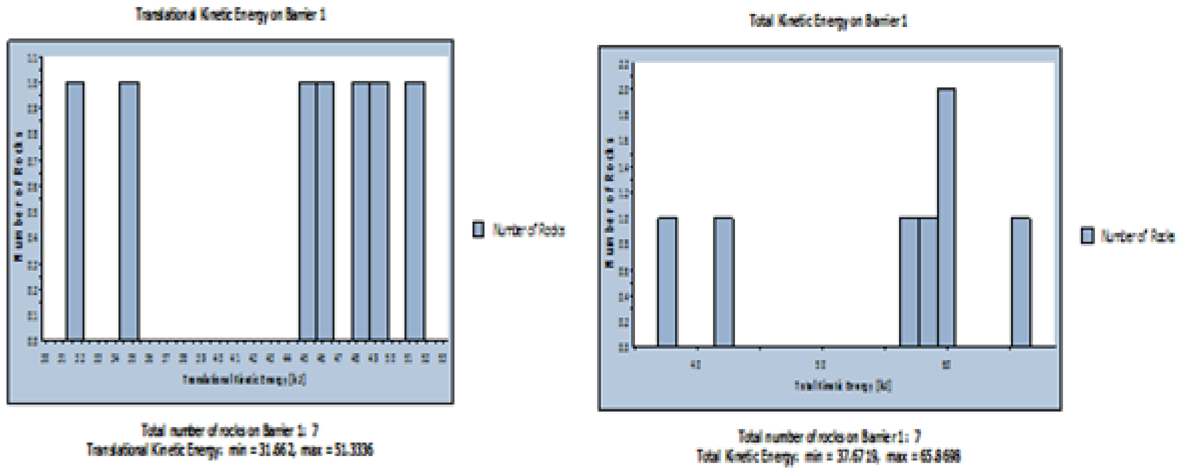
Figure31: *Analysis of falls on barrier at location 6 (a) translational velocity distribution; (b) translational kinetic energy distribution; (c) total energy distribution.*

Figures 32 and 33 show the rock fall impact in study location 7.



(a)

Figure32: *Accumulation of falls that impacted the barrier.*



(b) (c)

Figure33: *Analysis of falls on barrier at location 7 (a) translational velocity distribution; (b) translational kinetic energy distribution; (c) total energy distribution.*

Table3: *Results of Rock Fall Impacts on Barrier in Each Study Location*

Study Location	Translational Velocity (m/s)		Translational Kinetic Energy (kJ)		Total Kinetic Energy (kJ)		Max Intensity Level Zone
	Min	Max	Min	Max	Min	Max	
1	8.17787	8.64124	33.4388	37.3355	53.8098	61.2119	Medium
2	0.7839933	12.6604	0.307275	80.1431	0.60747	81.2705	Medium
3	3.49308	7.88745	6.10079	31.106	9.51268	42.148	Medium
4	4.02036	5.92175	8.08163	17.5335	12.5885	27.9493	Low
5	4.09181	13.1737	8.37145	86.773	10.8924	92.0602	Medium
6	7.08083	12.4334	25.069	77.295	40.6205	92.566	Medium
7	7.95764	10.1325	31.662	51.336	37.6719	65.86.98	Medium

Previous researches established the used of total kinetic energy values obtained from rock fall analysis to characterize the damage capacity of rock falls into three groups which are; high (> 300 kJ), medium (30–300 kJ), and low intensity (< 30 kJ). Therefore, an attempt to predict rock fall hazard zoning based on the total kinetic energy for this study by classifying the intensity hazard level zone, the results of rock fall model of each location summarized in Table 3 showed location 1, 2, 3, 5, 6 and 7 at the medium intensity hazard level zone, while location 4 marked at low intensity hazard level zone.

4. CONCLUSION

In conclusion, the influence of rockfall by predicting the intensity hazard level zone in the study area show that study location 1, 2, 3, 5, 6 and 7 has respectively, total kinetic energy of approximately 61.2 kJ, 81.3 kJ, 42.1 kJ, 92.1 kJ, 92.6 kJ and 65,9 kJ which pose risk of medium intensity hazard level zone, while study location 4 which has total kinetic energy of 27.9 kJ is at risk of low intensity hazard level zone. Although, rock fall influence capable of causing motality and damaging structures should also be expected in areas with low intensity hazard level zone. Therefore, barriers with capacity >300 kJ is required to adequately mitigate/handle the influence/vulnerability of rockfall in the study area.

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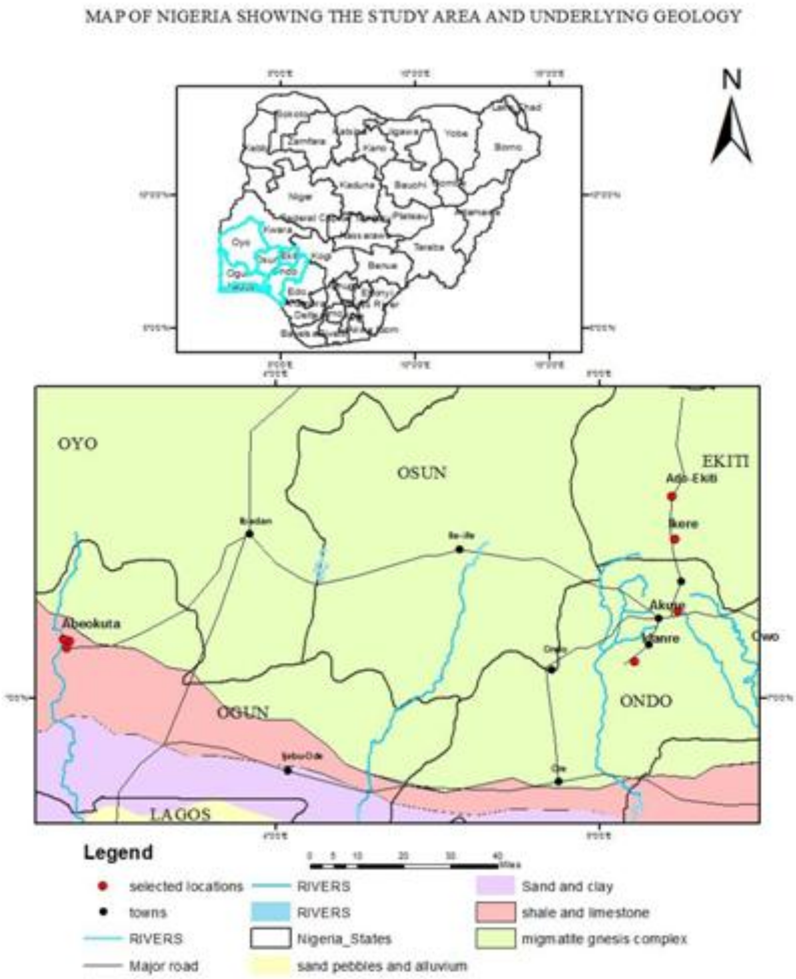

Figure 34: *Geological map of the study locations (NGSA)*

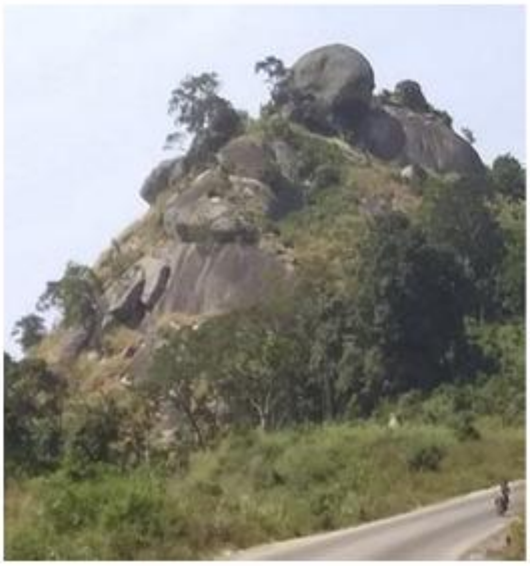

Plate1: Pictorial view of study location 1

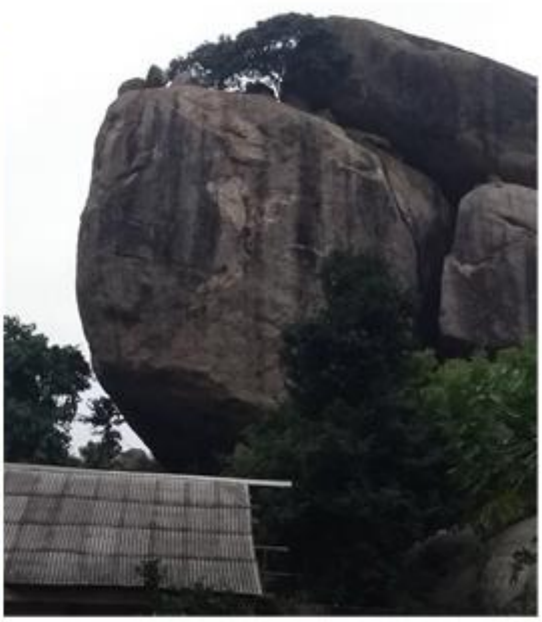

Plate 2: Pictorial view of study location 2

Plate 3: Pictorial view of study location 3

Plate 4: Pictorial view of study location 4

Plate 5: Pictorial view of study location 5

Plate 6: Pictorial view of study location 6

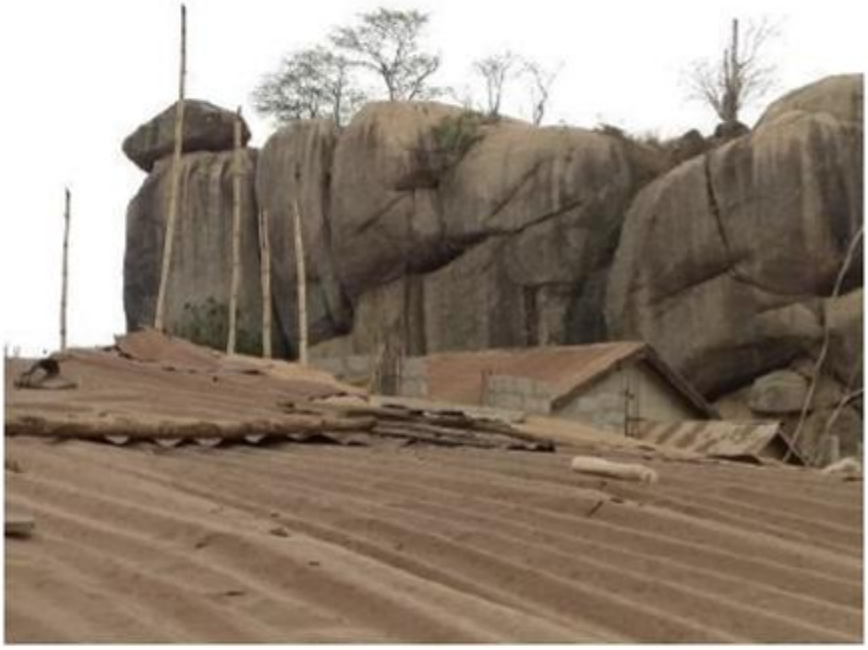

Plate 7: Pictorial view of study Location 7

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