An improved hazard assessment chart for rock falls in near vertical blocky rock environments

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Abstract

The purpose of the study was to perform rockfall stability analysis and develop an improved rockfall hazard matrix chart using the R518 road in Limpopo as the case study. The study entailed structural mapping, wedge simulation using stereonet plots. The RocFall software was then used to identify the parameters that influence the occurrence of rockfall. The software was also used to monitor the variations in the kinetic energy of rolling, bouncing or falling rocks. The effects of the initial height and velocity of falling rocks on the final destination of fragments were also explored. Results showed that the selected area along the R518 road consists of joints and bedding planes. These features weaken the rock mass and create wedges that can potentially fall. Simulations with RocFall, on the other hand, indicated that slope height, vegetation density, slope angle, the velocity of the falling rock largely contribute to the extent that the broken rock could reach. From the empirical and numerical findings, an improved rockfall hazard rating chart was proposed. The chart was found to be suitable for the rating of level of rockfall hazard along highways and roads.

1. Introduction

The assessment of rockfall hazards is continuously performed because the unpredictable nature of rockfall events. Analytical tools are a significant part of the assessment routine of rockfalls as they provide relevant information for numerical simulations. They are however anchored on the determination of the properties of rock mass such as rock strength, water pressure, and joint orientation among others. The concept of rockfall is one of the oldest that has been widely documented along river banks, slope cuts, and mountain ranges (Corominas et al., 2005; Mineo et al., 2018). Historically, rockfalls have been established as the “detachment of a rock from a steep slope along a surface on which little or no shear displacement takes place” (Cruden and Varnes, 1996). This is because the belief has been that rockmass descends very quickly by falling, bouncing and rolling. Another school of thought believe that a clear distinction should be made between detachments and rockfalls. Selby (1982) for example consider a rockfall as a small mass movement to contrast with the detachment of an individual rock. The latter involves large-scale rockmass in the form of rockslides and rock avalanches (Cruden and Varnes, 1996).

Several scholars have restricted the use of the term rockfall based on maximum kinetic energy (Spang and Rautenstrauch, 1988). Others (e.g. Whalley, 1984) have done the same based on volumetric terms such as debris falls (< 10 m³), boulder falls (10–100 m³), block falls (> 100 m³), cliff falls (104–106 m³) and Bergsturz (> 106 m³). In recent studies, the terms rockfall, rockslides and rock avalanches are often used in non-equivalent meaning with no consensus on the actual definition (Hungr et al., 1999; Chau et al., 2003; Dussauge-Peisser et al., 2002; Guzzetti et al., 2003).

Rockfalls are widespread in mountain ranges, coastal cliffs, volcanos, river banks, and slope cuts. Although most take place in remote places, they also threaten residential areas and transport corridors (Chau et al., 2003; Corominas et al., 2005). Their unpredictable nature is often a cause for concern by authorities and decision-makers. Rockfalls can be of limited size but their underlying processes are
extremely rapid with high kinetic energies and damaging capabilities. After an extensive study of rockfall events, Turner and Jayaparakash (2012) were able to demonstrate that small volumes of rocks may cause significant damage and traffic disruption. Petley (2012) argued that losses due to landslides and rockfalls are concentrated in countries lacking appropriate resources and research capacity. Rockfalls may be mitigated with stabilization and protection works. But more often than not, engineers have to make difficult judgements based on large uncertainties associated with the prediction of the size and frequency of the potential events.

Rockfalls are the most common type of slope movement that make rock cuts along transportation corridors in mountainous regions hazardous (Corominas et al., 2017; Ansari et al., 2018; Asteriou and Tsiambaos 2018; Zhu et al., 2018). It is essential to understand the deformation characteristics and failure mechanism driving the instability of slopes. Slope stability refers to the potential of the earth's surface material (soil and rocks) on inclined slopes to withstand or undergo movement (Sepulveda et al., 2005; Zhou et al., 2013). The strength and cohesion of the slope material as well as the amount of internal friction between material help in maintaining the stability of the slope. Stability is determined by the angle of the slope and the strength of the constitutive material. The steepest angle that a cohesionless slope can maintain the mass without losing its stability is referred to as its angle of repose. Slope stability also refers to the relationship between the driving and the resisting forces (Guzzetti et al., 2004; Papadopoulos and Plessa, 2000; Basharat and Yasir 2018; Chun et al., 2018; Korkanc, et al., 2018). The ratio of resisting forces to driving forces is known as the factor of safety of the slope. The gravitational force is evidently the main driving force acting on a slope. The gravity-induced driving force is directly proportional to the slope inclination. The existence of discontinuities in the rock leads to uneven distribution of strength and stress in all directions. Elastic properties of the rock mass are consequently altered leading to the disrupted balance of rock mass strength as well as landslides. The orientation of discontinuities is another major factor affecting rock stability and rock failure alike (Wyllie and Mah, 2004). The following are considered to be the main sources of rock slope failure: lithology, rockmass strength, and geological features. This is because the frequency, orientation and spacing within the network of existing discontinuities determine the quality of the rockmass (Hoek and Bray, 1981). Rockfalls can also be triggered to a limited extent by the degree of weathering, cleft water pressure, and erosion (Budetta, 2004; Fanos and Pradhan 2019).

Rock slope failures can be classified depending on the type and degree of structural control. The most encountered rock slope failures include planar, wedge, toppling, and circular failures (Abellan et al, 2006; Copons and Vilaplana, 2008; Aqeel 2018). The geometry of the slope, the characteristics of the potential planes of failure, surface drainage, and groundwater conditions are the main internal factors controlling rock slope stability. Rainfall, seismicity, and man-made activities, on the other hand, are external factors. The combination of these factors is responsible for the conditions of stability of a slope. Conventional kinematic and limit equilibrium analysis techniques have been tested on cases of rockfalls. Success cases investigated involve simple slope geometries and basic loading conditions. However, these conventional methods can neither account for rock discontinuities nor can they provide information behind the mechanism responsible for the failure. Numerical techniques such as the traditional
Lagrangian Finite Element Method are bridging the gap (Eberhardt et al., 2003 & 2004). Indeed, the hazard matrix chart proposed by Lateltin et al., (2005) and Ferrari et al. (2017) rate hazard based on the kinetic energy of the rock mass has been the common technique utilized in predicting the hazard rating of the slope. However, the chart itself does not consider for example the effect of vegetation density, slope height, slope angle among others, when rating slope hazard. The present study attempts to bridge this gap.

In this study, rockfall analysis is performed using both analytical and numerical approaches. The two approaches are applied to the location along the R518 road in Limpopo province, South Africa that are exemplified in Fig. 1. The combination of analytical and numerical approaches is aimed at developing another hazard rating chart, this time, for rockfalls. Here also, the proposed chart is tested to the study area and to other roads in the mountainous environment. Finally, prediction results obtained from the proposed chart are benchmarked against established charts.

2. Geological Setting Of The Study Area (Waterberg)

The Waterberg group is a gently malformed succession of red beds preserved in two main structural domains on the Kaapvaal part, specifically (a) Associate in nursing east-west elongated domain delimited by the Zoetfontein-Melinda Faults within the north and therefore the Thabazimbi-Murchison Lineament within the south and (b) a nor'-nor'-west elongated domain located between the jap and western lobes of the Bushveld complicated termed the Central Bushveld domain. The domain between the Zoetfontein Fault and Thabazimbi-Murchison Lineament includes the most outcrop space of the Waterberg group, referred to as the Waterberg highland space, and two smaller outcrop areas to the west of Kanye in Japanese Republic of Botswana (Fig. 2). The Central Bushveld domain includes the Nylstroom syncline outcrop space of the Waterberg highland and also the Middelburg space Additionally, there square measure variety of tiny erosional outliers between Middelburg and Nylstroom, the most important of that is at Rust Diamond State Winter (Fig. 2).

The type space for the Waterberg cluster is within the Waterberg tableland Associate in Nursing here it's described by an ~ 5-kilometer-thick red bed succession of conglomerate, stone and sedimentary rock with minor volcanics particularly in its lower half. The lithostratigraphic subdivision of the Waterberg cluster is complicated with totally different formation names used (a) among the assorted structural domains, (b) for identical stratigraphic unit across the border between Republic of South Africa and Republic of Botswana, and (c) at intervals a particular rock unit to point lateral facies changes (SACS, 1980; Carney et al., 1994; Dorland et al. 2006).

3. Research Approach

The study commences with eld observations along areas believed to be prone to rockfalls or reported to have experienced rockfalls. The observations strictly focused on identifying geological features that might cause the occurrence of the rockfall. The orientations of these features were measured together
with parameters such as slope height while loose rocks were identified. The density of the vegetation along the slopes was also estimated as it controls the rolling and falling of rocks down the hill (or the slope).

Kinematic analysis was utilised in an attempt to describe the translational failures that may occur around the wedge and plane formations present in the area of study. Nonetheless, for the analysis to make sense, several input parameters were needed. These include the structural composition of the rock mass and the geometry of the material (i.e. soil and rock). The effects of these parameters are critically evaluated to identify the possibility of the material to fail. In this study, kinematic analysis was carried out using Stereonet plots generated by the DIPS simulator (Rocscience 2001). DIPS was chosen because it has been reported to have the ability to visualize and determine the kinematic feasibility of the rock slope using friction cones, daylights and toppling envelopes (Rocscience, 2001a).

Further, the Rock Mass Rating were determined using geological mapping data. Geotechnical mapping followed the common procedure required to rate the quality of the rock mass. The key parameters that were measured are listed in Table A1.

The identification of the parameters in Table A1 was aimed at compiling input data for later numerical simulation work. The information was also to be used in the classification of the rock mass of the study areas. Indeed, the parameters capture the mechanical behaviour of the rock mass and assist in designing appropriate support system for the area. The parameters in Table A1 included the documentation of the set of joints, their spacing, and their persistence amongst others.

Finally, the RocFall simulator was used to generate the falling/rolling trajectories of individual or multiple rocks upon detachment. RocFall is a rock trajectory simulator that makes an inventory of the mechanical energies of the rock mass as it rolls, impacts, bounces down the slope, and overshoots into the road past the hill toe. The inventory is solved for the velocity and position of individual rock blocks. RocFall model also includes input parameters from fieldwork such as the height of the slope and the properties of the rock.

4. Results And Discussions

4.1 Field Observations

Field observations are primarily used to provide a broad view of what is happening on the ground. The information collected on site guides the methods that can be implemented to assess the problem at hand. Six sites prone to rockfall were identified as shown in Fig. 1 above. From an observational point of view, site 1 was dominated with blocky rock mass dominated by bedding planes as shown in Fig. 3. The planes are dipping and striking at the same pattern. Furthermore, the common rock type identified is partial metamorphic sandstone with minor beds of the conglomerate between sandstone layers. Owing to that, the overall rock mass is dominated with small and large joints that can create wedges along the sedimentary layers. This complex structural geology influences the generation of a blocky and fractured
rock mass. It was also observed that most boulders were loose and could fall anytime. This makes rockfall monitoring along the road a challenging exercise. This state of affairs is worsening since broken rocks are generally cleared from the road before evidence collection is conducted.

It should be indicated that all selected sites are not supported by roof bolts, wire mesh, or the likes. As such, the rock mass is not glued together to the point that a small movement can initiate rockfall. Weathering and erosion are noted to be taking place in a rapid pace across the municipality. The stability of the rock mass is therefore expected to deteriorate with time.

In sites 2 to 6, the rock mass is similar to that found in the first site with slight differences noted for the density of fracturing, slope height, and bedding planes. Similar to the observations from site 1, sandy red soil dominates the top layers of the strata. Low density and far spread vegetation coverage is associated with the sites (see Figs. 4).

Slope height was found to range between 12 m and 19 m across the six sites. Some small rock fragments have been observed spread at the slope toes. It is believed that rockfall has been continuously occurring but due to road maintenance the evidence is regularly removed from the road. Lastly, vegetation and trees growing in the perimeter of the slopes were observed in some section to rapidly disintegrate the rock mass (see for example Fig. 3). This weakens the rock mass and leads to rock sliding down the slope.

4.2 Kinematic analysis of the rock mass along the R518 road

Rock mass rating or rock mass classification is a technique recommended by ISRM (1978 & 2007) for assessing the geomechanical conditions of a slope. The six sites were assessed following the rock mass rating. The assessment was done only in accessible areas while mapping was conducted along exposed slopes along the road. Several parameters were considered; they include joint persistence, spacing, opening, in-filling, roughness, uniaxial compressive strength (UCS), dip-immersion and hydraulic conditions. All parameters were measured and analyzed along the scanlines for each discontinuity. The orientation of discontinuities was also analyzed and plotted for the sets of joints and bedding. The Fisher distribution method was used for this purpose (Mineo et al. 2018).

Based on the rock mass rating obtained, the overall rock mass was classified as a fair rock mass (see Table A1). To be more precise, the rock mass in the region was found to range from class 54 III fair rock to class 56 III fair rock. This simply means from a kinematic point of view that several weak zones or wedges that can fail exist within the rock mass (see Fig. 5–10). And from the stereonets, the unfavourable kinematic orientation of discontinuities leads to state that the most likely failure would be planar sliding.

These results support the visual evidence collected on site where wedges have been noted to develop due to multiple discontinuities with irregular orientations. It can also be argued that toppling is another possible mode of failure that can occur in the study area. This is because some discontinuities dip into
the facing slope. Small and large wedges were also plotted from the stereonets presented in all sites (see for example Fig. 5). In addition to this, similar bedding planes were identified in all the sites (see Figs. 5–10 for comparison). In conclusion, the area of study is a weak to moderate rock mass with dip-dominated bedding and multiple major and small joints. This makes the rock mass unstable and creates several wedges. It is therefore likely that rock failure in the six sites occur through planar sliding and toppling.

4.3 Analysis of the final deposit of the rockfall

It is always important for the final deposit of the rockfall to be estimated. This ensures that remedial action is taken based on the extent of the hazard. There exists at the moment no analytical method that can accurately predict the final deposit of the rockfall. However, numerical tools such as the RocFall simulator provide an approximate solution to the rockfall deposit problem. In this study, the RocFall simulator was used to estimate the final rockfall deposit based on the trajectories of blocks generated. Input parameters such as rock mass properties, slope geometry, block size among others were taken into consideration. The scenarios that were considered included the estimation of the final deposit at constant slope height; however, falling rocks subjected to different slope height and different initial velocities. A detailed analysis of the variation in kinetic energy was done throughout the journey of falling rocks.

4.3.1 Impact of slope height on the final deposit of the rockfall

The RocFall simulator was used to compute the various trajectories of rocks falling down the slope as a function of slope height. The locus of these trajectories was to give insight on the final deposit of the broken rock.

Based on the simulation results, slope height contributes substantially to the rolling distance of falling blocks and therefore to the extent of the deposit. See in Fig. 11 for instance that when the height is about 5.5 m from the road, the falling rock spreads out at the vicinity of the road. Some rock fragments are expected to bounce less than 2.5 m while other settle immediately after hitting the road (see Fig. 11a). It is crucial to indicate that the road width also plays a major role in the rolling motion of fragments. Simply put, with a 8 to 10 m wide road as is the case here, most of the falling fragments are expected to end their rolling motion in the middle of the road. By increasing the slope height to 9.8 m while keeping all other input parameters unchanged, the picture changes as shown in Fig. 11b. For one, fragments are predicted to roll over the entire road length into the river; and two, a large deposit of fragments can be potentially formed farther away from the toe.

Additional simulations were performed in order to get a better understanding of the effect of slope height. Various heights were considered in line with the observation reported in Sect. 2 as follows: 12.5 m, 14.5 m, and 19 m. As can be noted in Fig. 12a&amp;b, most fragments experienced bouncing at a wide spacing and subsequently roll over into the river floor. It also appears that the final deposit of rolling fragments is controlled by the kinetic and potential energy rather than the kinetic energy alone. Indeed, slope height controls the velocity of the falling rock; at the toe, this energy is converted into rolling motion that then
defines the extent of the final deposit. When comparing slope heights of 12.5 m and 14.5 m, simulation results show that the bouncing and rolling of fragments increase rapidly with height. Furthermore, a large quantity of rolling rock is estimated to be deposited away from the road. This large fraction of material also generates sharp curves after hitting the river floor (see Fig. 12b). It may therefore be argued that the height of a slope has an impact on the final destination as well as the spread of rolling fragments.

To confirm these findings, let us look at the simulation for the slope height of 19.0 m in Fig. 18. Similarly, to the 14.5 m high case, it is noted that the falling fragments are predicted to all deposit into the river after rolling, bouncing through the slope and the road. The other observation is that the simulated bouncing height at the final deposit was great since blocks hit the road aggressively. Unfortunately, in this case, RocFall does not model the fragmentation or rock due to impact. That is why the use of the simulator is generally limited to qualitative analysis.

Finally, in terms of the kinetic energy, it can be seen that the slope height is a determining factor for the rolling velocity and the final deposit of broken rock. So, in a sense, high slopes are more dangerous than small ones. This is indeed supported by Fig. 13 where the fraction of fragments bouncing off higher has risen.

### 4.3.2 Distribution of the total kinetic energy during rockfall

The distribution of kinetic energy during rockfall can be extracted from the RocFall simulation model. The outcome of that exercise is presented in this section with the aim of getting insight on the rockfall process from an energetic point of view. However, only the kinetic energy along the slope, the road, and the slope leading into the river were considered in the analysis.

Figure 14 is an example of the outcome of the analysis; it shows that kinetic energy is rapidly lost when the rock bounces off or hits back the road. The other observation is that kinetic energies associated with the different legs of the full trajectory all range between 0 kJ and 100 kJ.

The frequency distribution of kinetic energy is provided along in Fig. 19 and in other cases as shown in Figs. 15–20. Arguably, the kinetic energy is observed in all cases to rapidly increase when a fragment hits the road. This is because the velocity of the projectile is at its highest before it slows down and recovers with a bounce. Subsequent to this, the predicted kinetic energy along the trajectory of a rock fragment upon hitting the road the second time is not high. This is captured in the energy distribution coming with each pair of plots in Fig. 15–20.

The loss of kinetic energy that can be inferred from first principles as far as physical sciences are concerned is reproduced in the simulation outputs. Indeed, a comparative look at the energy distributions in Figs. 15, 16 and 17 for example shows that energy is spread at the second hit. While the distribution is skewed to the left in Fig. 15 indicating high energy levels, that in Fig. 16 is right-skewed. Impact events in Fig. 17 are captured by the right tail of the distribution.
A summarised understating of the simulation outputs in Fig. 15–20 is that the kinetic energy distribution is dependent on the height of fall of the rock. In the next section, an attempt is made to explore the effects of the initial velocity of the falling rock. In doing so, a richer picture of the contribution of the potential and kinetic energies on the final rock deposition can be drawn.

**4.3.3 Impact of Rockfall Velocity on the final deposit of the rockmass**

In this section, simulation results are reported on the contribution of the starting velocity as part of the rockfall. Initial velocities of various fragments making up the slide were allocated between 1.5 and 3 m/s. The idea is to mimicked the ejection of blocks as a result of water pressure, superficial torrent, or internal stress for example.

Figure 21 shows how significant the effect of the initial falling velocity is on the trajectories assumed by rock fragments. Indeed, fragments roll and spread out differently between 1.5 and 2.0 m/s. The significant input that the initial velocity has on final deposition should also be noted.

Further evidence is rendered in Fig. 22 where the initial velocity has increased from 2.0 to 2.5 and 3.0 m/s. Here also, the final deposit is seen to be strongly dependent on the initial velocity of blocks.

What seems evident from Figs. 21 and 22 is that the extent of the final deposition is governed by the initial velocities of falling rock fragments. One may argue, as a first approximation, that the final distance reached by rolling, tumbling, and falling rocks is directly proportional to velocity. The simulation results presented in this section open the possibility for further enquiry around rockfall deposition. It is also suggested that the recurrence of rockfall around any of the six sites from high grounds is possible. This is because lots of loose boulders are observed in the upper part of the slopes. While the area has some vegetation that could help slow down tumbling rocks, the great falling height is concerning. As such, even a relatively small rock fragment can cause great damage and should therefore be regarded as a serious hazard along the road. Multiple geological features within the slopes should also be equally treated as hazard. And although the simulation illustrated in Figs. 21 and 22 provides some insight on rockfall dynamics and deposition, the absence of actual data for validation is limiting the analysis. Empirical models become the best available alternative. It is in this light that the next section proposes a hazard matrix for rockfalls and applies it to the six sites located in the study area (refer to Fig. 1).

**4.4 Development of the rockfall hazard assessment chart**

A number of procedures exist for assessing rockfall hazards worldwide with the most recent being the Evolving Rockfall Hazard Assessment. Known as ERHA, the procedure has been developed as a hazard matrix chart for rockfall (Lateltin et al., 2005; Ferrari et al., 2017).

Figure 23, illustrates the principle used in the ERHA chart to identify the most hazardous areas along a slope. The chart consists of matrix cells labelled column-wise as low, medium and high according to the state of activity. The latter grows proportionally with the probability of occurrence and intensity of events
(Lateltin et al., 2005; Ferrari et al., 2017). Based on the energy level of the rockfall process, the hazard level can now be estimated.

In a sense, the matrix chart rates hazards based on the kinetic energy of the rock mass. It does not take into account the starting height of rocks and the existing vegetation coverage over the slope. Furthermore, the matrix itself does not provide some indication of slope parameters and rockfall conditions. Due to such limitations, the chart cannot be used to compare the six sites in Fig. 1. It is therefore proposed to repurpose the hazard matrix chart in Fig. 28 with the inclusion of components such as vegetation density, rock size, and slope height. This is based on the findings from the structural mapping, the stereonet plots, and the rockfall simulations discussed in early section of the study. The proposed chart is to capture aspects of the kinetic energy and the potential energy with the latter being an indicator of slope height.

Rock size is the next parameter included as part of the proposed chart; this is because the hazard level of a rockfall increases with the size of rock involved. Talking about vegetation coverage, it can be seen that this factor has been disregarded in the hazard rating of rockfalls along the road (see Fig. 23).

In this study, it was found that the density of vegetation contributes positively to the hazard rating of the rockfall along the roads. In fact, based on Fig. 24, a remotely sensed image of vegetation coverage of the study area was constructed. It was denoted that in most part of the study area was rockfall events has been reported in areas composed of bare land or in a transaction of bare-land to dry vegetation. Nevertheless, it was also discovered that there is some area with bare land but there is no rock fall, therefore, this observation gave researcher to look closely into other factors which might have interaction with vegetation coverage towards the influence of rockfall and the final deposit of the rockfall. Owing to that, it was also observed that in areas where the section is covered with bare-land, rock particles (pebble and boulders) were noted to be deposited on the other part of the road, while in bare-land to dry vegetation, the final deposit of rock pebbles or boulder where mostly at the toe of the road slope. This observation gave an impression that the rolling of the dislocked rock unit might have been affected by the density of the vegetation. It makes sense that when the vegetation is denser the rolling rocks are mostly sucked along the slope before the even reach the road, furthermore, the speed of the rolling rock can be reduced as it interacts with vegetation.

Nevertheless, the analysis and observation has proven that vegetation has some effect on the speed which the rolling rock unit came maintain, in fact, when there is high density of vegetation it is expected that the rolling rock speed will be reduced with distance, owing to that as the rock units rolls it interact with vegetation branches while reducing the speed of rock rolling.

The second aspects of interest were to looking into the impact of slope angle of the influence of rockfall initiation. Based on the remotely sensed images showing the slope angle of the study, it was observed all denoted rockfall points are within the slope angle ranging $35^\circ$ to $81^\circ$ (Fig. 25). The analysis has shown that the steepness of the slope could have contributed toward rockfall. Therefore, the numerical simulation together with remotely sensed images can be integrated to develop an improved hazard rating chart for rockfall.
Lastly, the hazard matrix was divided into three zones: low-risk, moderate risk, and high-risk zones. In the end, all the above were integrated in a compact manner in the proposed improved hazard matrix chart given in Fig. 26. The improved chart consisted of kinetic energy, potential energy (height), vegetation density, rock mass size and slope angle. The chart attempts to closely reproduce the reality of what is observed on the ground. However, the chart differs from its predecessors as it gives the user the ability to assess the rockfall hazards at different slope height and slope angle. This is important when comparison of sites is needed especially when other factors remain substantially unchanged. The other aspect of the proposed chart is that the impact of vegetation coverage on the rockfall rate can be explored.

All factors denoted across the chart were based on the numerical simulations, observations, remotely sensed information. Indeed, the chart appears to show realistic predictive tool which can be implemented in conditions which are similar to the presented study area.

The use of the improved hazard matrix chart to rockfall problems is discussed next to ascertain its performance. Consider the real-life case studies that the present study is based upon. It makes sense to start off by assuming for example a rock mass of 1200 kJ in kinetic energy detached from a slope of maximum height 20 m. Three scenarios can be considered in the area of study: low to very low vegetation density, moderate vegetation density, and high-density vegetation.

The new hazard matrix chart shows that rockfalls are rated as high-risk when the area is covered in low to very low density vegetation. However, as the vegetation increases to moderate density, the rockfall hazard rating falls under moderate risk zone. Further vegetation coverage upgrades the rating to that of a low-risk zone as shown in Fig. 27.

The second trial also revealed similar results as the first. Indeed, vegetation coverage helps reduce the hazard rating of rockfalls while acting as a blockage to rolling. Finally, one should note that the developed chart can be read from a rock size scale instead of vegetation density and vice-versa.

5. Schemes To Prevent Rock Falls

Based on the results of the study several suggestion has been documented to ensure rockfalls could be prevented in the study area. Such schemes include: Installation of areal coverage support system such as wire mesh, shotcrete among others and installation of roof bots across steep slopes within a square pattern. Nevertheless, the provided recommendations are not life time active system, the deteriorate with time and as such new support system has to be installed and by so doing the deterioration of the rockmass also occur and some loss rocks may fall during that process.

6. Conclusions

The aim of this study was to assess the hazard level of six sites identified along the R518 and R523 roads in the Thulamela Municipality. First, based on the in situ mapping, the study area was deemed a fair rock mass according to the rock mass rating system. In addition to this, the area is dominated with multiple geological features that create instability. The situation is further exacerbated by the low-density
vegetation and loose boulders in the area. It is anticipated that if no further remedial action is contemplated, the area should be considered as a high-risk zone area.

Second, geological features were performed using stereonet plot so as to identify potential wedges. The results showed that the study area consists of multiple wedges that could fall at any given time. Simulations were performed using the RocFall software to identify the factors that influence the final deposition of rock fragments. Slope height, vegetation density, and rockfall velocity were shortlisted as a result. This was later used to develop a new hazard matrix chart for rockfalls along highways and roads. The combination of surface measurement and numerical simulation was intended to bridge the gap the analysis of rockfall and its hazards prediction. The outcome of the endeavour was the development of an improved hazard rating chart that is inclusive of factors such as rock size or vegetation coverage. The proposed chart is expected to add new knowledge when used as a complementary tool to existing and established tools such as the ERHA chart. The next level of effort should be to perform detail analysis of cases with the new hazard rating chart. Equally important should be the development of techniques for the prediction of the time to failure.

**Declarations**

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**Conflict of Interest Statement**

The author wishes to confirm that there are no known conflicts of interest associated with this publication, furthermore, there has been no financial support given to influence the outcome of this work.

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Figures
Figure 1

Sentinel-2B true color image of the study area. Landslide locations are superimposed. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 2

Geological map of the study area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 3

(a-b). Poor quality rockmass with lose rock at the upper part of the road slope and very steep slope

Figure 4

(a-b). General view of Site two, with geological feature throughout
Figure 5

a-b. Stereonets of the studies rockmass showing the contour plots of the common discontinuities and the unstable kinematic patterns in Site 1

Figure 6

a-b. Stereonets of the studies rockmass showing the contour plots of the common discontinuities and the unstable kinematic patterns in Site 2
Figure 7

a-b. Stereonets of the studies rockmass showing the contour plots of the common discontinuities and the unstable kinematic patterns in Site 2

Figure 8

a-b. Stereonets of the studies rockmass showing the contour plots of the common discontinuities and the unstable kinematic patterns in Site 4
Figure 9

a-b. Stereonets of the studies rockmass showing the contour plots of the common discontinuities and the unstable kinematic patterns in Site 5

Figure 10

a-b. Stereonets of the studies rockmass showing the contour plots of the common discontinuities and the unstable kinematic patterns in Site 6
Figure 11

Rockfall trajectory of the designed slope with height of 5.5 m (b) Rockfall trajectory of the designed slope with height of 9.8 m.

Figure 12

(a) Rockfall trajectory of the designed slope with height of 12.5 m (b) Rockfall trajectory of the designed slope with height of 14.5 m
Figure 13

Rockfall trajectory of the designed slope with height of 19.0 m
Figure 14

Total kinetic energy distributed at the upper section on the slope

Figure 15

Total kinetic energy distributed at the slope toe
Figure 16

Total kinetic energy distributed at the bouncing shadow

Figure 17

Total kinetic energy distributed when hitting the ground for the second time
Figure 18
Total kinetic energy distributed as the rockmass re-start the rolling after re-bouncing

Figure 19
Total kinetic energy distributed at the upper section of the slope after the road
Figure 20

Total kinetic energy distributed at the river floor

Figure 21

1.5m/s total velocity distributed for a rockfall trajectory simulation, (b) 2m/s total velocity distributed for a rockfall trajectory simulation. The width of the study area road is about 12.5m
Figure 22

2.5m/s total velocity distributed for a rockfall trajectory simulation, (b) 3m/s total velocity distributed for a rockfall trajectory simulation. The width of the study area road is about 12.5m.

Figure 23

Hazard matrix (After, Lateltin et al., 2005; Ferrari et al., 2017)
Figure 24

Distribution of vegetation coverage in the study area.
Figure 25

Distribution of Slope angle across the study area.
Figure 26

Newly developed Hazard Matrix for Rockfall in Highways (roads)
Figure 27
Application of the newly developed hazard matrix for rockfall in highways (roads)

Supplementary Files
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- AppendixAandB.docx