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# Prediction of Rockfall from Highwall Slope in an Open Cast Mine

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## Abstract

*Rockfalls in mines represent one of the most hazardous events for miners, posing significant risks to safety, equipment, and operations. These incidents occur when rock or debris falls from the walls of a mine, often without warning, and can be triggered by geological factors, blasting practices, ground vibration, water infiltration, stress redistribution and time-dependent behaviour of rock. Apart from this, the bench parameters, such as the slope angle of the bench, the friction angle of the material, bench height and width, affect the rockfall. The rockfall incidents history that occurred in the past several years suggest that rockfalls in opencast mines led to the fatal injuries of many individuals. The problems faced due to rockfalls are not repetitive, but they are disastrous in opencast mines once they occur. So, it is necessary to investigate the rockfall in an opencast mining industry. It is also observed from the literature that the kinetic energy of a rockfall helps determine the intensity of rockfall in a mine. Understanding these factors and implementing preventive measures and rapid response strategies is crucial in mitigating rockfall risks. Hence, this study investigates rockfall phenomena in a high wall open cast by determining the kinetic energy of a rockfall. A parametric study has been conducted to determine the effect of various bench parameters on the kinetic energy of rockfall. A predictive model is developed to determine the kinetic energy of rockfall concerning various factors affecting rockfall. The predictive model is also validated using three case studies of high opencast mines. The results from the predictive model and the numerical model for the case study mines match the predictive model that can predict the rock fall intensity for opencast mines. The study also aims to assess the potential risks posed to workers, equipment, and infrastructure in highwall opencast mines. The findings provide valuable insights for implementing appropriate safety measures and developing effective strategies to mitigate rockfall hazards.*

**Keywords:** *Highwall, Kinetic Energy of Rock Fall, Opencast Mine, Rockfall*

## 1.0 Introduction

Rockfalls continue to be an ongoing issue in surface mining operations. The blend of natural factors and the methods used in mining contributes to this relentless challenge. They involve loosening rock, descent, and movement of a single piece of rock or multiple fragments, which primarily engage with the slope of an open cast mine, as depicted in Figure 1[1]. Typically, the movement of individual rock pieces involves limited interaction with each other, and rockfall is characterised by their swift nature that can cover extensive areas. Despite typically involving small amounts of material, their high velocity means that rockfalls can inflict considerable damage and potentially lead to loss of life.

Rockfall can be defined as follows. Falling, leaping, and rolling of individual rocks (Rock size < 50cm) and blocks (Rock size > 50cm), whereby the total volume does not exceed 100m$^2$. Rockfall is a natural phenomenon in which individual stones, pebbles, or boulders become dislodged from their original position and proceed to roll, slide, fall, or bounce down a slope. Sudden shifts of

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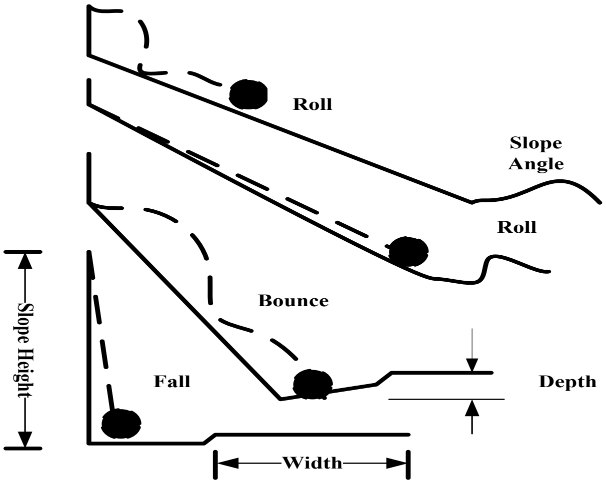


**Figure 1.** Rock falls on slopes[1].

individual blocks or clusters or isolated blocks or cohesive masses of unbroken rocks dislodged from steep inclines in a high wall opencast mine is a common phenomenon. A rockfall occurs when a portion of rock (referred to as a block) breaks away due to sliding, toppling, or falling from a vertical or nearly vertical cliff. It then descends the slope, either bouncing and flying in ballistic paths or rolling along talus or debris slopes[3]. This process involves the downhill motion of boulders (originating from natural inclines) or rock blocks (from man-made cuts), which, without adequate containment, can wreak havoc on structures in their trajectory or pose a significant hazard to public transportation routes[3-10].

In discussing the unique conditions of high wall mining operations, it's crucial to note that rock detachments can arise from natural slopes above the orebody and man-made slopes (such as benches and berms). Additionally, quarry operations, mainly using explosives, can instigate rock detachments. Moreover, the geometry of the quarry and the properties of the rock mass are in a state of constant evolution. Often, workers are required to perform tasks on benches, berms, and in quarry yards positioned beneath slope faces, sometimes for extended durations. It's observed that accidents related to rockfalls in a high wall mining operation typically result from a sequence of five factors: 1) The presence of a detached rock block on the quarry slope, 2) This block nearing its equilibrium threshold, 3) A triggering event causing the block to become unstable, 4) The trajectory of the falling block intersects with benches, quarry roads, or the yard at the base, and 5) The block impacts a worker or machinery in its descent[11].

The distribution of kinetic energy from rockfalls is critical in determining the appropriate type of protective structures needed to lower risk levels. This classification is guided by a danger map, where kinetic energy is segmented into three categories: Low (kinetic energy less than 30kJ), Moderate (kinetic energy between 30kJ and 300kJ), and High (kinetic energy greater than 300kJ[12].

In the event of a rockfall, individuals often find it impossible to dodge or take protective action, significantly elevating the risk of injuries and fatalities[13]. Rockfalls pose a critical threat to both human life and machinery and structures situated at the base of high walls in opencast mines, making them a major concern in such mining operations. The temporary halt of mining activities for safety evaluations due to rockfalls can lead to considerable economic impacts[14,15]. Although the direct costs linked to rockfalls may be lower compared to those related to extensive slope failures, the frequency and severity of accidents and fatalities they cause are alarmingly similar, a fact emphasised by numerous researchers. Moreover, these events can cause noteworthy financial losses due to the pause in production needed to address safety concerns[16].

Despite the implementation of safety measures, rockfall-induced incidents continue to occur. Between 2017 and 2021, six reported accidents were attributed to rockfalls, leading to 17 deaths and 4 injuries. This emphasises the critical need for comprehensive research into rockfall phenomena in opencast mines at this crucial time[17]. The accident statistics of the same is provided in Table 1.

Investigating rockfall in opencast highwall mines is a critical safety concern for mining operations. To mitigate these risks, numerical modelling can simulate the behaviour of rock masses and predict the likelihood and severity of rockfall incidents. The investigation involves collecting geological and geotechnical data and using it to create a digital model of the Highwall mine. This model can be used to perform numerical simulations and identify areas where rockfall is most likely to occur. In addition, numerical modelling can be used to assess the potential impact of a rockfall on mine infrastructure and personnel.

**Table 1.** Accident Analysis of Rockfall from 2017-2021[17]

| Sl. No. | Name of the Mine | Year | Number of Fatalities | Brief cause |
|---|---|---|---|---|
| 1 | Chosira/Bhot Range Marble Mine | 2017 | 03 | The accident occurred due to a fall off the side having a height of about 10-15M. |
| 2 | Rewat Dungri Range Marble mine | 2018 | 02 | A mass of rock from a hanging wall measuring 6m suddenly fell through a height of about 36m |
| 3 | Jamdiha Stone Mine | 2018 | 01 | Falling of a thick stone piece measuring from a height of 13 to 15m |
| 4 | Granite Building stone Quarry mine | 2020 | 02 | Falling a mass of stone |
| 5 | Rampura Agucha Mine | 2021 | 02 | Heavy boulders Detached |
| 6 | Mining site quartz stones, Lachhuda village, Bhilwara district of Rajasthan | 2021 | 07 | Stone mine collapsed |

Overall, this research investigates the rockfall potentiality in high wall opencast mines using numerical modelling and developing a predictor equation to estimate the rockfall in advance, which is essential for ensuring the safety of mining operations. By identifying potential hazards and developing effective mitigation strategies, mining operators can prevent accidents and minimise the impact of rockfall incidents, ultimately leading to a safer and more efficient mining operation.

## 2.0 Numerical Modelling

Numerical modelling serves as an effective instrument for examining rockfall phenomena in high wall open cast mines. These models are capable of replicating various conditions and forecasting potential rockfall threats. This enables mining engineers to pinpoint high-risk zones and implement suitable strategies to either prevent or lessen the risk effectively. In this study, RocFall$^{3D}$ has been used to study the bench geometry on rockfall in a mine[18].

### 2.1 Selection of Material

Selecting rock types for rockfall analysis in high wall open cast mines is essential to accurately assess the potential rockfall hazards and design effective rockfall protection measures. The rock types commonly used for rockfall analysis in opencast mines include granite, marble, schist, basalt, slate, limestone, gneiss, sandstone, and dolerite, as these are typically found in the mine area and have different characteristics that affect rockfall behaviour.

The range of applications for rockfall analysis with these methods encompasses calculating the potential energy of descending rocks, forecasting the path and speed of these falling rocks, and evaluating the efficacy of rockfall protective strategies. Additionally, this analysis helps pinpoint high-risk areas and formulate suitable mitigation tactics to diminish the dangers associated with rockfalls.

Each rock type has its specific characteristics that can affect rockfall behaviour. For example, granite is typically solid and durable, while marble is relatively weak and prone to weathering. Basalt is often characterised by its columnar jointing, while slate has a strong foliation and can be prone to splitting along planes. Limestone can have various properties depending on its depositional environment, and dolerite can be prone to jointing and fracturing.

## 2.2 Influencing Factors Used in the Model

The following are the factors considered in the model:

### 2.2.1 Angle of Slope

As highlighted in the literature review, the geometry of the slope significantly influences rockfall behaviour, with slope angle being a key parameter examined in parametric studies. Three distinct scenarios based on slope angle emerge: (1) for angles less than 45°, rocks tend to roll, (2) for angles ranging from 45° to 75°, rocks accelerate and bounce, and (3) for angles exceeding 76°, rocks free fall directly from the slope's peak[19]. So, the range for slope angle taken for creating a model is 30°-90° with an interval of 10°.

### 2.2.2 Bench Height

As mentioned in the literature survey, slope geometry plays an essential role in rockfall, as Bench height is one of the parameters of a slope geometry taken for parametric study. According to the DGMS statutory, a bench height above 6.5m is considered a high wall. Hence, the range bench height is 10m-60m at an interval of 10m.

### 2.2.3 Bench Width

As mentioned in the literature survey, slope geometry plays an essential role in rockfall, as bench width is one of the parameters of a slope geometry taken for a parametric study, which ranges from 6 m to 18 m at intervals of 6m.

### 2.2.4 Friction Angle

The friction angle can estimate the potential energy of falling rocks and the distance they may travel before coming to rest. The range of friction angle taken for modelling is 20°- 40° (Patton, 1966) at the interval of 5° as shown in Table 2.

## 2.3 Simulation of Highwall in RocFall$^{3D}$

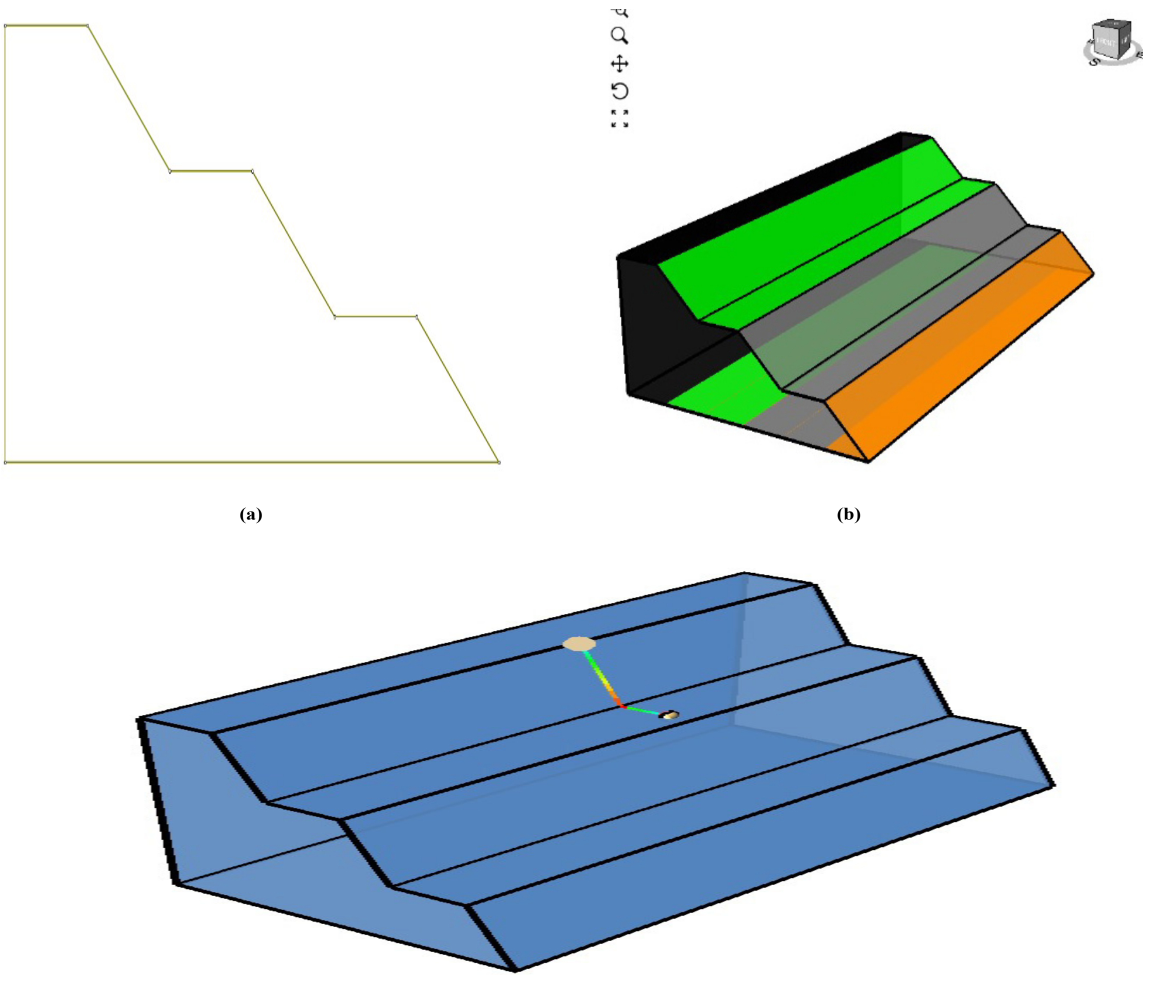
The simulation of benches is done using RocFall$^{3D}$ (RocScience, 2000), considering a case study M/s. Big Rock Quarry & Crushers (Pvt) Ltd., Ekarool P.O, Balussery, Kozhikode District, Kerala, which forms part of the Malabar region of Kerala, predominantly a land of hills and valleys. The simulation of the model involves a) the formation of benches, b) assigning material properties, and c) Estimating the rockfall, as shown in Figures 2 (a) – (c). Normal restitution and tangential restitution are considered to be 0.35 and 0.85. The material properties are considered as mentioned in Section 2.2.

# 3.0 Parametric Study

Investigating rockfall in a highwall open cast mine using Rocfall$^{3D}$ software involves using computer modelling software to simulate potential rockfall scenarios in the

**Table 2.** Range of parameters used in the study

| Bench height | Bench width | Slope angle | Friction angle |
|---|---|---|---|
| 10m, 20m, 30m, 40m, 50m, 60m | 6m, 12m, 18m | 30°, 40°, 50°, 60°, 70°, 80°, 90° | 20°, 25°, 30°, 35°, 40° |



(a)

(b)

(c)

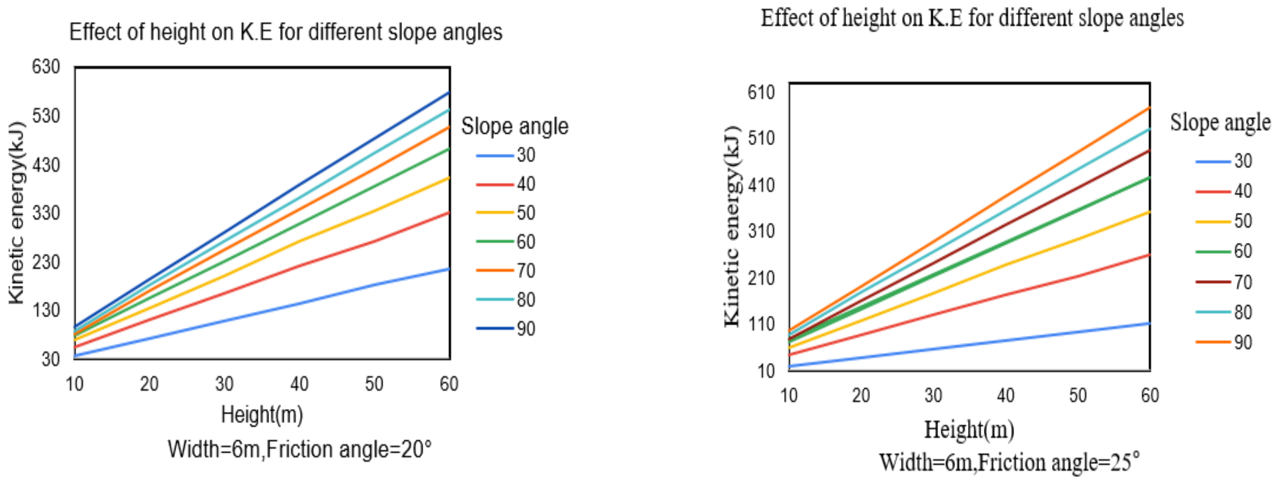
**Figure 2.** Step-by-step modelling procedure to determine the Rockfall. **(a)** Formation of the bench, **(b)** Assigning material properties **(c)** Rockfall prediction in Rocfall$^{3d}$.

mine. The software uses data on the parameters of slope geometry such as bench height, Bench width, slope angle, and rock parameters like friction angle, factors that can affect the intensity of the rockfall. By inputting this data into the software, engineers and geologists can simulate various scenarios, including the size and trajectory of potential rockfalls, and evaluate the risk to personnel and equipment working in the mine. The results of the RocFall$^{3D}$ modelling can help mine operators make informed decisions about the safety of the mine and the need for additional safety measures. It can also help identify areas of the mine that may require more frequent monitoring or maintenance to ensure the safety of workers and equipment.

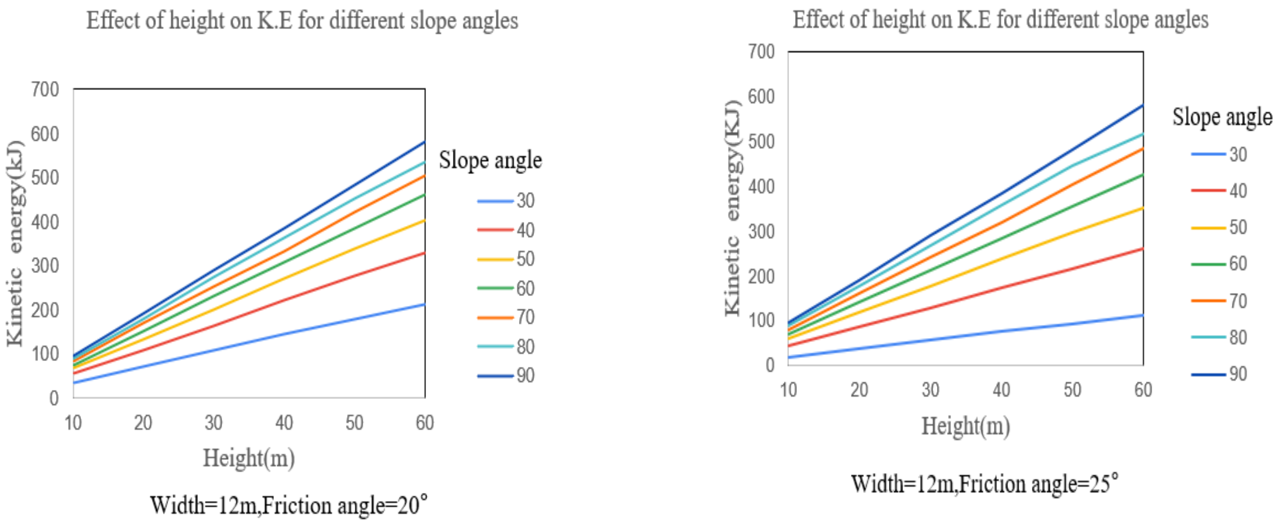
From the parametric study of Kinetic energy, the results of the simulated models show that as the slope height and angle increase, the kinetic energy of falling rock increases. It observed that friction angle increases the kinetic energy of falling rock decrease, but as slope angle increases, friction angle has lesser impact on kinetic energy, which means that kinetic energy increases with a material having high friction angle when the slope angle is high. It is observed that bench width does not influence the kinetic energy of falling rock.

### 3.1 Effect of Height on Kinetic Energy for Different Slope Angles

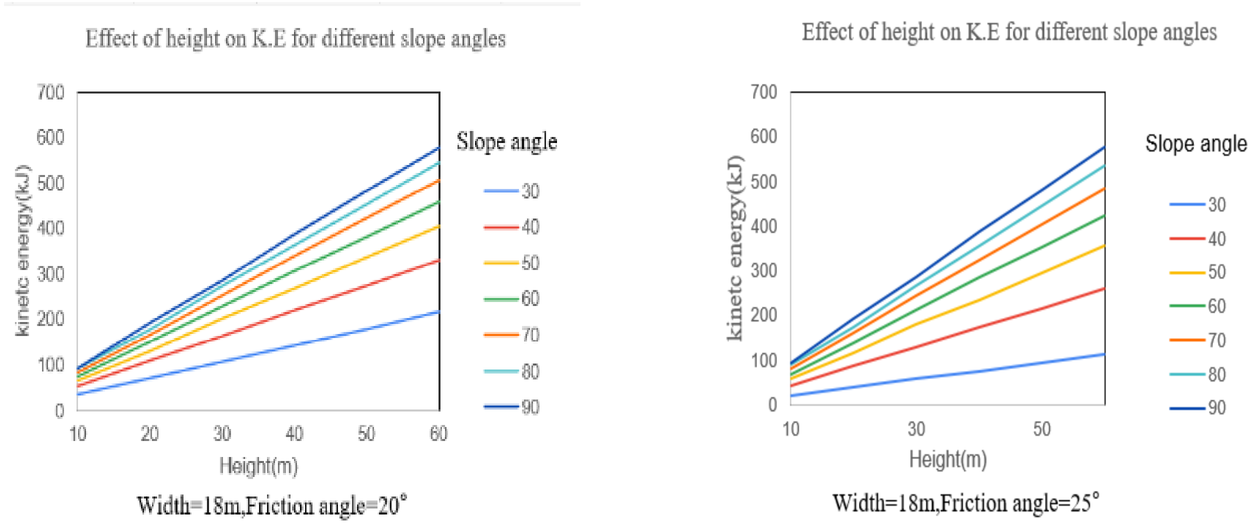
The graph represents the effect of height on kinetic energy for different slope angles, which shows that for a constant bench width and friction angle, with increasing the height of the slope, kinetic energy increases, and also, as slope angle increases, kinetic energy increases, which show in Figures 3 (a) - (c).



(a)



(b)

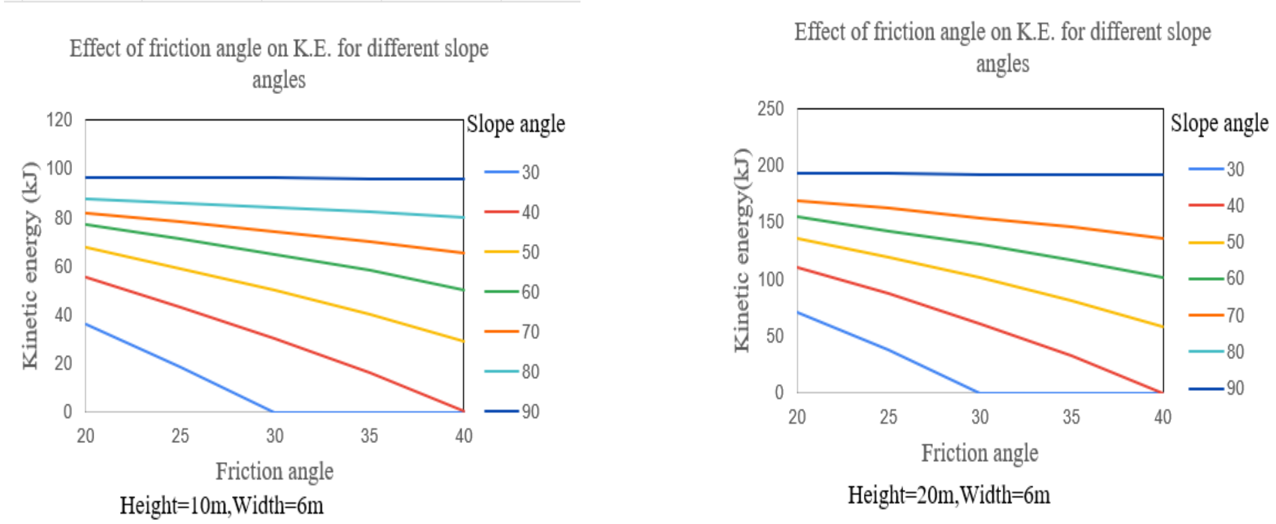


**(c)**

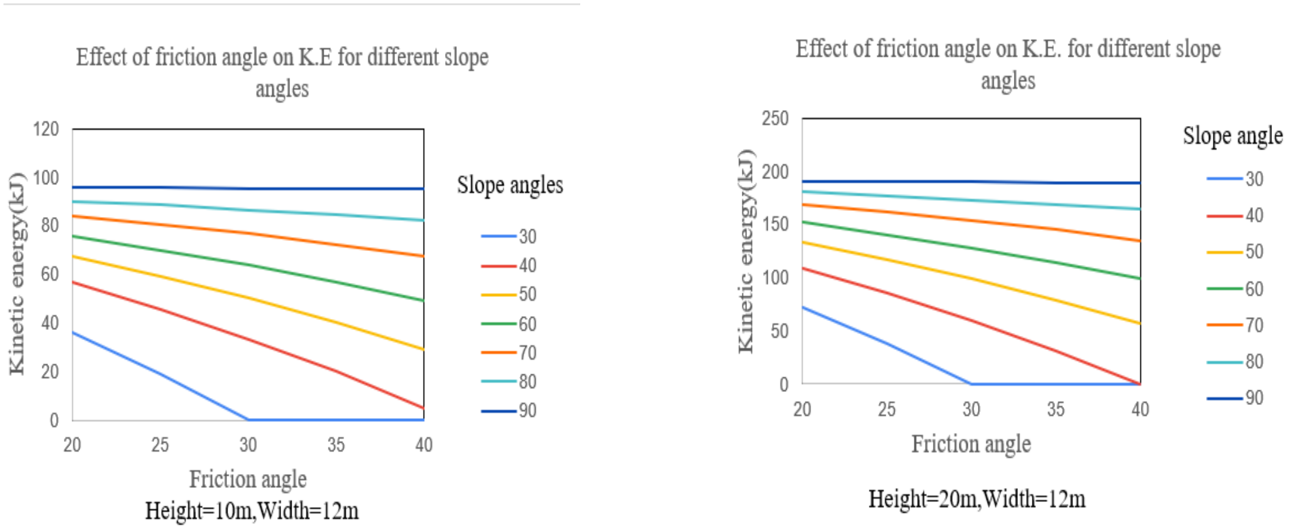
**Figure 2.** **(a)** Effect of height on kinetic energy for different slope angles with width(6m), friction angle (20°-40°), **(b)** Effect of height on kinetic energy for different slope angles with width(12m), friction angle (20°-40°), **(c)** Effect of height on kinetic energy for different slope angles with width(18m), friction angle (20°-40°).

## 3.2 Effect of Friction Angle on Kinetic Energy for Different Slope Angles

The graph represents the effect of friction angle on kinetic energy for different slope angles, which shows that for a constant bench height and bench width, with increasing the friction angle of material, kinetic energy decreases. However, as the slope angle increases, the friction angle has less impact on kinetic energy, which is shown in Figures 4 (a) - (c).



**(a)**



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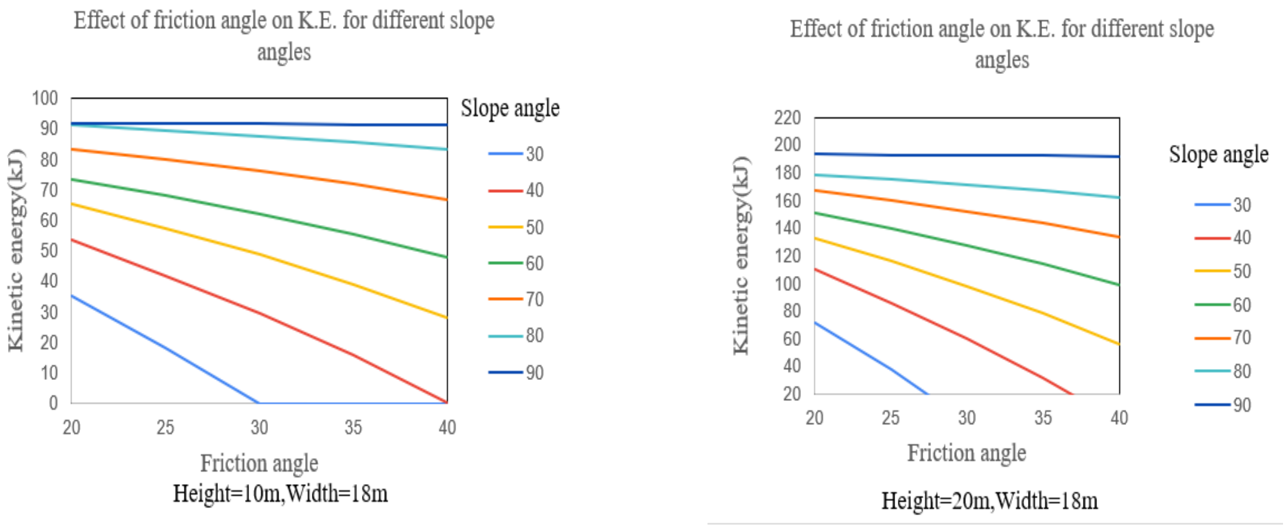
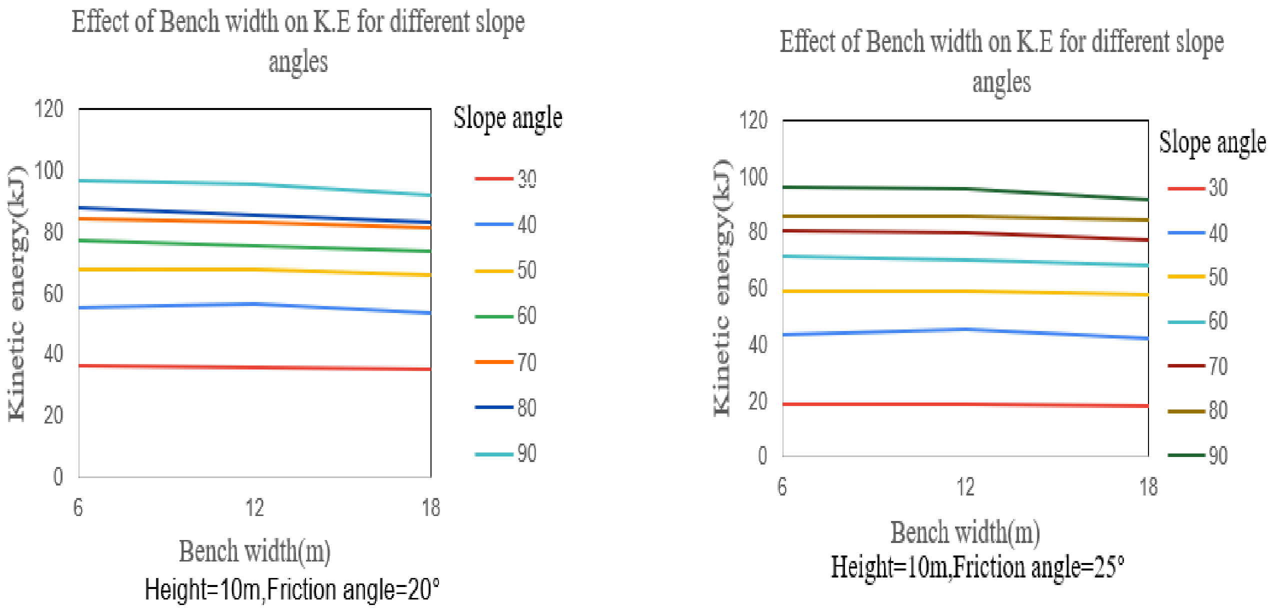


**(c)**

**Figure 4.** **(a)** Effect of friction angle on kinetic energy for different slope angles with width (6m), and height(10m-60m). **(b)** Effect of friction angle on kinetic energy for different slope angles with width (12m), and height (10m-60m). **(c)** Effect of friction angle on kinetic energy for different slope angles with width (18m), and height(10m-60m).

## 3.3 Effect of Bench Width on Kinetic Energy for Different Slope Angles

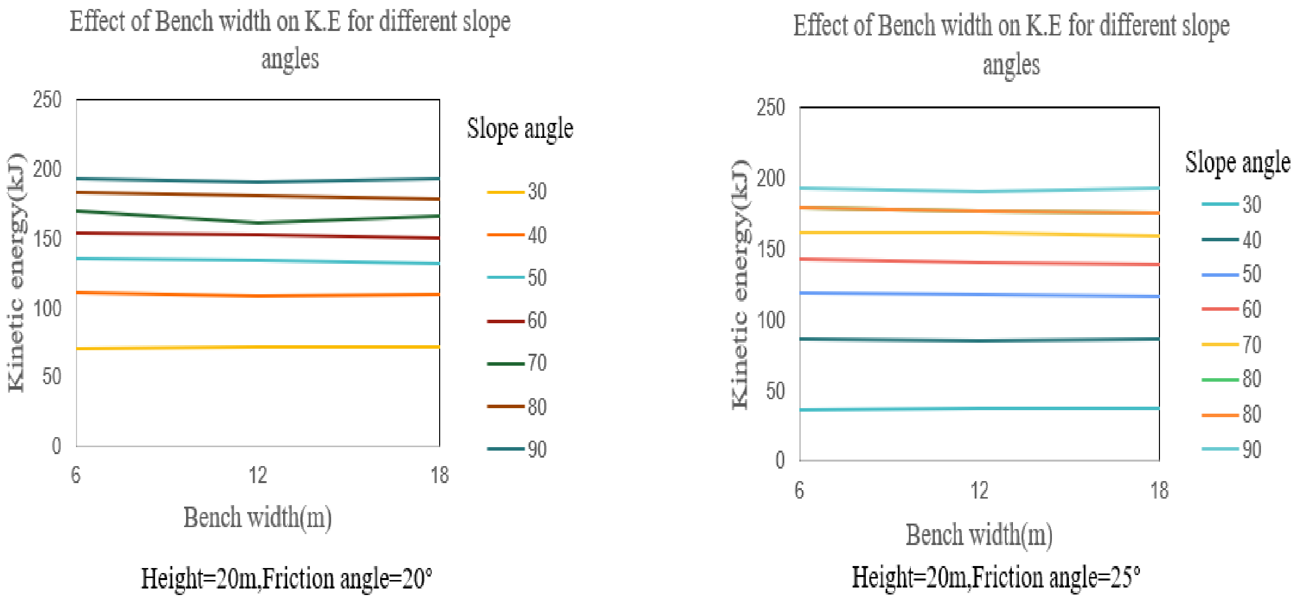
The graph represents the effect of bench width on kinetic energy for different slope angles, which shows that a constant height and friction angle with changing bench width does not have much impact on kinetic energy, and as slope angle increases, kinetic energy increases, which are shown in Figures 5 (a) - (f).



Height=10m,Friction angle=20°

Height=10m,Friction angle=25°

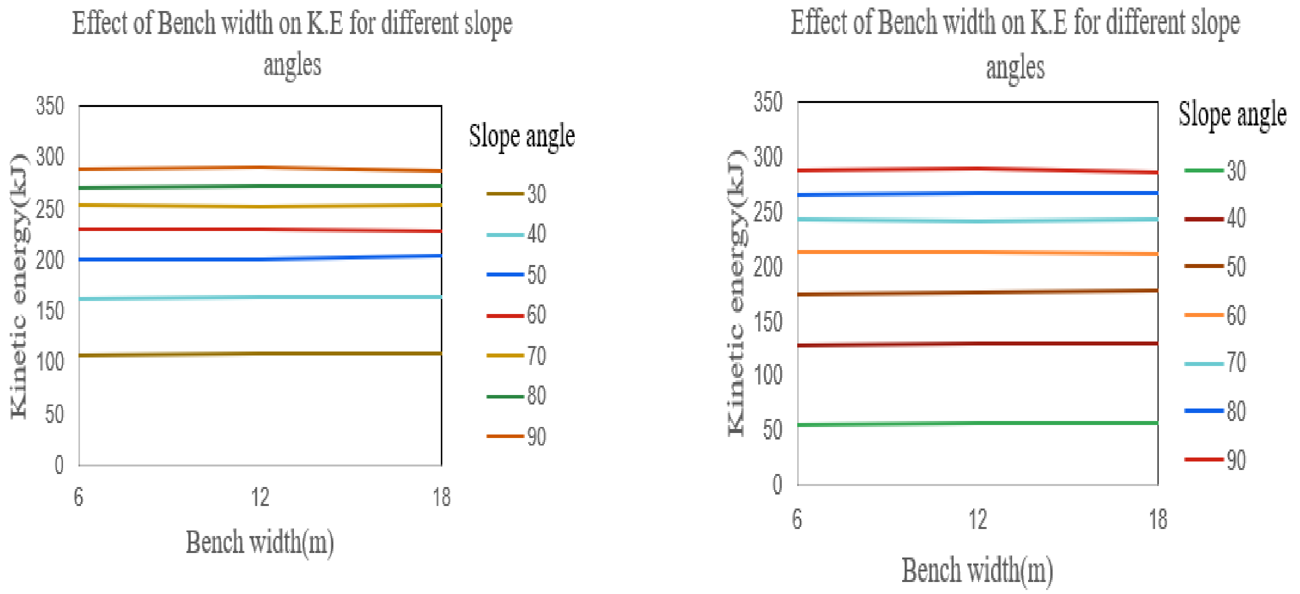
**(a)**



Height=20m,Friction angle=20°

Height=20m,Friction angle=25°

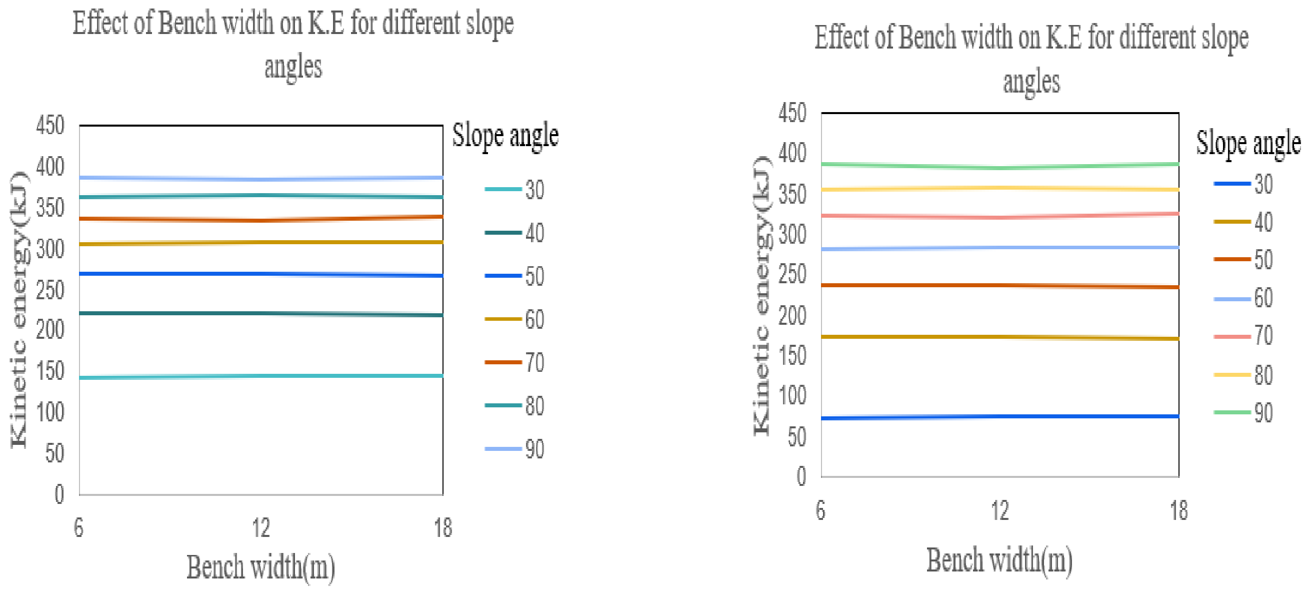
**(b)**



Height=30m,Friction angle=20°

Height=30m,Friction angle=25°

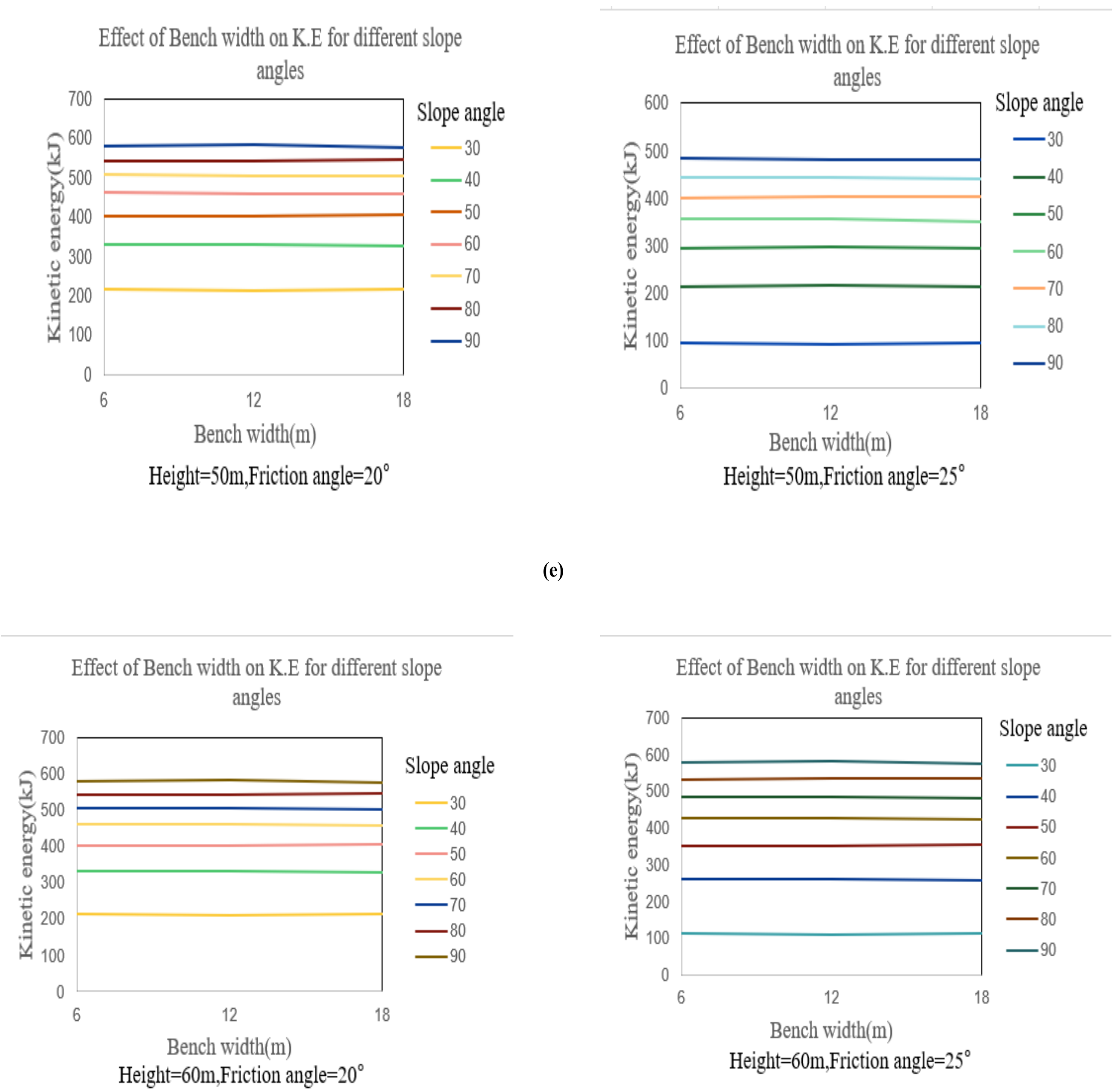
**(c)**



Height=40m,Friction angle=20°

Height=40m,Friction angle=25°

**(d)**



(e)

(f)

**Figure 5.** **(a)** Effect of bench width on kinetic energy for different slope angles with height(10m), friction angle (20°-40°), **(b)** Effect of bench width on kinetic energy for different slope angles with height(20m), friction angle (20°-40°), **(c)** Effect of bench width on kinetic energy for different slope angles with height(30m), friction angle (20°-40°) **(d)** Effect of bench width on kinetic energy for different slope angles with height(40m), friction angle (20°-40°), **(e)** Effect of bench width on kinetic energy for different slope angles with height(50m), friction angle (20°-40°), **(f)** Effect of bench width on kinetic energy for different slope angles with height(60m), friction angle (20°-40°).

## 4.0 Predictive Model

The models are developed to predict the rockfall intensity based on the concept of kinetic energy by the regression modelling from the parametric study results. Regression modelling is a suitable tool for deriving a predictive equation when there is a complicated interaction between two or more variables. Statistical regression analysis methods have been used for the prior estimation and prediction of problems in various facets of engineering. Based on this, regression analysis can be extensively used in mining. Regression analysis is done to determine the relationship between predictors and response variables. The number of complex interactions between the dependent and predictor variables will decide the model's performance. The identified influential parameters through the numerical simulation-based parametric study are slope height, bench width, friction angle, and angle of the slope, which are considered for regression modelling, and best-fit interactions among them are determined. After a detailed literature review, linear regression analysis is considered in this research work. Linear regression modelling estimates the kinetic energy and determines the influence and significance of parameters on the desired response[20].

Linear regression analysis is performed using the SPSS software package to predict the kinetic energy equation considering parameters like slope height, bench width, friction angle, and slope angle. The response considered is kinetic energy. The linear regression model for kinetic energy is generally expressed with the standard equation like $Y = b1\ (x1, x2, x3 \ldots) + b_o$ where Y is the dependent, b1 = slope of the line, x1, x2, x3 are the predictor variables, and b0 is constant. The generalised equation used to represent the response is given by Equation (4.1).

$$Y=\Sigma_0^n X_n+C_0 \qquad (1)$$

The predictive Model for predicting kinetic energy using the linear regression model is shown in Equation (2). Input Parameters for regression analysis for a rockfall are slope height, bench width, friction angle, and slope angle; the output parameter is kinetic energy. It is observed that the estimated standardised beta coefficient (β) for slope height, bench width, slope angle, and friction angle are 0.807, -0.107,1.059, and -0.841, respectively, as shown in Table 3. The obtained equation for kinetic energy is given by Equation (2).

$$K.E = 0.807H + 1.059\theta - 0.841\phi - 0.107W \qquad (2)$$

where K.E express kinetic energy in kJ, H is the height in meters, θ is the slope angle in degree, Φ is the friction

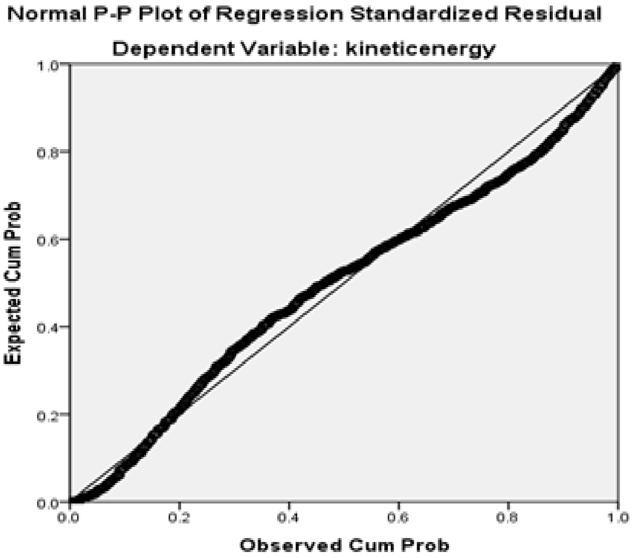


**Figure 6.** Normal probability plot of expected cum probability versus observed cumulative probability of kinetic energy.

**Table 3.** Variables in the predictive Model for kinetic energy (KE)

| Variables in the equation | Standardised Beta Coefficient (β) | Standardised Error |
|---|---|---|
| Friction angle | -0.841 | 0.267 |
| Slope angle | 1.059 | 0.113 |
| Bench width (m) | -0.107 | 0.487 |
| Slope height (m) | 0.807 | 0.807 |

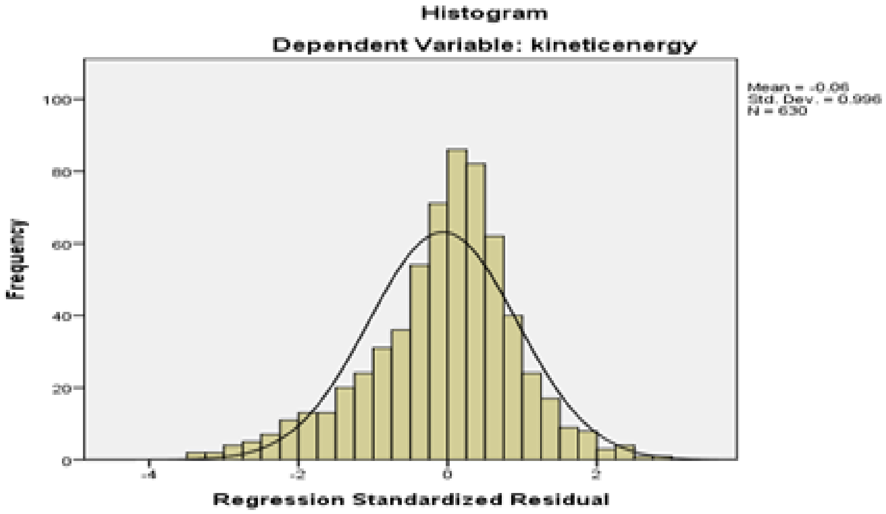


**Figure 7.** Normal distribution of the frequency versus standardised regression residual of kinetic energy.

angle of the material, W is the bench width in meters, and the $R^2$ of the predictive model is 0.936.

Out of 4 parameters, the standardised beta coefficient is positive in the case of slope height and slope angle, whereas the slope's friction angle and bench width are negative. The positive value in the standardised beta coefficient indicates slope height, Slope angle, and kinetic energy increase. The negative value in the standardised beta coefficient of friction angle indicates that kinetic energy decreases as friction angle increases.

Figure 6 represents the Normal distribution of the frequency versus standardised regression residual of kinetic energy; hence, the obtained equation is valid and reliable and can be considered for future rockfall prediction in different opencast mines. Figures 6 and 7 indicate that the model is realistic, reasonable, and well-fitting.

## 5.0 Validation

The regression model is validated by considering three case study mine: Big Rock Quarry and Crushers Limited, Black Diamond Rock Products Limited and V K Rocks Private Limited. The statistical models developed based on the kinetic energy of rockfall are used to predict the intensity of the rockfall hazard of the mines. A numerical model is simulated for a geometry slope of the below-mentioned case studies, and it is validated by results obtained by the regression model and the results obtained by the RocFall$^{3D}$.

### 5.1 Big Rock Quarry and Crushers (Pvt) Ltd

The study was carried out at a granite building stone quarry of M/s. Big Rock Quarry and Crushers (Pvt) Ltd., Ekarool

**Table 4.** Bench parameters of M/s. Big Rock Quarry and Crushers (Pvt) Ltd

| **Bench Height** | **Bench width** | **Slope angle** | **Friction angle** | **K.E through the Regression model** | **K.E through Rocfall software** | **RockFall Prediction** (Jaboyedoff *et al.,* 2005) |
|---|---|---|---|---|---|---|
| 6m | 6m | $65^0$ | $31^0$ | 46.96 kJ | 47.78 kJ | Moderate |

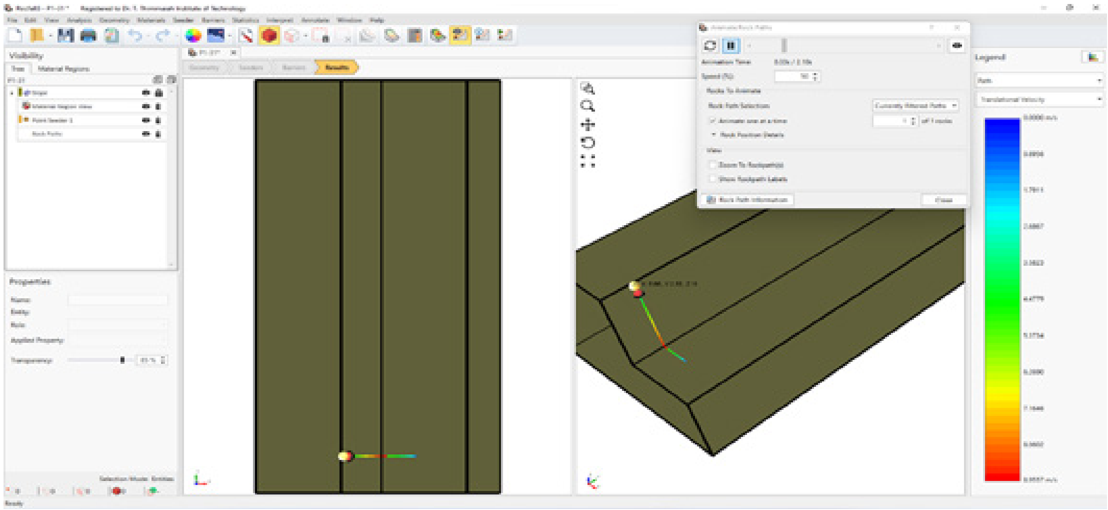


**Figure 8.** The model of granite building stone quarry.

P.O, Balussery, Kozhikode District, Kerala, which forms part of the Malabar region of Kerala, predominantly a land of hills and valleys. The mine works with the conventional opencast method with a bench system, and the mode of operation is semi-mechanised. Considering the chosen mode and method and the geological characteristics of the ore body, the quarry pit is configured with benches maintained at approximately 6 meters in height and width and a slope angle of $65^0$. Figure 8 illustrates the model of the case study for this particular mine.

The kinetic energy calculated for the M/s. Big Rock Quarry & Crushers (Pvt) Ltd is, through the developed predictive model, 46.974 kJ, and from the numerical model, 47.37 kJ, as shown in Table 4. Suggesting that the rockfall occurrence would be in the moderate range in both models.

It observed that the results obtained from the regression model and software are approximately equal, so the predicted model is valid.

## 5.2 Black Diamond Rock Products Limited

The research site is located in Ayyampuzha, Ernakulam District, within the Malabar region of Kerala, which is characterised by its hilly terrain and valleys. Ernakulam specifically denotes the mainland area of the dual cities of Ernakulam and Kochi in central Kerala, India. In alignment with the selected mode and method, and considering the geological attributes of the ore body, the quarry pit is structured with benches reaching a maximum height of approximately 5 meters and a minimum width of 5 meters while maintaining a slope angle of $70^0$ from the horizontal. The model. The model of the case study for this mine is shown in Figure 9.

The kinetic energy calculated for Black Diamond Rock Products Limited through the developed predictive model is 51.559 kJ, and from the numerical model is 52.78 kJ, as shown in Table 5. Suggesting that the rockfall occurrence would be in the moderate range in both models.

**Table 5.** Bench parameters of black diamond rock products limited

| **Bench Height** | **Bench width** | **Slope angle** | **Friction angle** | **K.E through the Regression model** | **K.E through Rocfall software** | **RockFall Prediction** (Jaboyedoff et al., 2005) |
|---|---|---|---|---|---|---|
| 5m | 5m | $70^0$ | $31^0$ | 51.55 kJ | 52.78 kJ | Moderate |

It observed that the results obtained from the regression model and software are approximately equal, so the predicted model is valid.

### 5.3 V K Rocks Private Limited

The study area is located in Pooyapally, Kollam District, an old seaport and city onthe Laccadive Sea coast of the Indian state of Kerala. The mine is at a distance of 13 Km from Kottarakkara and 25 Km from Kollam. The mine uses the conventional opencast method, a bench system, and mechanised operations. By this mode and method, and taking into account the geological characteristics of the ore body, the quarry pit is structured with benches reaching a maximum height of around 7 meters and a minimum width of 5 meters while maintaining a slope angle of $54^0$ from the horizontal. The model of the case study for this mine is shown in Figure 10.

The kinetic energy calculated for V K Rocks Private Limited is through the developed predictive model,36.22 kJ, and from the numerical model is 38.10 kJ, as shown in Table 6. Suggesting that the rockfall occurrence would be in the moderate range in both models.

It observed that the results obtained from the regression model and software are approximately equal, so the predicted model is valid.

## 6.0 Conclusion

In this study, the intensity of rockfall is determined by using parameters like bench height, Bench width, Slope angle, and Friction angle. Results from simulated models based on the parametric study can conclude that as the slope angle increases, the intensity of rockfall increases, and as the friction angle increases, the intensity of rockfall decreases. A slope having a high friction angle has a lesser impact on the intensity of the rockfall when the slope angle is higher, and bench width has no impact on the intensity of a rockfall. Using the 630 models created in

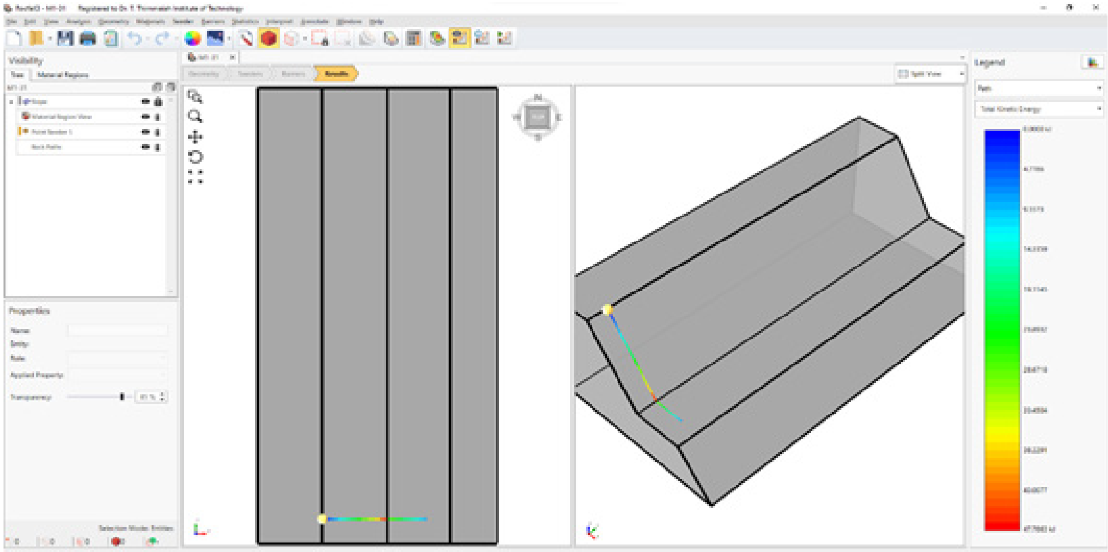


**Figure 10.** Model of V K Rocks Private Limited.

**Table 6.** Bench parameters of black diamond rock products limited

| **Bench Height** | **Bench width** | **Slope angle** | **Friction angle** | **K.E through the Regression model** | **K.E through Rocfall software** | **RockFall Prediction** (Jaboyedoff et al., 2005) |
|---|---|---|---|---|---|---|
| 5m | 5m | $70^0$ | $31^0$ | 36.22 kJ | 38.10 kJ | Moderate |

Rockfall software, Linear regression analysis is performed using the SPSS software to determine the predictive model for the intensity of rockfall. The predictive models were developed to predict the intensity of rockfall. Based on the predicted model for kinetic energy, the parameters that influence the order are slope angle, slope height, friction angle, and bench width, respectively. In the validation study, the predicted equation to find the intensity of a rockfall is applied by taking a case study of 3 case study mines. The results from the predictive model are compared by creating a model in Rocfall$^{3D}$ software. Both results are approximately equal, so the predicted equation is reliable and valid. The results suggest that the 3 case study mines have a chance of moderate rock fall during mining based on the predictive and numerical models. Hence, based on the above results, it can be concluded that the predictive model to determine the intensity of rockfall can be used in the field to determine the intensity of rockfall hazards. Determining the kinetic energy of rockfall helps with safety concerns, and efforts are made to minimise or control rockfall events to ensure the well-being of workers and the efficiency of mining operations. Furthermore, the findings of this investigation will contribute to improving safety protocols, geotechnical design, and environmental management strategies in highwall opencast mines. The results will aid in developing effective rockfall prevention and control measures, enhance worker safety, optimise mining operations, and ensure sustainable mining practices.

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## 8.0 References

1. Fanos AM, Pradhan B. Laser scanning systems and techniques in rockfall source identification and risk assessment: A critical review. Earth Syst Environ. 2018; 2(2):163-82. https://doi.org/10.1007/s41748-018-0046-x
2. Gerber W. Guideline for the approval of rockfall protection kits. SAEFL, Documentazione; 2001.
3. Varnes DJ. Slope movement types and processes. Transportation Research Board Special Report. 1978; 176:11-33.
4. Price DG, Knill JL. The engineering geology of Edinburgh Castle rock. Geotechnique. 1967; 17(4):411-32. https://doi.org/10.1680/geot.1967.17.4.411
5. Chen H, Chen RH, Huang TH. An application of an analytical model to a slope subject to rockfalls. Bull Int Assoc Eng Geol. 1994; 31(4):447-58. https://doi.org/10.2113/gseegeosci.xxxi.4.447
6. Labiouse V, Descoeudres F. Possibilities and difficulties in predicting rockfall trajectories. Joint Japan-Swiss scientific Seminar on impact load by rock falls and design of protection structures, Kanazawa; 1999.
7. Bozzolo D, Pamini R. Simulation of rock falls down a valley side. Acta Mech. 1986; 63(1):113-30. https://doi.org/10.1007/BF01182543
8. Guzzetti F, Crosta G, Detti R, Agliardi F. STONE a computer program for the three-dimensional simulation of rock-falls. Comput Geosci. 2002; 28(9):1079-93. https://doi.org/10.1016/S0098-3004(02)00025-0
9. Lee K, Elliott G. Rockfall: Application of computer simulation to design of preventive measures, planning, design and implementation of debris flow and rockfall hazards mitigation measures. Association of Geo-Technical Specialists and Hong Kong Institution of Engineers, Hong Kong; 1998.
10. Berger F, Dorren L. Objective comparison of rockfall models using real size experimental data. Disaster mitigation of debris flows, slope failures and landslides. 2006: 245-52.
11. Alejano LR, Stockhausen HW, Alonso E, Bastante FG, Oyanguren PR. ROFRAQ: A statistics-based empirical method for assessing accident risk from rockfalls in quarries. Int J Rock Mech. 2008; 45(8):1252-72. https://doi.org/10.1016/j.ijrmms.2008.01.003
12. Jaboyedoff M, Dudt JP, Labiouse V. An attempt to refine rockfall hazard zoning based on the kinetic energy, frequency and fragmentation degree. Nat Hazards Earth Syst Sci. 2005; 5(5):621-32. https://doi.org/10.5194/nhess-5-621-2005
13. Schumm SA, Chorley RJ. The fall of threatening rock. Am J Sci. 1964; 262(9):1041-54. https://doi.org/10.2475/ajs.262.9.1041

14. Ferrari F, Giacomini A, Thoeni K. Qualitative rockfall hazard assessment: A comprehensive review of current practices. 2016: 2865-922. https://doi.org/10.1007/s00603-016-0918-z
15. Ferrari F, Giacomini A, Thoeni K, Lambert C. Qualitative evolving rockfall hazard assessment for highwalls. Int J Rock Mech. 2017; 98:88-101. https://doi.org/10.1016/j.ijrmms.2017.07.013
16. Giacomini A, Thoeni K, Santise M, Diotri F, Booth S, Fityus S, *et al*. Temporal-spatial frequency rockfall data from open-pit highwalls using a low-cost monitoring system. Remote Sens. 2020; 12(15). https://doi.org/10.3390/rs12152459
17. DGMS. https://dgms.gov.in/
18. RocScience. RockFall Software for risk analysis of falling rock on steep slope. RocScience Inc., Toronto; 2000.
19. Ritchie AM. Evaluation of rockfall and its control. Highway Research Record. 1963.
20. Raja S. Influence of structural discontinuities on slope stability [Dissertation, M.Tech Thesis], Karnataka India: National Institute of Technology; 2013.