IJSCET

INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
ISSN: 2180-3242 e-ISSN: 2600-7959

Vol. 17 No. 1 (2026) 288-302
https://publisher.uthm.edu.my/ojs/index.php/ijscet

Optimal Slope Angles and Berm Configurations for Rockfall Hazard Reduction Using Discrete Element Modelling and Statistical Analysis

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DOI: https://doi.org/10.30880/ijscet.2026.17.01.018

Article Info

Received: 29 November 2025
Accepted: 12 March 2026
Available online: 23 July 2026

Keywords

Rockfall, slope angles, discrete element method, statistical analysis, destruction distance, kinetic energy

Abstract

Construction on hilly terrains in Malaysia increases the risk of rockslides, which pose a threat to lives and infrastructure. Despite extensive studies on rockfall dynamics, the influence of slope angles on the destructive reach and kinetic energy (KE) of falling boulders remains unclear. This study aims to identify the slope angles that influence impact distance and KE across various slope geometries, providing valuable insights for protective design measures. Slope angles (ranging from 15º to 90º) and ratios, as defined by the Jabatan Kerja Raya Malaysia (JKR) standards, were analysed using the Discrete Element Method (DEM) and statistical analysis. The study took into account slope angles, slope ratios, and boulder properties. The results indicated that destruction distance peaks at a slope angle of 60°, with the most hazardous slopes occurring between 45° and 60°. KE increased significantly between 35° and 60°, with the near-vertical slopes (up to 90°) generate the highest energy due to greater gravitational forces. Slope ratios of 1:1 and 2:1 produce longer destruction distances and higher KE values, with the 2:1 ratio (63.43°) being particularly critical. Berms were found to effectively reduce both the destruction distance and KE, particularly at slope ratios of 3:1 and 4:1. These findings provide quantitative design guidance on critical

slope angles and berm configurations for reducing rockfall hazards based on DEM modelling aligned with JKR slope design standards.

1. Introduction

In recent years, housing and infrastructure construction on hilly terrain in Malaysia has placed significant emphasis on slope engineering due to the shortage of flat or gently undulating land. This shift was prompted by the devastating Highland Towers landslide in 1993, which resulted in significant loss of life and highlighted the vulnerabilities associated with development on steep terrain. Since then, Malaysia has experienced a series of landslides and rockslides, many of which have been linked to the practice of cutting into mountainsides and hilly regions for high-rise construction [1-2]. In addition, human activities such as deforestation, slope excavation for road construction, and land clearing for agriculture and infrastructure development have placed further strain on hill slope areas and contributed to the occurrence of landslides and rockslides [2-5]. These hazards cause substantial economic losses each year and pose serious threats to public safety and infrastructure [2,5]. As development continues to expand into mountainous regions, exposure to rockfall hazards has increased significantly, making the understanding and management of rockfall risks an important challenge in slope engineering and hazard mitigation [6-7].

Rockfalls are a common type of landslide in the tropical hilly regions such as those found in Malaysia, posing significant risks to infrastructure and public safety. A rockfall occurs when a portion of rock detaches from the slope and slides, topples, or falls from the slope face, often bouncing, rolling, or flying along its path [8]. This rapid movement process can result in significant travel distances, leaving little time for evacuation or protective measures and increasing the risk of injuries and fatalities. Predicting rockfall behavior remains challenging due to the complexity of controlling factors, including variability in slope geometry, poorly defined initial conditions, uncertain material properties, and the sensitivity of analysis methods to small variations in input parameters [8-10].

Once a rock begins to move downslope, slope geometry becomes one of the primary factors controlling its trajectory and motion characteristics. Key geometrical parameters such as slope angle, slope height, and curvature significantly influence the movement characteristics of falling rocks, including their velocity, kinetic energy, and travel distance [11-14]. These parameters directly affect rockfall trajectory, impact energy, and runout behavior during rockfall events. Therefore, understanding the influence of slope geometry on rockfall behavior is essential for the design and implementation of effective mitigation strategies.

Slope modification techniques such as benching and berm construction are widely applied in slope engineering to reduce rockfall hazards [15]. Berms act as intermediate barriers that intercept falling rocks and reduce their travel distance and impact energy. Alteration to slope geometry through design considerations such as benching, planar surfaces, and controlled slope degradation can improve the effectiveness of rockfall mitigation efforts [15-16]. However, the influence of slope geometry on rockfall behaviour, particularly in terms of destruction distance and energy transfer, remains insufficiently understood and requires further investigation.

Extensive research has investigated various aspects of rockfall processes, including rock detachment mechanisms, trajectory behavior, hazard assessment, and mitigation strategies. For instance, Sazid [17] analyzed rockfall hazards along the Al-Hada Road using field observations and trajectory analysis, while Triana and Hermawan [18] assessed rockfall susceptibility using the slope mass rating (SMR) method. Ge et al. [19] further examined rockfall stopping positions and energy dissipation, and Hantz et al. [20] discussed key concepts for quantitative rockfall hazard and risk analysis. In addition, studies have evaluated rockfall impacts on infrastructure and protective structures [21-22]. Mitigation approaches include analytical tools such as hazard mapping as well as engineering measures like ditches, embankments, cable nets, rockfall galleries, and rockfall fences [23-25]. Collectively, these studies have improved the understanding of rockfall hazards and supported the development of engineering solutions for slope protection.

In recent years, numerical modelling techniques have been increasingly used to analyze rockfall behavior and rock–ground interactions. Among these approaches, the Discrete Element Method (DEM) has gained considerable attention due to its ability to simulate the motion of discrete particles and capture complex interactions between falling rocks and slope surfaces [26-28]. DEM-based approaches have been widely applied to investigate rockfall dynamics, trajectory prediction, and the influence of different geological and geometrical factors on rockfall behavior. For instance, Santangelo et al. [29] employed the STONE software for three-dimensional kinematic simulation of rockfall trajectories. Ge et al. [19] applied DEM to investigate the rockfall movement characteristics and the influence of boulder shape on rockfall behaviour through rigid-body modelling. Mohamed et al. [25] further integrated DEM simulations with Terrestrial Laser Scanning (TLS) data and rock mass classification systems to evaluate rockfall behavior on natural rock slopes. These studies demonstrate the capability of DEM-based modelling to capture complex rockfall dynamics and provide valuable insights into trajectory prediction and impact energy estimation under varying slope conditions.

Despite these advances, the influence of slope geometry on rockfall destruction distance and kinetic energy remains insufficiently investigated. In particular, limited studies have systematically evaluated the combined effects of slope angle, slope height, and berm configuration within a unified numerical modelling framework. A clearer understanding of these relationships is essential for improving slope design and enhancing the effectiveness of rockfall mitigation strategies.

The destruction distance (Dd) associated with rockfall is a critical parameter for assessing potential damage to infrastructure and risks to human safety. This distance, often referred to as the roll-out distance, represents the maximum travel distance of a boulder after detaching from a slope. Accurate prediction of this parameter is essential for effective hazard mitigation and infrastructure protection. Various studies have developed models and methodologies to improve the prediction of rockfall destruction distance. Huang et al. [30] successfully applied the K-nearest neighbour (KNN) algorithm to predict rockfall destruction distance, demonstrating robustness against varying parameters such as slope angle and block mass. Senanayake et al. [31] employed regression models, including both multilinear and non-linear approaches, to predict KE and final destruction distance in open-pit mines. Similarly, the kinetic energy (KE) generated by falling boulders plays a crucial role in determining the severity of impact and potential damage caused by rockfall events. The magnitude of KE is primarily influenced by the mass and velocity of the falling rock, with higher velocities producing greater impact forces [32].

Although these predictive models and factors provide valuable insights, the complex interplay of various factors in rockfall events require continuous refinement of prediction techniques to enhance reliability and safety in vulnerable areas. Therefore, understanding both destruction distance (Dd) and kinetic energy (KE) is essential for designing engineering solutions such as rockfall barriers and energy absorption structures. This study contributes to rockfall hazard assessment by systematically quantifying the influence of slope geometry on destruction distance and kinetic energy using DEM simulations aligned with slope design considerations.

Therefore, this study aims to evaluate the influence of slope geometry on the destruction distance (Dd) and kinetic energy (KE) of falling boulders on granite rock slopes. Rockfall analysis was conducted using the Discrete Element Method (DEM) implemented in GeoRock 2D, employing the lumped mass method to estimate the destruction distance (Dd) and maximum kinetic energy (KE) generated by boulders under different slope geometries. The analysis considers key geometrical parameters including slope angle, slope height, and the number of berms constructed along the slope.

2. Materials and Methods

This section outlines the methodologies employed in the slope risk assessment study, focusing on model establishment and parameter determination. The approach includes discrete element analysis and rockfall simulations to evaluate the impact of slope angles and the presence of berms on rockfall behavior.

2.1 Model Establishment and Parameter Determination

In slope risk assessment, various guidelines have been established to evaluate the vulnerability of slopes based on their inclined angles, resulting in distinct classifications. Specifically, Class I represents the mildest terrain grading, encompassing slopes with angles less than 15°. Class II pertains to slopes ranging from 15° to 25°, while Class III includes slopes within the 25° to 35° range, signifying a moderate level of risk. Slopes exceeding 35° fall under the Grade IV category, indicating the highest risk level, with many guidelines prohibiting development on such slopes [33-36]. In the context of this research, slopes with angles between 0° and 35° are referred to as "standard slopes," while those with angles exceeding 35° are designated as "steep slopes."

In this study, two different models were designed based on varying slope angles and slope ratios to determine the maximum distance of boulders and the KE of rockfall from various slope geometries. Fig. 1(a) illustrates the discrete element analysis of the slope for Model A, while Fig. 1(b) presents the discrete element analysis of the slope for Model B. The first model, denoted as Model A, employs different slope angles: 15°, 25°, and 35° for standard slope angles, 60°, 75°, and 90° for steep slope angles [33,36]. For all cases, the slope height was maintained at 50 m to ensure a consistent reference geometry across simulations. The selection of a constant slope height allowed the influence of slope angle on rockfall behavior to be evaluated independently, while also providing sufficient vertical distance for the development of rockfall velocity and kinetic energy during descent.

The second model denoted as Model B, was developed to evaluate the influence of slope ratio and the presence of berm structures on rockfall behavior. The height-to-width ratios considered were 1:4, 1:3, 1:2, 1:1, 2:1, 3:1, and 4:1, while maintaining the same slope height of 50 m for consistency with Model A. Berms were used for the steepest configurations (3V:1H and 4V:1H) as a comparative scenario to assess whether intermediate interception surfaces could reduce rockfall runout and kinetic energy under steep slope conditions. These steep configurations are expected to generate higher rockfall velocities and impact energies due to the increased slope inclination [30]. For these cases, eight berms with a height of 6 m were incorporated along the slope profile to simulate a benched slope geometry commonly used in high rock slopes to intercept falling blocks and promote energy dissipation through repeated impacts [13,16]. The parameters for slope Model A are presented in Table 1, and Table 2 provides the parameters for slope Model B consistent with typical slope configurations adopted in rockfall modelling studies [17,20]

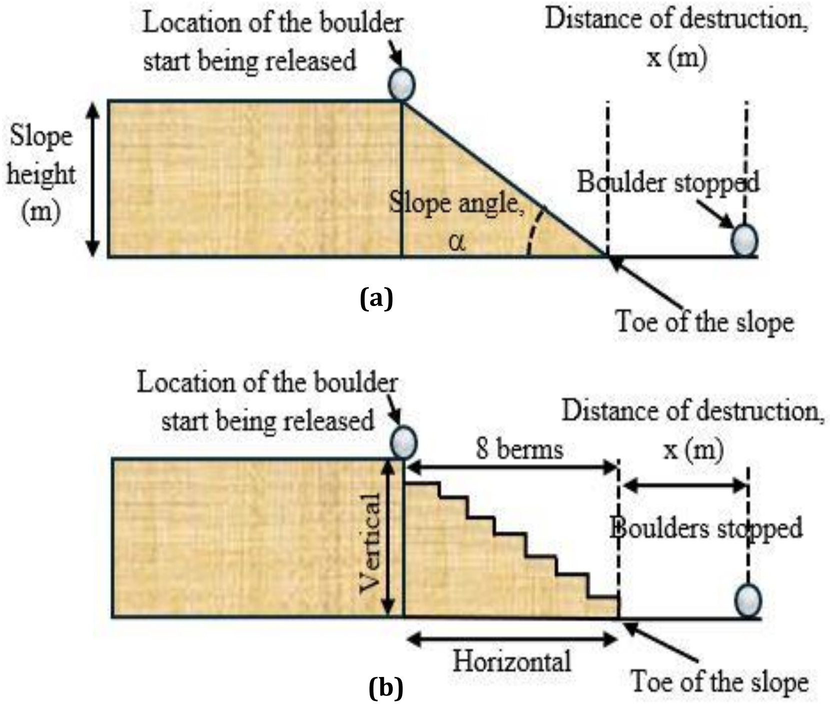

Fig. 1 *Discrete element analysis of the slope for (a) Model A; (b) Model B*

Table 1 *The parameters for slope Model A*

Slope Model	Slope Classification	Slope Material	Slope Angle, α (°)	Berms
A1			15	-
A2	Standard slope	Granite	25	-
A3			35	-
A4			60	-
A5	Steep slope	Granite	75	-
A6			90	-

Table 2 *The parameters for slope Model B*

Slope Model	Slope Classification	Slope Material	Slope Ratio (V: H)	Berms
B1			1:4	-
B2	Standard slope	Granite	1:3	-
B3			1:2	-
B4			1:1	-
B5	Steep slope	Granite	2:1	-
B6			3:1	8
B7			4:1	8

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For both models, rockfall analysis was simulated using the GeoRock 2D software through the lumped mass method. In the lump mass method, the falling boulder is assumed to be a concentrated single point, disregarding its size and shape [17, 20, 37]. The following assumptions were made when using the lumped mass approach in the GeoRock 2D software for analysis: a plan outline, a slope profile similar to a broken line consisting of straight-line segments, a point boulder and negligible air resistance.

The study utilised slope and boulder parameters derived from existing literature relevant to granitic terrain, which were applied consistently across all slope models. This approach allowed for a focused analysis of how varying slope angles affect the behaviour of boulders during descent and impact within a granitic landscape. These parameters served as foundational settings for slope and boulder characteristics in the numerical simulation, as detailed in Tables 3 and 4, respectively. In the simulation, boulders with a diameter of 3 m and a spherical shape were rolled on each slope model with different angles, height-width ratios, and berm structures. The coefficients of restitution for normal and tangential directions were determined to be 0.9 and 0.8, respectively. These values were derived from experimental data reported in studies [17, 33, 38], which investigated the impact behavior of slightly weathered granite (grade II). The granite parameters employed in this study include a constant elasticity modulus of 32×10^3 MPa and a specific weight of 2700 kg/m^3, which align with Karagianni et al. [39] and Yu et al. [40]. The determination of these granite parameters involved laboratory tests on grade II weathered granite, including uniaxial compression tests to assess the mechanical properties and elasticity of the granite samples, as well as specific gravity tests to ascertain the material's density. Initial velocities in the x and y directions were set at 1 and -1, respectively, to replicate the conditions generated when the boulder begins to move.

Table 3 *Setting parameters of the slope for numerical simulation*

Parameters of Slopes	Values
Number of slope Models tested (Model A)	6
Number of slope Models tested (Model B)	7
Number of trajectories per slope model	100
Normal COR for slope (Rn)	0.9
Tangential COR for slope (Rt)	0.8
Height of slope (m)	50

Table 4 *Setting parameters of the boulder for numerical simulation*

Parameters of Boulders	Values
Shape of boulder	Sphere
Diameter of the boulder (m)	3
Initial x velocity (m/s)	1
Initial y velocity (m/s)	-1
Elasticity modulus of boulder (MPa)	32×10^3
Specific weight of boulder (Kg/m^3)	2700

2.2 Discrete Element Method: GeoRock 2D Software Modelling

In the DEM, the combination of the lumped mass method and GeoRock 2D software was employed to simulate rockfalls effectively. Fig. 2 summarizes the technique used to generate rockfall simulation in GeoRock 2D software. Firstly, the slope profile and material characteristics were defined to achieve the desired slope configuration, as specified in Table 1. Next, to initiate the rockfall simulation, several parameters of the boulder, such as its shape, diameter, initial x-axis and y-axis velocities, were defined based on the specifications stated in Table 2. The boulder's position on the slope was also defined at this stage. Once the parameters were set, the simulation job was submitted for analysis, during which the lumped mass method was applied as previously indicated. The software then processed the simulation and displayed the results in graphical formats and detailed reports, which were saved for further evaluation in statistical analysis. This process was repeated for the other slope models to determine the distance of destruction and KE for various slope configurations.

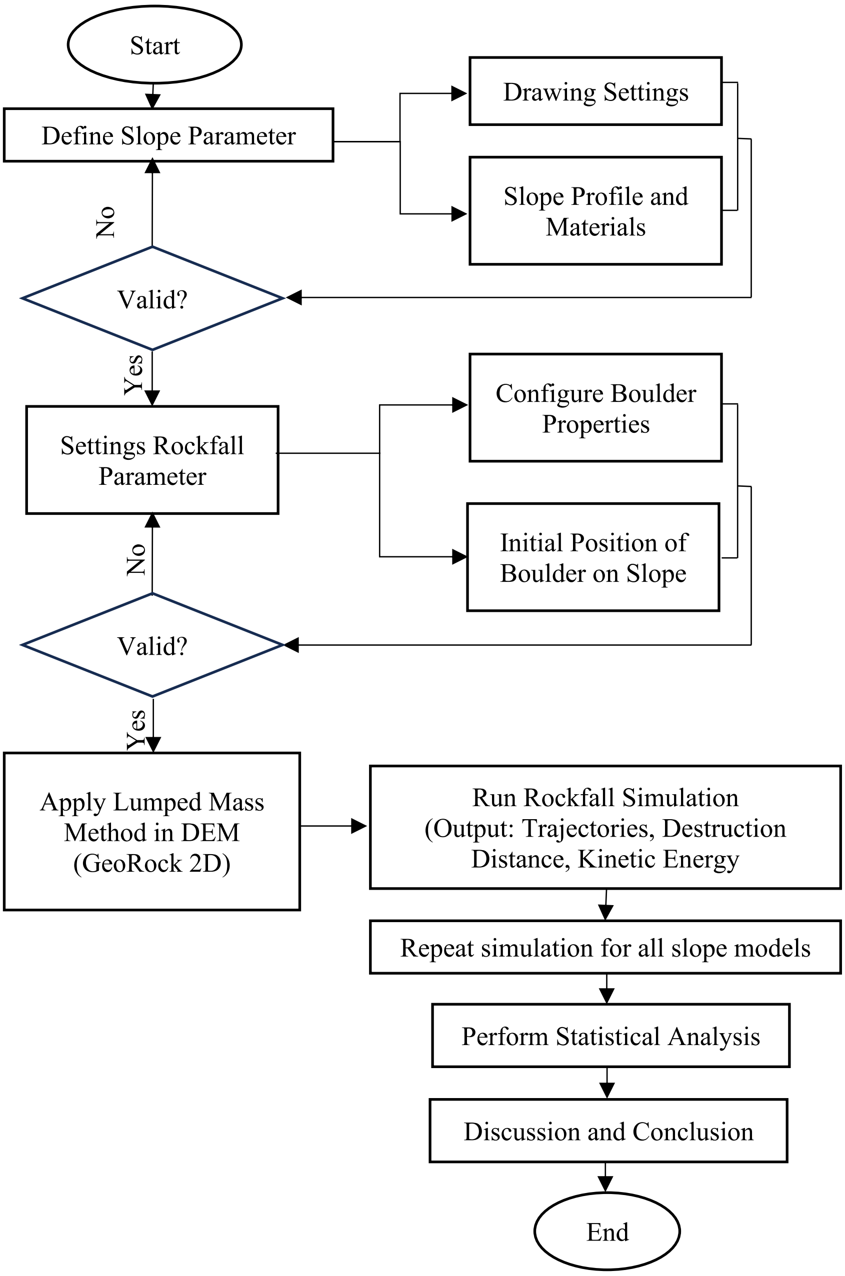

Fig. 2 *Procedure for rockfall simulation in GeoRock 2D software*

3. Results and Discussion

The simulation results obtained from the GeoRock 2D analyses are presented and discussed in this section to evaluate the influence of slope geometry on rockfall behavior. The analysis focuses on two key parameters which are the destruction distance (Dd) and kinetic energy (KE) of falling boulders. These parameters are important indicators for assessing potential rockfall hazards and the effectiveness of slope design. The results are analyzed under different slope conditions, including variations in slope angle, slope ratio, and berm configurations, to identify the critical slope geometries that may lead to higher rockfall risks.

3.1 Destruction Distance and Kinetic Energy based on Various Slope Angles

Fig. 3 visually represents the slope geometries and rockfall trajectories associated with various slope angles using GeoRock 2D software. Fig 3(a) depicts the slope with an angle of 15°, Fig. 3(b) depicts the slope with an angle of 25°, Fig 3(c) depicts the slope with an angle of 35°, Fig. 3(d) depicts the slope with an angle of 60°, Fig. 3(e) depicts the slope with an angle of 75°, and Fig. 3(f) depicts the slope with an angle of 90°. The corresponding numerical outputs are presented in Table 5, while Fig. 4(a) and Fig. 4(b) present the relationships between slope angle and destruction distance, and slope angle and kinetic energy (KE), respectively.

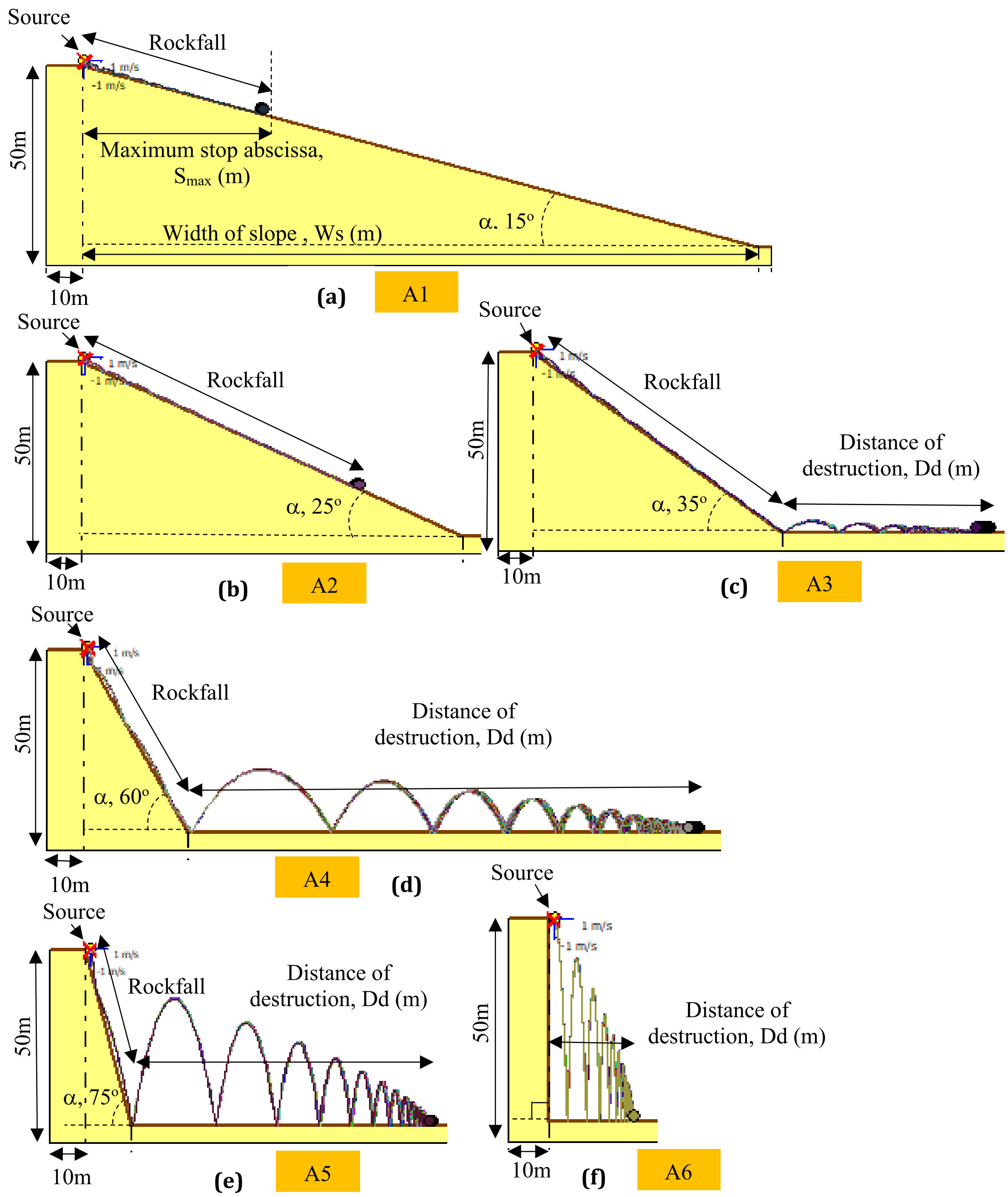

Fig. 3 *GeoRock 2D software illustration of the slope geometry and rockfall trajectories for various slope angles: (a) 15o; (b) 25o; (c) 35o; (d) 60o; (e) 75o; and (f) 90o*

Table 5 *GeoRock 2D output for slopes with different slope angles for Model A*

Sn	Nt	Sa, α (°)	Ws (m) (1)	S_{max} (m) (2)	Dd (m) (3=2-1)	KE_{max} (kJ)	KE_{avg} (KJ)
A1	100	15	186.6	49.95	0	1302.28	552.95
A2	100	25	107.26	78.41	0	3207.12	1221.64
A3	100	35	71.41	130.65	59.24	6250.71	2059.07
A4	100	60	28.87	168.51	139.64	13061.40	2892.08
A5	100	75	13.4	98.77	85.37	17433.20	4391.91
A6	100	90	0	20.85	20.85	18746.31	6236.17

Note: Sn= slope number; Nt= number of tested; Sa=slope angle; Ws= width of slope from boulder released to the toe of the slope (m), S_{max} = maximum stop abscissa (m), Dd= distance of destruction, x (m), KE_{max} = maximum kinetic energy of the boulder for one hundred trajectories (kJ), KE_{avg} = average kinetic energy of the boulder for one hundred trajectories (KJ)

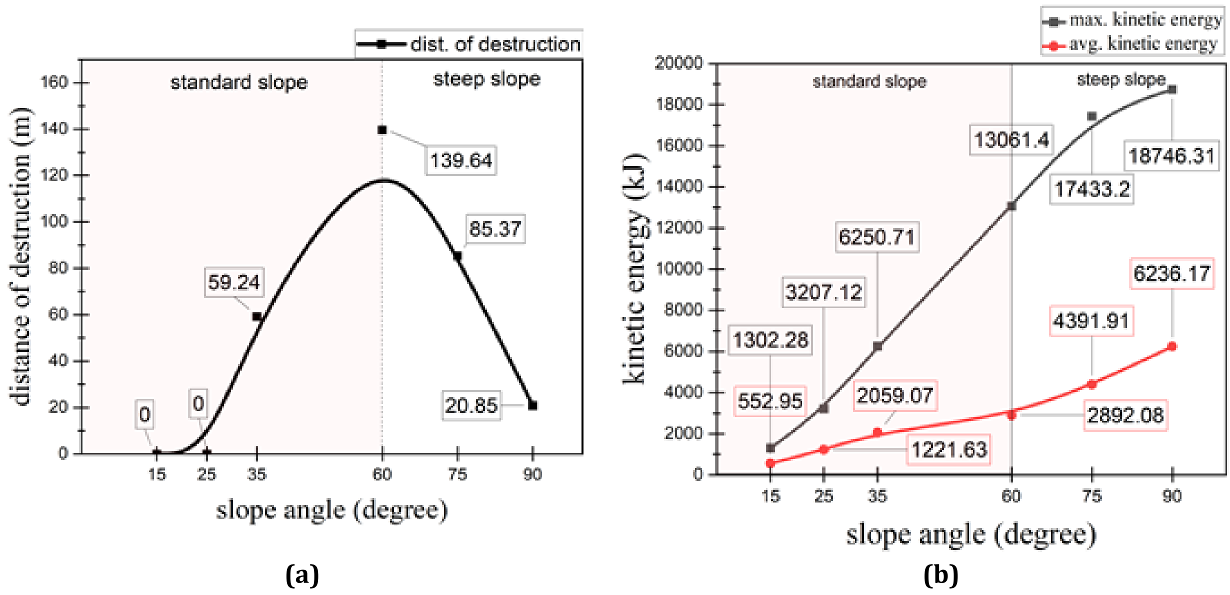

Fig. 4 *Analysis of Model A based on (a) Slope angle versus the distance of destruction (m); (b) Slope angle versus the kinetic energy of the boulder (kJ)*

The statistical analysis depicted in Fig. 4(a) revealed that for gentle slopes with angles ranging from 15° to 25°, the distance of destruction caused by falling boulders is consistently zero. This indicates that the boulders came to a halt before reaching the slope toe. However, as the slope angle progressively rose, the destruction distance (Dd) experienced a sharp rise until it reached its peak at a slope angle of 60°. Beyond this point, the distance of destruction began to decline for steeper slopes. The maximum destruction distance recorded in this study was 139.64 m at 60°, indicating that intermediate-to-steep slopes may produce the longest runout distances. This trend is consistent with observations reported by real-world case studies of rockfall events by Guzzetti et al. [41], who found that maximum rockfall runout distances frequently occur on slopes ranging between 45° and 60°. At these angles, the slope is steep enough to generate high acceleration while still allowing multiple impacts and rebounds, enabling boulders to travel further downslope. In contrast, very steep slopes such as 75° and 90° promote rapid vertical descent with fewer rebound trajectories, which reduces the horizontal runout distance.

On the other hand, Fig. 4(b) provides insights into the relationship between the slope angle and the KE of falling boulders. As the slope angle increased, both the maximum and average KE rose, peaking at a slope angle of 90°, with a maximum KE of 18,746.31 kJ. This behavior occurs because steeper slopes provide greater gravitational acceleration, allowing falling boulders to convert potential energy into higher KE during descent. Furthermore, as the slope angle increased, the frequency of energy changes experienced by falling rocks decreased. This results in fewer collisions with slope surfaces, shorter contact times, and reduced energy dissipation during rockfall events. Similar findings have been reported in previous rockfall studies, where slope inclination was identified as a critical parameter influencing boulder velocity and impact energy [11, 37, 42].

Notably, the KE of boulders increased more rapidly for slope angles between 0° and 60° than for slope angles 60° to 90°, particularly between 35° and 60°. The increase in KE at moderate angles (between 35° and 60°) can be attributed to effective acceleration due to gravity and optimal energy transfer dynamics. As the slope angle increased, the gravitational force component acting along the slope also increased, enhancing the boulder's acceleration and KE. This phenomenon is consistent with findings in studies that explore boulder dynamics and slope stability [43-45]. In contrast, at steeper angles, the increase in friction and energy dissipation upon impact led to a slower growth rate of KE. Research indicates that as slope angles exceed a certain threshold, the effects of friction and the dynamics of motion change significantly, resulting in a more complex interaction that reduces the rate of KE increase. This aligns with observations in studies that examine the impact of slope angle on energy loss during rockfall events [46].

The results presented in this study underscore the profound influence of slope angle on both the distance of destruction and the KE of boulders during their descent. These findings have crucial implications for accurately evaluating potential hazards and implementing appropriate protective measures in regions susceptible to rockfalls.

3.2 Destruction Distance and Kinetic Energy based on Various Slope Ratios and Number of Berms

Fig. 5 provides a visual representation of the slope geometry and rockfall trajectories associated with different slope ratios and the presence of berms using the GeoRock 2D software. Fig. 5(a) depicts the slope with a 1:4 ratio, Fig. 5(b) depicts the slope with a 1:3 ratio, Fig. 5(c) depicts the slope with a 1:2 ratio, Fig. 5(d) depicts the slope with a 1:1 ratio, Fig. 5(e) depicts the slope with a 2:1 ratio, Fig. 5(f) depicts the slope with a 3:1 ratio and Fig. 5(g) depicts the slope with a 4:1 ratio. The corresponding numerical results are summarized in Table 6, while Figure 6(a) and Figure 6(b) illustrate the relationships between slope ratio and Dd, and slope ratio and KE, respectively.

Based on the statistical analysis presented in Fig. 6(a), it was observed that the distance of destruction caused by falling boulders was zero for slope ratios of 1:4, 1:3, and 1:2. Subsequently, the distance of destruction experienced a sudden increase at a slope ratio of 1:1. After that, it increased slightly and reached a maximum value of 140.02 m at a slope ratio of 2:1. This behavior reflects the increased gravitational acceleration along steeper slopes, which allows boulders to gain greater velocity and travel further downslope. However, with the inclusion of berms in the slope design, the Dd decreased drastically and returned to zero, demonstrating the significant effect of berms in intercepting rockfall trajectories. Berms act as intermediate barriers that disrupt boulder motion, reduce bounce heights, and promote energy dissipation through repeated impacts [47].

On the other hand, Fig. 6(b) showcases the relationship between the slope ratio and the KE of falling boulders. As the slope ratio transitioned from a gentle slope to a steeper slope, the maximum KE of the boulders steadily increased until it reached a peak value of 15326.47 kJ at a 2:1 slope ratio. This reflects the increasing gravitational component acting along the slope surface as the slope becomes steeper [48]. However, when berms were incorporated in the 3:1 and 4:1 slopes, the maximum KE decreased significantly due to repeated impacts with the berm surfaces, which dissipate energy during the rockfall trajectory. Interestingly, the average KE reached its maximum value at the 3:1 slope ratio, which can be attributed to the combined effect of steep slope geometry and multiple impact interactions with berm structures. Although individual impacts reduce instantaneous energy, the overall trajectory dynamics allow boulders to maintain relatively high energy levels during descent [49].

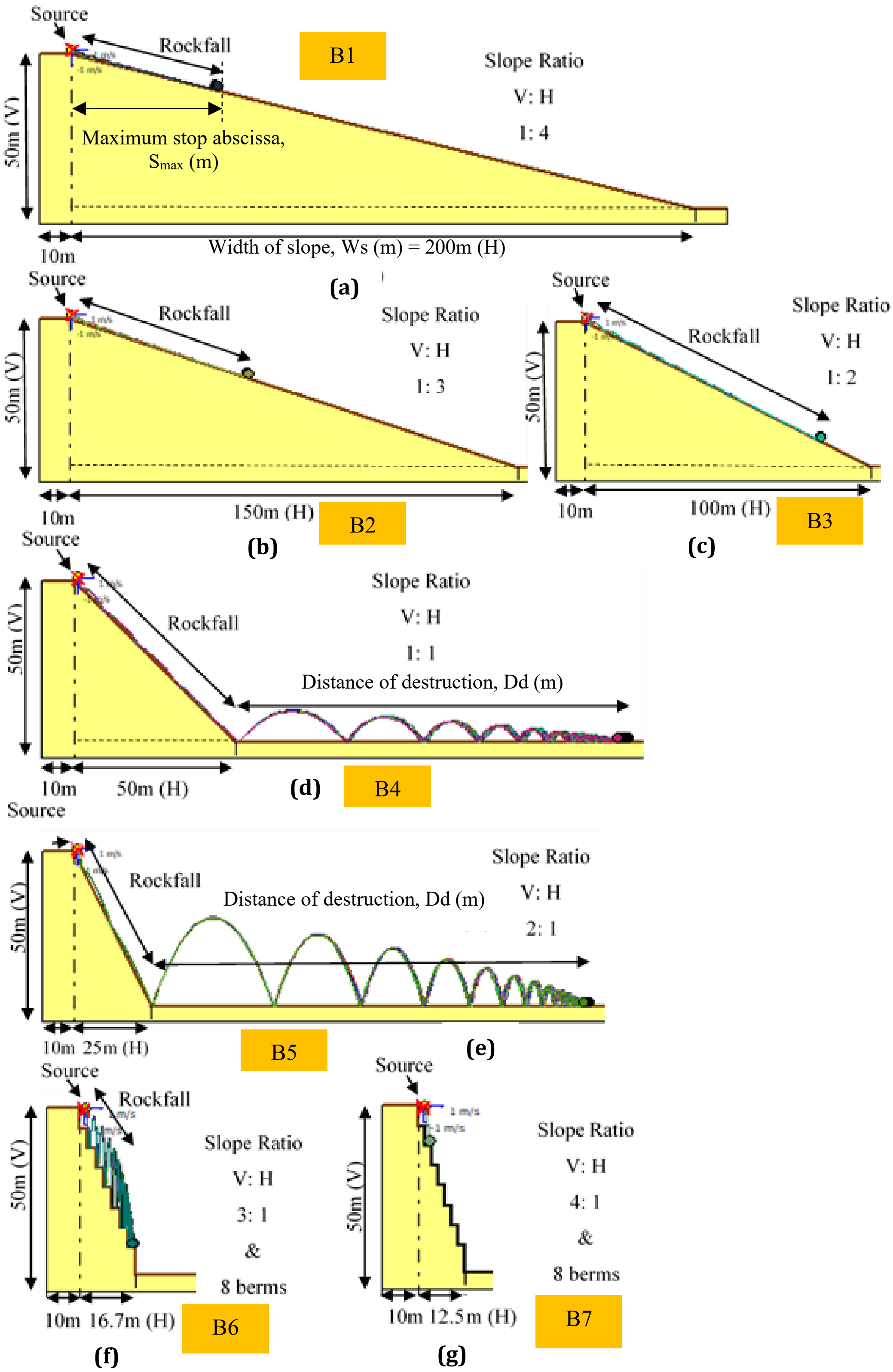

Fig. 5 *GeoRock 2D software illustration of the slope geometry and rockfall trajectories for various slope ratios and number of berms; (a) 1:4; (b) 1:3; (c) 1:2; (d) 1:1; (e) 2:1; (f) 3:1 with 8 berms; (g) 4:1 with 8 berms*

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Table 6 *GeoRock 2D output for slopes with different slope ratios and number of berms for Model B*

Sn	Nt	Sr (V:H)	Nb	Ws (m) (1)	S_{max} (m) (2)	Dd (m) (3 = 2 - 1)	KE_{max} (kJ)	KE_{avg} (kJ)
B1	100	1:4	0	200	47.12	0	1171.15	498.52
B2	100	1:3	0	150	59.96	0	1845.58	752.59
B3	100	1:2	0	100	82.64	0	3599.09	1369.47
B4	100	1:1	0	50	171.06	121.06	9995.47	2477.86
B5	100	2:1	0	25	165.02	140.02	15326.47	3533.26
B6	100	3:1	8	16.67	16.13	0	7934.28	4726.28
B7	100	4:1	8	12.5	0.96	0	4513.80	4337.81

Note: Sn = slope number; Nt = number of tests; Sr = slope ratio (vertical:horizontal); Nb = number of berms; Ws = width of slope from boulder release to the toe of the slope (m); S_{max} = maximum stop abscissa (m); Dd = distance of destruction, x (m); KE_{max} = maximum kinetic energy of the boulder for one hundred trajectories (kJ); KE_{avg} = average kinetic energy of the boulder for one hundred trajectories (kJ).

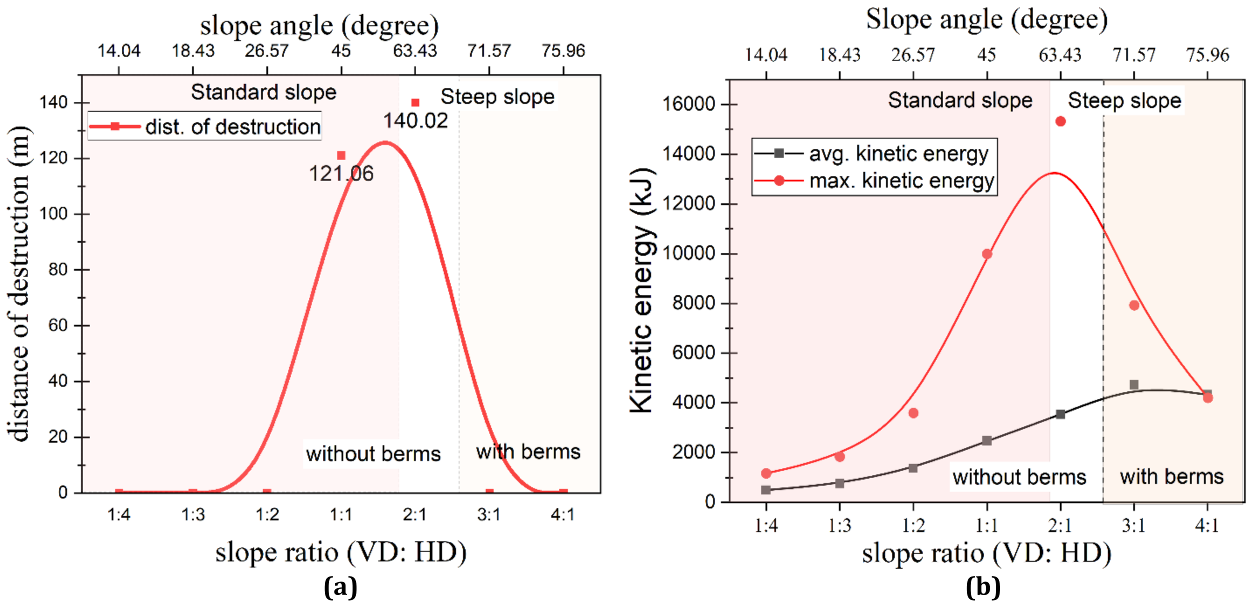

Fig. 6 *Analysis of Model B based on (a) Slope ratio versus the distance of destruction (m); (b) Slope ratio versus the kinetic energy of the boulder (kJ)*

When the slope ratio increased further to 4:1, both maximum and average KE declined. This reduction is primarily due to increased collision frequency and energy dissipation caused by repeated interactions with berm surfaces and the slope face [50]. By converting slope ratios to slope angles, the 2:1 slope ratio corresponds to approximately 63.43°, which closely aligns with the critical slope angle range identified in Section 3.1. This result confirms that slopes within the 60° range represent a critical condition for rockfall hazards, where both destruction distance and kinetic energy reach high values.

Previous studies have also reported that berms and benches are effective rockfall mitigation measures, as they intercept falling blocks and reduce runout distances by dissipating kinetic energy through successive impacts [47]. Properly designed berm systems can therefore significantly reduce the potential damage caused by rockfall events.

Nevertheless, the effectiveness of berms depends on the slope condition and construction stage. During the construction phase, slopes may not yet be fully stabilized, which can limit the ability of berms to effectively capture falling blocks. In contrast, once slopes are fully established and berms are properly integrated into the slope design, their effectiveness in reducing both destruction distance and rockfall energy is significantly improved [51]. These findings highlight the importance of incorporating appropriate slope geometry and berm configurations in rock slope design to reduce rockfall hazards and improve slope safety.

4. Conclusions

This research investigated the impact of slope angle and slope ratio on rockfall behavior, particularly the distance of destruction and the KE of falling boulders, using GeoRock 2D simulations. The results demonstrate that slope geometry plays a critical role in controlling rockfall dynamics and associated hazards in hilly terrains.

The analysis showed that destruction distance increased with slope angle and reached its maximum at approximately 60°, after which it decreased on steeper slopes. This indicates that intermediate slopes between 45° and 60° represent the most critical condition for rockfall hazards in terms of destruction distance. In contrast, the maximum KE continues to increase with slope angle and reaches its peak at 90°, reflecting the stronger gravitational acceleration acting on falling boulders along steeper slopes. A rapid increase in kinetic energy was observed between 35° and 60°, suggesting a critical transition range where gravitational acceleration significantly influences rockfall dynamics.

The analysis of slope ratios further confirmed these findings. Steeper slopes such as 1:1 and 2:1 produced greater destruction distances and higher kinetic energy values. The 2:1 slope ratio, corresponding to an angle of approximately 63.43°, was identified as the most critical configuration in the simulation results. However, the introduction of berms significantly reduced both destruction distance and kinetic energy, particularly for the 3:1 and 4:1 slope configuration. This demonstrate that berms can effectively intercept falling boulders and promote energy dissipation during rockfall events.

From an engineering perspective, these findings provide practical guidance for rock slope design and hazard mitigation. Slopes within the range of approximately 45° – 60° should be carefully evaluated during rockfall risk assessments due to their potential to generate longer runout distances and significant impact energy. The incorporation of berms or benches should therefore be considered in slope design to intercept falling blocks and reduce rockfall hazards. These mitigation strategies are consistent with sustainable slope engineering practices aimed at improving long-term slope stability and protecting nearby infrastructure and communities in hilly environments.

Overall, this study contributes to a better understanding of the influence of slope geometry on rockfall behavior and provides practical insights that may assist engineers and planners in developing safer slope design and effective rockfall mitigation strategies for hillside developments.

Acknowledgement

Communication of this research is made possible through financial assistance from the Ministry of Higher Education (MOHE) via the Fundamental Research Grant Scheme (FRGS/1/2024/TK02/UTHM/03/2) and Universiti Tun Hussein Onn Malaysia (UTHM) through GPPS grant (Vot Q601).

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contributions to the paper as follows: ***study conception and design:*** *Mohd Firdaus Md Dan, Aziman Madun, Faizal Pakir, Khaidir Abu Talib, Nordiana Mohd Mustaza, Dayang Zulaika Abang Hasbollah;* ***data collection:*** *Muhammad Aminuddin Khalid, Eka Kusmawati Suparmanto;* ***analysis and interpretation of results:*** *Muhammad Aminuddin Khalid, Aizat Mohd Taib, Aniza Ibrahim;* ***draft manuscript preparation:*** *Muhammad Aminuddin Khalid, Mohd Firdaus Md Dan. All authors reviewed the results and approved the final version of the manuscript.*

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