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Influence of Slope Shape and Surface Roughness on the Moving Paths of a Single Rockfall

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Abstract**—**Rockfall is a kind of irregular geological disaster. Its destruction time, space and movements are highly random. The impact force is determined by the way and velocity rocks move. The movement velocity of a rockfall depends on slope gradient of its moving paths, height, slope surface roughness and rock shapes. For effectively mitigate and prevent disasters brought by rockfalls, it is required to precisely calculate the moving paths of a rockfall so as to provide the best protective design. This paper applies Colorado Rockfall Simulation Program (CRSP) as our study tool to discuss the impact of slope shape and surface roughness on the moving paths of a single rockfall. The analytical results showed that the slope, m=1:1, acted as the threshold for rockfall bounce height on a monoclinal slight slope. When JRC < 1.2, movement velocity reduced and bounce height increased as JCR increased. If slope fixed and JRC increased, the bounce height of rocks increased gradually with reducing movement velocity. Therefore, the analysis on the moving paths of rockfalls with CRSP could simulate bouncing of falling rocks. By analyzing moving paths, velocity, and bounce height of falling rocks, we could effectively locate impact points of falling rocks on a slope. Such analysis can be served as a reference for future disaster prevention and control.

Keywords**—**Rockfall, Slope Shape, Moving Path, Surface Roughness.

I. INTRODUCTION

LANDSLIDES mostly happen after torrential rain or earthquakes. Rockfalls may occur on cliffy rocky slopes at any time, which will block the traffic and seriously threaten the safety of the residents living on slopes. The movements of rockfalls are divided into freefalling, bouncing, rolling and sliding. Moving paths are categorized into source area, moving area and threatened area [1]. Geometric pattern of slope, geometric patter of falling rocks, slope, rock material and contact properties create impact on the movements of falling rocks [2-3].

The geometric patterns of slope include slope height, slope gradient, slope surface, etc. Surface roughness may change the moving paths of rockfalls. Surface roughness influences the contact angles of falling rocks and changes moving velocity by rolling and sliding [4]. Ritchie [5] carried out an experiment based on the falling rocks. It was found that surface roughness influences the behavior pattern of falling rocks. Rolling or sliding patterns turned into bouncing ones. Surface roughness (S) led random changes of contact angles of falling rocks. The size of falling rocks (R) was relatively associated with surface roughness. When R/S value was greater, the falling velocity was higher while the bounce height was smaller [6]. When R/S increased, falling velocity and bounce height increased accordingly. When slope is less than 45°, bounce height increased [2].

The geometric patterns and material properties of falling rocks will influence rockfall behavior. Wadell [7] defined sphericity and roundness. The movements of rockfalls differed after collision of side or angle with slope. When sphericity and roundness increased, rock bouncing times reduced with increasing bounce height [1]. Rock shapes also created impact on horizontal movement, rolling energy and movement pattern of falling rocks [3]. Through numerical study, Azzoni, etc. [8] pointed out that the volume of falling rocks created minor impact when the velocity of rockfall reached a certain range. Okura [9] and other scholars proposed that the bouncing distance of falling rocks of same size was not influenced by their mass. Pfeiffer and Bowen [2-3] suggested that falling rocks of low strength crashed upon collision, which mitigated their bouncing effect.

The moving paths of a rockfall could be obtained by experimental methods, computational modeling and empirical analysis. The experimental methods were divided into field studies [6-10] and physical modeling [11]. However, field studies were time and cost consuming and had analytical results limited to local conditions. Therefore, they were not available for statistical and parameter analysis. Computational modeling was divided into lumped mass method [12~15] and rigid body method [14-16]. In the lumped mass method, a falling rock was assumed to be a single material point by being ignored its shape, size and rotary effect upon moving. In the rigid body method, the geometric shape of a falling rock could be simulated. Ritchie [6] applied empirical analysis to induce the relationships between movement patterns of a rockfall and slope. Azzoni et al. [17] proposed that the horizontal movement of a rockfall on a monoclinal slope was 10% of slope length based on the results of affected areas of a rockfall and field studies. However, the actual conditions of a rockfall were significantly influenced by slope shape and surface roughness, which acted a limitation to empirical analysis.

The moving paths of a rockfall were not simply a linear

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relationship. The key issue for rockfall studies lied in how the surface and landforms could be reflected through the analysis. Nevertheless, the scholars did not further explore the impact of slope shape and surface roughness while making predictions of moving paths of a rockfall. With advance development, Colorado Rockfall Simulation Program (CRSP) [18] has been successfully applied to many scientific and engineering issues. This program can be used to simulate large-scale and complicated non-linear calculations. The theory focused on 2D single-rock rigid body method. It was assumption that (1) the resilient energy of rocks were affected by normal restitution coefficient and tangent restitution coefficient; (2) falling rocks did not break and separate during movement and the size and shape of rocks remained the same upon analysis; and (3) when the movement distance of rock bouncing was less than rock radius, the program automatically change the mode from bouncing to rolling. Therefore, this paper applied this program to simulate rockfall movements and discuss the impact of slope shape and surface roughness on the moving paths of a rockfall so as to improve prediction accuracy.

II. DESIGN OF SIMULATION TEST

This paper applied simulation and statistical analysis to consider the interactions between the factors by focusing on a single geometric slope and predicted rockfall movements. It also discussed the impact of slope shape and surface roughness on the moving paths of a rockfall. The simulation experiment was planned as follows:

Table 1 lists the mechanical parameters for rock materials. Rock shapes were one of the major factors dominating a rockfall movement. In the past, the simulation of a rockfall was based on 2D or 3D sphere. This paper explored the impact of various slope shapes and surface roughness on the moving paths by observing Discoidal at diameter of 1.2m and thickness of 0.3m. In addition, rock strength directly influenced bouncing coefficient and rocks of low strength easily broke upon collisions [2-3]. Generally, the elastic modulus of rocks ranges from 40~70 GPa and Poisson's ratio is 0.2~0.3 [19]. The restitution coefficient created impact on the movements after rocks contacted slopes. The normal restitution coefficient (e_n) and tangent restitution coefficient (e_t) were shown. When e_n and e_t =1, it stood for total resilience; while e_n and e_t =0, it stood for non-resilience [4]. The e_n and e_t of general are 0.5 and 0.95 respectively. Regarding stack layers of coarse rocks, e_n is 0.35 and e_t is 0.85[1].

Figure 1 shows the slope shapes of simulation test. The section of typical surface roughness was shown in Fig. 2. In addition to the geometric shapes of rocks, slope shapes were also a major factor influencing the movement of a rockfall. Surface roughness directly dominated contact angles. Surface roughness was illustrated in Fig. 3. The roughness of a slope was shown by roughness angles. That is, the included angle between rough surface and average slope. The roughness angle was calculated by applying equation (1).

$$i_{\max} = \tan^{-1}\left(\frac{S}{R}\right) \tag{1}$$

Where $i_{\max}$ is the maximum roughness angle; S is the relief height; and R is the slope length at the roughness angle.

TABLE I THE MECHANICAL PARAMETERS OF ROCK MATERIALS

Density (kg/cm^3)	2650
Modulus of elasticity, E (Gpa)	50
Poisson Ratio, v	0.25
Normal Restitution Coefficient, e_n	0.5
Tangent Restitution Coefficient, e_t	0.95

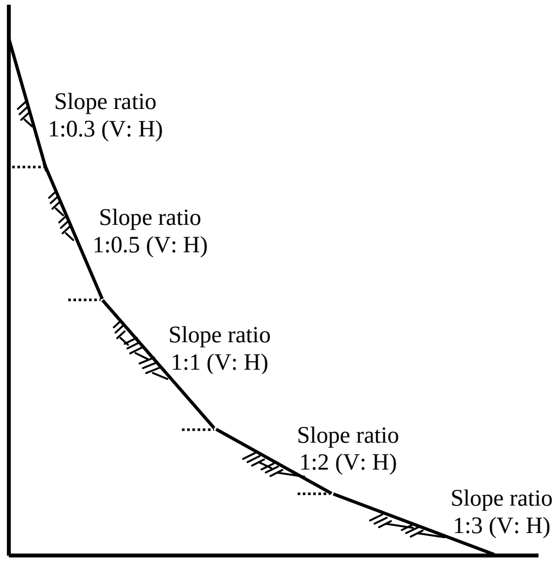


Fig. 1: The slope shapes of simulation test.

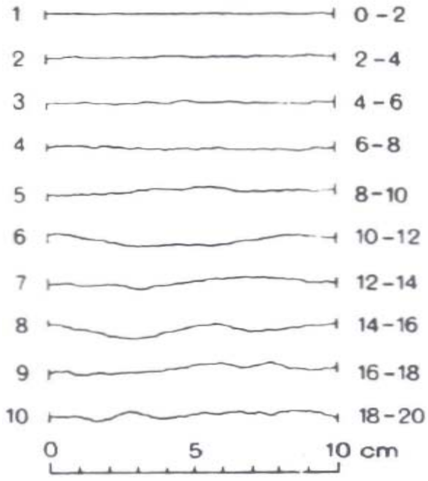


Fig. 2: Typical roughness profiles for JRC ranges [20].

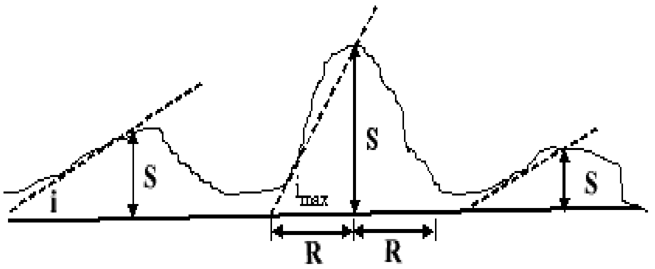


Fig. 3: Schematic diagram for Surface roughness. Adapted and modified from Pfeiffer (1989) [2]

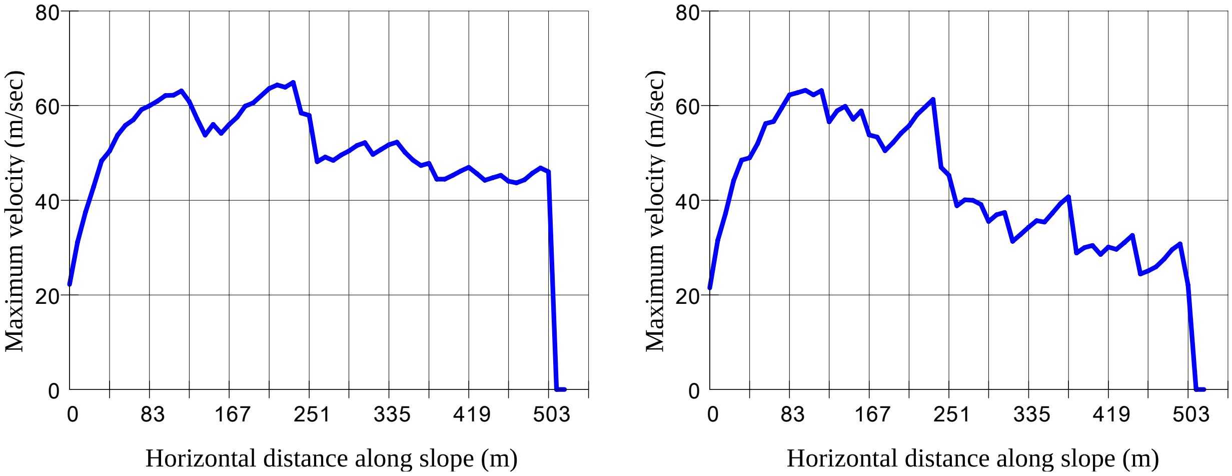
For simulating the properties of field slope roughness, the variations of roughness were taken into consideration. The slope roughness was shown by Joint Roughness Coefficient (JRC). The slope was divided into first, middle and last sections. Assume JRC = 0.2, 0.4, 1.0, 1.2, 1.8 and 2.0 so as to make an analysis. The slope ratio (vertical and horizontal) was 1:3, 1:2, 1:1, 1:0.5 and 1:0.3 respectively; the simulated slope height was 480m and rockfall location （x_0, y_0）＝（0, 480）and falling distance h_0 = 0m. The horizontal and vertical preliminary velocity of a rockfall was 3m/s and -3m/s respectively. Based on the above conditions, the impact of slope shape and surface roughness on the moving paths of a rockfall was explored.

III. RESULTS OF THE ROCKFALL SIMULATIONS

The moving paths of a single rockfall on a monoclinal slope were obtained. The 100 simulations on five slope shapes and six of surface roughness were made by using Discoidal rocks. Based on the analysis on geometric patterns of slopes and sensitivity presented by surface roughness, the levels of impact were discussed by bounce height and moving velocity. Bounce height and moving velocity of a single rockfall at any horizontal distance on a slope were obtained through the calculations of the program. According to the statistics presented from the simulations, the maximum, minimum and average bounce height and moving velocity at a horizontal distance were obtained.

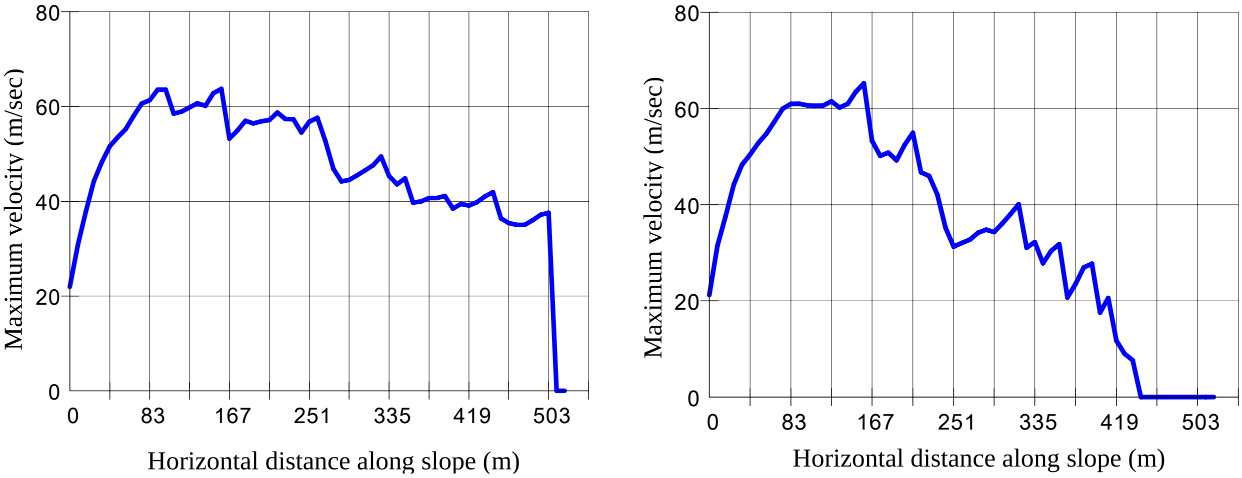
TABLE II SIMULATIONS ANALYTICAL RESULTS STATISTICS BY USING DISCOIDAL ROCKS MASS

Slope		Height of bounce (m)		Velocity (m/s)		
Vertical to horizontal ratio	Surface roughness	Maximum value	Average value	Maximum velocity	Average velocity	Standard deviation
1：0.3	0.2	33	15	45	38	3.37
	0.4	46	22	47	35	6.03
	1.0	49	25	47	30	8.5
	1.2	50	22	47	30	8.76
	1.8	47	20	47	30	9.71
	2.0	49	21	47	28	9.32
1：0.5	0.2	30	13	60	50	4.46
	0.4	45	16	62	47	8.08
	1.0	58	18	60	39	11.94
	1.2	69	19	59	38	12.76
	1.8	61	19	58	40	11.32
	2.0	54	19	61	37	12.73
1：1	0.2	20	7	63	49	5.61
	0.4	32	8	59	41	7.8
	1.0	28	8	53	29	10.35
	1.2	30	6	53	26	11.36
	1.8	26	7	55	27	11.7
	2.0	28	6	49	25	10.82
1：2	0.2	10	3	50	40	3.85
	0.4	18	4	51	29	6.82
	1.0	16	3	37	18	7.97
	1.2	12	3	36	15	7.8
	1.8	7	2	34	15	7.99
	2.0	9	3	20	12	5.41
1：3	0.2	8	2	43	34	3.53
	0.4	9	2	40	18	6.98
	1.0	3	1	23	14	0
	1.2	1	1	13	13	0
	1.8	0	0	0	0	0
	2.0	0	0	0	0	0



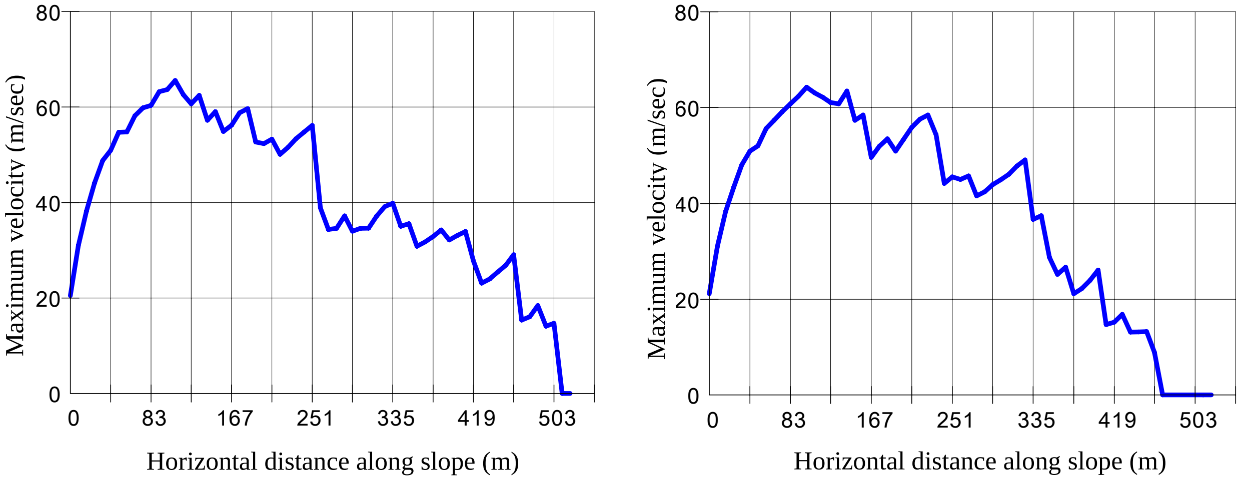
(a) Analysis using JRC=0.2

(d) Analysis using JRC=1.2



(b) Analysis using JRC=0.4

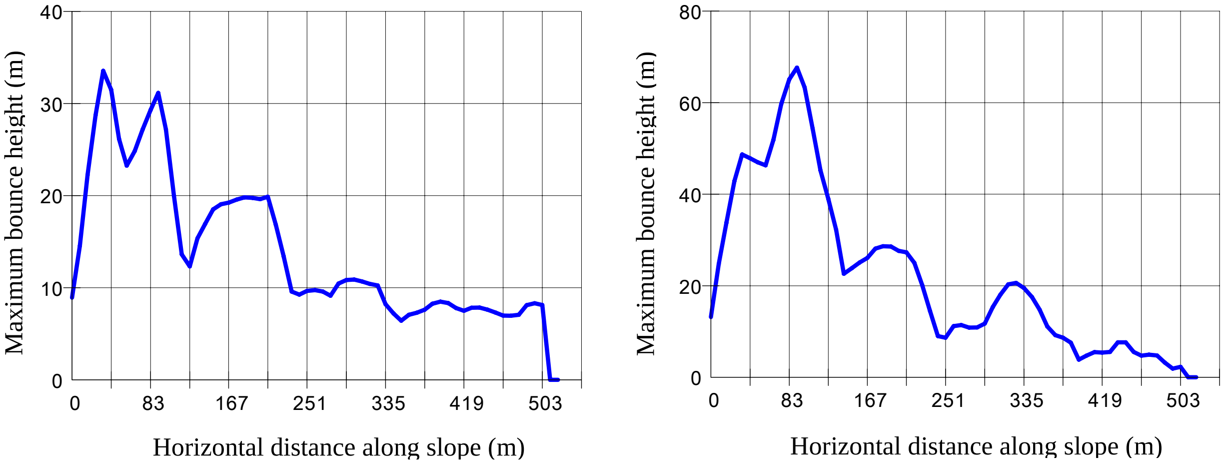
(e) Analysis using JRC=1.8



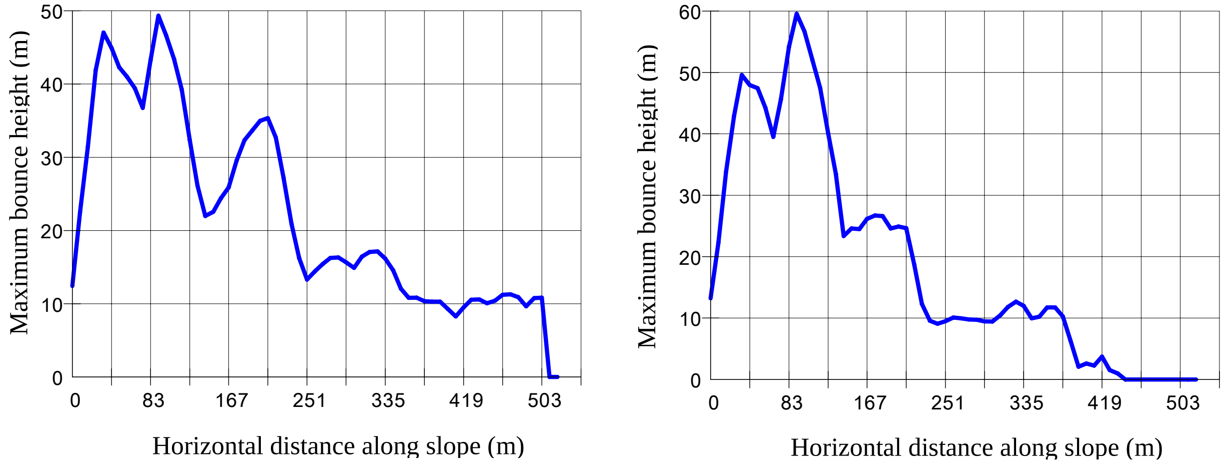
(c) Analysis using JRC=1.0

(f) Analysis using JRC=2.0

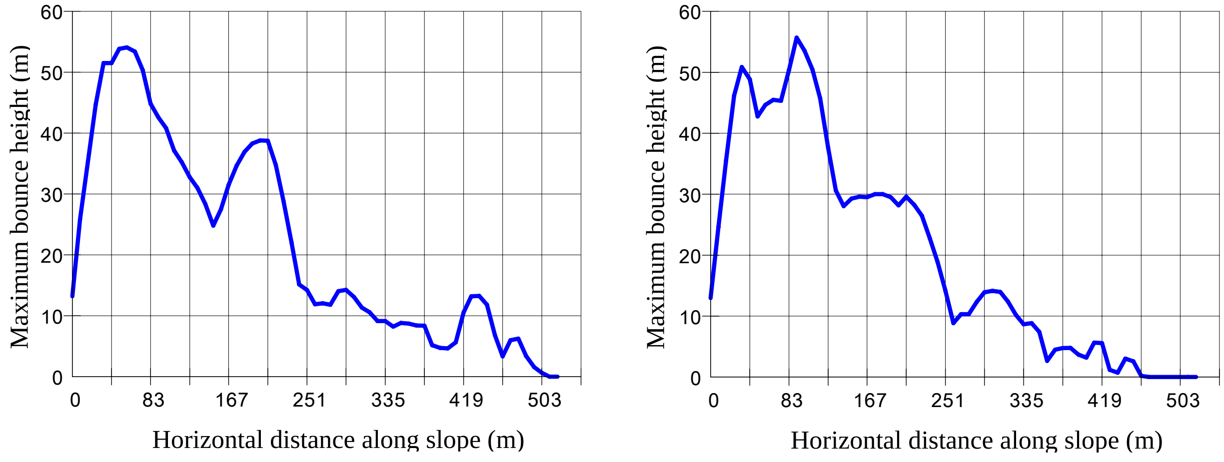
Fig. 4: Influence of the maximum velocity by surface roughness during a rockfall.



(a) Analysis using JRC=0.2 (d) Analysis using JRC=1.2



(b) Analysis using JRC=0.4 (e) Analysis using JRC=1.8



(c) Analysis using JRC=1.0 (f) Analysis using JRC=2.0

Fig. 5: Influence of the maximum bounce height by surface roughness during a rockfall.

The analytical and statistical results of simulations by using Discoidal rocks were shown in Table 2. Figure 4 shows the maximum velocity by surface roughness during a rockfall. Figure 5 shows the maximum bounce height by surface roughness. The observations on Table 2 and Figure 4 indicated that the velocity of a rockfall did not increase as slope ratio increased. At the sections of five different slope ratios, the fastest average velocity, reaching 63m/sec, was obtained when the slope ratio = 1:1 and 1:0.5. The observations on Table 2 and Figure 5 suggested that the moving velocity was obtained when JRC = 0.2 and 0.4. Bounce height did not increase as slope ratio and JRC increased. The maximum bounce height, reaching 69m, was obtained when JRC=1.2. In the simulations based on the five slope sections, the result showed that the greatest impact was created on bounce height when slope ratio m > 1 : 1 and JRC = 1.2. When slope ratio m < 1 : 1, greater impact was created on bounce height if JRC = 0.4. In Figure 5, the results showed that no bounce occurred when m=1:3 and JRC = 1.8 and 2.0. The movement turned to rolling or sliding.

IV. DISCUSSION

This paper aimed at discussing the impact of slope and surface roughness on the moving paths of a rockfall. For achieving the purpose, simulation and statistical analysis was applied. Under the same analytical conditions on a single geometric slope, slope and surface roughness were changed to observe the variations of rock bouncing and movement velocity in order to analyze the impact of slope and surface roughness on the moving paths of a rockfall.

1. The impact of slope

Figure 6 shows the rock bounce height on slope ratio and surface roughness. In Figure 6, rock bounce height decreased as slope ratio increased. When m≧ 1 : 1, bounce height significantly increased. When the m = 1 : 0.5, the maximum bounce height was obtained. It was because the moving paths were mainly formed by freefalling when m≧1. When m < 1 : 1, the energy of a falling rock diminished after collision and its movement turned out to be rolling. The threshold for bounce height on a monoclinal slope came at m=1 : 1. Greater slope ratio created bounce more easily, otherwise it was easy to cause rolling or sliding. Therefore, the times of a rockfall colliding slopes decreased when the slope ratio was greater. Such result is the same as that shown in the study where Ritchie [5] proved that slope shape created impact on the moving paths of a rockfall.

Figure 7 and 8 show the relationships which demonstrated the impact of slope ratio and surface roughness on the maximum velocity and average velocity of a rockfall, respectively. It was learned from the figures that the maximum velocity of a rockfall did not decrease as slope became mild. Meanwhile, the average velocity decreased as the slope became mild. The maximum velocity and average velocity were obtained when slope ratio was at m = 1 : 0.5. When m≧1 : 1, the velocity of a rockfall significantly became greater. It was because a rockfall turned to be bouncing and there were fewer contacts with slope surface and less energy reduction when m≧1 : 1. When m < 1 : 1, there were more collisions with slope surface causing greater energy reduction and a rockfall turned to be rolling or sliding. Therefore, greater collision energy of a rockfall at a certain point was created when slope ratio and velocity were greater.

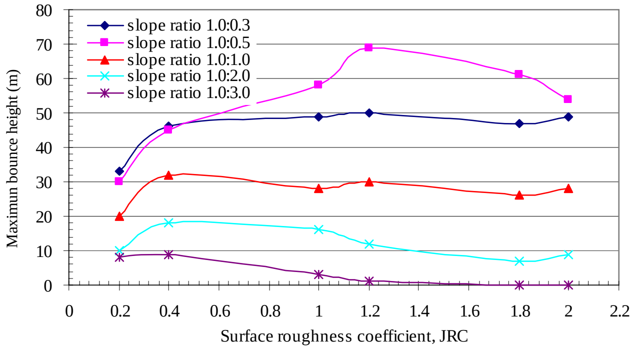


Fig. 6: Influence of the rock bounce height on slope ratio and surface roughness.

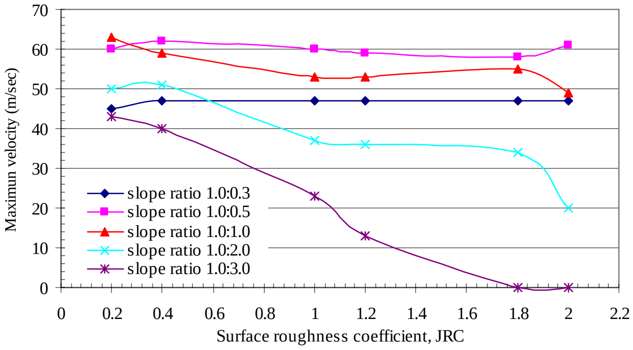


Fig. 7: Influence of the maximum velocity on slope ratio and surface roughness.

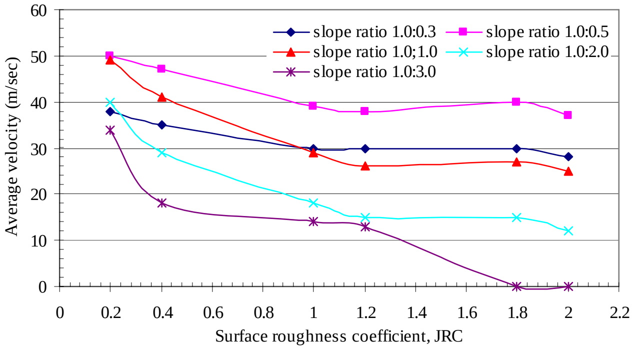


Fig. 8: Influence of the average velocity on slope ratio and surface roughness.

2. The impact of surface roughness

From Fig. 6 it is obvious that the significant relationship was shown between bounce of a rockfall and roughness angles. The degree of impact was determined by JRC. Bounce height increased as JRC increased. However, when $m \geqq 1:0.5$ or $JRC > 1.2$, bounce height significantly decrease. When $m \leqq 1:3$ and $JRC \geqq 1.8$, surface roughness created almost no impact on a rockfall. It's because the falling energy decreased after collisions and a rockfall quickly turned to rolling or sliding. From Fig. 7 and 8 it is obvious that the maximum movement velocity and average movement velocity decreased as JRC increased. The maximum velocity was obtained when $m \geqq 1:0.5$ and $JRC = 1.2$. When $JRC < 1.2$, the velocity decreased and bounce height increased as JRC increased. This was because a rockfall gradually turned to be rolling from bouncing, which led to velocity reduction. When $m \geqq 1:1$, a rockfall presented a freefalling pattern or bouncing patter. There were fewer contacts between falling rocks and slope surface. Therefore, the impact of JRC on a rockfall became less accordingly. Thus, it was proved that bounce height increased and movement velocity decreased if the slope ratio remained the same and JRC increased.

The reason for the above result was that the movement of a rockfall turned to be rolling or sliding after bouncing. Another reason contributing to such result was that roughness angles caused higher bounce of a rockfall and consequently there were fewer contacts with slope surface and less total energy reduction. However, when the roughness angle reached up to a certain degree, the collision angle mitigated a rockfall's moving energy and bounce height of a rockfall decreased accordingly. Therefore, it was learned that the moving energy decreased as there was longer distance from the hilltop. As a result, it was found that the uncertainty of a rockfall was extremely high and the variations of the moving paths of a rockfall were caused by different conditions.

V. CONCLUSIONS

Rockfalls are one of the geological disasters often occurring in the mountainous areas. The study on a rockfall requires precise predictions on its moving paths so as to provide effective response and design for solving the problems brought by rockfalls. This paper applied simulation and statistical analysis to analyze bounce height and movement velocity of a rockfall and explored the impact of slope shape and surface roughness on the moving paths of a single rockfall. The results showed that surface roughness easily caused changes of the moving paths of a rockfall. The more irregular the surface was, the easier the rockfall was from rolling or sliding to bouncing. The slope ratio $m=1:1$ acted as the threshold. A rockfall showed a bouncing pattern when there was a greater slope ratio, otherwise it was easy to cause rolling or sliding. It was proved that the best protective point and protective facilities could be selected as long as the moving paths of a rockfall could be precisely predicted because the bounce height and movement velocity of a rockfall could be controlled by locating the collision points on the slope during its movement. As a result, the danger and risks brought by a rockfall could be mitigated.

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