International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:6, No:1, 2012

Simulation and Statistical Analysis of Motion Behavior of a Single Rockfall

Iau-Teh Wang, Chin-Yu Lee

***Abstract*—**The impact force of a rockfall is mainly determined by its moving behavior and velocity, which are contingent on the rock shape, slope gradient, height, and surface roughness of the moving path. It is essential to precisely calculate the moving path of the rockfall in order to effectively minimize and prevent damages caused by the rockfall. By applying the Colorado Rockfall Simulation Program (CRSP) program as the analysis tool, this research studies the influence of three shapes of rock (spherical, cylindrical and discoidal) and surface roughness on the moving path of a single rockfall. As revealed in the analysis, in addition to the slope gradient, the geometry of the falling rock and joint roughness coefficient (JRC) of the slope are the main factors affecting the moving behavior of a rockfall. On a single flat slope, both the rock's bounce height and moving velocity increase as the surface gradient increases, with a critical gradient value of $m = 1:1$. Bouncing behavior and faster moving velocity occur more easily when the rock geometry is more oval. A flat piece tends to cause sliding behavior and is easily influenced by the change of surface undulation. When $JRC < 1.4$ the moving velocity decreases and the bounce height increases as JRC increases. If the gradient is fixed, when JRC is greater, the bounce height will be higher, while the moving velocity will experience a downward trend. Therefore, the best protecting point and facilities can be chosen if the moving paths of rockfalls are precisely estimated.

***Keywords*—**rock shape, surface roughness, moving path.

I. Introduction

SLIPS and falls are serious problems. Mostly, landslides tend to happen after heavy rain or earthquakes [1]. However, rockfalls may happen anytime on steep rock slopes, threatening the residents in mountain communities. There are several types of moving behaviors of rockfall, namely freefalling, bouncing, rolling and sliding. The moving path can be subdivided into three sections: source area, moving area, and threatened area [2]. The moving behavior of a rockfall is affected by the geometry of the slope, the geometry and material properties of the falling rock, and material properties of the slope and the rock [3], [4].

The geometry of the slope includes factors such as: slope height, gradient, shape, surface undulation etc. The moving path of a rockfall will be altered by the surface roughness and undulation.

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A slope is more irregular when its roughness angle is greater, thereby affecting the collision angle, and changing the moving velocity of its rolling and sliding modes [5]. Through in situ testing, Ritchie (1963) [6] discovered that rockfall behavior is affected by the surface undulation and changes from rolling and sliding modes to bouncing mode. He also pointed out that on a slope of an angle smaller then 45°, the falling rock loses kinetic energy after the bouncing and changes to rolling mode. On a slope of an angle between 45°~ 60°, the falling rock still retains the energy to keep accelerating downward, and moves downward by continuously bouncing. On a slope of an angle above 60°, the falling rock mainly free falls. Roughness and undulation of the surface (S) cause random changes in the collision angles of falling rocks. Rock size (R) and surface undulation are correlated to each other. Rocks falling speed increases when the R/S value increases, while the bounce height decreases [6]. On a slope with a gradient which is greater than 45°, the falling velocity increases relatively and the bounce height decreases when the R/S value increases. However, the bounce height will increase when the angle of the slope is less than 45° [3].

Both the geometry and material property of a falling rock affect the rockfall behaviors. Wadell (1932) [7] indicated that the number of bounces is reduced and the bounce height increases when the sphericity and roundness increase. A rock's moving behavior will be different after its collision with the slope on its sides or corners. The geometries of rocks also affect the shifting, revolving energy, and moving modes of their moving behaviors. Azzoni *et al*. (1995) [8], [9] pointed out that a rock's volume has limited influence when it reaches a certain velocity through numerical study. Okura (2000) [10] and other scholars pointed out that the bouncing distance is not affected by the rock mass when rocks are of the same size. Pfeiffer and Bowen (1989) [3] indicated that rocks with low hardness break in collision and minimize the bouncing reaction.

The moving path of a rockfall can be obtained by applying Experimental Methods, Computational Modeling, or Empirical Analysis. Experimental Methods are divided into two types: Field Studies [6], [11] and Physical Modeling [12]. However, Experimental Methods are too expensive and time consuming and the results, which are regional, are not suitable for other statistical and parametric researches. Computational Modeling is divided into two types: Lumped Mass Method [3], [13]–[15] and Rigid Body Method [8], [13]. Lumped Mass Method presumes that the rock is one single lumped mass, while Rigid Body Method can simulate the geometry of a rock. Ritchie

(1963) [6] summarized the relationship between rockfall moving modes and the slope gradient based on Empirical Analysis. Azzoni and Freitas (1995) [9] indicated that under a single slope the range of the shifting movement is ten percent of the length of the slope, based on his observation in rockfall disaster areas and the results of field studies. Nevertheless, the real situation is significantly affected by the environment of the site and this constitutes a limitation of Empirical Analysis.The moving path of a rockfall is not a simple linear relationship. Determining how to reflect site conditions in the analysis is the key issue in rockfall researches. However, concerned scholars did not further discuss the influence of rock's geometry and surface roughness on the prediction of rockfall moving paths. With advances in its development, Colorado Rockfall Simulation Program (CRSP) has been successfully applied to many scientific and engineering issues [15]. The CRSP was developed for the purpose of modeling rockfall behavior and to provide a statistical analysis of probable rockfall events. This analysis can be used as a tool to study the behavior of rockfalls. The model is a two dimensional representation of the most probable rockfall path as determined by the field investigator. Therefore, this paper has applied this program to simulate rockfall movements and discusses the impact of rock shape and surface roughness on the moving paths of a rockfall in order to improve prediction accuracy.

II. Design of Simulation

This research applies Simulation and Statistical Analysis and looks into the influence of factors such as a rock's geometry and surface roughness on rockfall moving paths on a slope with a single geometry, with the consideration of the interaction between factors. Plans of the simulating experiments are as followed:

A. Description of Simulation Method

The simulations assume that the detachment of the loose boulders occurs on the highest outcrops of the sections in question. The main parameters required to assist the design of remedial measures and to determine slope can be obtained through an analysis of the trajectories and characteristics of rockfalls.In the CRSP program, analyses of rockfall moving paths can simulate three rockfall moving modes of a single 2D falling rock, namely free falling, bouncing, rolling and sliding. *The program also presumes:*

1) The bouncing of a rock is affected by Normal Restitution Coefficient (e_n) and Tangent Restitution Coefficient (e_t).
2) The falling rocks do not break or separate when moving and their sizes and geometries remain fixed in the analyses.
3) The program automatically changes from a bouncing mode to a rolling mode when a rock's bounce distance is less than its radius. The rock starts falling with the initial velocity (V_{0x}, V_{0y}) from the position (x_0, y_0) on time frame t_0. After that, if it is freefalling, its moving path (x, y) can be represented by the parabolic rockfall moving path Equation (1).

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} x_0 + (t - t_0)v_{0x} \\ y_0 + (t - t_0)v_{0y} - \frac{1}{2} g (t - t_0)^2 \end{bmatrix} \quad (1)$$

To model rockfall behavior, CRSP uses numerical input values assigned to slope and rock properties. The model applies equations of gravitational acceleration and conservation of energy to describe the motion of the rock. The statistical variation observed among rockfalls is modeled by randomly varying the angle at which a rock impacts the slope within limits set by rock size and the slope characteristics. A comparison of rock velocity and bounce height obtained from the tapes with CRSP prediction, provides a site specific analysis of rockfall with output of velocity and bounce height statistics at various on the slope.

B. Rock Mass

The geometry parameters of a rockfall are shown in Table Ⅰ, and its material parameters are listed in Table II. Rock shape is a key factor which affects the moving behaviors. In the past, a 2D or 3D ball was mainly used to simulate rockfall moving behavior. Three types of rock shape are applied in this research: spherical, cylindrical and discoidal rocks. The slope gradient and surface roughness are varied to study the moving paths. In addition, Restitution Coefficient is directly affected by the rock hardness. Rocks with low hardness tend to break up in collision with the surface [3], [4]. Generally, the elastic modulus of a rock is between $40 \sim 70$ GPa and Poisson's Ratio (v) is around $0.2 \sim 0.3$ [16]. The Restitution Coefficient will change the moving behavior after the rock hits the slope. The Restitution Coefficient includes Normal Restitution Coefficient (e_n) and Tangent Restitution Coefficient (e_t). If the ratio of e_n and e_t is 1, the collision is totally elastic [4]. When the ratio is 0, there will be no bouncing at all. The e_n of a rocky slope is 0.5, and its e_t is 0.95. The e_n of a coarse rock layer is 0.35, and its e_t is 0.85 [2].

TABLE I
ROCK MASS GEOMETRY PARAMETERS

Rock shape	Spesification		
	Diameter	Length	Thickness
Spherical	1.2m	--	--
Cylindrical	0.6m	3.2m	--
Discoidal	1.2m	--	0.8m

TABLE II
MATERIAL PARAMETERS OF ROCK MASS USED IN THE SIMULATIONS

Density (kg/cm^3)	2650
Modulus of elasticity, E (Gpa)	50
Poisson Ratio, v	0.25
Normal Restitution Coefficient, e_n	0.50
Tangent Restitution Coefficient, e_t	0.95

C. Slope Shape and Surface Roughness

Four types of slope are shown in Fig. 1 with the gradients (vertical and horizontal) of 1:2, 1:1, 1:0.5 and 1:0.3, independently. Beside the rock geometries, the slope shape is also an important factor which influences the rockfall moving paths. The bounce angle is directly affected by the surface roughness and undulation. Figure 2 is an illustration of the slope's surface roughness and undulation. The roughness angle is used to indicate the roughness of a slope, representing the angle between the undulating slope and the average slope [3]. The roughness angle is calculated by Equation (2). In the equation, $i_{\max}$ is the largest roughness angle, S is the height of the undulation, and R represents the length of the base of the slope.

$$i_{\max} = \tan^{-1}\left(\frac{S}{R}\right) \tag{2}$$

The rockfall's moving path is influenced by the undulation of the slope. With larger roughness angles, slopes are more irregular and the bounce angles will be changed. In order to simulate the ground undulation, Joint Roughness Coefficient (JRC) is used to show the roughness of slope sections, which is shown in Fig. 3 [17]. This parameter is taken into consideration in the CRSP analyses to simulate a slope with a height of 320 meters. The original position of the rock is $(x_0, y_0) = (0, 320)$ and its falling distance $h_0 = 0m$. The horizontal and vertical primary speeds are $3m/s$ and $-3m/s$, respectively. Through this experiment, this research aims to discuss how the rock's shape and surface undulation affect the moving path of a rockfall.

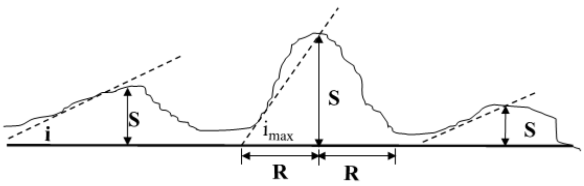


Fig. 2 Schematic diagram for surface roughness. Adapted and modified from Pfeiffer (1989) [3]

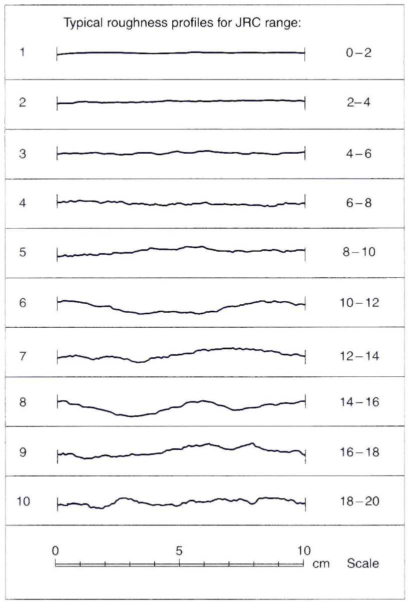


Fig. 3 Typical roughness profiles for JRC ranges. [17]

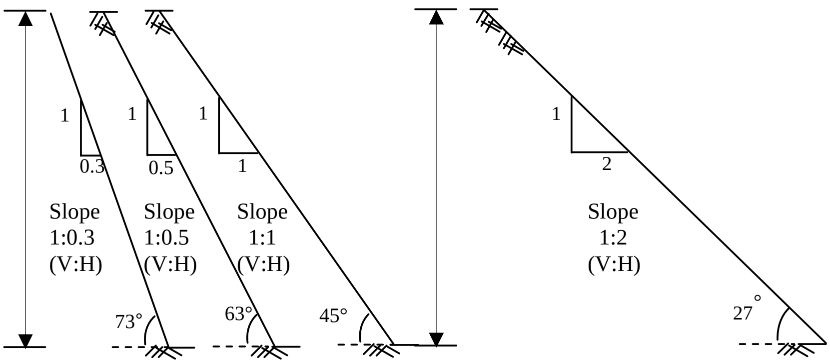


Fig. 1 Schematic diagram of boulders along different types of slopes. Adapted and modified from Ritchie (1963) [6]

III. Results of Rockfall Simulations

One thousand times of simulation were conducted to study how rocks of three shapes (spherical, cylindrical and discoidal) fall on slopes with four gradients and ten types of roughness. The program can compute a single rock's bounce height and moving velocity when moving any distance on the slope in each of its calculation. Statistical Analyses are applied to study the bounce height, moving velocity, and kinetic energy based on the number of simulation runs. The bounce height and moving velocity are also used to discuss the extent of influence of rock shape and landscape sensitive analysis.

The statistic results of rockfall tests on Spherical rocks are shown in Table III. Figures 4 and 5 indicate the highest bounce height and fastest moving velocity on slopes with different gradients. The results of these analyses show positive correlation between three factors: bounce height, moving velocity and kinetic energy, and the gradient independently. Rockfall bounce height increases as the slope gradient increases. The bounce height shows an obvious upward trend when the slope gradient $m \geq 1:1$, and the rockfall has the maximum bounce height when $m = 1:0.3$. The reason is that the moving path is mainly one of free fall when $m \geq 1$, and the rockfall changes to rolling movement after the energy loss in the collision when $m < 1:1$. Therefore, the gradient $m = 1:1$ is regarded as the critical value on a single flat slope. Bouncing behavior happens more easily when the slope gradient is greater, and rolling and sliding movements happen more readily when the gradient is smaller. Thus, the number of rockfall collisions is reduced when the slope gradient increases. This result is equivalent to Ritchie (1963) [6] and Pfeiffer *et al*. (1989) [3] analyses of the gradient's influence on the rockfall moving modes. As shown in Fig. 4, the bounce height changes as the JRC value varies. The bouncing behaviors of rockfalls are clearly correlated to the roughness angle, and the extent of influence depends on the JRC value. When $m > 1:1$ or $JRC \leq 0.8$, the bounce height has an upward trend. When $m \leq 1:1$ or $JRC > 1.0$, the bounce height is reduced as the surface roughness increases. As shown in Fig. 5, the moving velocity of the rockfall changes as the slope gradient and JRC value vary. Moving velocity and Kinetic Energy reduce as the JRC value increases when $m \leq 1:1$. The maximum moving velocity reaches $73.48\,m/s$ when $JRC = 1.6$.

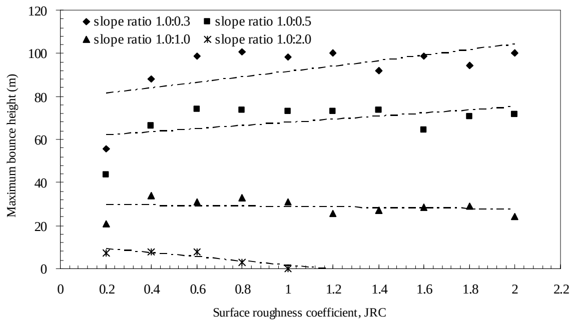


Fig. 4 Influence of slope and JRC on the bounce height of Spherical rockfall

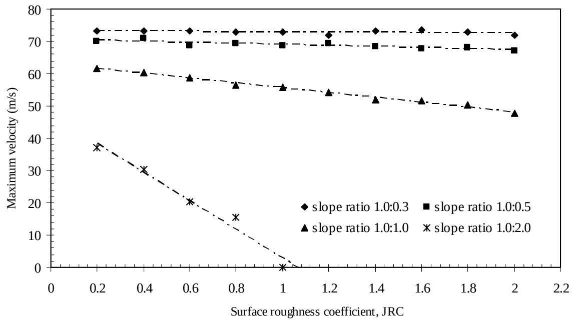


Fig. 5 Influence of slope and JRC on the velocity of spherical rockfall

Table IV shows the statistical results of the simulation analysis of cylindrical rocks. Figures 6 and 7 illustrate the results of the maximum bounce height and moving velocity simulation with different slope gradients. As revealed in the analysis, cylindrical rockfall behavior has a positive correlation with the slope gradient. The rockfall bounce height increases as the slope gradient increases, and it has an evident upward trend when $m \geq 1:1$. Cylindrical rocks on single flat slopes have the critical value $m = 1:1$. The bouncing behavior happens more easily when the gradient is greater. On the conversely, rolling or sliding behaviors happen more easily when the slope is gentler. This result is also the same as that of the analyses conducted by Ritchie (1963) [6] and Pfeiffer *et al*. (1989) [3]. As shown in Fig. 6, rockfall bouncing behavior is clearly related to the roughness angle. The rockfall bounce height changes as the surface roughness JRC value varies. When $m > 1:1$ or $JRC \leq 1.2$, the bounce height exhibits an upward trend. When $m \leq 1:1$ or $JRC > 1.4$, the bounce height is reduced as the surface roughness increases. As shown in Fig. 7, the rockfall moving velocity changes as the slope gradient and the surface roughness JRC value vary. The moving velocity and Kinetic Energy decrease as JRC increases when $m \leq 1:1$. The maximum moving velocity reaches $73.98\,m/s$ when $JRC = 2.0$.

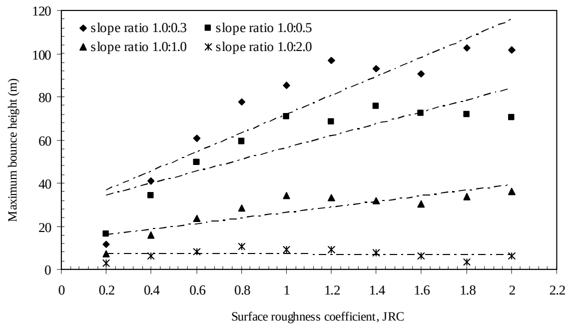


Fig. 6 Influence of slope and JRC on the bounce height of cylindrical rockfall

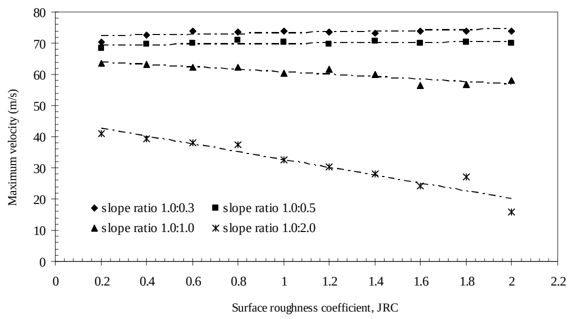


Fig. 7 Influence of slope and JRC on the velocity of cylindrical rockfall

Table V shows the statistical results of the simulation analysis of discoidal rocks. Figures 8 and 9 illustrate the results of maximum bounce height and moving velocity simulation with different slope gradients. As revealed in the analysis, discoidal rockfall behavior also has a positive correlation with the slope gradient. The bounce height exhibits an evident upward trend when $m \geq 1:1$. Discoidal rocks on single flat slopes have the threshold $m = 1:1$. The bouncing behavior more easily happens when the gradient is greater. Conversely, rolling or sliding behaviors happen more easily when the slope is gentler. As shown in Fig. 8, the bounce height exhibits an upward trend when $m > 1:1$ or $JRC \leq 1.0$. When $m \leq 1:1$ or $JRC > 1.2$, the bounce height is reduced as the surface roughness increases. As shown in Fig. 9, the rockfall moving velocity changes as the slope gradient and the surface roughness JRC value vary. The moving velocity and Kinetic Energy decrease as JRC increases when $m \leq 1:1$. The maximum moving velocity reaches $96.27\, m/s$ 96.27m/s when $JRC = 1.6$.

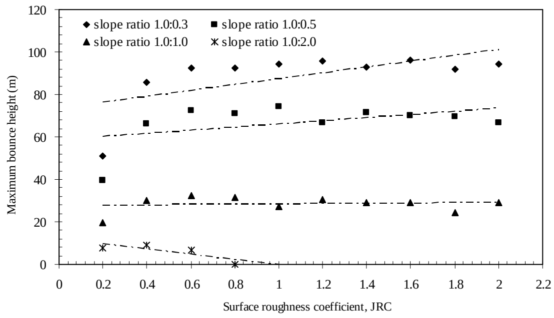


Fig. 8 Influence of slope and JRC on the bounce height of discoidal rockfall

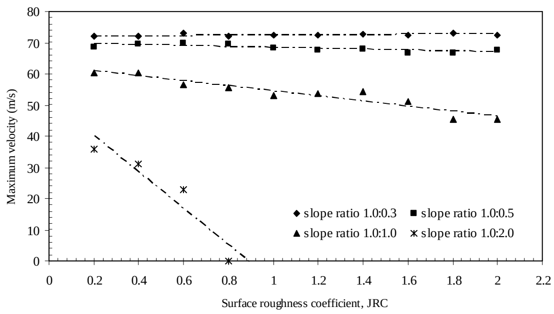


Fig. 9 Influence of slope and JRC on the velocity of discoidal rockfall

IV. Discussion

This research applies simulation and statistical analysis. By changing the slope gradient under the same analyzing conditions, this research discusses the influence of rock shape and surface roughness on the moving path on a slope of single geometry, based on the changes of bounce height and moving velocity.

A. Impact of Slope

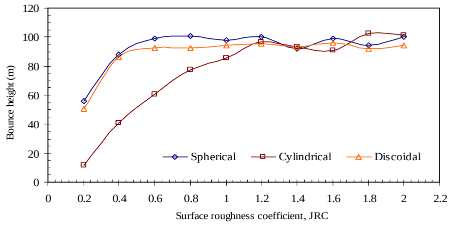
Figures 10 and 11 reveal the influence of the three rock shapes (spherical, cylindrical, and discoidal) on bounce height and moving velocity with different slope gradient and surface roughness. As shown in the figures, moving velocity and bounce height of the rockfall descend when the slope gradient is reduced. Followed by the discoidal shape, the spherical shape has the highest bounce height with the same slope gradient. The cylindrical shape has the lowest bounce height. When slope gradient $m = 1:0.3$ and $JRC > 1.4$, $m = 1:0.5$ and $JRC > 1.0$, $m = 1:1$ and $JRC > 0.8$, and $m = 1:2$ and $JRC > 0.6$, the overlapping phenomena will emerge. Thus, the overlapping point mentioned above is a threshold. When $m \geq 1:1$, moving velocity and bounce height of the rockfall exhibit an evident upward trend because rockfalls here mostly have bouncing movement and have less opportunity contacting the surface with less energy loss. When $m < 1:1$, cylindrical shaped rock has the highest bounce height. Discoidal shaped rock is the second and spherical shaped rock has the lowest bounce height. When the slope gradient $m = 1:2$ and $JRC = 0.8$ and 1.0, discoidal and spherical shaped rocks have no bouncing behavior because of the energy loss after the rock collisions, triggering the rolling or sliding movements. Hence, rockfalls have faster moving velocity on steep slopes where the collision has more energy. Conversely, rockfalls change quickly to rolling or sliding movement when colliding with the surface, when the gradient is smaller. Also, as shown in the figures, when $m < 1:1$, the moving velocity does not change too much with different JRC values. The reason is that rocks change quickly to rolling or sliding movement when the slope is gentler. Kinetic energy is reduced when the slope gradient decreases.

B. Impact of Surface Roughness

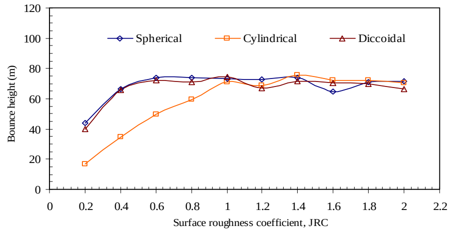
As shown in Fig. 10, under the same conditions, bounce height does not increase when JRC is increased. In Fig. 10-(a), when gradient $m = 1:0.3$ and $JRC > 1.2$, bounce height decreases slightly. Before bounce height overlapping occurs, bounce height increases when JRC increases. The reason is that the rock's moving path follows a parabolic line. Therefore, the bounce height is still increasing before the rock meets the peak on the parabolic line. After the overlapping, the existing roughness angle causes the increase in the bounce height and the range of the moving path increases. The result shown in Fig. 10-(a) can be found in Figs. 10-(b), 10-(c) and 10-(d). The result is due to the direct influence of surface roughness on collision angle and causes the moving behavior changing from rolling and sliding to bouncing. The second reason is that with the roughness angle, the rock will bounce even higher and get fewer chances to lose kinetic energy when contacting the surface. However, when the roughness angle reaches a certain value, the collision angle causes some kinetic energy loss and the bounce height will not be affected. Figure 11 reveals the fact that when gradient $m > 1:1$, rockfalls with different JRC tend to move at the same speed. If gradient $m \leq 1:1$, the moving velocity of the rockfall decreases when JRC increases. The reason is that part of the energy is transformed into potential energy; with less energy, the bouncing movement turns into the rolling mode and the moving velocity is reduced accordingly.

C. Impact of Rock Shape

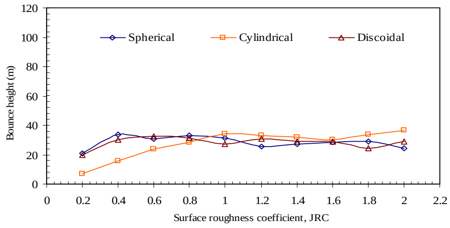
There is an apparent correlation between the rock shape and moving path. The extent of influence is related to surface roughness. Whether the rock collides with the slope on its sides or corners causes different moving behaviors. The rock shape also affects the energy and moving mode when the rock is sliding or rolling. As shown in Fig. 10, there are overlapping phenomena when gradient $m = 1:0.3$ with $JRC > 1.4$, $m = 1:0.5$ with $JRC > 1.0$, $m = 1:1$ with $JRC > 0.8$ and $m = 1:2$ with $JRC > 0.6$. Before the overlapping, the spherical shaped rock has the highest bounce height followed by the the discoidal shaped rock. The cylindrical shaped rock has the lowest bounce height. All of the bounce heights increase when the JRC increases. After the overlapping point, the cylindrical shaped rock has the highest bounce height while the discoidal shaped rock has the lowest one. Therefore, when sphericity is higher, the number of bounces will decrease while the bounce height will increase. A rock with high sphericity has better bouncing capability, while a flat or long rock moves mainly by rolling or sliding. As the results in Fig. 11 show, with all conditions remaining the same, moving speeds ranked from highest to lowest are as followed: cylindrical shape, spherical shape, and discoidal shape. It shows that when moving on a single slope, a rock with the sphericity close to oval tends to bounce and move at high velocity, while a flat piece is more likely to slide and be easily affected by the undulation of the slope.



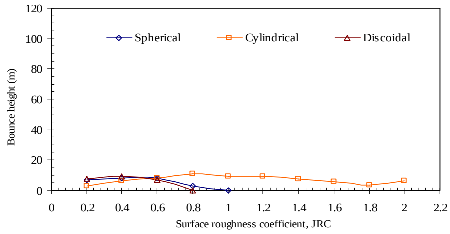
(a) Analysis using $m = 1:0.3$



(b) Analysis using $m = 1:0.5$

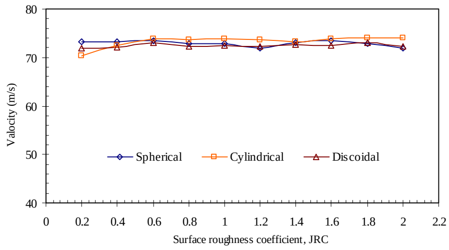


(c) Analysis using $m = 1:1$

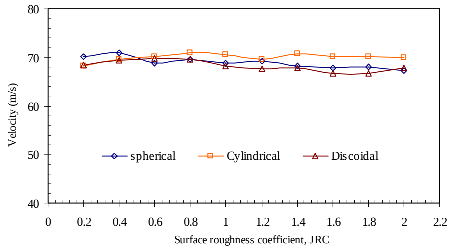


(d) Analysis using $m = 1:2$

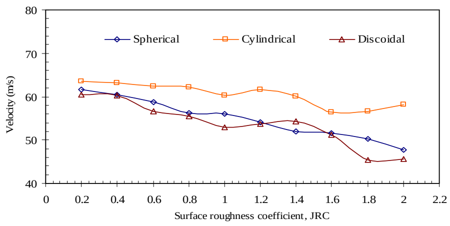
Fig. 10 Influence of rock shapes (spherical, cylindrical, discoidal) on bounce height with different slope and JRC



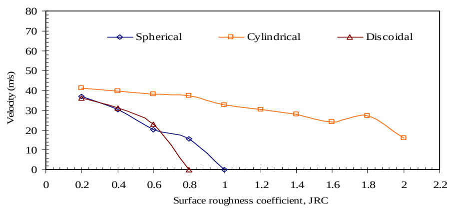
(a) Analysis using $m = 1:0.3$



(b) Analysis using $m = 1:0.5$



(c) Analysis using $m = 1:1$



(d) Analysis using $m = 1:2$

Fig. 11 Influence of rock shapes (spherical, cylindrical, discoidal) on moving velocity with different slope and JRC

TABLE III
STATISTIC RESULTS OF THE SIMULATION ANALYSIS OF SPHERICAL ROCKS

Slope		Height of bounce (m)		Velocity (m/s)		
Vertical to horizontal ratio	Surface roughness	Maximum value	Average value	Maximum velocity	Average velocity	Kinetic Energy(J)
1 : 0.3 (73°)	0.2	55.75	13.47	73.25	51.44	6762046
	0.4	87.83	31.19	73.32	52.13	6607449
	0.6	98.75	37.06	73.34	50.59	6659746
	0.8	100.79	37.5	72.87	50.36	6609083
	1.0	98.04	32.63	72.8	47.58	6573338
	1.2	100.15	31.25	71.83	45.29	6466922
	1.4	91.79	31.93	73.1	44.79	6590308
	1.6	98.81	32.17	73.48	44.27	6647158
	1.8	94.21	31.52	72.93	45.57	6641619
	2.0	100.19	33	71.96	45.09	6557875
1 : 0.5 (63°)	0.2	43.67	16.18	70.13	57.67	6320268
	0.4	66.36	24.12	70.89	53.52	6287798
	0.6	73.89	25.03	68.81	49.68	6220232
	0.8	73.71	25.69	69.47	45.46	6039070
	1.0	73.27	26.51	68.79	44.04	5888000
	1.2	72.83	25.21	69.22	43.02	6197709
	1.4	73.63	24.61	68.25	42.48	6137074
	1.6	64.43	23.29	67.79	42.04	5709799
	1.8	70.85	24.37	68.06	41.44	5867064
	2.0	71.58	22.72	67.19	40.54	5969580
1 : 1 (45°)	0.2	20.67	7.06	61.71	50.38	5409885
	0.4	33.8	9.53	60.45	42.47	4958008
	0.6	31.01	8.97	58.8	35.92	4712876
	0.8	33.04	8.11	56.32	31.13	4690081
	1.0	31.09	7.45	55.96	27.83	4178931
	1.2	25.67	6.48	54.09	25.61	4061879
	1.4	27.24	6.62	51.99	23.85	3867373
	1.6	28.43	6	51.54	23.51	3916482
	1.8	28.94	6	50.29	24.62	4101869
	2.0	24.41	5.91	47.65	24.81	3187464
1 : 2 (27°)	0.2	7.18	2.25	37.08	30.66	2113226
	0.4	7.97	2.74	30.38	20.26	1410001
	0.6	7.88	1.82	20.35	12.34	681549
	0.8	3.08	3.08	15.64	15.64	391394
	1.0	No Rocks	0	0	0	0
	1.2	No Rocks	0	0	0	0
	1.4	No Rocks	0	0	0	0
	1.6	No Rocks	0	0	0	0
	1.8	No Rocks	0	0	0	0
	2.0	No Rocks	0	0	0	0

TABLE IV
STATISTIC RESULTS OF THE SIMULATION ANALYSIS OF CYLINDRICAL ROCKS

Slope		Height of bounce (m)		Velocity (m/s)		
Vertical to horizontal ratio	Surface roughness	Maximum value	Average value	Maximum velocity	Average velocity	Kinetic Energy(J)
1：0.3 (73°)	0.2	11.69	1.5	70.31	47.77	6597034
	0.4	41.02	8.99	72.56	52.07	6729127
	0.6	60.86	18.4	73.79	53.79	6782262
	0.8	77.51	26.04	73.53	53.39	6669091
	1.0	85.44	31.04	73.86	51.7	6709934
	1.2	96.87	34.32	73.65	50.4	6739423
	1.4	93.16	37.59	73.19	49.42	6688774
	1.6	90.84	39.26	73.84	48.35	6768293
	1.8	102.47	40.92	73.93	48.11	6779866
	2.0	101.49	41.47	73.98	47.12	6728255
1：0.5 (63°)	0.2	16.52	6.07	68.27	61.78	6282408
	0.4	34.4	13.31	69.55	59.9	6298365
	0.6	49.44	19.05	70.11	57.91	6207494
	0.8	59.4	23.69	70.84	55.88	6346159
	1.0	70.7	28.07	70.48	53.19	6226756
	1.2	68.61	30.44	69.63	51.38	6188206
	1.4	75.61	31.24	70.76	50.63	6213245
	1.6	72.11	32.78	70.06	49.53	6276622
	1.8	72.02	32.47	70.22	49.16	6192145
	2.0	70.51	30.01	69.88	48.27	6093758
1：1 (45°)	0.2	7.02	2.5	63.65	58	5805230
	0.4	15.81	5.27	63.13	54	5551607
	0.6	23.84	7.77	62.37	49.8	5271667
	0.8	28.31	9.04	62.2	46.33	5361360
	1.0	33.98	10.26	60.22	43.24	4773616
	1.2	33.27	10.5	61.55	40.8	5086221
	1.4	31.76	9.83	60.02	38.25	4888279
	1.6	30.13	8.86	56.46	32.77	4385732
	1.8	33.83	9.07	56.69	34.19	4373257
	2.0	36.34	8.97	58.16	32.41	4548039
1：2 (27°)	0.2	2.73	0.98	41.12	38.68	2598772
	0.4	6.18	2	39.42	34.05	2397824
	0.6	8.23	2.52	37.99	29.77	2076964
	0.8	10.74	2.68	37.35	25.66	2034584
	1.0	9.08	2.57	32.55	21.85	1550424
	1.2	9.27	2.33	30.22	18.41	1311753
	1.4	7.68	1.95	27.97	14.74	1157601
	1.6	6.03	1.62	24.14	12.61	862640
	1.8	3.5	1.03	27.21	11.66	1030471
	2.0	6.48	2.24	15.77	10.21	367388

TABLE V
STATISTIC RESULTS OF THE SIMULATION ANALYSIS OF DISCOIDAL ROCKS

Slope		Height of bounce (m)		Velocity (m/s)		
Vertical to horizontal ratio	Surface roughness	Maximum value	Average value	Maximum velocity	Average velocity	Kinetic Energy(J)
1 : 0.3 (73°)	0.2	50.87	13.63	71.94	50.76	6655839
	0.4	85.95	29.05	72.03	50.56	6474178
	0.6	92.56	33.48	73.01	49.5	6606290
	0.8	92.35	32.69	72.22	48.53	6629152
	1.0	94.14	29.72	72.53	46.14	6597683
	1.2	95.53	30.37	72.28	44.5	6539090
	1.4	92.98	29.3	72.7	44.02	6492102
	1.6	96.27	29.39	72.5	43.63	6560985
	1.8	92.11	29.33	73.05	43.45	6598865
	2.0	94.39	28.52	72.36	43.09	6493756
1 : 0.5 (63°)	0.2	39.67	15.71	68.46	56.38	6185872
	0.4	66.05	22.52	69.41	52.17	6338115
	0.6	72.2	24.2	69.78	47.06	6091745
	0.8	70.86	25.16	69.5	44.5	6115277
	1.0	74.34	25.6	68.12	42.43	6046373
	1.2	66.8	23.68	67.65	42.05	6037925
	1.4	71.28	23.77	67.89	40.53	5867873
	1.6	70.1	22.01	66.75	40.53	6044567
	1.8	69.57	21.78	66.64	40.23	5600171
	2.0	66.53	21.98	67.77	38.34	6050340
1 : 1 (45°)	0.2	19.52	6.62	60.46	48.71	5333749
	0.4	30	9.09	60.31	40.8	5074872
	0.6	32.28	8.95	56.53	34.03	4469009
	0.8	31.54	8.22	55.47	30.65	4330590
	1.0	27.12	7.55	52.91	27.06	4120620
	1.2	30.57	6.38	53.69	25.35	4175234
	1.4	29.25	6.01	54.36	23.41	4036522
	1.6	29.27	5.82	51.14	23.15	3750436
	1.8	24.3	5.54	45.45	22.11	2948481
	2.0	29.13	6	45.51	22.54	2906158
1 : 2 (27°)	0.2	7.46	2.28	36.01	29.5	2136662
	0.4	9.11	2.29	31.05	19.72	1462652
	0.6	6.76	1.72	22.78	11.44	822111
	0.8	No Rocks	0	0	0	0
	1.0	No Rocks	0	0	0	0
	1.2	No Rocks	0	0	0	0
	1.4	No Rocks	0	0	0	0
	1.6	No Rocks	0	0	0	0
	1.8	No Rocks	0	0	0	0
	2.0	No Rocks	0	0	0	0

V. CONCLUSION

The estimation of moving paths in researches on rockfalls must be precise, so that it can provide effective protection measures and resolve the rockfall problems. This research studied the influence of rock geometries and surface roughness on the rockfall moving path based on numerical simulation and statistical analysis methods. As shown by the results of this research, rough and undulating slopes tend to cause changes in the rockfall moving paths. The more irregular the slope, the more easily the rockfall moving behavior will change from rolling or sliding to bouncing. The slope gradient $m = 1:1$ is set as the dividing point. Bouncing movement is more dominating when the gradient is greater, while rolling and sliding happen more readily when the gradient is smaller. Surface undulation of the slope directly affects the rock's collision angle, and the moving path easily changes from rolling or sliding modes to bouncing mode. The rock's shape has a clear relationship with its moving path, and the extent of influence is contingent on the JRC value. Rocks with higher sphericity have better bouncing capabilities, while flat and long rocks with lower sphericity mainly roll or slide. As a result, the problems of rockfalls are highly uncertain and rockfall moving paths vary significantly under different conditions. Thus, if the moving path of a rockfall can be precisely predicted, it is possible to choose the best protecting points and facilities as references to contribute to the planning of communities on mountain slopes.

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