Hindawi
Advances in Civil Engineering
Volume 2020, Article ID 3610651, 6 pages
https://doi.org/10.1155/2020/3610651

Research Article

Mitigation Method of Rockfall Hazard on Rock Slope Using Large-Scale Field Tests and Numerical Simulations

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Received 26 September 2019; Accepted 21 November 2019; Published 23 March 2020

Guest Editor: Young-Suk Song

This paper presents the mitigation of rockfall hazard on the large-scale rock slope using the field tests with numerical simulation. To this end, field tests including the pendulum test and real rock falling tests were performed to investigate the rock movements such as rotation, repulsion, and speed. In the simulation, the validation of the developed model followed by calibration processes was made on the field tests. In this study, a simple and new method was proposed to mitigate the rockfall hazard using the so-called sand pool made by ditching and then filling sand where the rock should be stopped or arrested. The results showed that the sand pool method was very effective and economical.

1. Introduction

The rock falling occasionally causes a disastrous situation when it falls down to the road and facilities. The conventional methods to protect or mitigate rockfall hazard are concrete barrier (rigid) or rockfall fence (flexible). These methods have somewhat drawbacks in terms of maintenance. For concrete barrier, it can be severely damaged when the rock hits continuously the barrier. In addition, the construction/reconstruction cost of concrete barrier is high [1]. For the rockfall fence, even though construction cost is comparatively low, the capability of protection is low and perforation of net may occur, the so-called bullet effect [2, 3, 4]. In this study, a simple and new method was introduced to mitigate the rockfall hazard using the so-called sand pool. The sand pool was made by ditching and then filling sand where the rock should be stopped or arrested. The capability of the sand pool to stop or arrest the rockfall was examined. Based on its capability, the size of the sand pool was determined. In order to examine the capability of the sand pool, the integrated field tests with numerical simulation were performed. In the field tests, a total of four pendulum tests using two large cranes and a concrete ball (1 ton) were performed to obtain the restitution coefficient of rock. The rock falling tests were also conducted on the real rock slopes to investigate the movements of rock such as rotation, repulsion, and speed. The rock was pushed at top of the slope which has 214 m of height and 230 m of length in the vertical direction and horizontal direction, respectively. When the rock falls, two major parameters governing the rock movement are the friction coefficient and restitution coefficient. As stated earlier, the restitution coefficient was obtained from the pendulum tests, whereas the friction coefficient was determined from the calibration process of numerical simulation on the representative slope. After calibration processes, the validation of the developed model was made on different sections of slopes where the field tests were performed. The results showed that the proposed sand pool method was very effective and economic. In addition, maintenance can be simply done by removing the arrested rocks and replacing sand without compaction.

2. Field Tests

Two field tests such as the pendulum test and rock-dropping test were conducted in the field. The details of each test are described in the following subsections.

2.1. Pendulum Test. A total of four pendulum tests using two large cranes and a concrete ball (1 ton) were performed to obtain the restitution coefficient of rock as shown in Figure 1.

Two out of four tests were performed on the upper part of the rock wall, and the others were done on the lower part of the rock wall. The details of the concrete ball used in the test are presented in Table 1.

The restitution coefficients were obtained by measuring the distance from the wall to the position where the concrete ball was bounced as presented in Figure 2 and were calculated as expressed in the following equation:

$$C_R = \sqrt{\frac{h_v}{H_v}}, \quad (1)$$

where C_R is the restitution coefficient, H_v is the initial distance from concrete ball to wall, and h_v is the maximum distance from the concrete ball to the wall after being bounced.

Figure 2 presents the initial and final positions of the concrete ball. Figure 2(a) shows the initial position of the concrete ball and measured distance from the wall before hitting the wall, representing H_v in equation (1). Figure 2(b) presents the final position of the concrete ball and measured maximum rebounded distance from the wall, representing h_v in equation (1). As a result, the constitution coefficient (C_R) was computed as 0.48 by substituting 8.39 for H_v and 1.91 for h_v in equation (1).

The test results are presented in Table 2. Potential energy, velocity, and restitution coefficient for all four tests are listed in the table. The velocity in the table was calculated when the concrete ball hit the wall.

As presented in Table 2, the average restitution coefficients of upper and lower parts of the rock wall were 0.52 and 0.4, respectively. From the literature [5], the range of the restitution coefficient is 0.8-0.9 for solid rock and 0.3 for soft rock. Hence, it can be said that the restitution coefficient from the pendulum test is in between reasonable range.

2.2. Rock-Dropping Test. The rock-dropping tests were conducted on the real rock slopes to investigate the movements of rock such as rotation, repulsion, and speed. The rock was pushed from the top of the slope which was 214 m high and 230 m long in the vertical direction and horizontal direction, respectively, as presented in Figure 3. This rock slope has berms with 15 m height and 4 m width. Total of 13 rocks were dropped, and the repulsion height, speed, and location where the rock hit were measured using a high-speed camera and drone. As seen in the figure, the trees in the berms reduced the energy of rock dropping and finally stopped the rock, resulting in that the most of rocks were stopped in the trees and a few rocks dropped down to the bottom.

From the test, the height of bounced rock from the berm was measured using the high-speed camera. In addition, the velocity of the dropping rock was measured by means of both high-speed camera and drone. The results are presented in Table 3.

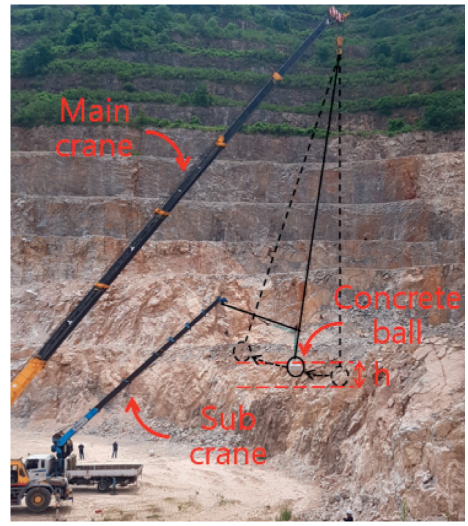
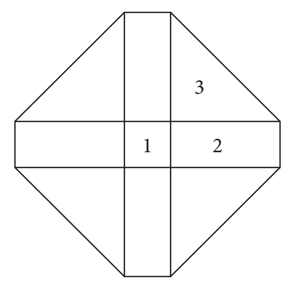


Figure 1: Overview of the pendulum test.

Table 1: Details of the concrete ball used in the pendulum test.

Weight (kg)	Shape	Size (cm)
1000		(1) 23×23 (2) 23×33 (3) 33×33

3. Numerical Simulation

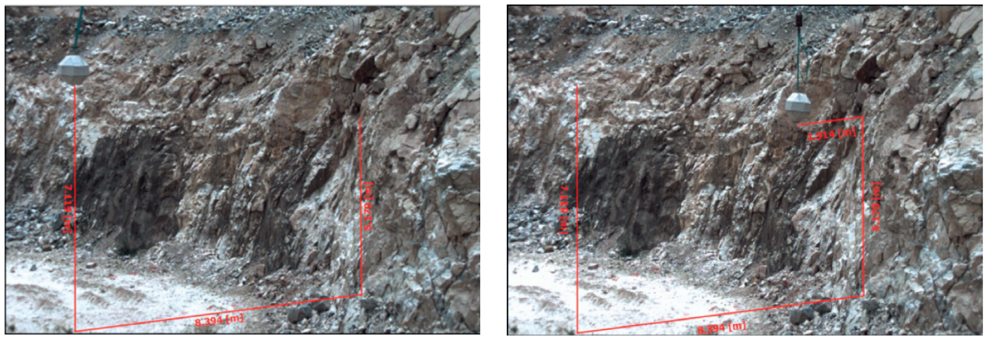
The numerical simulations were conducted using commercial finite element software, ABAQUS [6]. When the rock falls, two major parameters governing the movement of rock are friction coefficient and restitution coefficient. The restitution coefficient was obtained from the pendulum test, and friction coefficient was determined as 0.2 from the calibration process by comparing with the results of the field test (as shown in Figure 3(d)). The pendulum test was simulated to obtain damping coefficient which is an input parameter for the simulation.

As shown in Figure 4, the dynamic analysis was performed by considering the entering speed and repulsion speed of concrete ball of 5.54 m/sec and 2.21 m/sec, respectively.

From the simulation and calibration process, the damping coefficient of 800 was obtained as an input parameter for the real rock-dropping simulation.

In the simulation of rock dropping, the slope and rock were modeled as rigid and solid, respectively; the rock moved only by the gravity force, and its behavior was governed by restitution and friction coefficient as seen in Figure 5(a).

As presented in Figure 5(b), the dots in red represents the location of the touched ground and the solid line in red represents the rock movement from the simulation. Due to the environmental conditions in the field, Figure 5(b) showed a little discrepancy between the field test and simulation result.

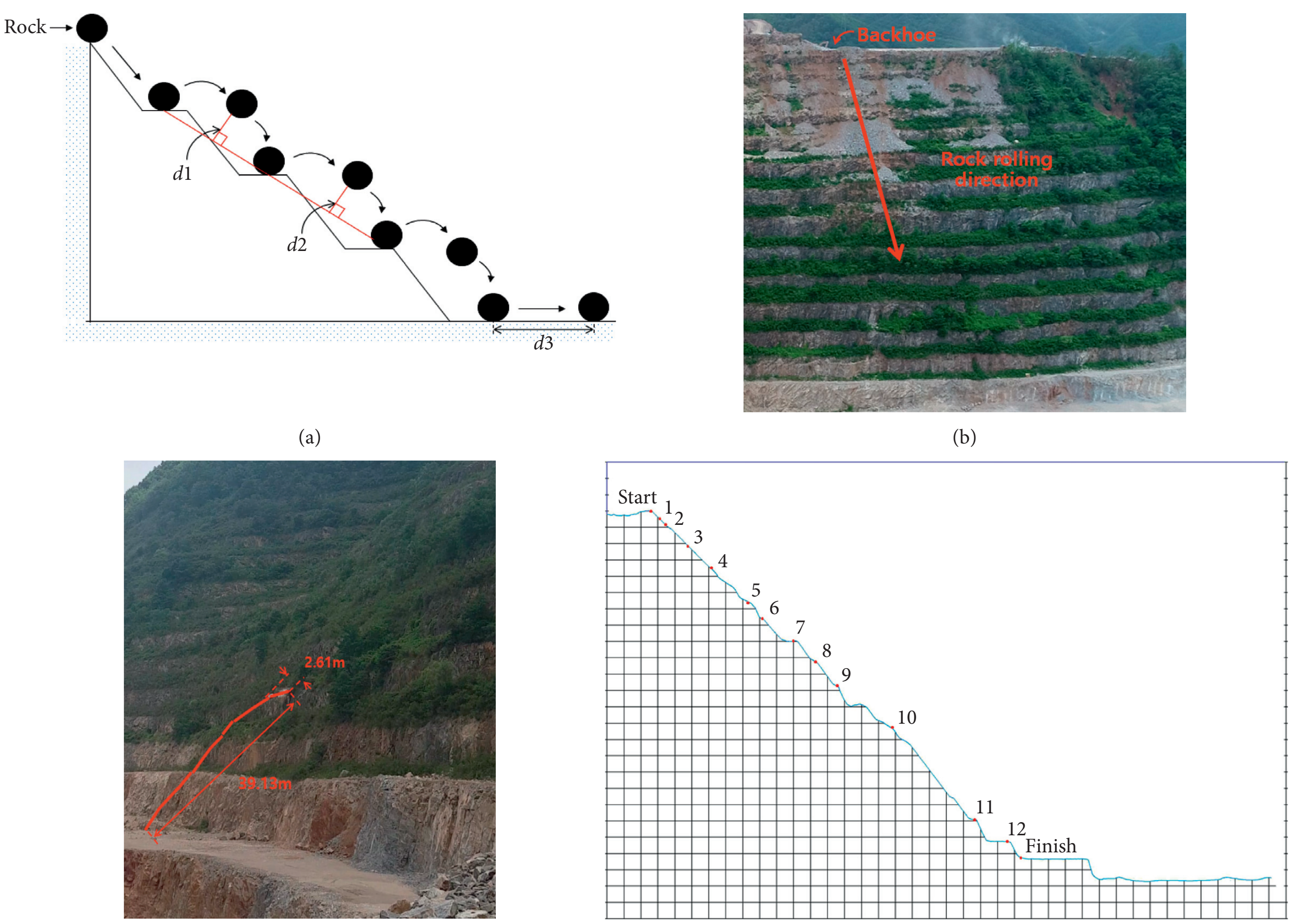


(a) (b)

Figure 2: Pendulum test for the restitution coefficient: (a) initial position; (b) final position.

Table 2: Pendulum test results.

Test		Energy (kJ)	Velocity (m/s)	C_R
Upper part	#1	19.11	6.18	0.48
	#2	18.52	6.09	0.56
Average		18.82	6.14	0.52
Lower part	#1	18.03	6.01	0.51
	#2	15.97	5.65	0.33
Average		17.00	5.83	0.42

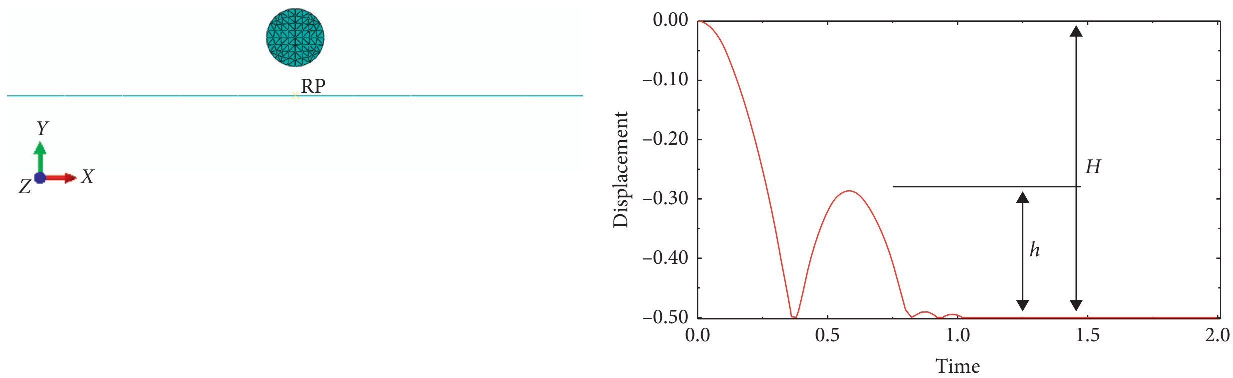


(a) (b) (c) (d)

Figure 3: Rock-dropping test: (a) measurement scheme; (b) dropping direction; (c) height measurement; (d) touching location.

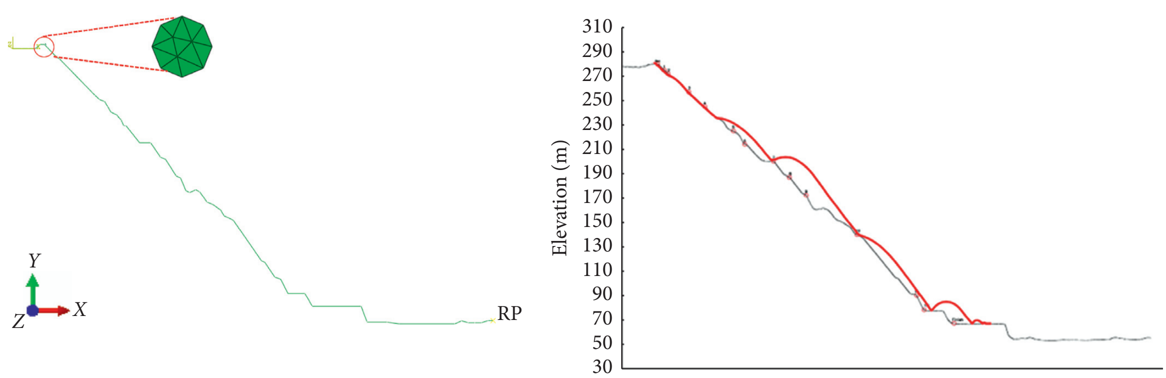
Table 3: Rock-dropping test results.

Height from berm (m)		Velocity of dropping rock (m/s)	
Maximum	5.24	Drone	9.9
Average	2.99	High-speed camera	10.1



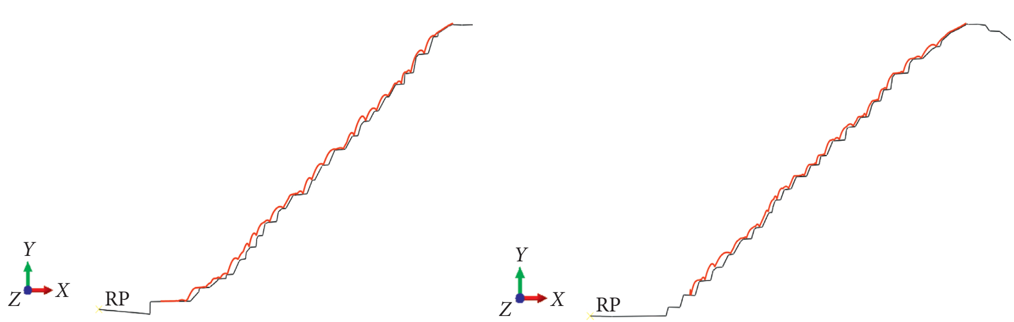
(a) (b)

Figure 4: Simulation of the pendulum test: (a) mesh for simulation; (b) result of simulation.



(a) (b)

Figure 5: Numerical simulation: (a) mesh for simulation; (b) simulation result.



(a) (b)

Figure 6: Continued.

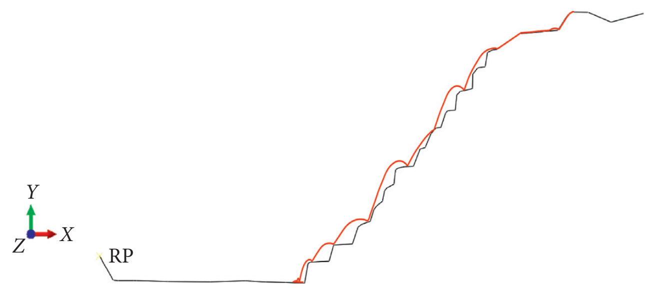


Figure 6: Rock-dropping simulation to which the developed model applied: (a) section 1; (b) section 2; (c) section 3.

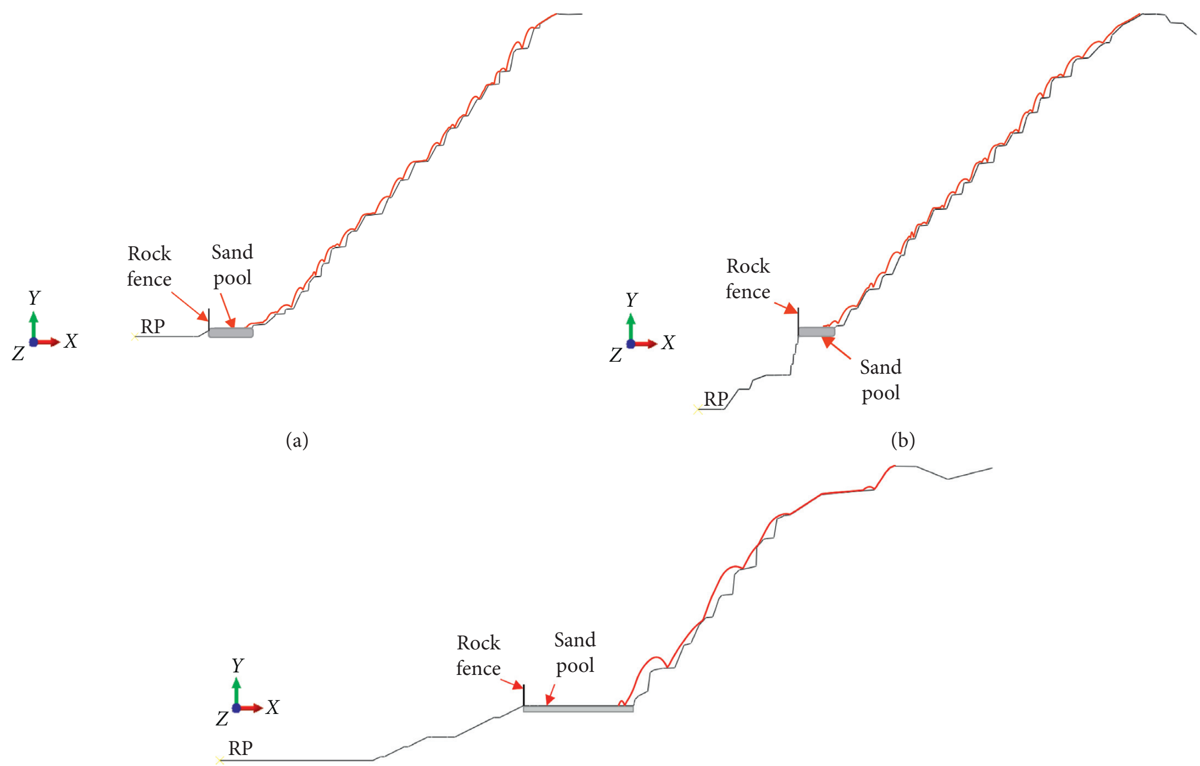


Figure 7: Results of rock-dropping simulations with sand pool: (a) section 1; (b) section 2; (c) section 3.

This discrepancy may be the fact that the real slope had many trees that enabled to reduce the rock movement (bounce, rotation, and speed), whereas the slope in the simulation was ideally/simply assumed; that is, the rock movement was controlled only by the restitution coefficient and friction of the slope. Despite of this discrepancy, it can be said that the result of simulation showed a good agreement with field test.

4. Mitigation Method

The developed model was applied to the three different sections of the slope as presented in Figure 6. These sections were selected from the real slope (as shown in Figure 3(b)).

As shown in Figure 6, the rock dropped down to the bottom and lower parts of the slope that might give a rise to a dangerous situation if there was a building or structure. For section 1, the long distance was needed to stop the rock compared to the other sections. This is because the rock jumps longer and spins more at a gentle slope as seen in Figure 6(c).

In order to mitigate/reduce the hazardous situation, the sand pool and rock fence were placed in the lower part of the slope for each section as shown in Figure 7. The high coefficient of friction was applied to the sand pool that is generally used in the simulation of arresting/stopping the golf ball in the sand trap. As seen in Figure 7, the rock was arrested/stopped in the sand pool with small movement compared to the results of Figure 6 that the rock rolled down to the bottom of the slope.

5. Conclusions

This study presents integrated field test-computational efforts to investigate the effects of newly developed mitigation method of rockfall hazard. Based on the test results and simulations, the following conclusions are made.

(i) The restitution coefficient of the rock slope obtained from the pendulum tests was 0.47 which is in between the reference value solid rock of 0.8 to soft soil of 0.3

(ii) The friction coefficient was obtained from the calibration process by comparing the rock-dropping test with the simulation.

(iii) The developed model was applied to the three different slope sections with/without sand pool. The rock rolled down to the bottom of the slope without sand pool. On the contrary, the rock was stopped/arrested after a small movement with sand pool.

(iv) The newly developed mitigation method provides a good advantage in terms of maintenance by simply removing the arrested/acculturated rocks.

Data Availability

The field test and numerical simulation data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport of the Korean government (Grant number 20CTAP-C152052-02).

References

[1] A. Patnaik, A. Musa, S. Marchetty, and R. Liang, "Full-scale testing and performance evaluation of rockfall concrete barrier," *Transportation Research Record*, vol. 2252, no. 1, pp. 27–36, 2015.

[2] A. Mentani, A. Giacomini, O. Buzzi, L. Govoni, G. Gottardi, and S. Fityus, "Numerical modelling of a low energy rockfall barrier: new insight into the bullet effect," *Rock Mechanics and Rock Engineering*, vol. 49, no. 4, pp. 1247–1262, 2016.

[3] N. Sashiharan, B. Muhunthan, T. C. Badger, S. Shu, and D. M. Carradine, "Numerical analysis of the performance of wire mesh and cable net rockfall protection system," *Engineering Geology*, vol. 88, no. 1-2, pp. 121–132, 2006.

[4] M. Spadari, A. Giacomini, O. Buzzi, and J. P. Hambleton, "Prediction of the bullet effect for rockfall barrier: a scaling approach," *Rock Mechanics and Rock Engineering*, vol. 45, no. 2, pp. 131–144, 2012.

[5] B. Peng, "Rockfall trajectory analysis: parameter determination and application," Thesis, University of Cantebury, Christchurch, New Zealand, 2000.

[6] Dassault System, ABAQUS/Standard User's Manual v. 6.14, Simulia, Johnston, RI, USA, 2014.