Identification and Mitigation of Rockfall Risk Zones

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***Abstract* — Rockfall cases are a natural and dynamic geologic process, commonly occur within mountainous areas near by the cliffs undercut by human for developing building or highway infrastructures. These paper objectives were to; (i) identification of slope surface parameters and simulating of rockfall trajectory, (ii) identification of rockfall risk zones, and (iii) mitigation of the rockfall risk zones. Manmade slope in the quarry at the Kloch, Austria was chosen as the case study in this paper. Seven Kloch slope surface parameters were identified, including; dynamic and static friction angles, normal and tangential damping, rolling resistance, amplitude of roughness, and frequency of roughness. Based on the simulation results, it was identified that the rocfall would yield the kinetic energy of 230 kJ, and the bouncing height was 0.5 m. This paper also identified the distance of rock blocks run-out on the flat ground near the slope toe (rockfall risk zones). The rockfall zones were then divided into 3 areas, e.i ; red zone, yellow zone, and green zone or safe area. The distance of red zone was 5.0-12.5 m from the x axis of the slope, yellow one was 12.5-17.5 m, and green one was > 17.5 m. Hence, in order to protect the red and yellow zones from the rockfall risks, it is recommended to construct a barrier located at a distance of 7.0 m form the x axis of the slope, with a minimum height of 1.0 m. The barrier type was proposed as a retaining wall (with a capacity to restrain the rockfall kinetic energy up to 500 kJ).**

Keywords — rockfall, risk zones, mitigation, simulation.

I. INTRODUCTION

Rockfall cases occur mainly in the mountainous areas or man-made cut off slope ones. Rockfall causes damage to buildings, housing and settlements, road infrastructures, and threatening of human life (Raymund M Spang, 2001a, b, and Kristen L. et al, 2003).

Figure 1. Rockfall cases occurred in the West Sumatra road ways.
(Source: private documentation, 2011)

Figure 1 shows that rockfall blocks reached road pavement beyond road shoulder in West Sumatra, Indonesia. In order to develop rockfall risk zones and by mean mitigating the magnitude of the rockfall impacts systematically, it is necessary to carryout simulation of the rockfall trajectory along the slope profile and calculating of the rockfall's kinetic energy as well as its bouncing height after hitting the flatter ground near slope toe (Kristen L. et al, 2003, Lawrence A. Pierson, C.E.G. Robert Van Vickle, R.P.G, 1993). This paper utilizes the experimental rockfall data in Kloch, Austria. These data are provided by the University of Vienna, Centre for Geomechanic, Austria. Twenty seven rock blocks with different sizes were dropped from the Kloch upper slope (Figure 2).

The trajectory and the rock blocks movement along the slope profile were then recorded (Appendix II and III).

Figure 2. Four examples of the different rock block sizes dropped down along the Kloch slope profile.
(Source: private documentation, 2011)

The size of rock blocks was varied from 0.008 m^3 to 0.029 m^3. The weight of the rock blocks was approximately 0.0232 ton up to 0.0841 ton. Once the rock blocks were dropped, the rockfall trajectory along the slope profile was then observed. The rockfall travel modes were identified in 3 types such as; rolling, free fall, and bouncing (Figure 3). The distance of the rockfall run-out on the flat ground close to slope toe is calculated horizontally.

Based on the experimental Kloch rockfall, the rockfall run-outs were measured. It was identified that the distance of the rockfall stationary on the flat ground were vary between 7.0-17.5 m from the x axis coordinate of the slope (Figures 3 and 4).

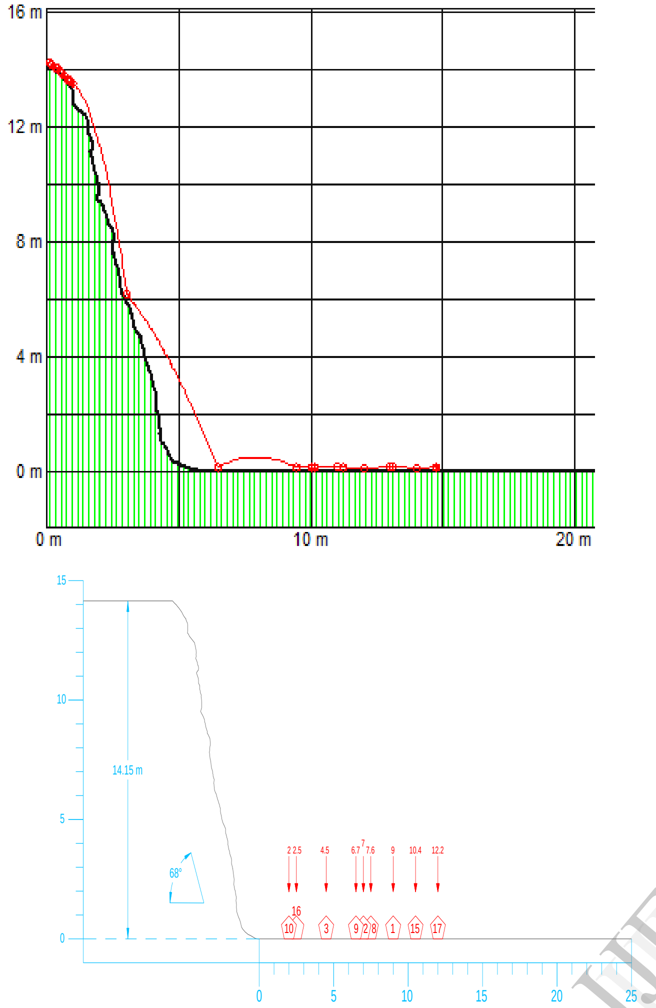

Figure 3. Simulated the rockfall travel modes and Kloch Slope Source: data simulation and private documentation, 2011

Figure 4. Kloch Slope Profile.
Source: private documentation, 2011

II. SLOPE QUALITIES

To determine the actual Kloch surface slope qualities, a simulation program of Rockfall 6.1 was applied. The slope surface quality was determined by the trial and error methods (comparing the assessment of real rockfall run-out along the Kloch slope, and rockfall simulation results) (Table 1 and Figure 3). Once the type of rockfall trajectory (as well as rockfall blocks run-out) from the simulation results comply with the experimental filed data, hence the parameters of Kloch slope qualities were identified.

Spang, 2003 recommended to obtain 7 (seven) slope surface parameters encompassing; dynamic fiction angles, static friction angles, normal damping, tangential damping, rolling resistance, amplitude of surface, and frequency of slope surface.

Base on simulation results (Table Appendix 1), it was summarized that the rockfall run-out distance between field data (3 x 9 rock blocks = 27 rock blocks) and rocfall simulations was considered acceptable (with an average of the deviation standard was 1.8%). Hence based on this try and error simulations, it was revealed that the slope surface quality was as follow; Dynamic Friction angle in case of sledding (Rg) was 30^{o}, Static Friction angle in case of static contact (Rh) was 35^{o}, Normal damping velocity during collision (Dn) was 0.2, Tangential damping parallel to the slope surface (Dt) was in between 0.92 to 0.95, Rolling resistance; energy loss of the rolling rock (Rw) was in between 0.25- 0.3, Rough Amplitude in the form of vertical distance (oa) was 0 to 0.05, Rough Frequency or horizontal distance (Of) was 0 to 1.

III. ROCKFALL SIMULATION

In order to identify the rockfall trajectory, it was obtained from the rockfall simulations (using 100 rockfall blocks), with the radius of rock blocks of 0.5 m. It was estimated that the rock blocks' weight was 2.9 tones / m3. The profile of passing rock blocks along the slope and the rock blocks' run-out on the flat ground can be seen in Figure 3 and Figure 4.

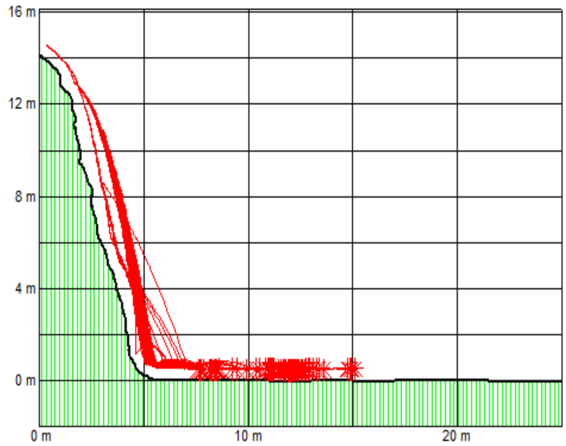

Figure 5. Profile passing rocks (Based on the real experimental data of rockfalls, 2011) and Rockfall simulation results. Source: Data Analyses, 2013

The Figure 5 above measured the location of the rockfall blocks stationary on the flat ground surface after they were losing their energy. It was identified that the distance of rockfall blocks stationary after hitting the ground level was calculated in between 2 m to 12.5 m from the slope toes (7.0-17.5 m from the x axis coordinate of the slope). The simulated results confirmed the experimental field data. It was also identified that the height of Kloch Slope was 14.0 m, with an average degree of 68^0 (Figure 5). The average mass of rock blocks was 2.9 ton/m3.

In order to reduce risk impacts of the rock blocks to destroy road pavement or building infrastructure close to the slope area, there is a need to provide adequate clear area > 10.0 meters from the slopes toes (Figure 4). Since there is a limited space for a clear area within a such hilly or mountainous environment, it necessary to construct rockfall barriers to restrain the rockfall energy kinetic as well as its run-out. Hence, it is necessary to establish the location of the rockfall barrier. It is recommended to locate rockfall barrier be close enough to the slope toe.

It is also highlighted that the constructed barriers should be able to restrain kinetic energy of the rockfalls striking the barriers. The constructed barrier should be also higher than the maximum rockfall bouncing high after hitting the ground level.

Based on the simulations for the 100 blocks of rockfalls (with a diameter of 0.5 m), it was revealed that the envelope curve for the total kinetic energies were > 230 kJ and rockfall bouncing height was up to 0,5 m. This can be seen in Figure 6.

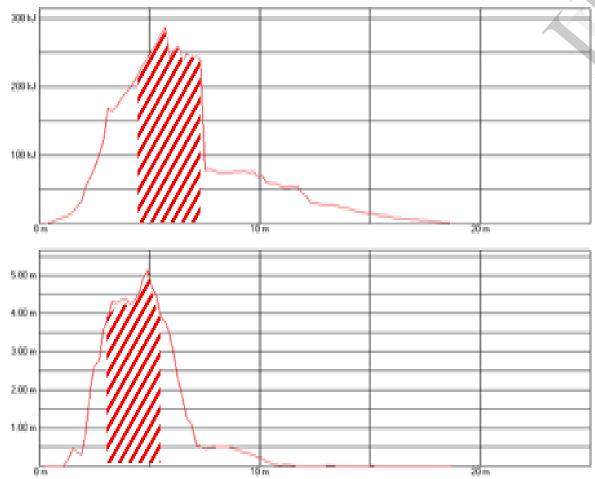

Figure 6. Distribution of kinetic energy and rockfall bouncing height. Source: Data Analyses, 2013

Based on the simulation results using 100 rock blocks, it was identified that there was 80% of the rock blocks movement and stationary on the flat ground will be at the distance of 12.5 m (form the x axis of the slope). The remaining 20% of the rock blocks movement will be stationary at the distance of 12.5 up to 17.5 m (Figure 7).

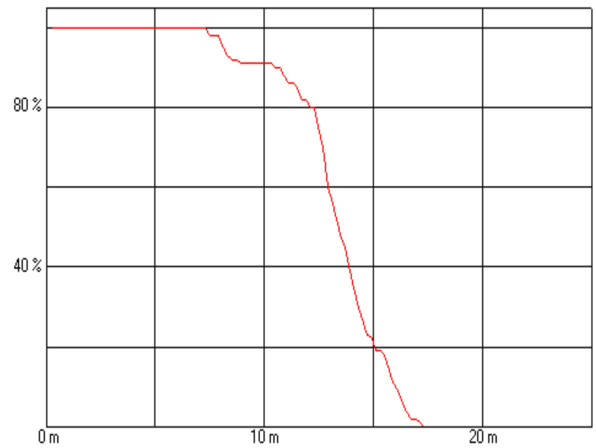

Figure 7. The probability of rock blocks run-out (%) versus the distance of the rockfall run-out (m). Source: Data Analyses, 2013

The number of rockfall blocks run-out on the flat ground tends to decline at a distance of 5.0 m up to 17,5 from the slope toe (Figure 7). The number of rockfall blocks hit on the flat ground is correspondence to the rockfall risk zone.

IV. ROCKFALL RISK ZONES

This paper presents 3 different risk zones for rockfall; (i) high risk zone, (ii) medium risk, and (iii) low risk (Figure 5). In fact, this rockfall risk zone also applied in many cases in the Europe (Papathanassiou G, Valkaniotis S, and Chatzipetros A. 2005).

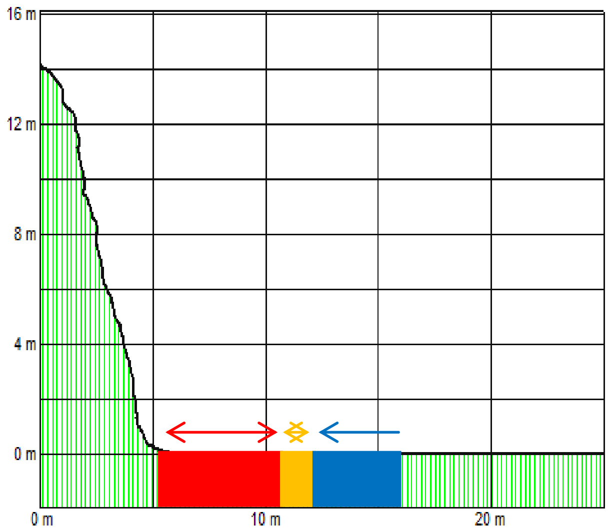

Figure 8. Rockfall risk zones.
Source: Data Analyses, 2013

Figure 8 describes, there is 80% of probability (of the number of rockfall run-out) within the red zone risk. There is 20% of probability (of the number of rockfall) may reach the yellow zone. The remaining blue zone is considered as safe zone (almost 0% probability of the rock may reach this area). In this case, it was designed to construct a barrier located at a distance of 2.0 m from the slope toe or 7.0 m form the x axis of the slope.

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V. DESIGNING OF ROKFALL BARRIERS

Rocfall barriers in this paper were designed based on the results of slope surface parameters above. The rock blocks radius (r) was estimated 0.5 m. After simulated using 100 rock blocks, it was obtained maximum kinetic energy was 230 kJ, with bouncing height of 0.5 m (Figure 10). In order to design appropriate slope barriers, it is commonly to use the following design criteria (Table 1).

TABLE I. ROCKFALLS KINETIC ENERGY, AND BOUNCING HEIGHT

Simulation	100 rocks (0,5 m size)
Kinetic energy (maximum)	230 kJ
Kinetic energy (minimum)	0.5 kJ
Kinetic energy (average)	53.8 kJ
Bouncing height (maximum)	0.5 m
Bouncing height (minimum)	0.0 M
Bounchng height (average)	0.1 m
Kinetic energy 80%	50 kJ
Bounchng height 80%	0.25 m

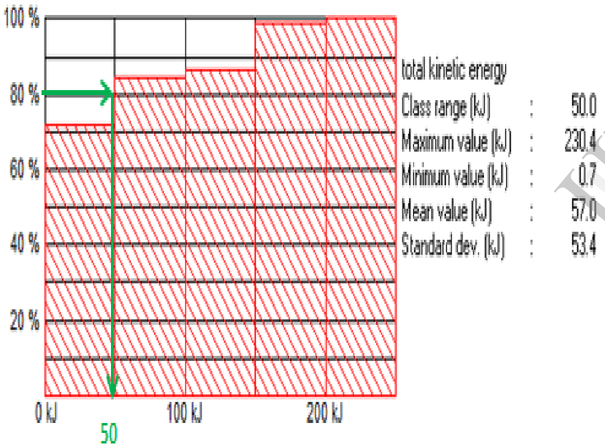

Figure 9. Histogram kinetic energy of rock blocks banging the rockfall barriers. Source: Data Analyses, 2013

In the state of the art analyses, it is recommended to design Rockfall barrier type was a retaining wall.

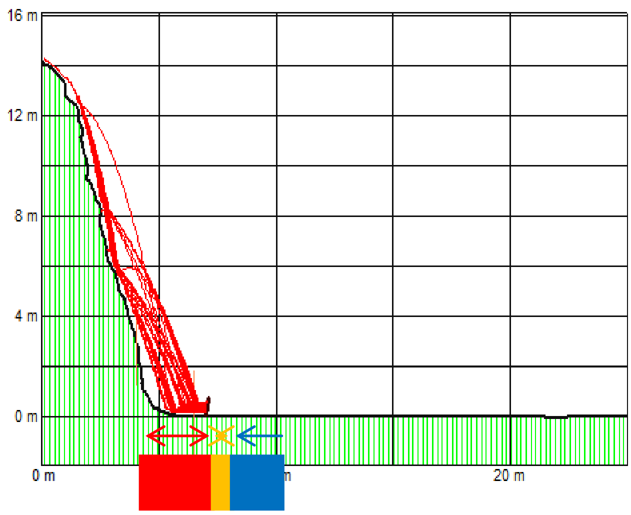

Figure 10. Rockfall risk zones.
Source: Data Analyses, 2013

Theoretically, the type of this concrete retaining wall is able to restrain the kinetic energy up to 500 kJ (>230 kJ of the maximum rock blocks kinetic energy). The height of the retaining wall was planned to become 1.0 m height (> 0.5 m of rockfall bouncing height).

VI. CONCLUSION

Based on the rockfall analyses results, it was identified 7 slope surface parameters appropriate to 14 m height of Kloch slope. Seven Kloch slope surface parameters were identified, including; dynamic and static friction angles (35^0), normal and tangential damping (0.2 and 0.95 consecutively), rolling resistance (0.2 to 0.3), amplitude of roughness (0), and frequency of roughness (1). These parameters were than treated as input data in the simulation of the designated Kloch rockfall. Based on the simulation results, it was establish rockfall risk zones into 3 areas, e.i; red zone (80% probability of the rockfall may reach this area), yellow zone (20% probability of the rockfall may stationary within this area), and green zone is safe area. The distance of red zone was 5-12.5 m from the x axis of the slope, yellow one was 12.5-17.5 m, and green one was > 17.5 m. The simulation also identified rockfall kinetic (energy when hitting a barrier located at of 2 m from the slope toe) was approximately 230 kJ, and the bouncing height maximum was 0.5 m from the ground level. Hence, for the rockfall mitigation scheme it is recommended to construct a retaining wall to control the rockfall risks (with minimum height was approximately of 1.0 m).

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TABLE APPENDIX II
COMPARING DISTANCES OF ROCKFALL RUN-OUTS BASED ON SIMULATION RESULTS AND FIELD EXPERIMENT DATA

No	Rockblock No.	Distance based on the simulation results (m)				Distance based on the field data (m)	Deviation standard
		1	*2*	*3*	*Average*		
1	1	9.02	8.95	9.02	9.00	9	0.0%
2	2	7.59	6.93	6.71	7.08	7	0.2%
3	3	4.62	3.37	5.34	4.44	4.5	0.3%
4	8	7.39	7.75	8.31	7.82	7.6	0.4%
5	9	8.22	6.76	5.51	6.83	6.7	0.3%
6	10	2.47	3.18	1.95	2.53	2	13.3%
7	15	9.58	10.01	9.76	9.78	10.4	0.6%
8	16	2.4	2.47	2.76	2.54	2.5	0.7%
9	17	11.96	12.03	12.21	12.07	12.2	0.1%
Average of the Deviation standards							1.8%

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TABLE APPENDIX III
VOLUME AND WEIGHT OF THE EXPERIMENTAL ROCK BLOCKS AND THE DISTANCE OF ROCKFALL RUN-OUTS

NO	Photo	Volume (m^3)	Weight per volume (t/m^3)	Weight (ton)
1		0.008	2.9	0.0232
2		0.029	2.9	0.0841
3		0.012	2.9	0.0348
4		0.012	2.9	0.0348
5		0.015	2.9	0.0435
6		0.008	2.9	0.0232
7		0.011	2.9	0.0319
8		0.008	2.9	0.0232
9		0.009	2.9	0.0261
10		0.011	2.9	0.0319
11		0.011	2.9	0.0319

Number	Rock Block Number	Distance from the slope toe
1	4	6.3
2	5	2.3
3	6	2
4	7	5.9
5	11	5.8
6	12	2
7	13	6.8
8	14	3.2
9	18	6.9
10	19	4.5
11	20	3.2
12	21	2.9
13	2	6.6
14	3	3.5
15	4	12.5
16	5	6.3
17	6	1
18	7	3
19	9	11.2
20	10	4.5
21	11	3
22	13	2.5
23	15	9.5
24	16	2.5
25	18	2
26	19	4
27	20	17.58

(Source: private documentation, 2011)