

Assessment of Rockfall Hazard Induced by Earthquake for Important Facility

I.Yoshida^a, Y.Kasuga^a, M.Sato^b, H.Nakase^b, and S.Nakamura^c

^aTokyo City University, Tokyo, Japan

^bTokyo Electric Power Services Co.,Ltd, Tokyo, Japan

^cNihon University, Koriyama, Japan

Abstract: Simple point mass simulation method with random numbers is proposed for numerical simulation of rockfall. The proposed method considers only bounce, ignoring rolling and slide of the falling rock. The proposed method is applied to simulations of a rockfall experiment with a model slope and small stones for its validation. The simulated result shows very good agreement with experiment result in terms of cumulative distribution of coordinate where falling rocks reach. This study also proposes a method for rockfall hazard assessment with the proposed simple point mass method. A hazard curve with respect to collision velocity and exceedance of probability can be evaluated by performing many runs of the point mass simulation like Monte Carlo Simulation. Impulse is used to consider severity of collision for the hazard assessment. The hazard with respect to impulse, which is called as collision hazard, can be calculated based on the estimated collision velocity and assumed rock size distribution. The collision hazard assessment is performed by the proposed method for a model site in mountainous terrain.

Keywords: Uncertainty, Hazard, Rockfall, Point Mass System, Slope

1. INTRODUCTION

Rockfall is one of a major natural hazard to a facility in mountainous terrain. Safety function of an important facility such as nuclear facilities shall not be significantly impaired in possible collapse of surrounding slopes. The stability of slope against earthquake is an important item in earthquake resistance design and probabilistic risk assessment in Japan [1]. A slope near an important facility has been sufficiently reinforced and can be noted as artificial slope. The failure probability of the artificial slope seems to be small enough in general, while natural slope near an access road to the facility or related structures seems to have higher failure probability. Risk/crisis management of access road to the facility or related structures has attracted attention recently. A methodology for seismic PRA (Probabilistic Risk Assessment) of a facility due to slope failure is proposed [2]. It is composed of three steps, 1) seismic PRA on slope failure, 2) assessment of collision hazard against falling rocks caused by the slope failure, 3) fragility assessment of a facility against the rock collision. This paper discusses the step 2), namely collision hazard against falling rocks.

It is difficult to predict the behavior of rockfall deterministically if a sophisticated simulation method such as Distinct Element Method (DEM) [3] is used because the movement of rockfall is strongly affected by small irregularity of slope surface and shape of falling rock. It is not practical to consider all the small irregularities in the simulation to predict rockfall behavior. Simple point mass simulation method with random numbers is proposed for numerical simulation of rockfall. The proposed method considers only bounce, ignoring rolling and slide of the falling rock. Randomness is considered in normal vector of slope surface in the proposed method. A random vector is generated by uniform random numbers and added to the normal vector so that the simulated moving direction of rockfall is fluctuated at every bounce. Calculation cost of the proposed method is much lower than that of DEM. The proposed method is applied to simulations of a rockfall experiment with a model slope and small stones for its validation.

This study also proposes a method for rockfall hazard assessment with the proposed simple point mass method. A hazard curve with respect to collision velocity and exceedance of probability can be

evaluated by performing many runs of the point mass simulation like Monte Carlo Simulation. The collision velocity is not enough to discuss damage to a structure. Impulse is used to consider severity of collision for the hazard assessment. The hazard with respect to impulse, which is called as collision hazard, can be calculated based on the estimated collision velocity and assumed rock size distribution. The collision hazard assessment is performed by the proposed method for a model site in mountainous terrain.

2. OUTLINE OF RANDOM POINT MASS METHOD

It is difficult to model every detailed roughness of slope and falling rocks. This study uses point mass method with random number to express the small roughness. Normal direction vector of slope surface is defined as \mathbf{r}_{n0} . In order to express the roughness, random vector \mathbf{r}_r is added to the normal vector \mathbf{r}_{n0} . The normal vector for rebounding of rocks is obtained by,

$$\mathbf{r}_n = \mathbf{r}_{n0} + \mathbf{r}_r \quad (1)$$

Direction of the vector \mathbf{r}_r is determined based on independent uniform random numbers, and its magnitude is determined by normal random number $N(0, \sigma_r)$. Namely the standard deviation σ_r controls the roughness of the slope and falling rocks. In this study, the standard deviation is called as roughness parameter. Only when the slope has no roughness and the falling rock is a true sphere, the roughness parameter is 0. In this case, falling rocks have no randomness in falling behaviour. Velocity vector \mathbf{v} of a falling rock just before collision to the slope is decomposed to normal and lateral component, $\mathbf{v}_n, \mathbf{v}_l$.

$$\mathbf{v} = \mathbf{v}_n + \mathbf{v}_l \quad \text{where,} \quad \mathbf{v}_n = (\mathbf{v} \cdot \mathbf{r}_n) \mathbf{r}_n, \quad \mathbf{v}_l = \mathbf{v} - \mathbf{v}_n \quad (2)$$

Velocity vector \mathbf{v} just after rebounding is expressed by,

$$\mathbf{v} = -c_n \mathbf{v}_n + c_l \mathbf{v}_l \quad (3)$$

where c_n is restitution coefficient for normal component, c_l is restitution coefficient for lateral component. The behaviour of rock in the air can be simply estimated by,

$$\mathbf{u}_{t+\Delta t} = \mathbf{u}_t + \Delta t \mathbf{v}_t + \frac{1}{2} (\Delta t)^2 \mathbf{g}, \quad \text{where, } \mathbf{g} \text{ is acceleration of gravity, } \mathbf{g}^T = (0, 0, -9.8) \quad (4)$$

If the vertical coordinate calculated by Eq.(4) with time increment Δt_1 is above the slope surface, time increment Δt_1 is increased to Δt_2 until the vertical coordinate with time increment Δt_2 is below the slope surface. The exact time increment to next rebounding should be between Δt_1 and Δt_2 . The exact time increment to the next rebounding is calculated by the following bisection method.

- 1) Initial values of before the rebounding Δt_1 and after rebounding Δt_2
- 2) Calculate vertical coordinate with $\Delta t_m = \Delta t_1 + \Delta t_2$
- 3) If the coordinate at Δt_m is above the slope surface, then $\Delta t_1 = \Delta t_m$, otherwise $\Delta t_2 = \Delta t_m$
- 4) If $\Delta t_2 - \Delta t_1$ is small enough, then stop, otherwise go to 2)

3. ROCKFALL EXPERIMENT AND ITS SIMULATIONS

To examine the characteristics of the distribution of scattered rocks after rockfall, laboratory experiments were performed, which are reported in [4,5]. Figure 1 indicates the outline of the experiment. The slope angle is 41 degree, height of slope is 80cm. 300 stones (model for rocks) were selected from stones that were 40–80 mm in diameter. After a stone is dropped, it was removed from the flat place below the slope and a next stone was dropped. The procedure of dropping a stone is as follows: (1) a stone is set at the shoulder of the slope and at its center, as shown in Figure 1; (2) the long side of a stone is set to be parallel to the inclination direction of the slope; and (3) a stone is pushed with a finger, little by little, until it drops. The stone falls and moves on the slope, then stops somewhere on the flat place. The coordinate X and Y where the falling stone model stops are measured. X is distances from the foot of the slope whereas Y is distance from the center line as shown in Figure 1. This procedure is repeated 300 times, consequently we obtained 300 coordinates of

place where the falling stones stop. Similar experiments with different slope angle or height are also performed. Five cases of experiment are performed [6] as summarized in Table.1

The distribution of the 300 coordinates of Case 2 and 3 are shown in Figure 2 as an example of the experiment results. The black solid circles indicate the distribution obtained by the experiment. Naturally the arrival locations have large uncertainty. It is impossible to reproduce the perfectly same trajectory of the falling stone even if the every condition is carefully set similarly [7]. In the figure the arrival positions obtained by the proposed point mass method are shown in green circles. It seems to indicate good agreement. In order to compare the results quantitatively, cumulative distribution of coordinates are calculated for both experiments and simulations. The point mass simulations are performed three times with different seed of random number. Figure 3 shows their cumulative curves. The simulation results show good agreement in terms of cumulative distribution though individual behavior of falling stone differs widely. It is not difficult to improve the agreement for a specific case, e.g., Case 3 if the parameters for the simulation are adjusted. It is important to obtain parameters to reproduce the experimental result of all cases. In order to check the reproducibility of all cases efficiently, percentile values 10%, 90% (50% only for X) of the cumulative distribution are used for the adjustment of input parameters. The comparison of the percentile values after the adjustment is summarized in Figure 4. The roughness parameter is 0.3, restitution coefficient for normal component c_n is 0.43. When deterministic value is used for the restitution coefficient for lateral component c_l , good result is not obtained. Therefore uniform random number between 0.85 and 1.05 is used for restitution coefficient for lateral component c_l .

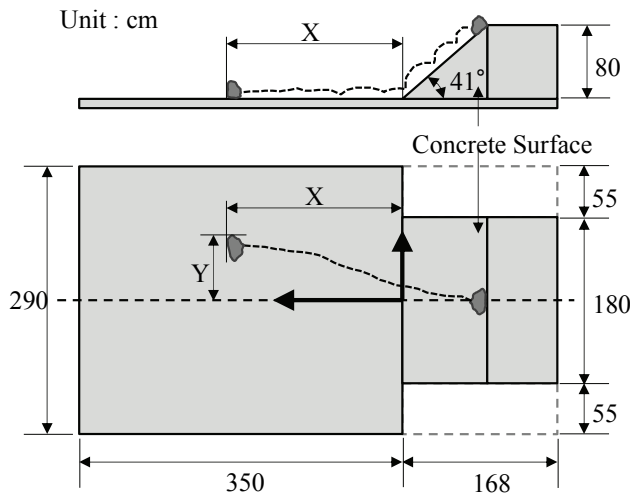
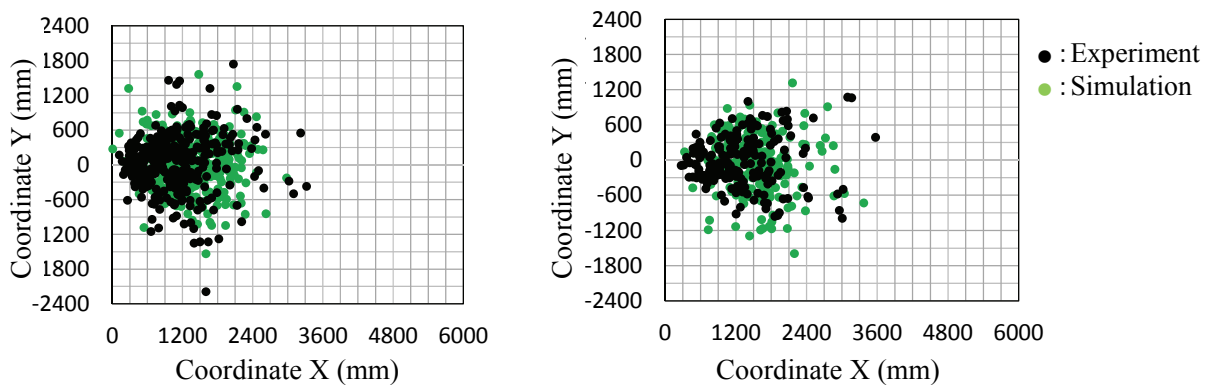


Figure 1: Sketch of Falling Stones Experiment, Case2

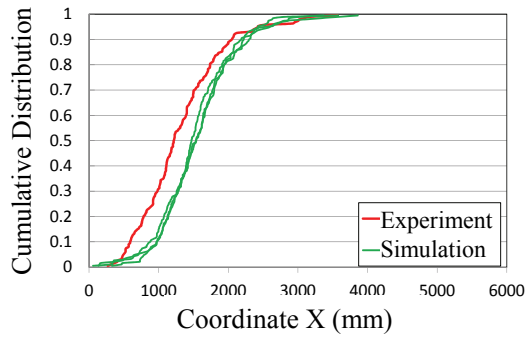
Case	Slope height (cm)	Slope angle
1	50	41
2	80	41
3	100	41
4	200	41
5	200	60



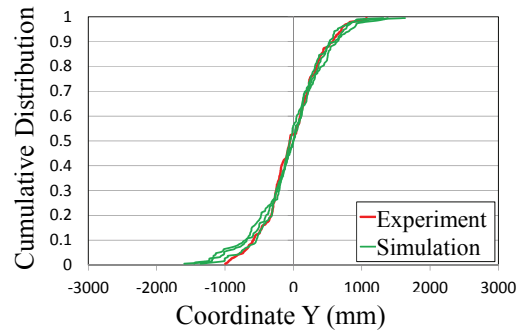
(1) Case 2, Height=80cm

(2) Case 3, Height=100cm

Figure 2: Comparison of Experiment and Simulation Result, Case 2 and 3

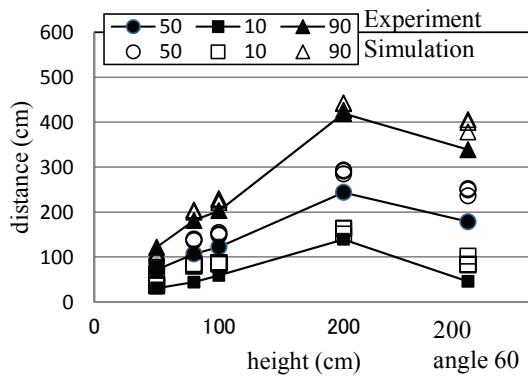


(1) X-Direction (from foot of the slope)

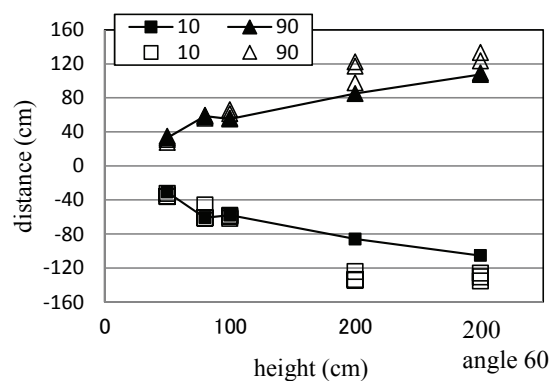


(2) Y-Direction (from center)

Figure 3: Comparison of Cumulative Distribution of Arrival Locations, Case 3



(1) X-Direction (from foot of the slope)



(2) Y-Direction (from center)

Figure 4: Comparison of Percentile Values of All Cases

4. ASSESSMENT OF COLLISION HAZARD FOR A MODEL SITE

The proposed total methodology for seismic PRA (Probabilistic Risk Assessment) caused by slope failure is composed of three steps as noted in the introduction, 1) Seismic PRA on slope failure, 2) collision hazard assessment, 3) fragility assessment of a facility against the rock collision. An example of collision hazard assessment, namely step 2), is shown in this chapter.

Digital elevation model data in Japan can be downloaded from Geospatial Information Authority of Japan. Figure 5 indicates the slope shape of a model site of which elevation data is obtained from the above web site. Four facilities, S-1, S-2, S-3, and S-4, are assumed for the assessment of rockfall hazard. Slope failure area due to earthquake should be estimated by step 1) (Seismic PRA on slope failure). The failure area is simply assumed as shown in Figure 5 in this case study. The point mass simulation is performed with same input parameters described in Chap.3 under the assumption that a falling rock is generated uniformly in the slope failure area. Figure 6 indicates the process and final condition of the point mass simulation. 50,000 particles are used in the simulation. The rocks fall mainly in two or three paths, mainly right and left side, as shown in Figure 6.

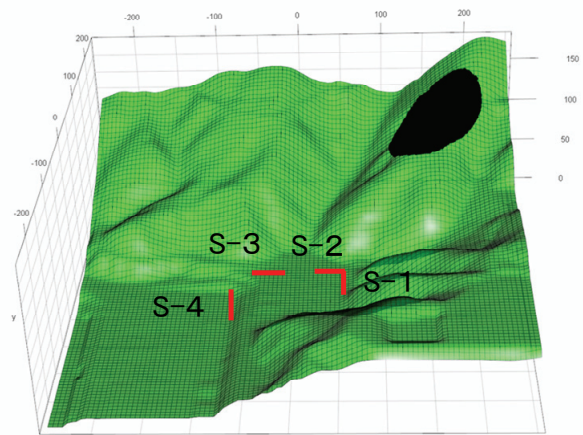
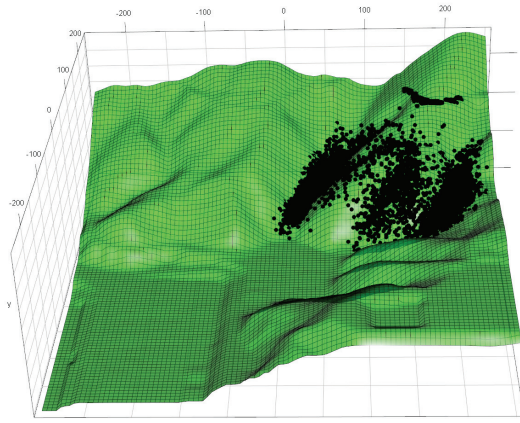
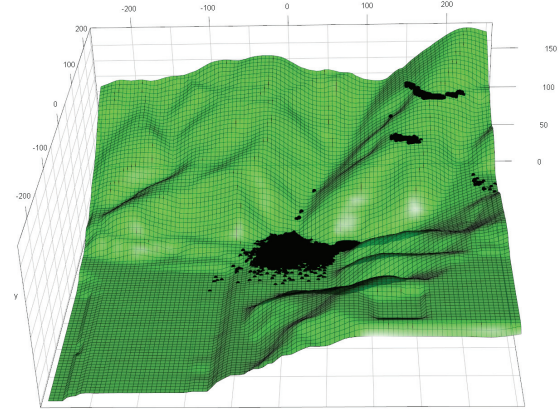


Figure 5: Model Slope and facilities S-1, S-2, S-3, S-4 for Rockfall Hazard Assessment



(1) Snapshot of Rock Falling



(2) Final Distribution of Falling Rocks

Figure 6: Process of Rockfall by Point Mass Simulation

Though 50000 particles are shown in the figure, the interactions among particles are not considered. DEM (Distinct Element Method) can consider the interaction among particles. The energy loss due to the interaction is ignored in the proposed method. This simplification seems to give conservative estimation in terms of arrival hazard or collision hazard. From the normal component of velocity when the falling rocks reach to the assumed facility, cumulative distribution of the normal velocity, which is referred as arrival hazard, is calculated. The arrival hazard curves for S-1, S-2, S-3, S-4 are shown in Figure 7. Normal velocities of 50,000 particles are used to calculate the curves. Basically the longer the distance from the slope to the facility, the smaller the arrival hazard is. The arrival hazards of S-1, S-2 indicate almost same level of probability of exceedance to the velocity. It is, however, noted that the probabilities are reversed at around 8 m/s. It seems that the complicated slope shape affect the probabilities.

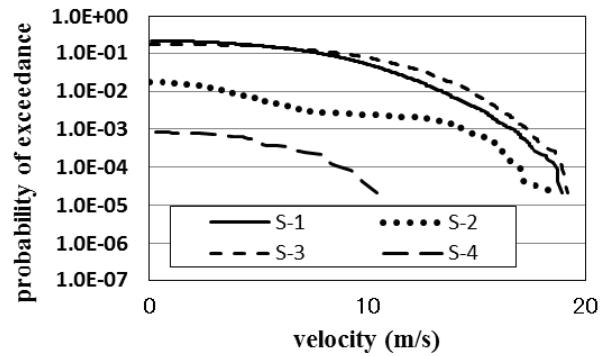


Figure 7: Arrival Hazard for S-1, S-2, S-3, S-4

Arrival hazard is not enough to discuss the damage to a facility because it provides only probabilistic information about velocity of colliding rock. Collision hazard is defined as cumulative distribution with respect to impulse to a structure. The collision hazard P_{imp} can be calculated based on the arrival hazard by the following equation.

$$P_{imp}(I) = 1 - \prod_{i=1}^k (1 - P_1(I/m_i))^{n(r_i)}, \quad I = m_i v = w \left(\frac{4}{3} \pi r_i^3 \right) v, \quad n(r_i) = \frac{c V_i}{\frac{4}{3} \pi r_i^3} \quad (5)$$

Hence v is normal velocity of a rock when the rock hit (arrives) the target facility. The term normal velocity means normal component of the velocity vector to the facility. r_i is radius of rock size i , $P_1(v)$ is arrival hazard, w is unit weight, m_i is weight of rock size i , V_i is volume of slope failure corresponding to rock size i , and c is effective ratio of whole failure volume to hazardous volume to a facility. In Eq.(5), k kinds of rock size are considered. We need to assume these parameters, the distribution of rock size and their volume in order to calculate collision hazard. Total volume of slope failure is assumed to be 50,000m³. It is assumed that c and k in Eq.(5) are 0.4, 4, radius of falling rock are 0.5, 1, 2, 4m, volume corresponding to each radius is 5,000m³ respectively. These parameters are simply assumed for this case study. When the method is applied to an actual site, cautious study is

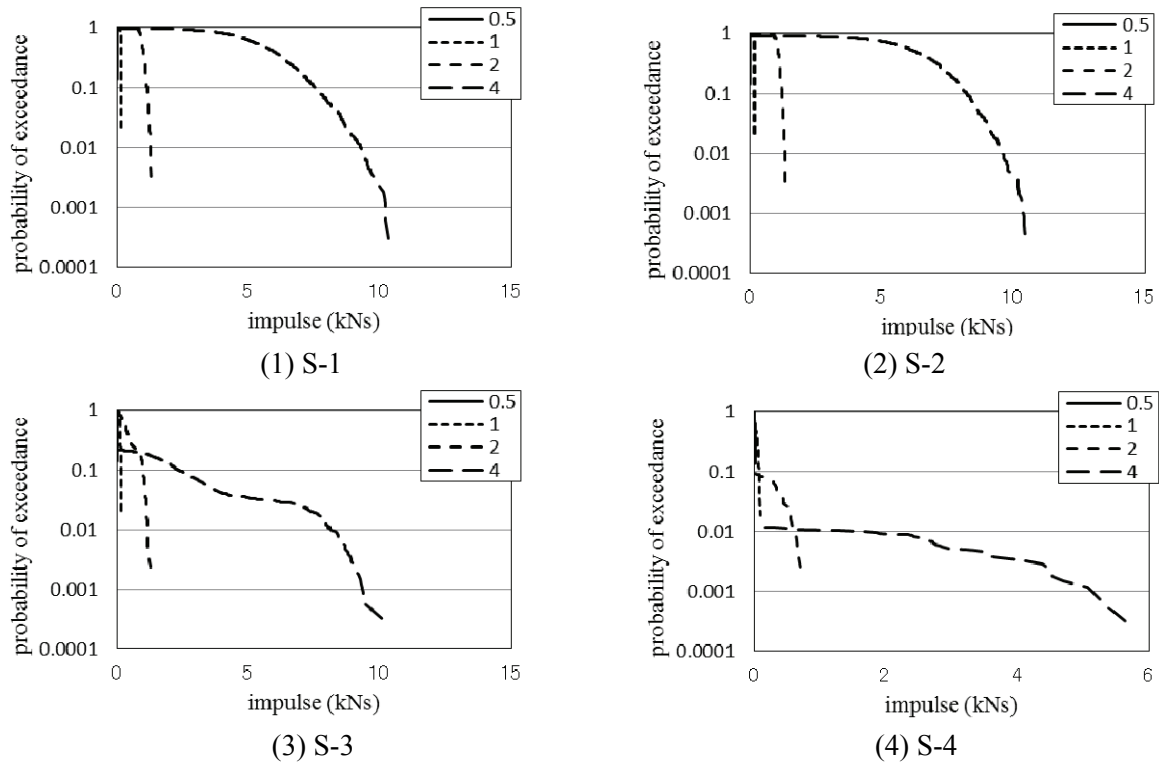


Figure 8: Collision Hazard with Rock Radius, 0.5, 1.0, 2.0, 4.0m

required to determine these parameters. Figure 8 shows collision hazard with these assumed parameters. The figures show collision hazard of each rock size. The total collision hazard is the envelope of these curves. The large rock (radius=4m) is dominant over small to large impulse in S-1 and S-2. The facilities in far area like S-3, S-4, small rocks are dominant in small impulse, but large rock is generally dominant in range of large impulse.

In the same way, the rockfall hazard in an artificial slope can be estimated. The slope near a very important facility is shaped and reinforced. In this study it is referred as an artificial slope. The location of an important facility is assumed at S-1, S-2, and S-3 as shown in Fig.9. The slope shape and assumed failure area are also indicated in the figure. The arrival hazard and collision hazard are estimated with same assumed parameters such as failure volume and rock size. The assumed location is very close the foot of slope. Inevitably many falling rocks collide with the facility. The concern is how large the impact of the collision is. The collision hazard indicates the impact in terms of impulse. In another study, we constructed the fragility curves of facilities. The conditional failure probability of facility can be estimated from the collision hazard and the fragility curves when the slope failure occurs. Total failure probability can be estimated by combining the seismic PRA on slope failure and the conditional failure probability.

5. CONCLUSION

Simple point mass simulation with random number is proposed in order to simulate behavior of falling rock. The simulated result shows very good agreement with experiment result in terms of cumulative distribution of coordinate where falling rocks reach. It is shown that the individual simulation result is strongly affected by the generated random numbers, but the random numbers have small influence on the cumulative distribution of the coordinates. The method to assess collision hazard is also outlined and demonstrated. Total failure probability, which is failure probability of a facility caused by nearby slope failure in seismic event, can be estimated by combining seismic hazard analysis, slope stability analysis, fragility analysis of a facility, and proposed collision hazard.

Though the simulation of falling stone experiment with a single set of parameter shows good agreement with experiments under several conditions such as height and angle of slope as illustrated in Chap.3, more study is required when it is applied to an actual slope. Influence by vegetation and nonlinearity on falling rock behavior (high energy loss) should be considered. We are planning a large scale experiment in an actual slope to understand the behavior of falling rocks more deeply. In the proposed method, a single parameter for both surface and rock roughness is used. The validity of this model should be tested in the experiments. Many parameters such as slope failure volume, radius of rock, are simply assumed in this paper. The method to determine the parameters is also one of future research topics.

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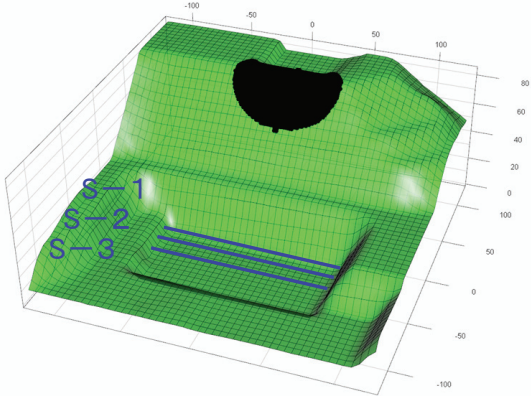
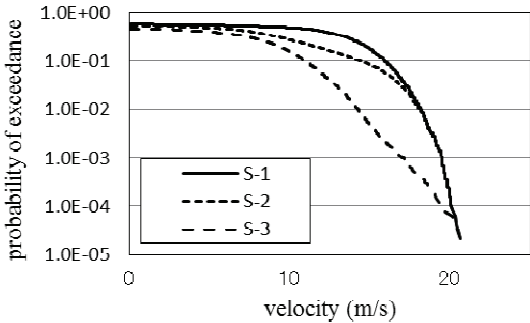
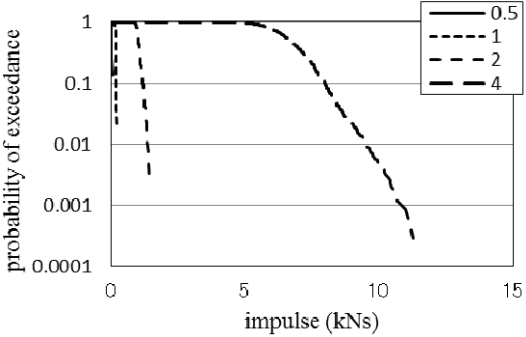


Figure 9: A Model of Artificial Slope and Location of Facility S-1, S-2, S-3



(1) Arrival Hazard



(2) Collision Hazard of S-3

Figure 10: Rockfall Hazard for Artificial Slope