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A METHOD TO ASSESS COLLISION HAZARD BY FALLING ROCKS INDEUCED BY EARTHQUAKE

Ikumasa Yoshida[1], Naoto Naito[2], Hitoshi Nakase[3], and Susumu Nakamura[4]

[1] Doctor of Civil Engineering, Professor, Department of Urban and Civil Engineering, Tokyo City University, Japan
[2] Doctor Course Student,
Civil Engineering and Industrial Management Engineering, Nagoya Institute of Technology, Japan
[3] Doctor of Civil Engineering, Specialist, Civil Engineering Center, Tokyo Electric Power Services Co., Ltd., Japan
[4] Doctor of Civil Engineering,
Professor of Civil Engineering Department, College of Engineering, Nihon University, Japan

ABSTRACT

Safety function of nuclear facilities shall not be significantly impaired in possible collapse of surrounding slopes induced by seismic events. Prediction of falling rock induced by slope collapse is becoming possible to some extent thanks to the progress of numerical simulation technique such as DEM (Discrete Element Method). It is, however, not realistic to predict how far the falling rocks reach and how seriously they affect structures in concern deterministically because large uncertainties are involved in the phenomenon. This study proposes a method to assess the probability of collision to the structures when a distribution of locations where falling rocks reach are obtained by numerical simulation or experiment. Severity of collision in addition to the probability is required in order to assess the influence on the structures more accurately. A collision hazard curve with respect to residual distance, which is defined as the moving distance from the structure when the falling rock does not collide with the structure, is proposed. The proposed method is applied to experiments of falling rocks in which stones are dropped from top of a model slope, and locations where the stones reach are recorded. Probability density function of falling rock locations is estimated from the recorded stone locations. Hazard on the assumed structures are evaluated by the collision hazard curves, depending on the location and size of the structures.

INTRODUCTION

In Japan, a slope sometimes exists near a nuclear power plant, and the stability of the slope when an earthquake occurs is an important assessment item (Atomic Energy Society of Japan, 2007) (Japan Nuclear Energy Safety Organization, 2013). Safety function of nuclear facilities shall not be significantly impaired in possible collapse of surrounding slopes induced by seismic events. To appropriately assess the effects of slope failure and to establish measures against slope failure are important tasks, and many studies have been performed to solve these problems. Prediction of falling rock induced by slope collapse is becoming possible to some extent thanks to the progress of numerical simulation technique such as DEM (Discrete Element Method), SPH (Smoothed Particle Hydrodynamics), MPM (Material Point Method), MPS (Moving Particle Semi-implicit) and so on. It is, however, not realistic to predict how far the falling rocks reach and how seriously they affect structures in concern deterministically because large uncertainties are involved in the slope failure phenomenon. Surface of slope has small roughness, and the falling rocks are not true spheres. It is impossible to collect all these data and consider them in the numerical prediction exactly. It is also difficult to reproduce exactly same slope failure in experiments even though every condition is kept in same with fastidious care. It is pointed out that unpredictable uncertainty (aleatory uncertainty) is involved in strong nonlinear phenomenon like slope failure (Yoshida, 2013).

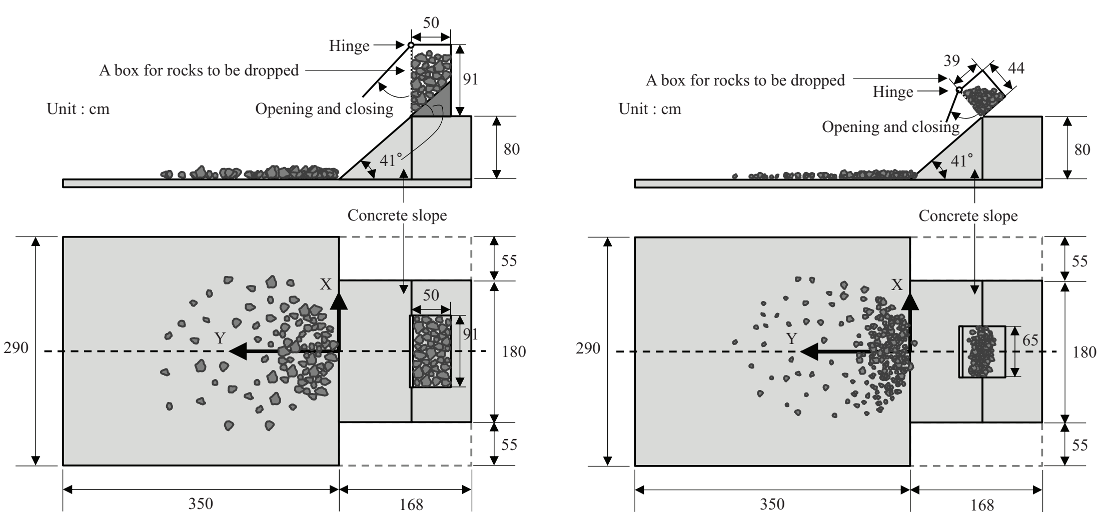
This study proposes a method to assess the probability of collision to the structures when a distribution of locations where falling rocks reach, which is referred as arrival location or position hereafter, are obtained by some numerical simulation or experiment. Severity of collision in addition to the probability is required in order to assess the influence on the structures more accurately. A collision hazard curve with respect to residual distance, which is defined as the moving distance from the structure when the falling rock does not collide with it, is proposed. The proposed method is applied to experiments of falling rocks in which stones are dropped from top of model slope, and arrival locations are recorded.

PROBABILITY DISTRIBUTION OF ARRIVAL POSITIONS OF FALLING ROCKS OBTAINED BY EXPERIMENTS

Overview of experiments performed by Tochigi et. al. (2009), Tochigi (2010)

To examine the characteristics of the distribution of rocks scattered after slope failure, experiments were performed in which two sizes (20−30 mm and 40−80 mm) of rocks were dropped individually (one by one) or simultaneously (as a group), which are reported in Tochigi et al. (2009) and Tochigi (2010). Rocks were selected based on Zingg’s shape classification. Figure 1 shows the experiments in which rocks were dropped as a group (simultaneous experiment). The amounts of rocks dropped in the simultaneous experiments were 10 and 50 kg. In the individual experiment, 300 rocks were selected from rocks that were 20−30 mm and 40−80 mm, and the arrival position of each individual rock was recorded. After a rock is dropped, it was removed from the flat plate below the slope and a next rock was dropped. The method of dropping a rock is as follows: (1) a rock was set at the shoulder of the slope and at its center, as shown in Figure 1; (2) the long side of a rock was parallel to the inclination direction of the slope; and (3) a rock was pushed with a finger, little by little, until it dropped. In the simultaneous experiment, a predetermined amount (10 or 50 kg) of rocks was placed in a box, the lid of the box was instantly opened, and the arrival positions of the rocks were recorded, as shown in Figures 1 (a) and (b). Table 1 shows four cases adopted in the present study.

Figure 2 shows the distribution of the arrival positions of the rocks in the four cases. As shown in this figure, no large difference was observed in the distribution of the arrival positions between cases 1a and 2a, and between cases 1b and 2b. However, both rock sizes of 20−30 mm and 40−80 mm moved longer distances in the individual experiment than in the simultaneous experiment. In the simultaneous

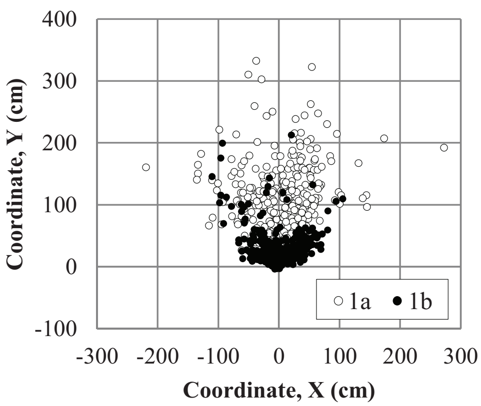


(a) Case 1b: 50 kg of rocks (40–80 mm) (b) Case 2b: 10 kg of rocks (20–30 mm)

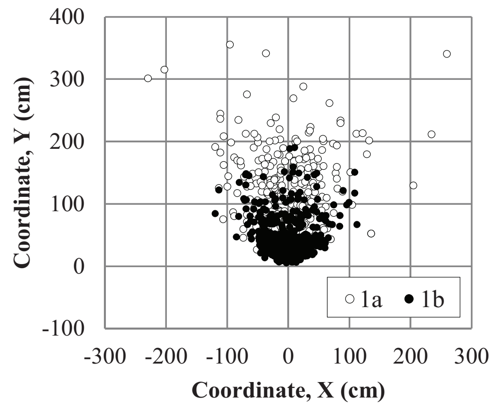
Figure 1. Outline of the experiments performed by Tochigi et al.

Table 1. Cases of the experiment for study.

Case	1a	1b	2a	2b
Size of rocks	40-80mm		20-30mm	
Method of dropping rocks	Individual	Simultaneous(50kg)	Individual	Simultaneous(10kg)
Number of rocks	300	177	300	442



(a) Size 40-80mm



(b) Size 20-30mm

Figure 2. Distribution of the arrival positions of falling rocks obtained in the experiments.

experiment, the rocks were concentrated around the slope foot, and were partially piled up. Apparently rocks in the individual experiment, Case 1a and 2a, reach far place from the slope foot than simultaneous experiments, Case 1b and 2b.

Assessment of the probability distribution of the arrival positions of the rocks

Cumulative distribution functions (CDF) of the arrival positions of the rocks in the X and Y directions are evaluated. A method to evaluate the CDF is explained with X direction of Case 1a as an example. The arrival positions of the rocks are sorted in ascending order with respect to coordinate value (x_i, $i = 1, \ldots, n$). Here, n represents the number of dropped rock. The cumulative probability of the coordinate value of the arrival position of a rock x_i is given as follows (Ang et al., 1977).

$$P(x_i) = p_i = \frac{i}{n+1} \tag{1}$$

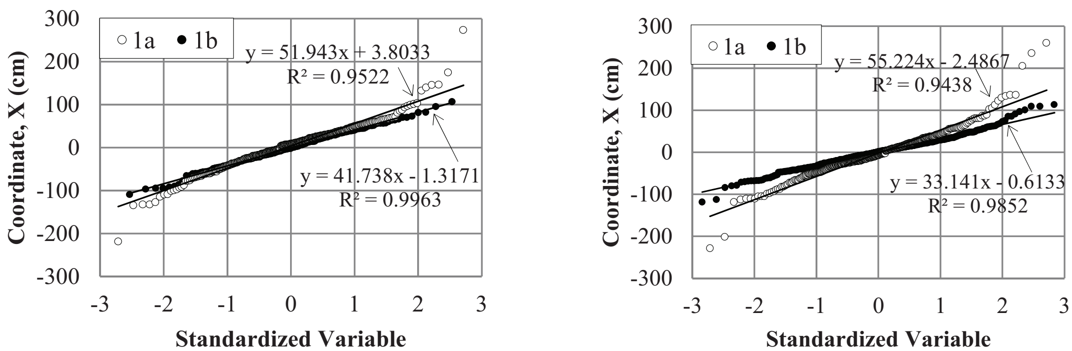
Figure 3 shows the relationship between coordinate value x_i and standardization variable z_i in Case 1a. The vertical axis represents the coordinate value x_i, and the horizontal axis represents the standardization variable z_i that is obtained as follows.

$$z_i = \Phi^{-1}(p_i) \tag{2}$$

Where Φ^{-1} represents the inverse function of the cumulative standard normal distribution. If the arrival positions of the rocks are modeled with a normal distribution, the relationship between coordinate value x_i

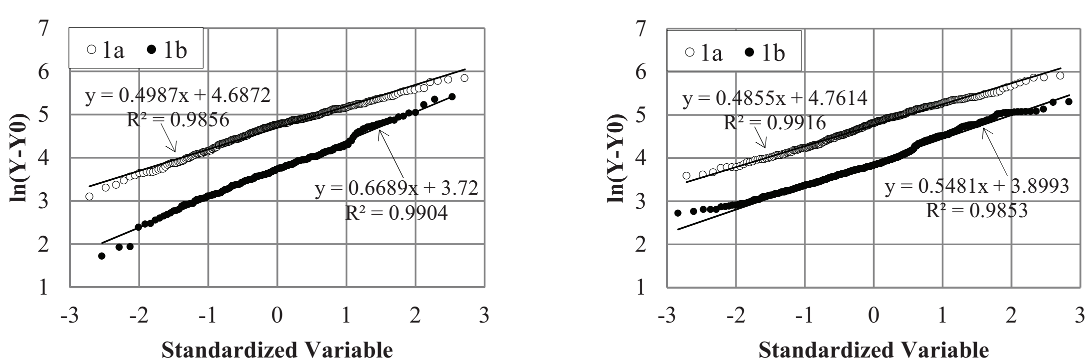
and standardization variable z_i is linear. As shown in Figure 3, the relationship between coordinate value x_i and standardization variable z_i is liner approximately, so that the case 1a can be modeled by using a normal distribution. The slope of the regression line represents the standard deviation, and its intercept represents the mean of the coordinate of arrival position. In addition to Case 1a, Figure 3 shows the relationship between coordinate value x_i and standardization variable z_i in the X direction in Cases 1b, 2a, and 2b. Some rocks were not on a straight line in Cases 1a and 2a in whiche the rocks were dropped individually. In Cases 1b and 2b, in which the rocks were dropped simultaneously, the coordinates of rocks are on lines approximately. The intercept of the lines, which indicates mean, was almost zero in each case. The slope of line (standard deviation) was smaller in Cases 1b and 2b than in Cases 1a and 2a.

The Y direction is modeled by a logarithmic normal distribution because the rocks were mainly concentrated at the foot of slope model, but some rocks reach far places. If the foot of the slope is used as the origin of the Y coordinate, some rocks stop at the slope, which means negative Y coordinate values. These rocks could not treated in the logarithmic normal distribution, so that origin in Y direction is shifted to Y_0. Figure 4 shows the relationship between the coordinate value x_i and standardization variable z_i in the Y direction when Y_0 = 10 cm is used. As shown in this figure, the relationship is approximately linear. The obtained means and standard deviations are used for calculation of the collision probability described below.



(a)40-80mm (b)20-30mm

Figure 3. Modeling of the arrival positions of falling rocks in the X direction by a normal distribution



(a)40-80mm (b)20-30mm

Figure 4. Modeling of the arrival positions of falling rocks in the Y direction by a logarithmic normal distribution, $\ln(Y-Y_0)$;Y_0 = 10cm.

METHODS TO ASSESS THE COLLISION PROBABILITY AND THE RESIDUAL DISTANCE HAZARD CURVE

Method of calculating the collision probability

Based on the evaluated cumulative density function, the collision probability and the hazard curve were assessed. The collision probability of a rock against an assumed structure is calculated using the following equation.

$$P_1 = \int_\Omega p(x, y)dxdy \tag{3}$$

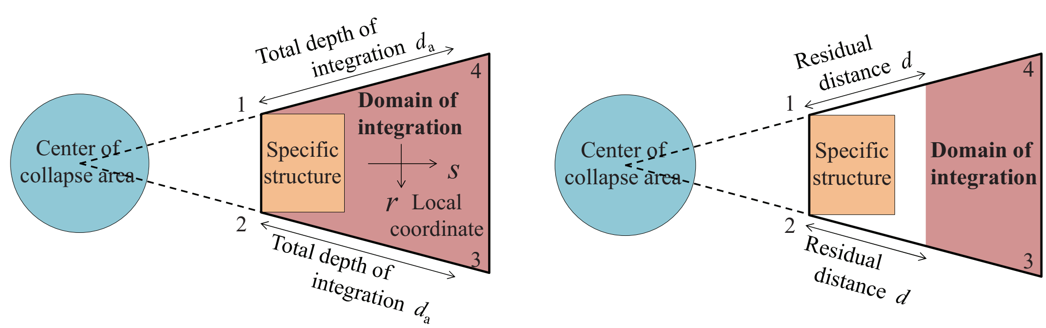
Where, $p(x, y)$ represents the probability density function of the arrival position of a falling rock. As shown in Figure 5 (a), the domain of integration is determined on the assumption that falling rocks move in a straight line from the center of the collapse region. Area behind the assumed structure is the domain of integration. Although the entire area behind the assumed structure should be integrated, the area with a certain length d_a is actually sufficient for integration. As shown in this figure, d_a is set to be large enough for the integration. Equation (4) expresses the two-dimensional integration for the calculation of collision probability. The integration is performed by using an interpolation function with quadrilateral elements (finite element method) (Bathe et al., 1979), because this method is suitable for the calculation of the residual distance hazard.

$$P_1 = \int_\Omega p(x, y)dxdy = \int_{-1}^{1}\int_{-1}^{1} p(r,s)\left|\mathbf{J}\right|drds \tag{4}$$

Coordinates x and y are a global coordinate system, and coordinates r and s are a local coordinate system. When n rocks drop, the probability P_n that one or more than one from n rocks collide with the structure can be calculated under the assumption of independence among rock fall events.

$$P_n = 1-(1-P_1)^n \tag{5}$$

Please note that the collision probability calculated with above equations indicates a conditional probability when a slope failure or rockfall occurs. In order to calculate total probability, further study is required as stated in conclusion.



(a) The local coordinates and the domain for the calculation of collision probability

(b) The domain of integration corresponding to the residual distance

Figure 5. The domain of integration regarding the arrival position coordinates for calculating the collision probability and residual distance hazard

Method of calculating residual distance hazard

This study proposes residual distance hazard which indicates cumulative probability corresponding to residual distance. The residual distance expresses the further travel distance of a falling rock if the rock does not collide with a structure, and represents the amount of energy when the rock collides with the structure. By integrating the domain shown in Figure 5 (b), the exceedance probability corresponding to the residual distance d can be obtained. Because the local coordinate s represents the direction of a straight line from the center of the collapse region, the collision probability of the event that the residual distance is greater than d, can be obtained by integrating the domain [-1 + $2d/d_a$, 1] for local coordinate s. Therefore, the probability $P_1(d)$ corresponding to the residual distance d, that is, the residual distance hazard curve, can be easily obtained.

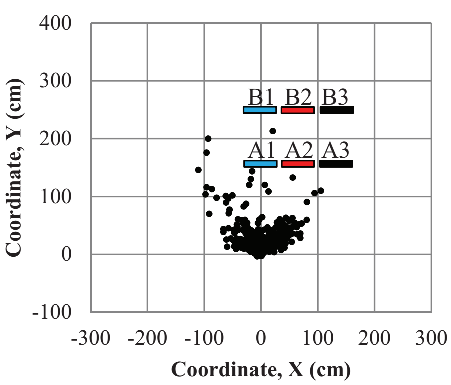
$$P_1(d) = \int_{-1}^{1}\int_{-1+2d/da}^{1} p(r,s)|\mathbf{J}|drds \tag{6}$$

EXAMPLES OF ASSESSMENT OF THE COLLISION PROBABILITY AND THE RESIDUAL DISTANCE HAZARD CURVE

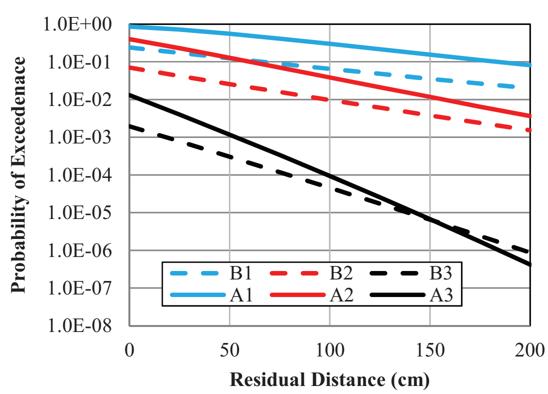
Based on the experimental results, the residual distance hazard curve is calculated for assumed structures as an example. The probability density distribution $p(x, y)$ appeared in Equation (6) is defined as Equation (7). A normal distribution is used for the x direction and a logarithmic normal distribution is used for the y direction. These two directions are assumed to be independent.

$$p(x,y) = \frac{1}{2\pi\sigma\varsigma y}\exp\left\{-\frac{(x-\mu)^2}{2\sigma^2} - \frac{(\ln(y-y_0)-\lambda)^2}{2\varsigma^2}\right\} \tag{7}$$

Where μ and σ represent the mean and the standard deviation in the X direction, respectively, and λ and ζ represent the mean and the standard deviation of ln(Y-Y_0), respectively, where, Y_0 = 10 cm. These means and standard deviations are shown in former chapter on the experiment. The coordinates of the collapse center are assumed to be (0, -92 cm).



(a) The position of a structure assumed for calculating the collision probability



(b)The residual distance hazard curve corresponding to the location of a structure

Figure 6. Examples of calculated residual distance hazard curve.

Figure 6(a) shows assumed structures A1, A2, A3, B1, B2, and B3. These structures are modeled by a segment without considering the shape. The regions behind the segments are integrated to obtain the collision probability. Figure 6(b) shows the calculated residual distance hazard curves of the experiment Case 1b (the size of the rocks: 40−80 mm, the amount of rocks: 50 kg; the rocks were dropped as a group). In Figure 6(b), the vertical axis indicates the exceedance probability. When the residual distance is zero, the exceedance probability expresses the collision probability. The number of rocks is n = 177 in this experiment case. As shown Figure 6(b), the exceedance probability decreases as the residual distance increases (the collision becomes more severe). When A2 is compared with B1, because A2 is closer to the slope than B1, the collision probability to A2 was slightly larger than that to B1. However, the collision probability to B1 with a residual distance > 60 cm is larger than that to A2. Thus, the residual distance hazard curve can be assessed based on the positional relationship between the slope and structures.

CONCLUSION

This study proposes a method to quantitatively assess the risk of slope failure to a structure with residual distance hazard when a slope fails. Future tasks are as follows:

(1) Collision velocity for collision hazard curve: Although the residual distance is related to the impact force when a rock collides with a structure, it does not have direct relation with collision energy and is not always easy to use. We try to estimate the relationship between the collision velocity and the residual distance.
(2) A method to assess a three dimensional slope shape and ground: We have already developed the method and are looking for application site.
(3) A method to assess the total probability: The proposed method estimates the conditional probability when slope failure or rockfall occurs. To estimate the total probability, seismic hazard analysis, slope failure analysis and falling rock analysis have to be treated comprehensively. In this study, a method to estimate conditional probability is proposed and discussed in the total framework.

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