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A LARGE SCALE TEST TO INVESTIGATE COLLISION HAZARD BY FALLING ROCKS AND SOIL FLOW DUE TO EARTHQUAKE

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ABSTRACT

This paper presents the results from a large scale test of falling rocks and soil flow due to earthquake. The behaviour and impact load characteristics of the rock-fall and soil-flow were measured by Particle Image Velocimetry (PIV) method using high speed CCD cameras and high capacity load cells, respectively. Also, the effectiveness of numerical methods, i.e., Material Point Method (MPM) (Sulsky et al., 1994 and 1995) for calculation of impact force of the soil-flow was investigated comparing the test results with simulation results.

INTRODUCTION

After slope failure due to unexpected ground motion at a nuclear facility, it was considered important to perform risk assessment in relation to slope stability by analyzing the behavior of rocks and soil. In this study, we focused on the behavior of rocks and soil after slope failure, and conducted a large-scale, rolling rock and flowing soil experiment using rock and sediment models on a large-scale slope. In this respect, we confirmed the effect of the behavior of rocks and soil on the reach and impact load. In this report, we also design an evaluation method for the behavior of rocks, and in relation to this, analyze the velocity of falling rocks and their rolling coefficients, based on the results of the rolling rock experiment. We also propose a calculation formula for the collision directional load of rocks, based on calculation formula related to the impact of falling rocks according to the rock fall measures handbook (Japan Road Association, 2000), and propose an evaluation method for the impact load of soil using the Material Point Method (MPM) (Sulsky et al., 1994 and 1995).

LARGE-SCALE ROLLING ROCK EXPERIMENT

Our experiment involved designing and building a large-scale slope, and dropping various rocks from the crown of the slope. The behaviour and impact load characteristics of the rock-fall and soil-flow were measured by Particle Image Velocimetry (PIV) method using high speed CCD cameras and high capacity load cells, respectively. The large-scale slope was constructed, as follows. A model slope was constructed using PC board with a width of 5.0 m. The slope consisted of three different segments. The bottom segment was flat and had a length of 7.5 m. The first part of the slope measured 5.7 m with a slope of 29^o, and the top part measured 5.0 m in length and had a 43^o slope (Figure 1). To understand the impact of the slope's protuberances on the behavior of the rock model, removable angle bars were installed on the slope at regular intervals. The impact load of the rocks was measured using a load meter with a capacity of 1.0 MN, which was installed on the front of the reaction wall on the flat portion (Figure 2). Spherical, massive, or planer samples with diameters of 20 and 40 cm were used as the rock models (Figure 3). The behavior of the rocks was filmed using a high-resolution camera, and measured using an image analysis process by the PIV method (Figure 4).

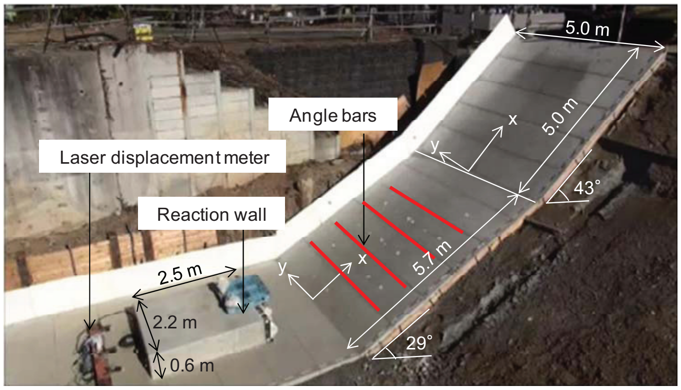


Figure 1. Large-scale slope model

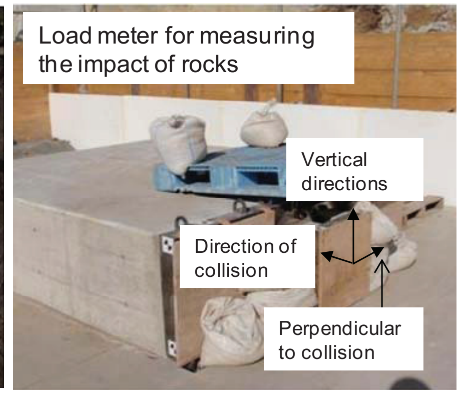


Figure 2. Reaction wall

(a) Spherical model (b) massive model (c) planer model

Figure 3. Rock models (20 cm)

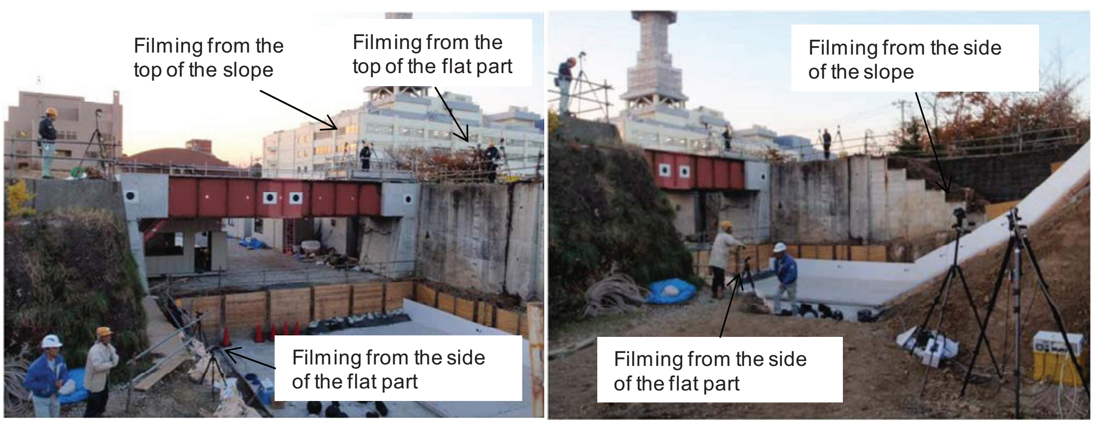


Figure 4. Setup for image analysis cameras

ANALYSIS OF ROCK BEHAVIOR

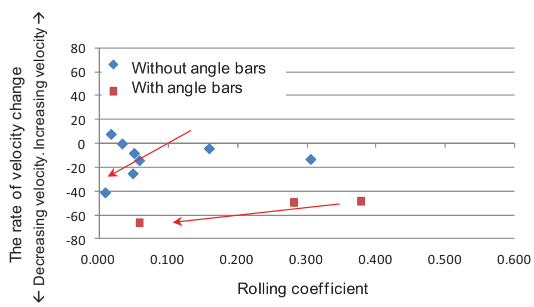
To understand the behavior of rocks on the flat portion of the ramp, we analyzed the rate of velocity change, the rolling coefficient, angular velocity, and the velocity of the rock at 4 m from the boundary between the flat portion and the angled portion. Image analysis data captured from the side of the channel were used for this analysis. The rate of velocity change *V'* (Equation (1)) was obtained by dividing the velocity measured at 4 m away from the boundary of the flat and angled portions, by the velocity measured at the boundary:

$$V' = (b - a) / a \tag{1}$$

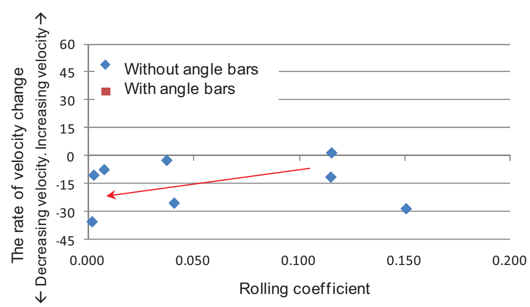
where *a* is the velocity at the boundary between the flat and angled portions, and *b* is the velocity at 4 m away from the boundary between the flat and angled portions. If the rate of velocity change is a large positive value, the velocity of the rock is considered to be increasing, and conversely, if the value is a large negative number, it is considered to be decreasing. The rolling coefficient was defined to determine whether a rock would slide or roll, and is expressed with Equation (2) (Naito et al., 2014):

$$Cr = (\omega \cdot \gamma) / v \tag{2}$$

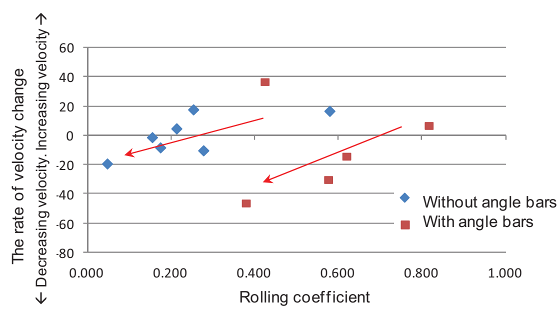
where *Cr* is the rolling coefficient, ω is the angular velocity, γ is the radius of the rock, and v is the velocity parallel to the impact surface. The tendency a rock has to slide can be determined by the size of the rolling coefficient: the smaller the coefficient, the greater the tendency to slide. The relationship between the rate of velocity change and the rolling coefficient at 4 m away from the boundary between the flat and angled portions is shown in Figure 5. The result shows that when the rolling coefficient was smaller, there was a stronger tendency for the rate of the velocity change to increase in a negative direction. In this respect, when the rolling coefficient was small and thus exhibited a sliding trend, regardless of the shape of the rock, there was a tendency for the velocity of the rock to decrease. Based on this observation, if a rock exhibits a rolling behavior there is only a slight decrease in the velocity, and thus the reach is far.



(a) Massive rocks



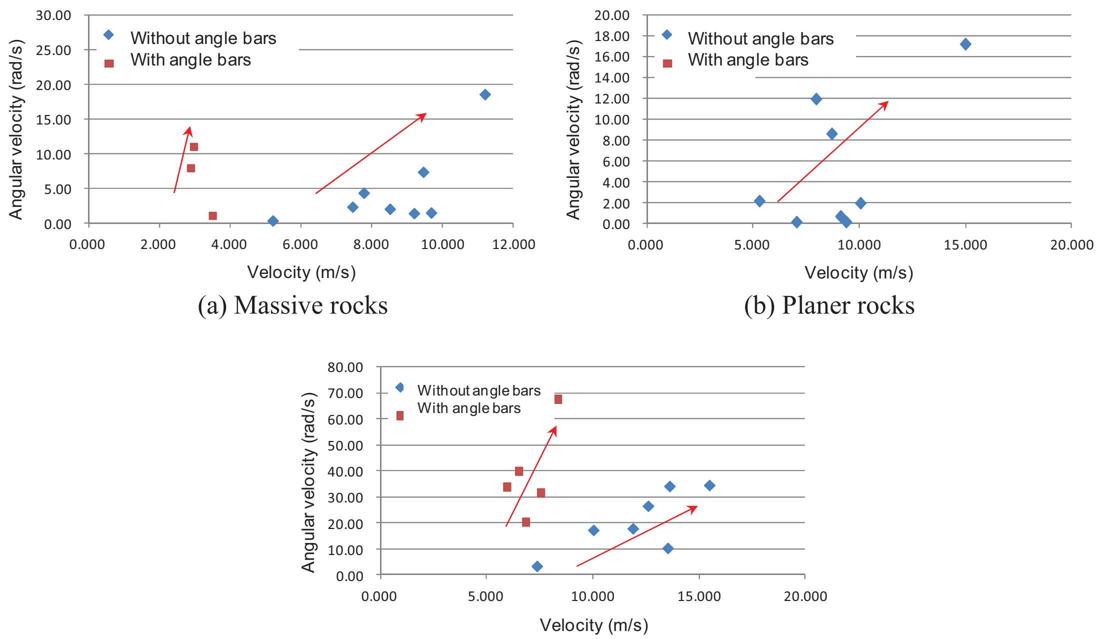
(b) Planer rocks



(c) Spherical rocks

Figure. 5. The relationship between the rate of velocity change and the rolling coefficient

We then analyzed the angular velocity in relation to the velocity at the boundary between the flat and angled portions. The angular velocity was obtained by first finding the rotation angle based on the displacement history of a marker previously made on the rock, and then dividing it by the speed of movement (the relationship is shown in Figure 6.) The results showed that when the velocity was high, the angular velocity tended also to be high. The inclination of the relationship between the angular velocity and velocity (i.e., the rolling coefficient) were larger when the angle bars were present, compared to when there were no angle bars. This observation shows that when the velocity is high the angular velocity is also high, and that if there is bounding behavior when the velocity is low then the rolling coefficient is large, and the rolling behavior becomes dominant. Therefore, if protuberances exist on the slope and the rock bounces, the velocity decreases and the reach becomes shorter in spite of the dominant rolling behavior.



(a) Massive rocks

(b) Planer rocks

(c) Spherical rocks

Figure. 6. The relationship between the angular velocity and the velocity

PROPOSING A CALCULATION FORMULA FOR THE IMPACT LOAD OF ROCKS

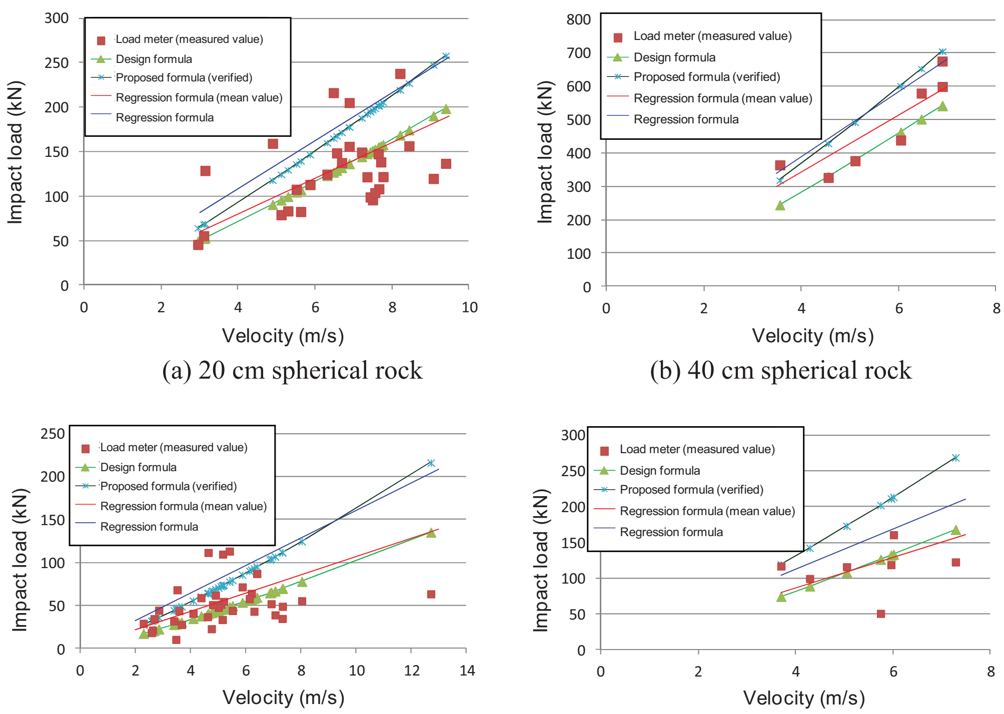
Equation (3) (the design formula) is used to calculate the impact load of falling rocks on a structure $P_{\max}$ (kN). This is the calculation formula for the impact of a falling rock according to the Rock Fall Measures Handbook (Japan Road Association, 2000):

$$P_{\max} = 2.108\,(m \cdot g)^{2/3} \cdot \lambda^{2/5} \cdot H^{3/5} \qquad (3)$$

where m is the falling rock mass (ton), H is the fall height (= $v^2/2g$: m), v is the velocity (m/s), g is the acceleration of gravity (m/s^2), and λ is the Lamé's constant (kN/m^2). This design formula is an equation in which Hertz collision theory is applied to the impact phenomenon when two spherical elastic bodies collide. To propose a calculation formula (the proposed equation) for the impact load of rocks based on the impact of falling rocks in Rock Fall Measures Handbook (Japan Road Association, 2000), the actual measured value of the impact load obtained from the large-scale rolling experiment, and the impact load calculated from the design formula were identified, and the construction of the proposed formula was then examined. Since the design formula was constructed based on the collision phenomenon of a spherical model, it was first identified using the regression formula (mean value) obtained from the relationship between the impact load of a spherical rock and the actual measured value of the velocity immediately before collision. To ensure that the design formula agrees with the regression formula, or is in close agreement with it, identification was made using Lamé's constant λ as a parameter. We also added a new coefficient α (which considers variations in the impact load) to the design formula determined here using Lamé's constant, which was identified using the regression formula that considers variations in the actual measured values (mean value $+1.0\sigma$). Results confirmed that with the use of a Lamé's constant value of 500 MN/m^2 and a coefficient α of 1.3, which considers variations in the impact load, the design formula and the regression formula of actual measured values were mostly in agreement (Figure 7(a) and (b)). With this coefficient, the proposed equation for the spherical rock is as follows (Equation (4)):

$$P_{\max} = \alpha \cdot 2.108\,(m \cdot g)^{2/3} \cdot \lambda^{2/5} \cdot H^{3/5} \tag{4}$$

where α is the coefficient (1.3 for spherical rock) that takes variations in the impact load into consideration. A previous study (Kawase et al., 2003) conducted an experiment where a plumb bob collided against concrete, and in which a Lamé's constant of 120 MN/m^2 was used–determined by identification of the experimental and analytical values–and the impact was evaluated using the design formula. In this respect, we consider that in our experiment (in which a rock collided with a concrete reaction wall), the impact load can be evaluated after obtaining a Lamé's constant of 500 MN/m^2 from identification of the experimental value.



(a) 20 cm spherical rock

(b) 40 cm spherical rock

(c) 20 cm massive rock

(d) 40 cm massive rock

Figure 7. Verification results using the proposed equations

We then examined the proposed equation in relation to a massive rock. We added the coefficient β, which takes variation in the rock's shape into consideration, to the design formula with a Lamé's constant of 500 MN/m^2. The formula was then identified using the regression formula (mean value) obtained from the actual measured value of the impact load by a massive rock. Furthermore, with the same method used for the spherical rock, we added the coefficient α, which takes the variation in impact load into consideration, and identified with the regression equation (mean value $+1.0\sigma$). Results showed that by using λ = 500 MN/m^2, α = 1.6, and β = 0.5, the regression formula of measured value and the proposed equation are mostly in agreement (Figure 7(c) and (d)). In addition, a similar identification was made for the planer rock, using α = 1.7 and β = 0.4, and it was again confirmed that the regression formula of the measured value and the proposed equation were in agreement. Taking these coefficients into consideration, we define the proposed equation (Equation (5)) for massive and planer rocks, as follows:

$$P_{\max} = \alpha \cdot \beta \cdot 2.108\,(m \cdot g)^{2/3} \cdot \lambda^{2/5} \cdot H^{3/5} \tag{5}$$

where α is the coefficient that takes the variation in the impact load into consideration (1.6 for massive rock and 1.7 for planer rock), and β is the coefficient that takes the rock shape into consideration (0.5 for massive rock and 0.4 for planer rock).

ANALYTICAL EVALUATION METHOD FOR SOIL BEHAVIOR

The behavior of rolling rocks and the impact load can be evaluated using the above method. We then examined the use of the evaluation method in relation to the behavior of flowing soil and the impact load.

Soil flow experiment

The slope model described above was firstly used to conduct a soil flow experiment. Figure 8 shows photographs taken before and after the large-scale flow experiment. At the reaction wall, which is located on the flat portion, the time history of impact load was measured by load meters. Crushed stone was used in the soil model for mechanical stabilization (M40 with a volume of 1.0 m^3), and it was compacted to a height of 0.2 m on a truck bed of 2.3 m × 1.9 m, with a density of ca. 18.5 kN/m^3 (see Figure 8). The bed was then tilted to an angle of 66.0 degree to allow the soil to flow. The results show that the sediment model collided with the reaction wall and accumulated in front of the wall (see Figure 8).

Analytical model

In this study, we focused on the use of the Material Point Method (MPM) (Sulsky et al., 1994 and 1995) as an analytical method, which is a type of particle method capable of handling large deformations that cannot be handled by the Finite Element Method (FEM). In addition, it does not require calibration of the analytical parameters, which are required for the Distinct Element Method (DEM) for stable analysis. Furthermore, compared to other particle methods such as SPH, it is easy to understand because the analytical flow of the MPM is close to FEM. We thus focused on the application of MPM in relation to the behavior of soil. To determine its applicability, we conducted a reproducibility analysis using the MPM in relation to the behavior of the soil model and the impact load obtained from the large-scale flow experiment. In the analytical model, the slope shape and the initial position of the soil model were determined based on the test conditions. The bottom surface of the slope and the reaction wall were modeled as the friction interface and the fixed boundary, respectively. Analytical parameters for the soil model were modeled using a bilinear model with a Drucker-Prager yield surface, based on the triaxial compression test results shown in Figure 9. The analytical parameters used are shown in Table 1.

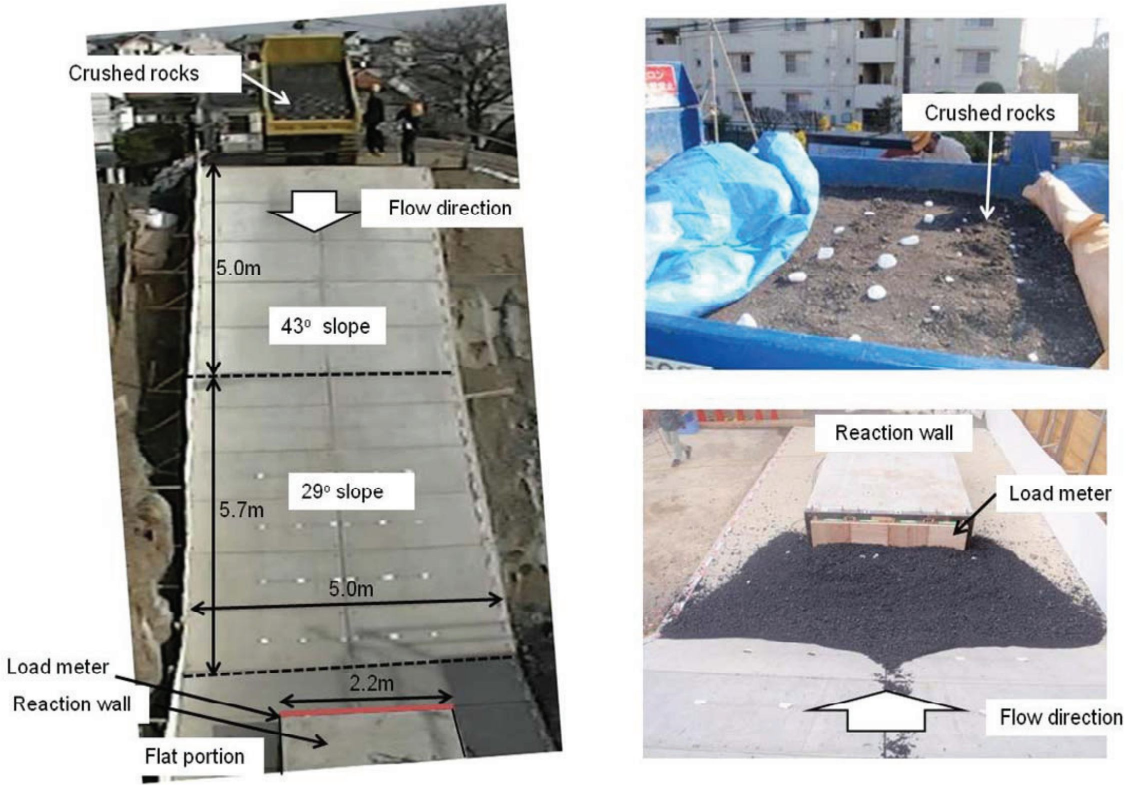


Figure. 8: Photographs before and after the large-scale flow experiment

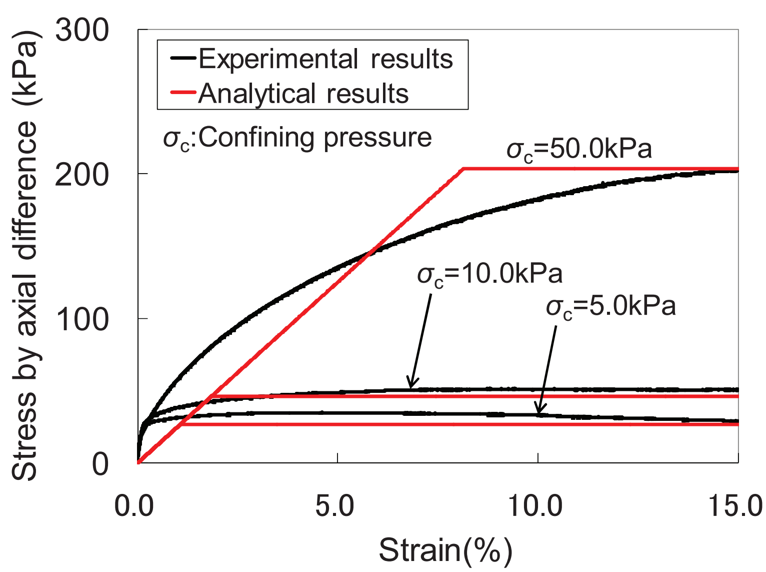


Figure. 9: Triaxial compression test results

Table 1: Analytical parameters

Items	Values
Elasticity coefficient (kN/m^2)	1.0× 10^3
Density (kg/m^3)	1.64×10^3
Poisson's ratio	0.30
internal frictional angle (degrees)	34.6
Dilatancy angle (degrees)	0.0
Cohesion (kN/m^2)	2.10
Tensile strength (kN/m^2)	0.0
Plastic modulus (kN/m^2)	0.0
Bottom surface friction angle (degrees)	30.0
Particle number	3,922
Mesh size (m)	0.20

Analytical results

Figure 10 shows a comparison between the experimental and analytical results for the impact load against the reaction wall in the large-scale flow experiment. Analytical results were initially larger than the experimental results; however, in the latter half of the experiment the values were mostly equal. The impact load in a sediment model is affected not only by the collision directional velocity, but also by the differences in friction and hardness of the sediment model and the reaction wall. However, in the analytical model used in our case, the reaction wall was modeled as a fixed boundary, and the impact was not taken into consideration. We consider that this is the reason for the differences observed between the experimental and analytical results. For example, in relation to the differences in hardness, a concrete panel measuring approximately 10-mm was installed in front of the load meter in our experiment. However, the analysis does not reflect the impact of this panel. It is considered that this discrepancy affected the difference in the size of the load at the initial stage.

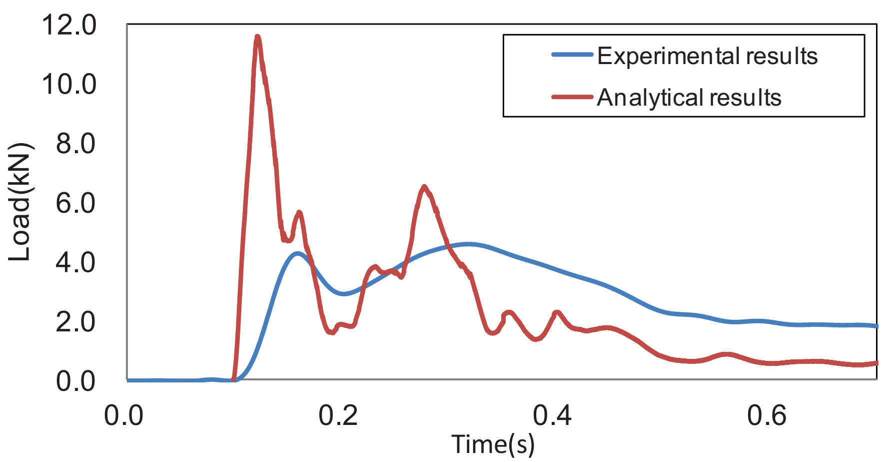


Figure 10. Time history of the impact load in the sediment model

CONCLUSION

This paper aims to design a method for evaluating the behavior of rocks, and to propose an analysis to determine the velocity of falling rocks and their rolling coefficients. In addition, it aims to propose calculation formulas for the impact loads based on the Rock Fall Handbook (Japan Road Association, 2000). The analytical study results were presented using MPM as an evaluation method for soil behavior. In the future, based on these results, we hope to further summarize toward the application to the actual design.

ACKOWLEDGEMENTS

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