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MOVEMENT OF ROCKFALL AND A STUDY ON ITS PREDICTION

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Abstract: We conducted rockfall experiments on a natural slope in order to study the movement mechanism of the falling rocks. Rockfall through a slope has different motions such as rolling, rotating, flight, colliding, dragging, etc. It is important to understand the relationship between all these motions. For example, change of velocity when the motion shifts from rolling to flight, rotation of the falling rocks during the flight, and collision of the rocks with slope surface or trees on the falling course must be clearly studied to understand the mechanism of rockfall movement. Similarly, a superficial falling course, falling distance and velocity, bouncing height, etc. must also be understood. This paper introduces and discusses the experimental results, and proposes a mathematical method for predicting the speed and bounce height of a rockfall.

1. INTRODUCTION

Almost three fourth of the land in Japan is mountainous. The geology of the whole country is fragile and complicated as it is under the influence of repeated orgenic movement. In addition, typhoon and seasonal variations in atmospheric pressure during summer cause excessive rainfall, and fall in temperature during winter causes snowfall and freezing of soil water. Furthermore, Japan belongs to the Pacific rim earthquake zone, so it experiences a greater number of earthquakes every year and is also a world leading earthquake-prone region. For this reason, slope disasters such as rockfall, debris flow, slope failure, and landslide occur every year, and sometimes, human lives are claimed along with the damage to property. Traffic is also interrupted and a serious influence on the local life is caused.

Figure 1. Map of Japan

About 77,000 which cause about rockfall, sites have been recognized all over the country, which cause about 4,150 road damage a year.[1)] It certainly increases the budget in construction works every year. Although rockfall counter measures are applied, rockfall prone areas are increasing every year due to road extension work and over confined degradation of slope materials.

It is therefore important to evaluate and estimate the response of a recognized rockfall site, its scale and time, the rockfall (i.e., velocity, bounce height, fall course, final position), rockfall forces (i.e., impact force, kinetic energy), etc., in order to implement a rockfall protection work.

The research mechanism of rockfall was first started in 1961 with an experimental study at Raiden[2)] cape of Hokkaido. Although a total of 16 on-site experiments have been conducted up until now, the mechanism of rockfall is still unclear in many aspects. For this reason, the perdition of rockfall movement with enough accuracy is yet to be made. This led the authors to conduct one move experimental study on the rockfall mechanism. The study took place at a natural slope in Nishitosa village of Kochi prefecture,(Figure 1) in October, 2000. As a result, the relations between change in velocity of the falling rocks while shifting of motion from rolling to freefall , rotation during freefall , and colliding with the slope or a tree, a superficial fall course, fall distance and velocity, bounce height, etc. were understood clearly.

This paper thus introduces the experiment at results. and a mathematical method to predict the speed and height of jumps of rockfall is proposed.

2. THE SLOPE SITE AND EXPERIMENTAL METHOD

The field experiment was conducted on a slope whose profile is shown in Figure 2. The slope is composed or, weathered sand rock and mud rock bed making alternate layers with a surface layer composed of gravel and silt over them. The thickness of the rock beds varies from 3 to 50 cm, whereas that of surface call layer varies from 2 to 5 cm, in the experiments, all together 69 blocks were dropped, of which 49were crushed sand rocks (16 ~200kg), 4 were sand rock (21~48kg), 3 were concrete spheres (16kg), and 13 were cubical concrete blocks (16kg). Two sets of experiments were conducted.

We conducted two kinds of experiments. First set was rolling type that consisted of placing a test block at the foot of the retaining wall shown in Figure 2 and allowing it to roll over the slope. It was conducted with 35 test blocks. Second set was freefall type. Which consisted of letting 34 test blocks fall freely from the top of the retaining wall. To capture the movement patterns (i.e., falling pattern) 2 the blocks in both the sets 2 tests, four digital video cameras (with imaging speed of 30 shots / second) were set on the course slope.

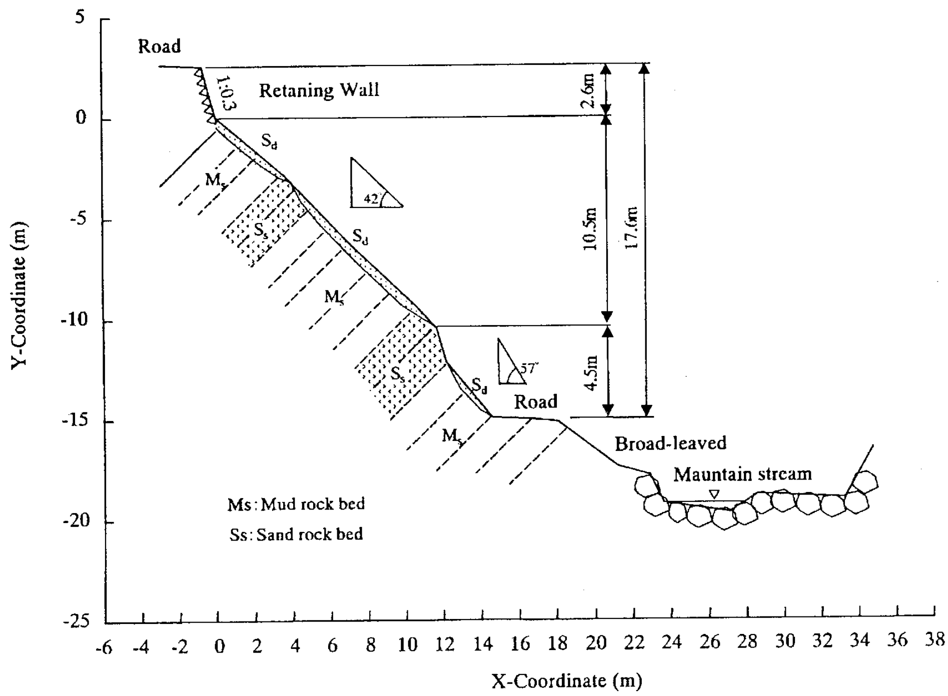
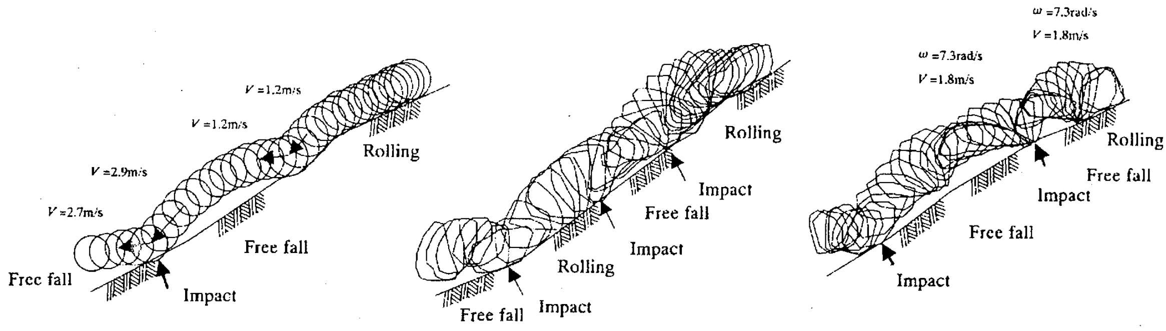


Figure 2. Profile of the experimental slope

3. THE MOVEMENT MECHANISM OF ROCKFALL

3.1 Initial motion of rockfall

Initial stages of motions of rockfall are shown in Figure 3. In first set 2 test blocks that had movement pattern changed to freefall from rolling was 23, and remaining 77% had movement pattern changed from rolling to sliding through rolling. It was also observed that when long and slender test blocks rotated and rolled about their, major inertial axis the movement pattern changed flight from the initial rotation of 1/2 to 2 / 3 (180-250 degrees). However, when the rotation was about the minor inertial axis, the movement pattern did not change to fight unless the blocks took two rotations. Velocity during the flight movement was observed to be 1.2-1.8m/s, and the angular velocities were about 7-8 rad/s. However, since the slope and the surface of a natural rock piece are complicated, destination of a fight movement becomes difficult, especially when the bounce height is small the movement is rolling type.



(a) spherical concrete block (D=25cm, 16.2kg)

(b) Irregular rock block (38 × 24 × 19cm,18.6kg)

(c) Irregular rock block (46 × 23 × 13cm,26.1kg)

Figure 3. Rockfall motion

3.2 Freefall

In Figure 4, the flight movement of rockfall during a freefall is shown. This is the case of second experiment set with cubical concrete blocks. It was observed that the blocks attained a flight movement with a slow rotation about the most stable inertial axis that passed through the center of the block. It was no table that the inertial axis changed with the movement and time.

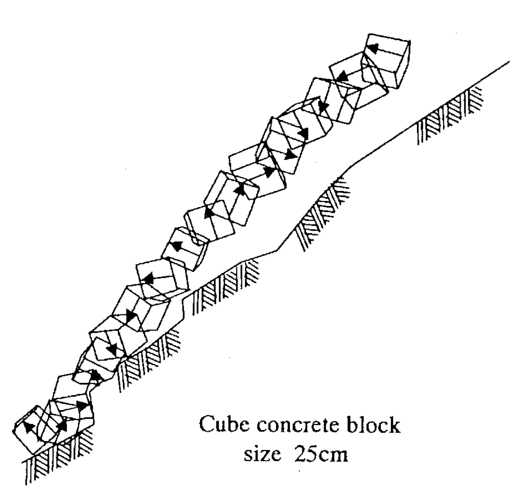


Figure 4 Freefall

3.3 Bouncing and impact

Figure 5 shows two cases of rockfalls with impact. Figure 5(a) is a case of irregular rock of mass 31.1kg, which resumes the freefall only after rolling a short course immediately after an impact on the slope, whereas Figure 5(b) is a case of similar block (mass 32.6kg), which resumes freefall immediately after the impact. This difference in movement is because of the loss of kinetic energy by the falling rock dye to plastic deformation of the slope ground, which absorbs the impact received from the rock block. However, the rock block remains in motion due to centrifugal force ever after the bounce becomes zero, and the centrifugal force makes the block roll over the slope for a moment. It was also noticed that when the angular speed was high, the freefall was achieved only after 1/8 rotation, but it was achiever after 1/2 rotation when the speed was low.

A case when rockfall collides with the road surface is shown in Figure 6. Here, the case is different from that of impact on the slope. Four of the dropped rock blocks remained on the slope, and 65 reached the road. Among the reached, bounced a little after colliding with the road (width f 3.5m) surface, or rolled and stopped on the road, 12 block jumped and stopped at the road shoulder, and seven of them jumped over the road shoulder.

The road had been built by cutting a mudrock slope where the rock weathering activity is high. Although the road material was earth and sand, the wad surface must have been harder than the slope material. However, about 70% of the rockblocks lost their kinetic energy in vertical direction after colliding with the road surface. The maximum bounce height attained by somc blocks was 0.5m, which after calculations gives the magnitude of the normal component of the rebounding velocity to be 3m/sec.

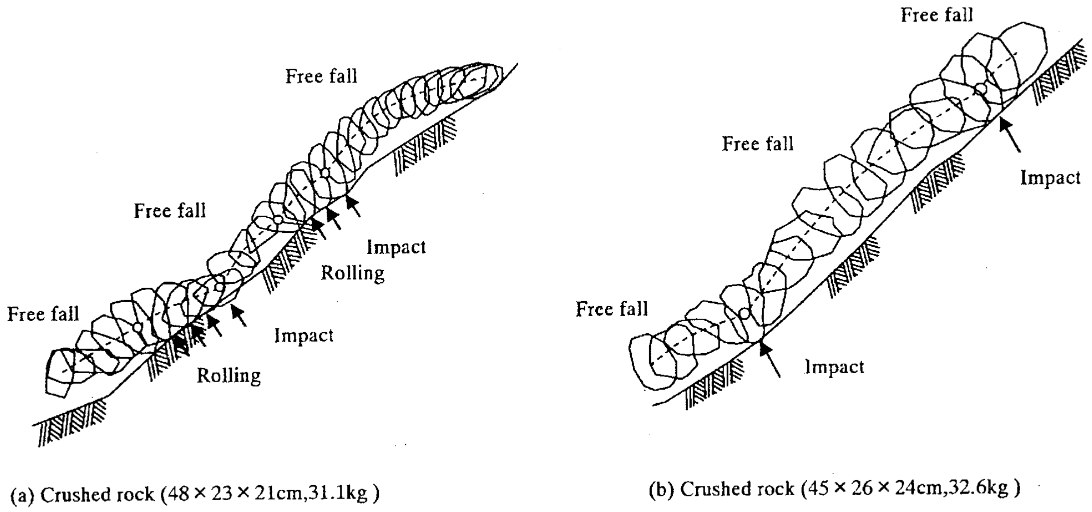


Figure 5. Impact and bouncing

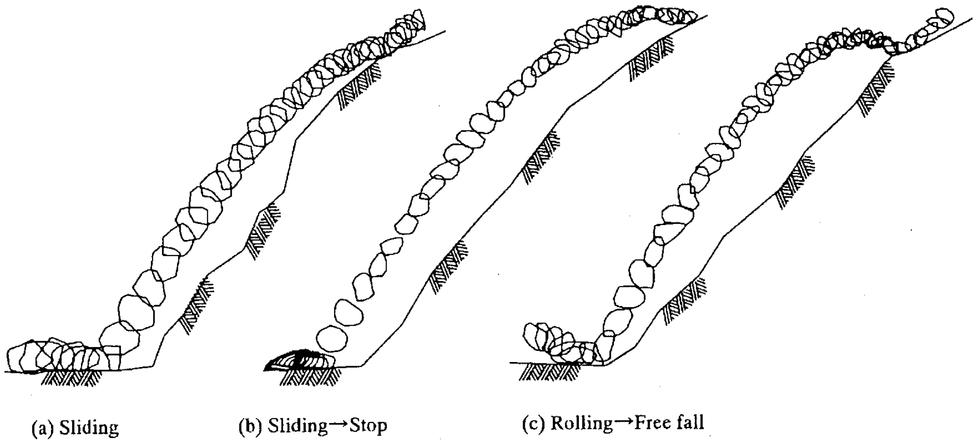


Figure 6. Collision with a road

3.4 Collision with trees

Among the 69 dropped blocks, eight collided with the trees. Two such examples are shown in Figure 7. In one cases when a rockblock under flight motion collided with the roots of trees, it was observed that the block was stopped between the tree and slope surface. In second case, the block hit the tree and rebounded but started rolling from the initial state (I.e., zero speed). When the angle of collision was small, some kinetic energy was absorbed by the tree but the flight motion was resumed with a clanged direction.

3.5 Rockfall course

The superficial fall courses of the dropped rock blocks are shown in Figure 8. The lines with arrow are the courses of block that were not stopped. The falling course of a rockblock is influenced by the contours of slope surface at initial positions. Moreover, when a falling block collides with a tree, a stump, or the exposed part of the base rock, the direction of movement is changed abruptly. Rockfall spread angle was 30 degrees (93% were in cluttered in 15 degrees) on the left and right from a line perpendicular to the contour of the initial position. This makes a total rockfall spread angle of 60 degrees, whereas the it was 40 degrees as obtainer by Sonohara, 45 degrees as obtained by Takamatsu, 70 degrees as obtained by Tsuriganwe, and 50 degrees as obtained by Gero.

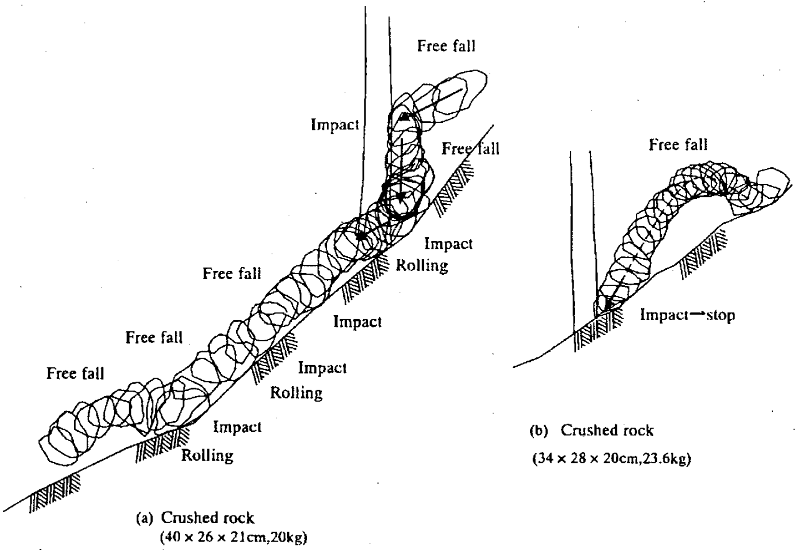


Figure 7 Collides with a tree

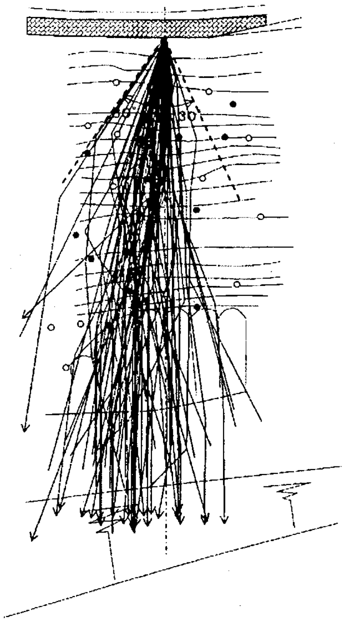
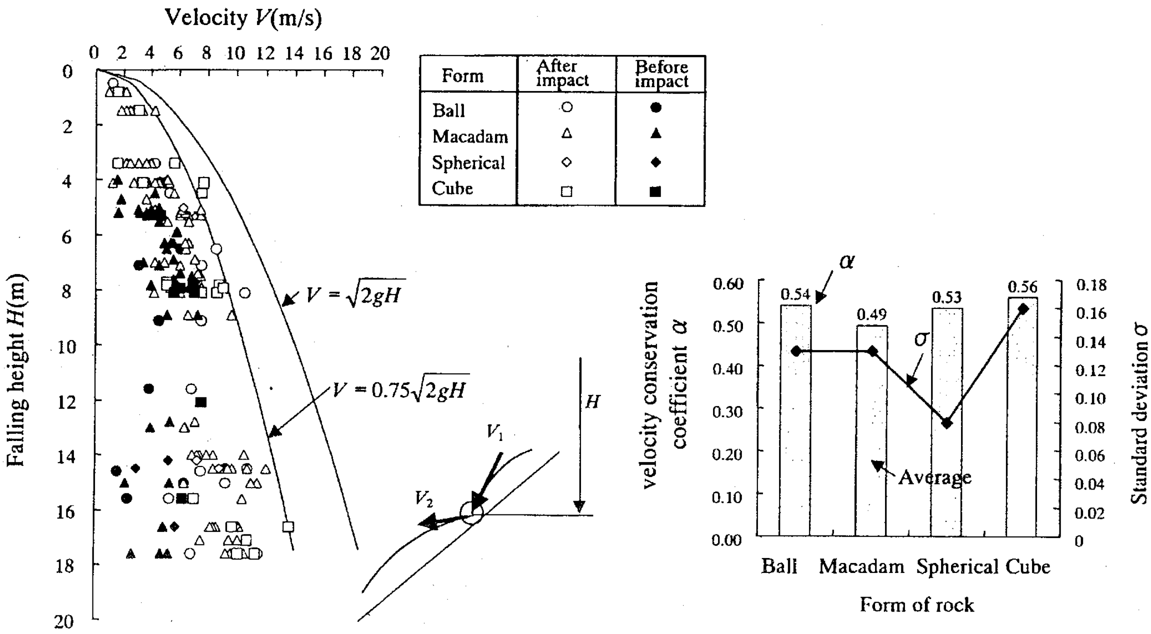


Figure 8 Fall course



(a)Relation between Falling height and velocity of rockfall

(b)Relation between Form of rock and velocity consetvation coefficient

Figure 9. Relation between height of fall and rockfall velocity

4. VELOCITY AND BOUNCE HEIGHT

4.1 Velocity

The distance moved by the test blocks was determined with the help of video images. As there were 30 images taken in one second, the falling velocity of the blocks could be computed. However, the fallingstone which separated greatly and exercised from the baseline excepted. Moreover, it askcd for the scale of the picture of a speed calculation position from the rockfall sizc and survey size of a picture. The center of gravity of a natural rock block was estimated by eye judgement.

Impact velocity and rebounding velocity wcre calculated by impact point of rockfall. The results are shown in Figure. 9 (a). Velocity conservation coefficient $\alpha \left(=V/\sqrt{2gH}\right)$ which includes the impact velocity in general is 0.75. Moreover, when An average and standard deviations of the velocity conservation coefficient are calculated for the shape of rock block, the minimum average value is obtained for crushed sand rocks and the maximum is, cube concrete blocks, as shown Figure 9(b).

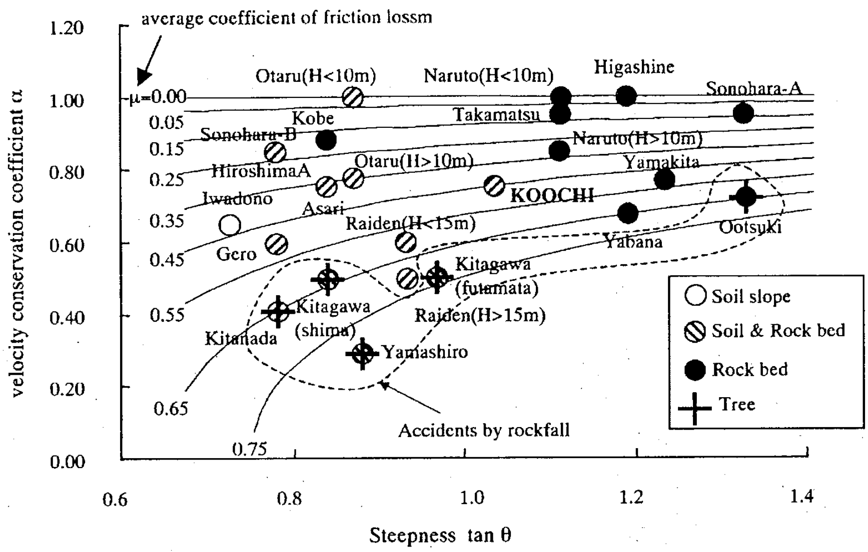


Figure 10. Velocity conservation coefficient

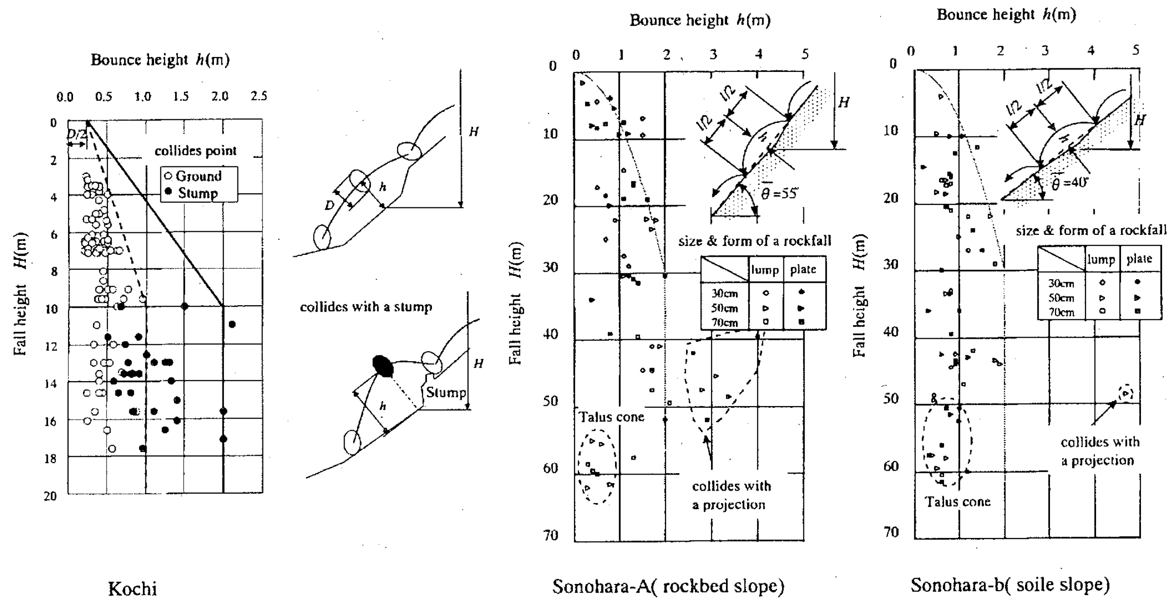


Figure 11. Bounce height

The relation between velocity conservation coefficient, α and average coefficient of friction lossμ is expressed as $\mu=(1-\alpha^2)\tan\theta$. Since the average angle of the slope is $\theta=46^\circ$, with a velocity conservation coefficient of 0.75, the average value for μ will be 0.45.

Figure 10 shows the relation between velocity conservation coefficient, average coefficient of friction loss, and average angle of the slope. The data used in the figure were obtained from experimental results and the accident caused by rockfalls. If average angle of the slope is small, velocity conservation coefficient will be small. Moreover, when there is a tree on the slope, the velocity conservation coefficient becomes smaller.

4.2 Bounce height

Figure 11 shows a relation between height of fall, H from initial point of rockfall and bounce height of a rockfall. Compared are the results of present study and those of Sonohara. The present study results showed that if a rock block does not hit a stump, bounce height is 1m or less, but if it hits a stump, a maximum of 2.1m bounce height was attained. This tendency is similar to that by Sonohara who reported that if there are no any projections, the bounce height does not exceed 2m even with a large falling height.

5. SIMPLE MATHEMATICAL METHOD TO PREDICT VELOCITY AND BOUNCE HEIGHT

5.1 Velocity

When a rock block falls off a slope of inclination θ, the energy balance equation for[an angle of inclination] the slope of θ, conservation of total mechanical it's motion is as shown in equation ①,where m is mass of the block, of is acceleration to gravity, H is height of fall, E_V is energy to velocity, E_R is energy due to rotation, and E_L is energy lost.

$$E_V + E_R + E_L = mgH \qquad (1)$$

Whenever a rock block collides with the slope, there is loss of energy. For this reason, the velocity becomes a irregular function of the height of fall. However, the equation (1) can be changed to equation ② if it is assumed that the energy loss is proportional the mass of falling block and the total distance of fall $H/\sin\theta$. The rotation at energy is expressed as a function of mass and velocity with a coefficient β.

$$\frac{1}{2}mV^2(1+\beta) + \frac{mC}{\sin\theta}H = mgH \qquad (2)$$

Thus, the rockfall velocity can be expressed from equation (2) as,

$$\left.\begin{array}{l} V = \alpha\sqrt{2gH} \\ \alpha = \sqrt{\dfrac{1}{1+\beta}\left(1 - \dfrac{C}{g\sin\theta}\right)} \end{array}\right\} \qquad (3)$$

Here, α is velocity conservation coefficient, C is slope constant (m/s^2) decided by the geology of a slope and existence of a tree, and θ is the mean angle of inclination of the slope. The velocity conservation coefficient, α as calculated from equation (3) is shown in Figure 12, together with the values obtained by others. It is often referred that the value of the rotational energy coefficient β is equal to 0.1. If the slope constant, C is set as per Table-1, the velocity of a rockfall can be predicted employing the formula (3). The velocity conservation coefficient tends to decrease with the increase in fall height H. Moreover, if the incidence angle with which a rock block collides with the slope is small, the rock block will decelerate significantly. Formula (3) can not take into account these effects, however. In order to increase the prediction accuracy, Carry out simulation analysis using a model taking into account the effect of resource on the velocity.

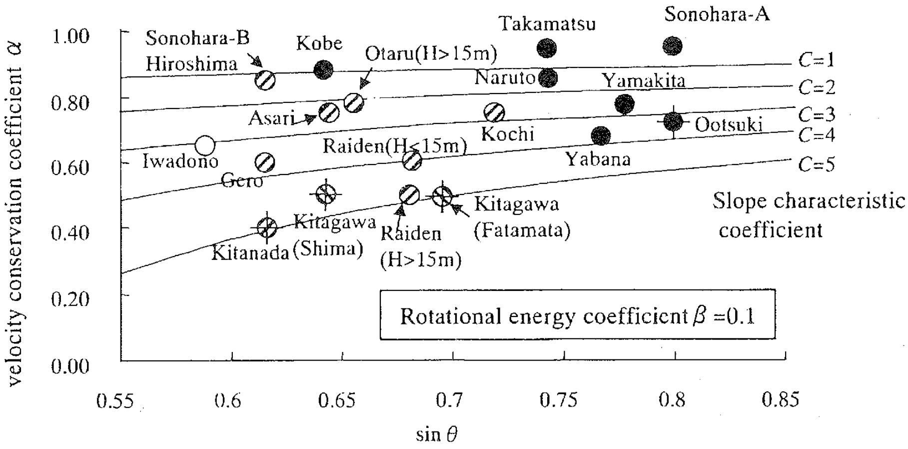


Figure 13. Velocity conservation coefficient

Table-1 Slope characteristic coefficient used for calculation of rockfall velocity

The kind of slope	trees on the slope	Slope characteristic coefficient C
rock bed	no standing tree	1
	Standing trees	3
Topsoil thin and base rock exposed in some places.	no standing tree	2
	Standing trees	3
soil	no standing tree	3
	Standing trees	4

5.2 Bounce height

Previous experimental result showed that, if the fall height of rockfall is high, the maximum bounce height becomes 2m. Although, the dynamic mechanism is not yet clear, an analytical formula based on the experience proves to be accurate, which is given in equation (4).

$$h = \frac{V_{rn}^{\ 2}}{2g\cos\theta} + r \qquad (4)$$

Where γ is equivalent radius of the rock block, θ is slope inclination angle, are V_{rn} is vertical component of the velocity, V_i with angle of incidence λ_i. Supposing the relation with the vertical component V_{in} of vertical velocity ratio R_n and incidence velocity is expressed with the hyperbola function of a formula (5), a formula (4) will turn into a formula (6) (Ushiro, 2000a).

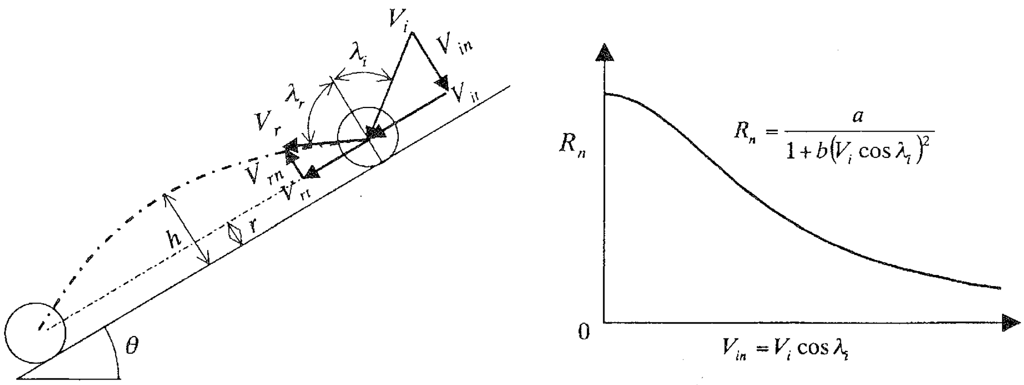


Figure 13. Notations

$$R_n = \frac{a}{1+bV_{in}^2} = \frac{a}{1+b(V_i \cos\lambda_i)^2} \tag{5}$$

There a and b are the hyperbolic constants and arc parameters decided by the geology of the slope.

$$h = \frac{1}{2g\cos\theta}\left[\frac{aV_i\cos\lambda_i}{1+b(V_i\cos\lambda_i)^2}\right]^2 + r \tag{6}$$

The value of λ_i is in the range of $\theta \leq \lambda_i \leq 90^{\circ}$.Observations have shown that the value of h calculated by above formula is accurate.

Figure14 shows bounce heights for a block with equivalent radius, r=0.5m and different slope characteristics based on the calculations by a= 1.0 and b= 0.014. Bounce height increases with the increase in the velocity of rockfall, and if the velocity crosses a limit, the bounce height will converge near 2m. Moreover, the validity of the analytical formula can be assured by showing greater bounce heights on sleeper slopes.

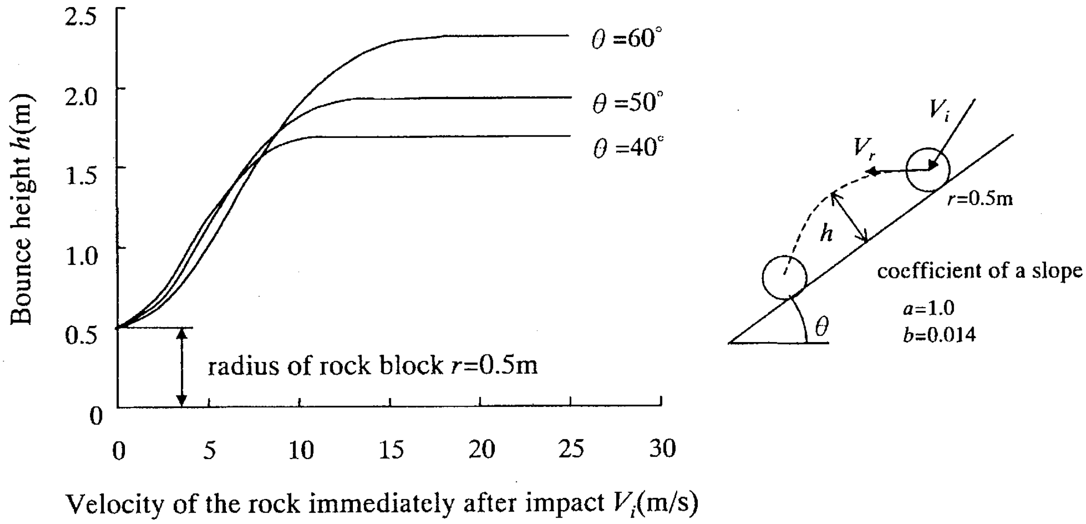


Figure 14. Bounce height as per the calculation

6. CONCLUSIONS

The conclusions of this study are:

i) The initial motion of a rockfall is rolling, and angular velocity changes by 7-8 rad/sec during a freefall.
ii) When bounce height is small, distinction between rolling and freefall is difficult. In case a freefall, the falling block rotates in 3-D.
iii) When a rock block slides or hits the surface, loss of kinetic energy is high, especially when the angle of incidence velocity is less..
iv) If a rock block hits a tree on the fall course, it will be stopped, but if the angle of hit is small, there will be less absorption of the kinetic energy by the tree and the rock block will continue its motion.
v) The direction of movement of a rockfall is influenced by the geographical feature of the first slope point that is hit by the rock block in addition.
vi) When roughness of the slope is less, the bounce height of a rockfall is 2m or less. However, bounce height increases when the rock block hits a projection such as tree,

stump or bed rock on a steep slope.

vii) The velocity of a rockfall can be predicted by using a formula proposed by the authors, which employ velocity convention coefficient α, which can be calculated once the mean angle of inclination of slope θ, slope constant C and rotational energy coefficient β are known.

viii)Similarly the bounce height can be predicted by taking into account the rebounding coefficient which depends on the vertical comportment of the velocity of the fall rock at the time of collision. The results obtained from the calculations showed good agreement will the precious experimental results.

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