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SIMULATION OF ROCKFALLS INDUCED BY EARTHQUAKES

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SUMMARY

A computer simulation method to reproduce the rockfall movement in rolling and bouncing modes has been proposed, and it is applied to actual rockfall events. The prediction of the rockfall movement after being triggered is appropriate by proposed method, despite of simplification of actual event. It is found that statistical simulation with a large number of calculations must be recomendable instead of a small number of calculations to predict endangered area of future rockfalls.

INTRODUCTION

Among earthquake hazards in mountainous areas, rockfalls are particularly dangerous because of their rapidity and lengthy distance of travel. Although the various mechanisms of failure have been studied, the post-failure mechanism has not been paid much attention. At present, therefore, the process of rockfall movement is not understood sufficiently. So as a first step to study the rockfall process, we tried to reproduce the rockfall movement using a computer simulation method. The method has been applied to actual rockfall events triggered by the Mammoth Lakes, California, earthquake sequence in 1980 and the Central Idaho earthquake in 1983. We have made a series of simulations for the field data: measured slope topography, roughly evaluated shape and density of rockfall masses, and compared the results with field evidences: travel distance from failure point to stop point, location of bounce marks stamped by rockfalling, and also interpretated the relation of the simulation results to actual events.

SIMULATION METHOD

Although the movement of rockfall mass down slope is a complicated process with many unknowns, the basic mechanics of bouncing, collision, and frictional rolling are well understood. At the present stage following approximations are introduced into our calculation to facilitate the simulation:

1) Boulder, rockfall mass, is considered as a sphere, disk,or cylinder.
2) Boulder is restricted to move within a vertical plane.
3) Slope is defined as a composite of connecting straight survey line.

Fig. 1 shows the flow chart of our computer simulation program(Ref. 1). Our program permits two calculating modes; one is bouncing mode and another is rolling mode. In the bouncing mode a parabolic trajectory of falling boulder is calculated. In the rolling mode a frictional rolling action of boulder along the slope is calculated. In the bouncing mode, collision of the boulder with the slope surface, and the perpendicular velocity after collision are calculated. If the velocity is smaller than a threshold velocity, the calculating mode transfers to rolling mode. Likewise in the rolling mode, when the boulder encounters slope convexity or hits concavity with a sufficiently large velocity, the boulder is launched into air and the calculating mode transfers to bouncing mode.

In our program, the frictional and viscous resistances, f and k, during rolling, the efficiency of collision, e, and the maximum possible ratio of parallel to perpendicular reactions on collision, μ, can be incorporated. In the present study, however, we assumed the coefficient of viscous resistance to be 0 and searched for an appropriate combination of coefficients, f, e, and μ, by trial and error to fit the computed results to the measured actual boulder movements, especially the attained distance, reach.

Measured data of slope was unrealistically smooth, because in the measurements we ignored undulations less than about 50 cm. In order to reproduce the uneveness of the slopes, we added randomness with maximum amplitude of 50 cm onto the slope shape between two measured points. Changing the random number series, we have made 300 simulations. Then we statistically have evaluated the simulation results.

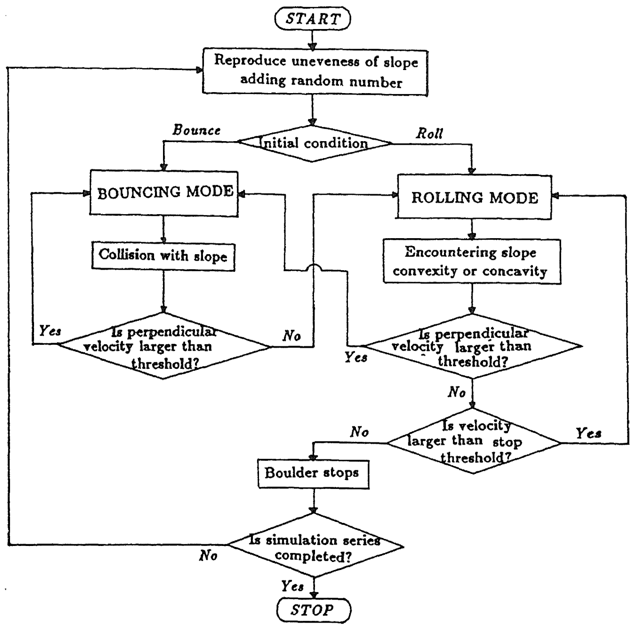

Fig. 1 Flow chart of the program.

FIELD DATA

Site1 – **McGee Creek, Mammoth Lakes (Ref. 2)**

The location of this site is near the McGee Creek Pack Station, about 12 km southeast of Mammoth Lakes, California. During the earthquakes and aftershocks, numerous boulders were dislodged from slopes north of the station. The most spectacular case was caused by a disk-shaped slate boulder that was dislogged from steep cliffs approximately 180 m above the pack station at a slope distance of about 350m. The boulder is 3.3 m in maximum diameter and 0.88 m thick. The boulder moved on its edge about an axis perpendicular to the disk faces.

The total horizontal travel distance of the boulder was 420.6m. Assuming the boulder underwent free fall from its position in the outcrop, it attained an initial velocity of about 12.5m/s at its first impact with the talus slope. The boulder's weight, assuming a specific weight of 2.5 tons/m^3 and based on its final dimensions, is 21.4 tons.

Site2 – McGee Creek, Mammoth Lakes (Ref. 2)

This site includes the movement path of a boulder about 60 m east of that of site 1. In this case, a spheroidal granite boulder derived from the moraine bounced down the slope toward McGee Creek Pack Station knocking down a corral fence and coming to rest near the center of the corral. We assumed that this boulder, with a weight of about 10.5 tons, came from an elevation of about 65 m above the valley bottom.

Site3 – Devil Canyon, Idaho

The Central Idaho earthquake of October 28, 1983, caused numerous rockfalls in which there were a few examples of individual boulders whose paths of movement could be traced. One such boulder path was traced at Devil Canyon, about 8 km north of the epicenter of the earthquake. The boulder is volcanic conglomerate measuring $1.45\times1.37\times1.09m^3$. The weight of the boulder is calculated at 2.9 tons. During its movement down the slope, the boulder remained intact except for its first impact, initial velocity of 7.5 m/s, after becoming dislodged from its outcrop position. At the first impact point, a few small pieces of the boulder were found embedded in the soil. Here, the boulder had been shaken from the outcrop and fallen 2.9 m onto a slope covered with scattered sagebrush, grass, and a few other boulders.

Site4 – Challis, Idaho

At the northern edge of the town Challis, Idaho, numerous houses sustained damage from fallen boulders triggered by the October 28, 1983 earthquake. The houses here are built at the foot of 80 to 100 m high slopes of rhyolite and volcanic sedimentary rocks. The rock outcrops at the tops of the slopes are highly fractured with open spaces between the fracture surfaces. Many large boulders are perched on top of other boulders. Below the outcrops, which rise above the slopes as much as 5 m, there are smooth talus slopes of about 18° in the average inclination.

The rock that produced the bounce marks at this site is a rhyolite boulder of dimensions, $3.33\times2.54\times2.49m^3$. The boulder's weight was calculated at 20.5 tons and was approximated as a sphere of 1.25 m radius. Its movement for about 50 m after being dislodged was by rolling. Near the bottom of the talus slope, the boulder began bouncing destroying a fence and a garbage can at the foot of the talus slope near a newly constructed house. About 30 m beyond, the boulder collided with the down stream abutment of a small bridge where it crushed part of the bridge decking and cracked the abutment. Approximately 15 m beyond the bridge, the boulder began rolling through the yard of another house. As it came to a stop at the edge of the house's front porch, it crushed part of the porch edge.

COMPUTATION AND RESULTS

Table 1 Data for simulations.

site	R(m)	M(t)	I(tm²)	f	μ	E_1	E_2	E_3	Δh(m)	$\dot{y}_0/\dot{\theta}_0$	reach	bounce sect. (m)
1	1.65	21.4	29.1	0.64	0.64	0.80	0.80	0.70	0.5	12.5 m/s	420.6	173 - 286
2	1.00	10.5	4.2	0.38	0.38	0.87	0.87	0.70	0.4	0.52 rad/s	242.8	87 - 216
3	0.65	2.9	0.49	0.53	0.48	0.75	0.68	0.60	0.2	7.5 m/s	280.0	25 - 228
4	1.25	20.5	12.5	0.33	0.33	0.80	0.80	0.70	0.4	0.52 rad/s	121.0	0 - 112

R: radius, M: mass, I: moment of inertia, f: coefficient of frictional resistance to rolling, μ: maximum ratio of parallel to perpendicular reactions on collision, $E_{1,2,3}$: efficiency of collision (see text for definition), Δh: maximum amplitude of random number, $\dot{y}_0$ and $\dot{\theta}_0$: initial value for velocity in m/s and angular velocity in rad./s, respectively, reach: measured attained distance of boulder, bounce sect. : section where bouncing mode predominated.

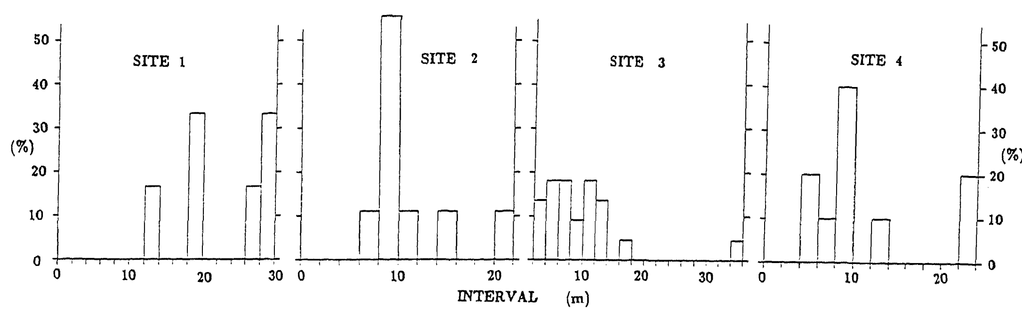

Fig. 2 Histograms of measured intervals between bounce points.

We applied our simulation method to actual rockfall events. The coefficients used in calculation are shown in Table 1. Efficiency of collision, *e*, was defined in three sections of slopes. These value were determined through a series of trial and error. As a criterion of fitting of the computed results to the observed ones we employed the reaches, distances attained, and intervals between bounce marks. Measured reaches are given in Table 1 and histograms of measured intervals are given in Fig. 2. As an example of trajectory of fallen boulder, a case of site 3, which attained the reach most close to the measured one, is shown in Fig. 3. We made 300 times calculations changing the random number series added on measured slopes for each site. Fig. 4 and 5 are histograms of the reach and intervals for the specific case in Fig. 3. The intervals were taken from a section along the slope indicated in Table 1 where the bounce mode was predominant.

At a first glance the disagreement of Fig. 2 and Fig. 5 was great. The most conspicuous difference between both histograms are that the measured data do not include shorter intervals, while the computed ones do a high percentage of shorter intervals. A closer examination, however, reveals that there is a common distribution in the middle range of intervals in both histograms, i.e. if we ignored shorter intervals in the computed histogram, it would resemble the measured one. This suggests a possibility that shorter intervals, which may have existed in reality, were overlooked in site investigation. In that case the comparison between the computed and measured intervals should be made after excluding shorter intervals from computed results. Based on this postulate, we introduced a criterion that the computed intervals shorter than the minimum observed interval or $2\pi R$, R being radius of boulder, for each site are excluded from computed intervals, and compared the distributions of computed reaches and average intervals (circles) with the measured values (triangles) in Figs. 6, 7, 8, 9. There is a common tendency that the observed points (triangles) are located somewhat higher than the distributions of computed points. This is likely caused by that the average observed intervals should tend to be large if some of the bounce marks were overlooked. Considering this reservation, the agreement of measured and computed results is acceptable at sites 2, 3 and 4.

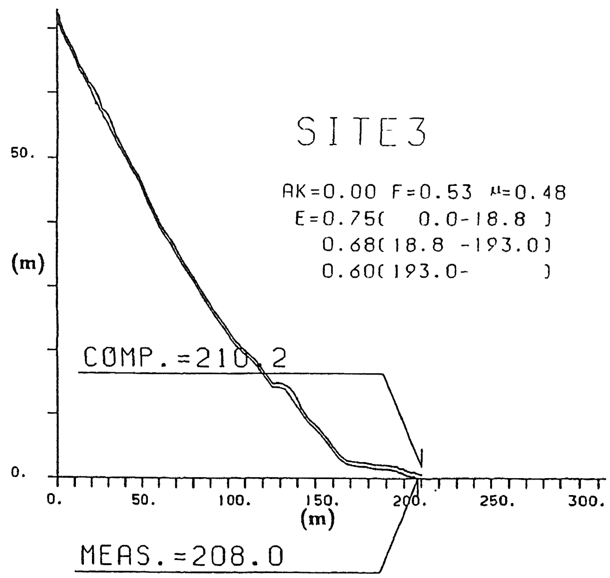

Fig. 3 Example of trajectory of boulder at site 3.

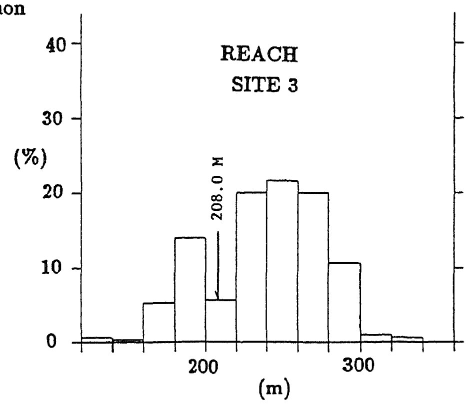

Fig. 4 Histogram of reaches of 300 simulations for site 3.

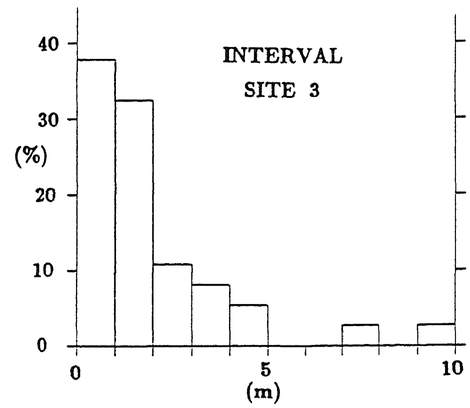

Fig. 5 Histogram of intervals of 300 simulation for site 3.

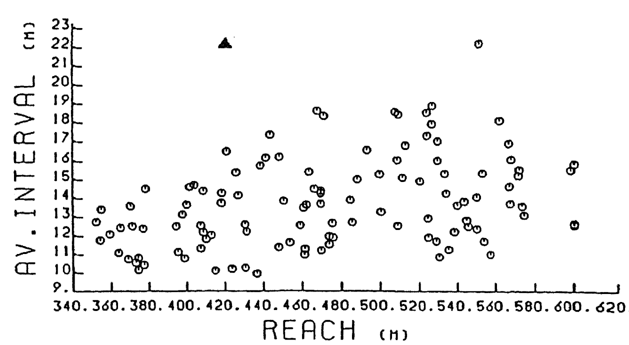

Fig. 6 Reaches and average intervals between bounce points of 300 simulations for site 1.

DISCUSSION

We discuss in this section about the agreement and disagreement between measured and computed results for the case of each site.

The agreement at site 1 is poorest. This may have been caused by that at site 1 the measured intervals were very large and observed mainly on the flat portion of the boulder path under the effect of repulsive force of trees hitted by the boulder which process could not be reproduced in the simulation.

In Fig. 8 for site 2, there is no computed point for reaches less than about 240 m (just about measured value). This is because, in simulations giving shorter reaches, the average intervals become smaller than 6 m, the smallest observed interval. But in the neighborhood of the observed data, there are some computed points with slightly larger reaches than the observed one, and the agreement between the simulated and observed result is not so poor considering the reservation cited above.

The agreement between the computed and observed results at site 3 is most satisfactory. The reason for the good agreement at this site may be that the topographic data of slope were most detailed, and as a consequence, the slope topography was most realistic causing bouncing mode to be predominant in simulations, and on the other *hand the least number of bounce marks were overlooked* at the site.

In Fig. 9 for site 4, a very small number of computed results are plotted, since in the simulations giving the reaches near the observed value, 121 m, most intervals were smaller than the smallest observed interval, 4 m (Fig. 2), so these points were not plotted. The length of the sampled topography was shortest at this site, and it was hard to reproduce realistic behavior of the boulder for such a short slope. In view of the limitation the computed distribution shown in Fig. 9 is not so apart from the observed one, and the simulation is acceptable.

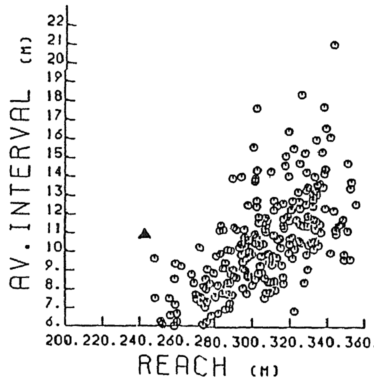

Fig. 7 Reaches and average intervals between bounce points of 300 simulations for site 2.

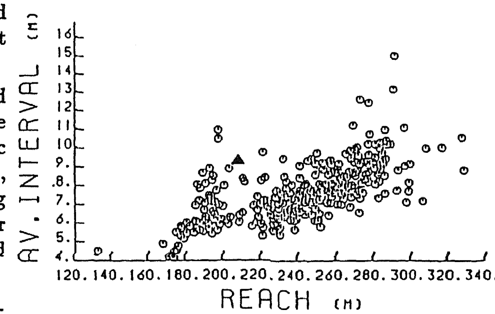

Fig. 8 Reaches and average intervals between bounce points of 300 simulations for site 3.

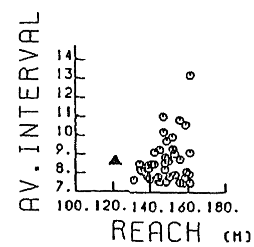

Fig. 9 Reaches and average intervals between bounce points of 300 simulations for site 4.

CONCLUSIONS

Through this study, the following conclusions for analysing rockfall events are obtained.

1) The simulations gave appropriate results, despite of simplification of actual rockfall movement.
2) The quality of simulation result is sensitive to the quality of measured topography data. The more detailed topography data is measured, the more appropriate result can be obtained. Similarly, more detailed boulder paths must be collected to evaluate the accuracy of the simulation results.
3) From our statistical study, we found that the simulation results of reach and interval distribute over very wide ranges. To predict the future rockfall reach and interval, therefore, it is very dangerous to define endangered area from only a small number of calculations. Statistical simulations must are recommendable.
4) The physical meaning of constants f, k, e, and μ in actual events still remains unclear. Further study about this is needed for the practical use of this method.

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The essential part of the program was prepared on VAX-11/780 at U.S.Geological Survey, Menlo Park, and most of the computations have been conducted on FACOM M-382 at the data processing center of Kyoto University.

REFERENCES

1. Kobayashi, Y., Harp, E.L. and Kagawa, T., Simulation of Rockfalls Triggered by Earthquakes, Rock Mechanics and Rock Engineering,(In preparation).
2. Harp, E.L. , Tanaka, K., Sarmiento, J. and Keefer, D.K. , The May 25-27, 1980 Mammoth Lakes, California earthquake sequence - earthquake-induced landslides, U.S.G.S. Map I-1612, (1984).