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Calibration of rock fall modeling parameters

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ABSTRACT

Rock falls can be a hazard for many facilities in mountainous terrain, particularly in areas with high rainfall and freezing temperatures, and where seismic events occur. Design of protection measures against rock falls, such as fences, barriers and sheds requires information on impact energy to determine the strength of the structure, and on trajectories to determine its location and size. This paper presents documentation on rock falls at five locations, in North America and Japan, involving impacts on rock, talus, colluvium, asphalt and concrete, for which values of the normal and tangential coefficients of restitution have been calculated. The field results show that the normal coefficient of restitution is related to the impact angle with coefficients of about 0.2 for normal impacts and values as great as 2.5 for shallow impacts. These values for the normal coefficient of restitution are essentially independent of the slope material. The tangential coefficient of restitution ranges between 0.3 and 0.8 and is related to the friction coefficient at the impact point, and is independent of the velocity and normal force. It is also shown that the calculated field values for the coefficients of restitution are consistent with the principles of impact mechanics.

1. Introduction

In mountainous terrain, infrastructure such as highways, railways and power generation facilities are often subject to rock fall hazards that can result in economic losses due to service interruptions and equipment damage, as well as injury to users and operators of these facilities. As an illustration of these hazards, Fig. 1 shows a car that struck a falling rock that passed through the windshield. Rock fall hazards are particularly severe in areas with heavy precipitation, frequent freeze/thaw cycles and seismic events [1–3], and the risk can be significant where the population density is high. These climatic conditions exist, for example, in the Alps and the west coast of North America. In contrast, climatic conditions in Hong Kong are not as severe as those in more northerly latitudes but rock fall risk can be severe because of the high population density [4].

Since the 1980s, a variety of rock fall protection measures have been developed that are now widely used and have significantly improved safety. These protection measures include ditches that can be designed to reasonably well defined criteria [5,6], and can be more effective if they incorporate barriers such as gabions or MSE walls constructed from locally available materials. In addition, a number of proprietary fence systems have been developed that use various configurations of high strength steel cables and wires. In some high hazard locations it may be appropriate to construct reinforced concrete rock sheds that incorporate energy absorbing features such as flexible hinge elements and a cushioning sand or Styrofoam layer on the roof [7,8].

Design of protection measures requires data for two basic parameters of the rock falls – impact energy and trajectory. That is, information is required on the mass and velocity of the fall to determine the energy capacity, and on the location of impact points and trajectory paths to determine the optimum location and dimensions of the barrier or fence.

Many modeling programs are available to simulate rock fall behavior, and these are widely used to design protection measures [9–12]. The reliability of modeling programs depends on a thorough understanding of impact mechanics and trajectory analysis, and having available precise data on actual rock falls to calibrate the models. The objective of this paper is to provide carefully documented data on actual rock events that can be used to calibrate modeling programs. In addition, the paper discusses the application of impact mechanics theory to the behavior of rock falls, and proposes relationships for tangential and normal velocity changes during the impact process.

2. Documentation of rock fall events

Data on rock fall events are available from both natural events where it has been possible to precisely map impact points and trajectories, and from carefully documented, full-scale rock

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Fig. 1. Moving vehicle struck rock fall that passed through the windshield.

Fig. 2. Mt. Stephen – barrier constructed with concrete blocks and steel mesh fence to contain rock falls and snow avalanches.

fall tests. These data have been collected for a variety of slope geometries and fall heights, and for slope materials comprising rock, colluvium, talus and asphalt. This section describes five events covering a range of situations that are intended to encompass many of the commonly occurring rock fall conditions. For each event, the site topography, geology and rock fall conditions are described, and values for velocity components are provided for typical impact conditions [13].

In calculating trajectories at sites where information on precise impact points and flight paths is not available, it is necessary to select the two end points for each trajectory and to make an assumption for the angle at which the rock leaves the slope surface. These data have been obtained from experience gained at other, fully documented rock fall sites and from only using trajectories that are realistic and mathematically feasible.

The insets in Figs. 3–7 show details of the normal and tangential velocity components at selected impact points, and the calculated coefficients of restitution that are defined as follows:

Normal coefficient of restitution,

$$e_N = -\frac{\text{final normal velocity, } v_{fN}}{\text{impact normal velocity, } v_{iN}} \quad (1a)$$

Tangential coefficient of restitution,

$$e_T = \frac{\text{final tangential velocity, } v_{fT}}{\text{impact tangential velocity, } v_{iT}} \quad (1b)$$

On the insets, the length and orientation of the arrow is proportional to the velocity vector, where the subscript "*i*" refers to values at the point of impact (time, $t = i$), and the subscript "*f*" refers to values at the end of the impact process (time, $t = f$). Further discussion on the definition of the coefficient of restitution is contained in Section 3.3. In all cases the rocks are also spinning with rotational velocity $(-\omega)$ radian s^{-1}, where clockwise rotation is negative.

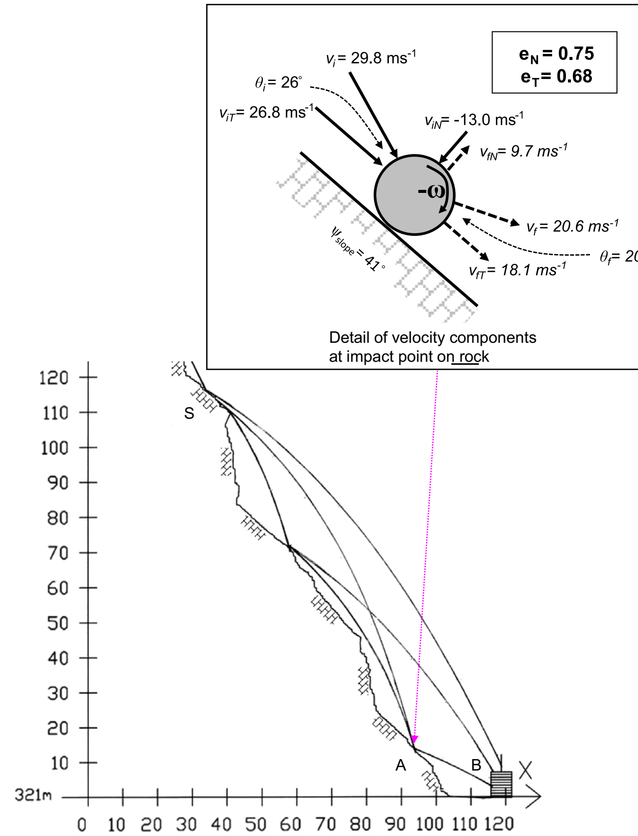

Fig. 3. Mt. Stephen – cross section of lower part of slope showing rock fall barrier and typical rock fall trajectories.

2.1. Impacts on rock slopes

Data have been analyzed for falls at locations in Canada, the United States and Japan, for slopes ranging in height from 2000 m to 15 m. The following is a discussion on falls at three of these locations where the falls impacted bare rock slopes.

2.1.1. Rock fall barrier, Mt. Stephen, Canada

Mt. Stephen in the Canadian Rocky Mountains is a source of rock falls and snow avalanches that originate on a rock face nearly 2000 m high at an overall slope angle of about 50°. The geology is a strong, massive, horizontally bedded limestone containing thin but widely spaced shale beds; the shale weathers more rapidly than the limestone resulting in the formation of overhangs and falls of the stronger rock. As shown in Fig. 2, it has been necessary to construct a barrier to protect a railway operating at the base of the slope.

The barrier comprises a double sided MSE wall built with precast concrete blocks (dimensions 1.5 m long, 0.75 m in section), supported with Geogrid and gravel fill between the walls, and a steel cable fence along the top of the wall. The total height of the structure is 11.6 m. Fig. 3 shows a typical section of the lower 120 m of the slope that was generated from an aerial Lidar survey of the site. Fig. 3 also shows a range of feasible trajectories of rock