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Theoretical study of rockfall impacts based on logistic curves

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ABSTRACT

The normal velocity curve of a falling boulder with time is fitted by a logistic curve. Without considering the rotational velocity, a logistic equation is used to fit the normal velocity curve and to derive a formula based on the momentum theorem for the normal impact force and penetration depth. Then the tangential force and the tangential coefficient of restitution (COR) are calculated based on the friction theory. The results of the proposed method indicate that the normal COR increases and the tangential COR decreases with the increasing of the stiffness of the ground material. When the total impact velocity is a constant, the incident angle has a great influence on the tangential COR, whereas the normal COR is mainly controlled by the properties of the ground material. The results also indicate that the maximum impact force suggested in this paper is comparable with that by the ASTRA in Switzerland and Japan Road Association (JRA). The penetration depth calculated using the proposed method is close to the result of the test and BIMPAM, while it is far less than that predicted by ASTRA or Pichler et al. (2005). The proposed method has the advantage of allowing systematic and theoretical calculation of the coefficient of restitution, the impact force and the penetration depth from any incident angle. The result will be more accurate if the rotational velocity is considered.

1. Introduction

Impact problems have drawn the attention of researchers in astrophysics, robotics, engineering geology and other disciplines who are interested in developing a theory to accurately predict impact behavior. Impact assessment includes four main theories: classical mechanics based on the impulse-momentum theorem,[1] elastic stress wave propagation,[2] contact mechanics[3] and large plastic strain theory.[4] These theories are applicable to various impact characteristics (velocity and material properties), assumptions and conclusions. With the recent development of numerical techniques, numerical simulations have increasingly been used, in addition to field tests,[5] to study the impact of rockfalls.[6] An excellent detailed critical review of rockfall characterization and analysis method can be found from a paper by Volkwein.[7]

Two parameters, the coefficient of restitution (COR) or rebound velocity and the maximum impact force, primarily determine the rockfall trajectory and the degree of damage, respectively. The COR, which is related to the physical and mechanical properties of the falling boulder and the ground material and to the incidence velocity, is an important parameter that reflects the dissipated energy during impact.

A number of rockfall models represent the rebound in a simplified way using one or two overall coefficients, which are called the COR. The COR is a function of the amount of boulder energy lost during the impact process. A few models use only one restitution coefficient, quantifying the dissipation in terms of either velocity loss[8] or kinetic energy loss.[9] An assumption regarding the rebound direction is necessary to fully determine the velocity vector after impact. The most common definition of block rebound involves its differentiation into tangential and normal CORs.[10,11] These coefficients are used conjointly and characterize the decreases in the tangential and the normal components of the falling block velocity, respectively. Thornton and Ning[12] derived formulae for the normal COR based on the Hertz[3] contact theory and the assumption that the materials have ideal elasto-plastic properties. Johnson[13] used the same assumption and proposed a model for the normal and tangential impact coefficients of restitution that was based on the Hertz[3] contact mechanics and tangential contact theory. An alternative approach is based on an impulse theory,[1,14] which involves the change in the momentum of the block during the compression and restitution phases of impact.[15] Several models have been developed to account for the dependence of the block velocity after rebound on the kinematic conditions before impact.[16,17] These models can be considered extensions of classical models based on constant restitution coefficients. In addition, very

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Table 1
Recommended values of the normal and tangential COR from various studies.

Sources	e_n	e_t
Wu (1985)[11]	0.20–0.80	0.60–0.90
Chau (2002)[16]	0.35–0.60	0.60–0.90
Agliardi (2003)[21]	0.25–0.65	0.60–0.85
Joachim (2003)[22]	0.30–0.53	0.70–0.99
Asteriou (2012)[19]	0.53–0.91	> 0.68
Chiessi (2010)[23]	0.35–0.60	0.60–0.85
Tang (2003)[24]	0.28–0.42	0.78–0.92

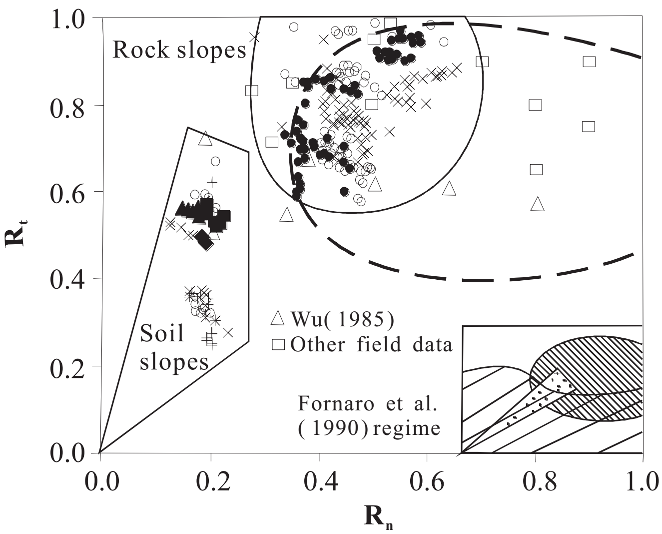

Fig. 1. The e_t–e_n space plotted by the rockfall data.[16]

detailed models have been developed for the interaction between a block and a slope with perfectly plastic or elasto-plastic behavior.[19] Only a few models account for the rotational velocity along the block path.[17-19] Many researchers have investigated the influence of the impact angle, which is complementary to the incident angle, on COR in rockfall impact mechanics. Wu[11] stated that increasing the angle of the impact surface causes the normal COR to increase independently of the mass and the tangential COR to decrease slightly. Asteriou et al.[19] found that the normal COR increased as the impact angle decreased, whereas the tangential COR was not affected until the impact angle was as large as 60°. Cagnoli et al. [20] observed that the normal COR decreased and the tangential COR increased when the impact angle increased. However, there is presently no theoretical formula or criterion that clearly provides ranges for the normal COR, e_n, and the tangential COR, e_t. The range of COR recommended in several studies is shown in Table 1 and Fig. 1. Generally, the COR is similar to the upper value when the surface consists of exposed bedrock and approaches the lower value when the surface consists of loose soil or clay.

In theory, the normal and tangential CORs both should not be more than 1.0 when a spherical boulder impacts on a smooth ground surface. However, in the field and lab tests, the normal or tangential COR can be larger than 1.0. The rough ground surface or angular boulder would change the rebound angle and thereby alter the normal and tangential rebound velocities. In terms of the conservation of energy, the ratio of rebound velocity to incident velocity is never greater than 1.0 without considering the rotational velocity. Then according to the characteristics of CORs, the rebound velocity could be distributed in three zones as shown in Fig. 2. In zone 1, the normal and tangential rebound velocities are both less than the incidence velocities. In zone 2, the normal

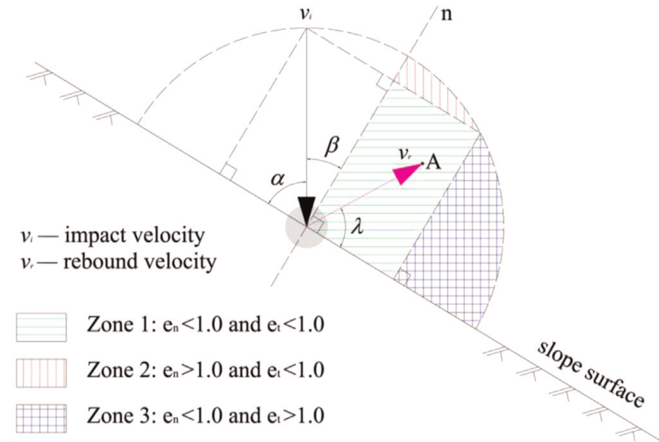

Fig. 2. Sketch of the COR distribution zone.

rebound velocity is larger than the normal incidence velocity, whereas the tangential rebound velocity is less than the tangential incidence velocity. In zone 3, the normal rebound velocity is less than the normal incidence velocity, whereas the tangential rebound velocity is larger than the tangential incidence velocity. Furthermore, the CORs are larger than 1.0 when the incident angles are larger than 70° according to Asteriou's test.[19] Larger incident angles are related to lower impact forces, and the rebound process is easy to alter when the impact force is small, it was certified by Heidenreich.[17]

Rockfall protection is an another important subject of study in rockfall impacts, and the impact force is the key parameter in designing protection structures. Investigations are essential for collecting data regarding the action of rocks on protection structures and then calibrating the numerical codes. Several half-scale and full-scale experimental studies have been conducted to determine the damping abilities of the cushion covering rockfall protection galleries (often called rock sheds) for design purposes.[25–28] Other testing programs were performed on gravel layers,[29] embankments[30] and composite structures.[27] Normally, gravel or other granular soil from the surroundings is used as the cushion layer. The main function of the cushion layer is to act as a shock absorber,[31] which distributes the contact stresses, reduces the accelerations of the boulder and increases the impact time. Designing the thickness of the cushion layer needed to eliminate the damage from a rockfall is a considerable problem, and the impact force needs to be determined. Based on impact tests, Schellenberg et al.[28] determined the reaction forces at the supports, the accelerations of the boulder and in the slab and the strains in the upper slab surface and in the bending reinforcement. In practice, the rockfall impact force usually is estimated using only empirical relationships based on experimental observations. Several semi-empirical or partly theoretical methods have been developed to determine the maximum impact force based on measurements of the rockfall impact force in field tests, such as the algorithms of the Japan Road Association (JRA)[32] and the recommendations by ASTRA in Switzerland,[33] and the Specifications for Design of Highway Subgrades (JTJ013-95) in China.[34]

ASTRA expressed the maximum force formula as follows:

$$f_{\max} = 2.8H^{-0.5}R^{0.7}{M_E}^{0.4}\ \tan\ \varphi(\frac{mV^2}{2})^{0.6} \tag{1}$$

where $f_{\max}$ is the maximum impact load (kN), H is the thickness of cushion layer (m), M_E is soil modulus obtained from a standardised plate bearing test on the soil cushion (kPa), φ is the internal friction angle of the cover layer (°), V is the impact velocity (m/s), and S is the penetration depth (m). The other parameters are as above.