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# Numerical approaches for rockfall analysis: a comparison

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**Abstract:** An important issue in the evaluation of potential hazard related to rockfalls is the quantitative prediction of the traveling distance of the falling blocks, which is necessary to identify the potentially endangered area. This information is also fundamental for the design of appropriate defensive works, which are intended to reduce the potential impact of the landslide on the population and facilities potentially at risk. The design of this type of protective measures typically requires, above all, the quantitative prediction of the final travel distance of the rock masses. Obtaining a reliable estimate of this quantity is complicated by the interaction of the rocks and the slope surface that can affect the behavior of the blocks at the impacts. Recently, several numerical techniques have been developed and applied to this purpose, based on the solution of the Newton's equations of motion for each block. The aim of this work is to compare the performance of two such approaches, namely the Colorado Rockfall Simulation Program (CRSP), and the Discrete Element Method (DEM). the CRSP method can describe the falling motion of blocks of cylindrical, spherical or discoidal shape, which translate and rotate in the vertical plane of motion. The motion of the block is determined by means of the parabolic equation of free-fall motion and the balance of total energy equation. The impact with the slope surface is modeled taking into account the block shape and size and the slope roughness. Upon impact with the slope surface, the normal and tangential components of the block velocity are reduced by means of suitable coefficients of restitution, $K_n$ and $K_t$, in the normal and tangential directions, respectively, to take into account the dissipation of energy due to inelastic deformations. The model is capable of considering the combination of free-fall, rebound, rolling and sliding motion that can occur for different slope roughness and block size. An alternative to the CRSP method, which appears particularly promising for its versatility, is represented by the DEM. In the DEM, the motion of the falling block under the action of gravity is computed by numerically solving Newton's equation of motion. In this work, the DEM code UDEC (Itasca, 1991) has been used to simulate the falling block and to model its fragmentation during rhe fall. In UDEC, each distinct element is a prismatic block that can be considered perfectly rigid or deformable. Each block in the model is subject to body forces (gravity) and contact forces exchanged at the contacts with other blocks or with rigid “walls”. These two approaches have been used to simulate a real case study occurred in a rock slope located in central Italy where several rockfall events occurred and were recorded by in-situ surveys from the local administration. The results of the study indicate that when an appropriate calibration of the physical parameters is carried out the different approaches can correctly reproduce the observed phenomena. The performance of the different approaches to rockfall simulation – the CRSP method and the Discrete Element Method, in the particular implementation of the UDEC code – with reference to observations from a real rock slope lead to two main conclusions. As far as the falling of a single block is concerned, both methods give comparable results that are in line with the available observations. However, while in the CRSP method a single set of restitution coefficients is sufficient to characterize the block behavior upon impact, the local damping coefficient introduced in UDEC to model the energy dissipation upon impact must be varied with block size, in order to model correctly the effect of block size on the observed traveling distance. On the other hand, a unique advantage of the DEM approach as compared to other methods derived from the lumped mass approach is the possibility of modeling the effects of rock fragmentation. The results of the simulations indicate that the position and the extension of the accumulation zone can be strongly affected by block fragmentation; in particular the traveling distance tends to decrease progressively with block fragmentation. Therefore, this particular aspect should be taken into proper consideration in the rockfall hazard evaluation whenever the possibility of block fragmentation is of concern.

***Keywords:*** *Hazard, Rockfall, Discrete Element Method (DEM).*

## 1. INTRODUCTION

Active rockfall hazard mitigation measures include both the design and implementation of suitable stabilization methods intended to reduce the likelihood of triggering, or the installation of defensive works aimed at reducing the potential impact of blocks on the population and facilities potentially at risk.

Protective measures against rockfall hazards are placed along the potential path of the blocks or close to infrastructures potentially at risk. The design of this type of protective measures typically requires, above all, the quantitative prediction of the final travel distance of the rock masses. Obtaining a reliable estimate of this quantity is complicated by the interaction of the rocks and the slope surface that can affect the behavior of the blocks at the impacts. However, recent progress in the field of numerical methods provides an opportunity to develop rational design strategies for protection methods against such phenomena.

In this work, two numerical methods, namely CRSP (Colorado Rockfall Simulation Program) and DEM (Discrete Element Method) have been used to assess the travel distances of blocks triggered from a marginally stable rock slope near Postignano, in central Italy. The outline of the paper is as follows. In Sect. 2, the specific case-history which has motivated the present study - the Postignano rockfall - is presented. Sect. 3 provides a brief outline of the CRSP and DEM approaches. Sect. 4 is devoted to the details of the numerical simulations, along with a summary of the main results obtained. Some concluding remarks are given in Sect. 5.

## 2. MOTIVATION: THE POSTIGNANO CASE-HISTORY

The slope instability phenomenon, which has motivated the present study, concerns a natural rock slope in calcareous rock formations - locally known as Scaglia, near the town of Postignano, in the central Italian Apennines.

The rock slope, oriented approximately along the W-NW direction, has an average dip of about 28°. In this area, the rock mass is composed of regular stratifications of limestone, with intercalations of thin, weak clay layers. The bedding planes are oriented almost parallel to the quarry front, and have an average dip of about 38°.

Due to the orientation of the bedding planes with respect of the slope face and to the presence of the weak clay layers between the hard calcareous strata, the upper part of the slope is in marginal stability conditions. Rockfalls have been reported on several occasions, and several tension cracks running parallel to the quarry face have been observed on the upper part of the slope.

The study area can be subdivided into three different zones: (a) triggering zone, (b) upper accumulation zone and, (c) lower accumulation zone. The triggering zone is located in the upper part of the rock slope and characterized by nearly vertical fronts (with average inclination of 75°). In this part of the slope the cropping-out formations are very fragmented and weathered; such feature determines the presence of several blocks in a condition prone to the collapse (Fig. 1a). The upper accumulation zone is positioned in the middle part of the rock slope, with average steepness of 40°. Here debris material, essentially derived from the fragmentation of impacting rock masses, deposits with a very varied grain-size: from few centimeters up to few decimeters (Fig. 1b). The lower accumulation zone is situated at the base of the rock slope and characterized by limited steepness of less than 10°. Blocks of large size (up to 5 cubic meters) stop in this area, producing a significant risk for the Provincial road located near by the bottom of the slope (Fig. 1c).


**Figure 1.** Pictures of the different zones of the study area: a) triggering zone; b) upper accumulation zone; and, c) lower accumulation zone.

In this work, motivated by the case-history of the Postignano rockfall, the potentialities offered by the DEM have been explored by means of a program of numerical simulations and compared to simplified approach for rockfall analysis, as discussed in the following Sect. 3.

## 3. NUMERICAL APPROACHES FOR ROCKFALL ANALYSIS

### 3.1. CRSP method

The name CRSP is the acronym of "Colorado Rockfall Simulation Program", which identifies a code developed by Pfeiffer (1989) and Pfeiffer et al. (1991) for rockfall simulation. The code simulates rockfall events at a site from data describing slope geometry, materials, surface roughness and block size.

As compared to earlier, simpler methods based on the lumped mass approach (e.g., Piteau & Clayton, 1976), the CRSP method can describe the falling motion of blocks of cylindrical, spherical or discoidal shape, which translate and rotate in the vertical plane of motion. The motion of the block is determined by means of the parabolic equation of free-fall motion and the balance of total energy equation. The impact with the slope surface is modeled taking into account the block shape and size and the slope roughness. Upon impact with the slope surface, the normal and tangential components of the block velocity are reduced by means of suitable coefficients of restitution, $K_n$ and $K_t$, in the normal and tangential directions, respectively, to take into account the dissipation of energy due to inelastic deformations. The model is capable of considering the combination of free-fall, rebound, rolling and sliding motion that can occur for different slope roughness and block size.

### 3.2. Discrete Element method: the UDEC code

An alternative to the LM and CRSP methods discussed above, which appears particularly promising for its versatility, is represented by the Discrete Element Method (DEM). In the DEM, the motion of the falling block under the action of gravity is computed by numerically solving Newton's equation of motion. The method was originally introduced for the deformation analysis of fractured rock masses by Cundall (1971), and later applied to micromechanical studies of analogue granular materials (in 2- and 3-d) by a number of researchers; among others, see e.g., Cundall and Strack (1979); Bardet (1994); Tamagnini et al. (2005). Applications of the DEM to the modeling of debris flows and avalanches have been presented, e.g., by Calvetti et al. (2000); Gonzalez et al. (2002); Calvetti and Nova (2004); Salciarini et al. (in press).

In this work, the DEM code UDEC (Itasca, 1991) has been used to simulate the falling block and to model its fragmentation during the fall. In UDEC, each distinct element is a prismatic block, which can be considered perfectly rigid or deformable. Each block in the model is subject to body forces (gravity) and contact forces exchanged at the contacts with other blocks or with rigid "walls" (Fig. 2).

In our study, the blocks are assumed rigid. Thus the deformation of the system is due only to the elastic compliance of joints, and to inelastic joint sliding and opening. The contact normal and tangential stresses are computed by means of the following constitutive equations in incremental form:

$$\Delta\sigma_n = -k_n \Delta u_n \qquad \Delta\tau = -k_s \Delta u_s \tag{1}$$

where $\Delta\sigma_n$ and $\Delta\tau$ are the normal and tangential stress increments at the contact; $\Delta u_n$ and $\Delta u_n$ are the normal and tangential components of the relative displacement at the contacts, and $k_n$ and $k_s$ represent the normal and tangential elastic stiffnesses at the contacts. The normal and shear stresses at the contacts are subject to the following limitations:

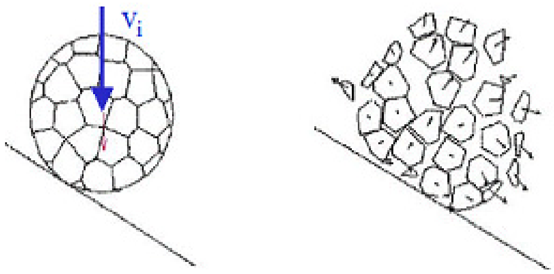


**Figure 2.** A UDEC model of a fractured rock boulder.

$$\begin{aligned} |\tau| &\le c + \sigma_n \tan\phi \qquad &\text{(Mohr-Coulomb sliding condition)} \\ \sigma_n &\ge -t \qquad &\text{(Contact opening condition)} \end{aligned} \tag{2}$$

where $c$, $\phi$ and $t$ represent the joint cohesion, friction angle and tensile strength, respectively.

The motion of each block in the DEM model is determined by numerically integrating the Newton equations of motion, using a central difference explicit algorithm. In order to simulate the energy dissipation due to inelastic impacts between blocks, damping forces and moments can be introduced in the balance of momentum and moment of momentum equations. In UDEC, damping forces and moments can be computed using either Rayleigh damping or local damping models. In this last case, the damping coefficient $\alpha$ is linked to the fraction of critical damping $D$ by the relation:

$$\alpha = \pi D \tag{3}$$

As the amount of damping introduced with the local damping model is independent of the frequency of the dynamic loading applied to the model, this approach has been adopted in the present study.

## 4. NUMERICAL SIMULATIONS

The three methods mentioned above have been used for a series of numerical simulations of rockfall events in the Postignano slope. The simulations have been carried out considering the following steps. First, the geometry of the slope and the mechanical properties of the blocks have been defined. Then, a calibration phase has been conducted to estimate the appropriate model constants describing the behaviour of the block at the impact, by comparing the computed results of a single block fall with the observed positions of fallen blocks on site. Finally, the effects of block fragmentation on the computed travelling distance have been investigated.

### 4.1. Single block fall

The in-situ observations of the position of fallen blocks with sizes ranging from 0.2 to 2.0 m in average diameter indicate that the traveling distances of such blocks fall in the range between 110 and 220 m, with traveling distances increasing with block size.

In the CRSP simulations, spherical blocks of radius equal to 0.1, 0.5 and 1.5 m have been considered. The slope roughness has been set to 2 m, which is typical for talus and firm soil slopes (Jones et al., 2000). The values of the travelling distances obtained with $K_n$ = 0.41 and $K_t$ = 0.87 are given in Fig. 3. These values compare reasonably well with the in situ observations.

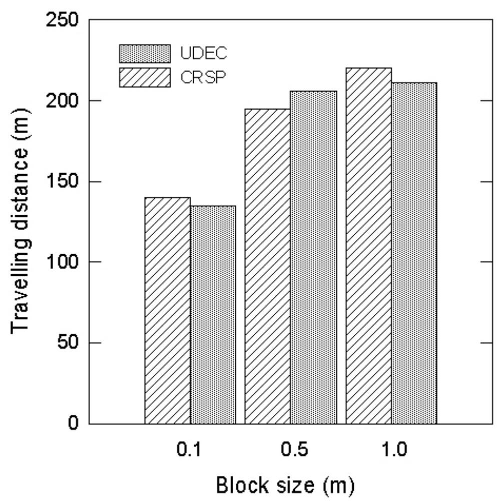


**Figure 3.** CRSP and UDEC simulations: traveling distance vs. block size.

In the UDEC simulations, 3 different squared-shape blocks with the same masses of those considered in the CRSP simulations have been considered. The material parameters adopted in the simulations are $\rho$ = 2350 kg/m$^3$, $k_n = k_s$ = 50 GPa, and $\phi$ = 30° which are typical of calcareous rock formations (Itasca, 1991). In the simulations, the values of the travelling distances are significantly affected by the damping parameter $\alpha$. In order to obtain comparable results with the previous series of simulations (see Fig. 4), the value of $\alpha$ must decrease with increasing block size $L$, as indicated in Tab. 1.

**Table 1**. Damping coefficients used in UDEC simulations.

| $L$ (m) | $\alpha$ (-) | $D$ (%) |
|---|---|---|
| 0.2 | 0.90 | 28.6 |
| 0.9 | 0.43 | 13.7 |
| 1.8 | 0.30 | 9.5 |

The comparison between the experimental data and the results of the two series of numerical simulations indicates that, while a single set of restitution coefficients can lead to reasonably good predictions with the CRSP model, the proper selection of the damping coefficient in UDEC is a critical issue, as this parameter appears to depend on the block size.

### 4.2. Effect of block fragmentation

The effects of block fragmentation on the falling trajectories of the block fragments have been investigated by repeating the DEM simulations considering the largest block ($L$ = 1.8 m) subdivided into 4, 16 and 64 square fragments, respectively (Fig. 4). In the simulations, the effect of block size on damping previously

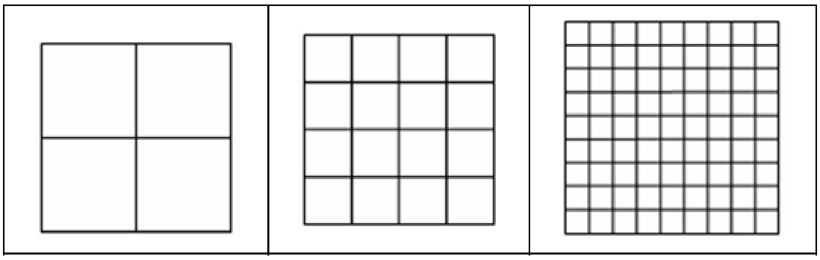

**Figure 4.** Sketch of block fragmentation considered.

observed has been taken into account by assigning the values of $\alpha$ according the fragment size, using the correlation given in Tab. 1.

The final positions of the distinct elements for the two cases with 16 and 64 fragments are shown in Figg. 5 and 6. For the block with fragments of relatively large size, the final traveling distances of the fragments are contained in a relatively narrow range, between 110 and 160 m. All the fragments gather in the lower accumulation zone. On the contrary, for the block with smallest fragments, the falling pieces spread over a larger area, with traveling distances in the range between 40 and 110 m. Moreover, most of the rock mass stops in the upper accumulation zone, never reaching the bottom of the slope.

This result is in qualitative agreement with the in situ observations on the Postignano slope, where a large debris deposit of block of relatively small size is actually found in the same area, as noted in Sect. 2. It is worth noting that the possibility of modeling block fragmentation upon impact is a unique feature of the DEM approach, not available in the CRSP and simpler approaches such as the lumped mass method. This should be considered in the rockfall hazard evaluation whenever the possibility of block fragmentation is of concern.

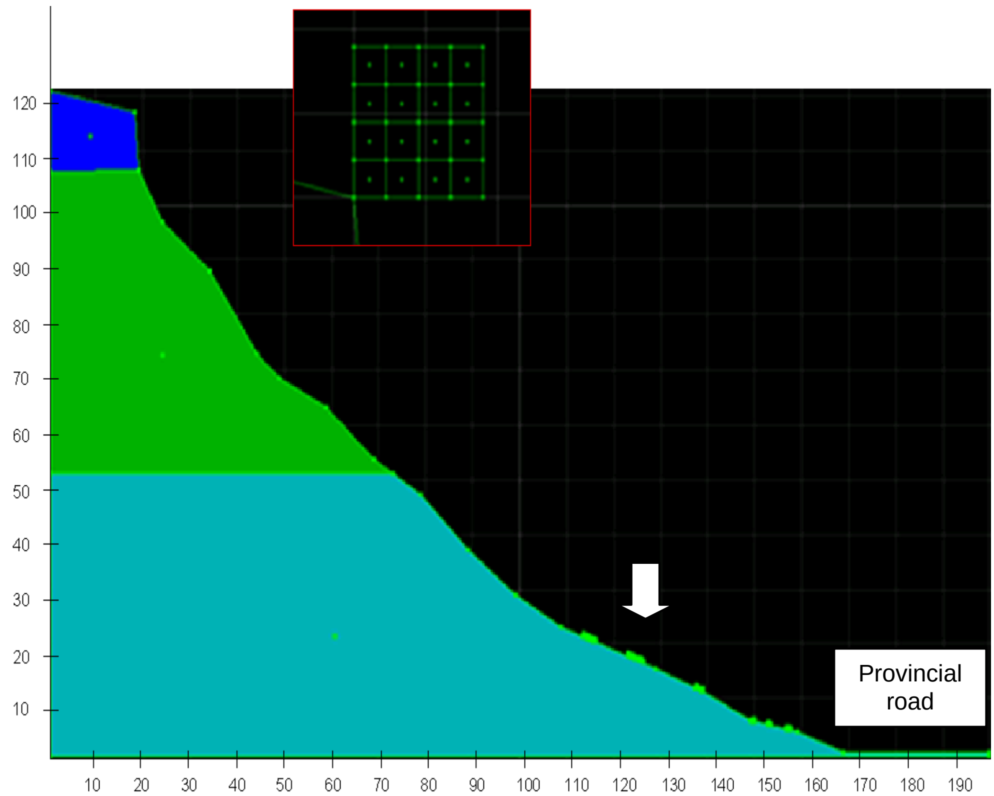


**Figure 5.** Results obtained for a block subdivided into 16 fragments. The white arrow indicates the position of the final deposit.

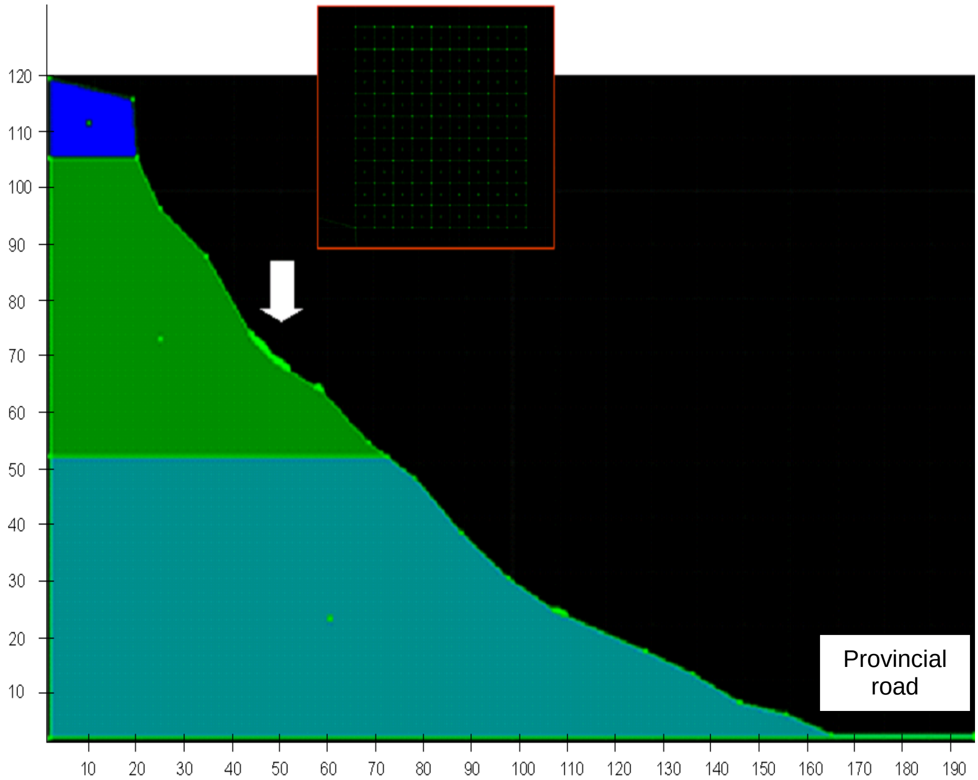


**Figure 6.** Results obtained for a block subdivided into 64 fragments. The white arrow indicates the position of the final deposit.

## 5. CONCLUDING REMARKS

In this work, the performance of two different approaches to rockfall simulation - the CRSP method and the Discrete Element Method, in the particular implementation of the UDEC code – has been compared with reference to observations from a real rock slope located in central Italy, where several rockfall events occurred and were recorded by in situ surveys from the local administration.

As far as the falling of a single block is concerned, both methods give comparable results, which are in line with the available observations. However, while in the CRSP method a single set of restitution coefficients is sufficient to characterize the block behavior upon impact, the local damping coefficient introduced in UDEC to model the energy dissipation upon impact must be varied with block size, in order to model correctly the effect of block size on the observed traveling distance.

On the other hand, a unique advantage of the DEM approach as compared to other methods derived from the lumped mass approach is the possibility of modeling the effects of rock fragmentation. The results of the simulations indicate that the position and the extension of the accumulation zone can be strongly affected by block fragmentation. Therefore, this particular aspect should be taken into proper consideration in the rockfall hazard evaluation whenever the possibility of block fragmentation is of concern.

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