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Discrete element modeling of debris-avalanche impact on earthfill barriers

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A B S T R A C T

One of the key elements in any integrated strategy for the mitigation of landslide hazard is the design of appropriate defensive works, which are intended to reduce the potential impact of landslides on the population and facilities potentially at risk. In this work, the Discrete Element Method (DEM) has been used to assess the effectiveness of earthfill barriers, which are widely used as protection structures against granular avalanches and debris flows. In the DEM approach, the discrete soil/debris elements are modeled as two-dimensional circular particles that interact through cohesive-frictional sliding contacts. A parametric study based on a case-history from a marginally stable rock slope near Assisi, in central Italy, has been conducted. The parametric study has been performed to examine the influence of the geometry of the sliding mass, slope and barrier, and strength properties of the granular mass on the main design parameters for the barrier. Results show that the barriers considered are all effective in retaining the debris mass; less than 6% of the initial rock mass passes the barrier. The predicted efficiency of the barriers is primarily affected by: (i) barrier height; (ii) run-out distance; (iii) macroscopic friction angle of the debris; and (iv) size of the storage area left between the barrier and the slope base. For the limited range of values considered, the slope angle has only a minor impact on the computed results.

1. Introduction

Landslide hazard mitigation measures include both the design and implementation of suitable stabilization methods intended to reduce the likelihood of slope failure, and/or the installation of defensive works aimed at reducing the potential impact of landslides on the population and facilities potentially at risk (e.g., Lo, 2000). Defensive works are of particular importance in those cases when the stabilization of the potentially unstable soil or rock mass is not practicable or not economically possible.

Protective measures against hazards associated with rapid slope movements, such as debris flows and debris avalanches, include a variety of barriers such as rock/boulder fences, deflection berms, gabions and earthfill barriers, which are placed along the potential flow path where the debris is transported and deposited or close to infrastructures potentially at risk.

The design of this type of protective measures typically requires the quantitative prediction of: (i) the final run-out distance of the debris mass and the vertical run-up distance of the debris on the barrier slope; (ii) the forces transmitted to the barrier at impact and in at-rest conditions. Obtaining a reliable estimate of these quantities is complicated by the interaction of the debris and the barrier. However, recent progress in the field of numerical methods for the lagrangian analysis of discrete particulate systems provides an opportunity to develop a rational design strategy for earthfill barriers as well as other protection methods against debris avalanches.

In particular, the Discrete Element Method (DEM) appears particularly promising for the modeling of debris avalanches. In the DEM, the motion of a granular mass subject to gravity is simulated by numerically solving Newton's equation of motion for each particle considered as an individual body. The method was originally introduced for the analysis of rock mechanics problems 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); Tommasi et al. (2008).

A major drawback of the DEM in the applications to flow-like landslides is represented by the difficulty of taking into account the effects of the fluid phase in fluid-saturated granular bodies. Differently from rock or debris avalanches, the interaction between solid and fluid phases represents a distinctive feature of debris flows and is responsible for their unique destructive power, since the presence of a nearly incompressible pore fluid can affect significantly the interplay between granular friction and grain collisions, and enhance the debris mobility, see Iverson (1997). Attempts to extend the DEM formulation to the description of two phase granular media have been made by Shafipour and Soroush (2008) and

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Zeghal and El Shamy (2008), with reference to the analysis of soil behavior under undrained conditions.

Recently, great progresses have been made in the mathematical and numerical modeling of the propagation of flow-like landslides by means of depth-averaged continuum models, based on the pioneering work of Savage and Hutter (1989). Early studies and part of the more recent literature were limited to dry (one-phase) flows (see, e.g., Savage and Hutter, 1989; Savage and Hutter, 1991; Mangeney-Castelnau et al., 2003). Iverson (1997) and Iverson and Denlinger (2001) first addressed the problem of multiphase flows and of the important role played by the pore fluid in controlling the debris flow run-out and arrest conditions. Further developments of this approach can be found, e.g., in Pitman and Le (2008) and Pelanti et al. (2008). However, when the presence of a pore fluid is not of concern, a definite advantage of the DEM approach with respect to depth-averaged continuum models is represented by the possibility of reproducing quite complex behaviors of the granular mass based on very simple constitutive equations defined at grain contacts, characterized by a small number of material parameters with a clear physical meaning.

In this work, the DEM has been used to assess the effectiveness of an earthfill barrier installed to protect a transportation corridor from a marginally stable rock slope near Assisi, in central Italy. A series of DEM simulations has been conducted to investigate the effect of: (i) geometry of the sliding mass; (ii) geometry of the slope; (iii) geometry of the barrier; and (iv) strength properties of the granular mass on the effectiveness of the barrier and on the forces exerted by the debris on the barrier, both at the impact and in static equilibrium conditions.

The outline of the paper is as follows. In Section 2, the specific case-history which has motivated the present study – the Torgiovannetto landslide – is presented. Section 3, after a brief outline of the Discrete Element Method, provides the details of the numerical models used in the DEM simulations. A summary of the main results obtained from the parametric study is given in Section 4. Some concluding remarks and suggestions for further investigations are given in Section 5.

2. Motivation: the Torgiovannetto landslide

The slope instability phenomenon which has motivated the present study concerns an artificial rock slope in a calcareous rock formation – locally known as "Maiolica" – in an abandoned stone quarry in Torgiovannetto, near the town of Assisi, in the central Italian Appennines (Graziani et al., 2007).

A plane view map of the quarry area is shown in Fig. 1. The main front of the quarry, oriented approximately along the SE-NW direction, has an average dip of about 38°. 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 quarry 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, characterized by a global factor of safety not exceeding 1.15, as reported by Graziani et al. (2007). Limited slope failures 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 (Fig. 1).

A campaign of in situ measurements conducted by Graziani et al. (2007) – including topographic surveying of the slope surface, monitoring of tension cracks opening with extensometers and measurement of horizontal displacements along five verticals through inclinometer tubes – has shown that the upper part of the slope is subject to movements of the order of 1 mm/day in the direction of the bedding planes. The analysis of the available rainfall data indicates that such movements are associated with periods of heavy rainfalls, when the increase of pore pressures in the rock mass causes a reduction of the shear strength along the stratification planes.

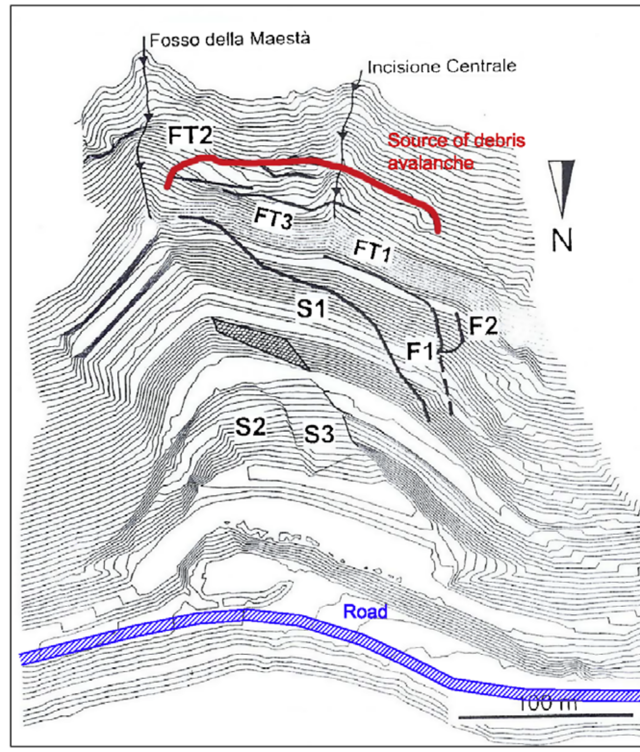

Fig. 1. Plan view map of the quarry area. Black lines indicate subvertical tension cracks. The shaded area indicates the location of a slope failure that occurred on December 2005 (From Graziani et al. (2007)). Note: elevation contour interval is 2 m; the positions of main tension cracks, joints and bedding planes are marked with the symbols FT, F and S, respectively.

The potential for catastrophic failure indicated by recorded slope movements and tension crack openings has led the local authorities to close a suburban road passing at close distance to the dismissed quarry. Due to the actual state of fracturing of the rock, a potential evolution of the slow sliding movement towards a debris avalanche has been considered likely. In order to minimize the potential risk and to restore traffic to the road, the local authority has decided to build an embankment barrier.

In this work, motivated by the case-history of the Torgiovannetto slide, the potentialities offered by the DEM have been explored by means of a program of numerical simulations, specifically conducted to assess the impact of some fundamental geometrical and mechanical factors on the effectiveness of the barrier, as discussed in the following Section 3.

3. DEM modeling of the debris–barrier interaction

In the evaluation of the potential hazard resulting from full mobilization of the rock mass, the debris avalanche is described by means of the DEM, modeling the debris mass as a mechanically equivalent assembly of particles of circular shape. A brief outline of the basic principles of the DEM approach is given in the following Section 3.1; the details of the particular DEM implementation adopted in the simulations and the characteristics of the numerical models considered are provided in Sections 3.2–3.4.