Micromechanical modelling of rainsplash erosion in unsaturated soils by Discrete Element Method

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A B S T R A C T
The rainsplash erosion is one important mechanism in natural and artificial slopes and the raindrops impact contributes to the amount of solids conveyed at the outlet of a mountain basin. Rainsplash erosion involves individual (or small clusters of) soil particles, it is a dynamic (temporally and spatially variable) process and mainly occurs in unsaturated soils where capillarity forces allow steep slopes to be stable. The Discrete Element Method (DEM) was firstly applied in this paper for the analysis of rainsplash erosion assuming realistic rainfall intensities, and a range of both slope steepness and capillary forces in a parametric analysis. The DEM numerical results highlight the specific role of the slope steepness, capillarity force, and rainfall intensity towards the final volume of the solid eroded from the ground surface at the computational domain. It is also valuable that the numerical results are in good agreement with literature formulations, and increasing power law functions were found to relate well the eroded volume to rainfall intensity.

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1. Introduction

The rainsplash erosion consists in the mobilization of soil particles from the ground surface due to the impact of the rain droplets (Kinnell, 1990; Hudson, 1995; Kinnell, 2005). Specifically, rainsplash erosion is a gradual cumulative process, which involves the sequential displacement of individual particles of soil (or clusters), which are detached and displaced downwards from the zones where the droplets fall. Thus, the process occurs at a particle scale, is time-dependent (dynamic) and also spatially-variable because the local arrangement of the uppermost solid particles affects their chance to be mobilized or not. Nevertheless, this process can affect large areas – up to hundreds of square meters – during a heavy rainstorm, and huge amounts of solid material can be conveyed to the outlet of a mountain basin.

A complication to this process often derives from the unsaturated soil condition of the very first centimetres of the ground surface. In fact, unsaturated soils are characterized by an additional cohesion among the solid particles which depends on the matric suction, i.e. the difference of air-pressure (\( u_a \)) to pore water pressure (\( u_w \)), and it is well-known that soil suction relates to soil volumetric water content (through the so-called retention curve), soil conductivity (expressed by the soil conductivity curve), and to the specific hydraulic boundary conditions which are applied by the atmosphere at the ground surface.

In principle, during the impact of each rain droplet the suction is modified at the impact area. Thus, the rainsplash erosion is somehow regulated by the time-space evolution of the soil suction at the ground surface. These cascading processes are still challenging to be modelled at particle scale during a dynamic process such the impact of a rain droplet.

Rainsplash erosion is one of the transport mechanisms in coarse-grained cohesionless materials. A typical example is that of short steep slopes, such as bench terrace risers (van Dijk, 2002, 2003). Rainsplash may lead artificial unprotected excavations to overcome their serviceability limit. Along natural slopes, the threat that rainsplash may mobilize high amounts of solid particles must be seriously taken into account because hyperconcentrated flows may be generated, as observed in real case histories (Cascini et al., 2014; Cuomo et al., 2015).

Thus, the interest to have accurate quantitative estimates of the rainsplash erosion spans from agriculture practices to the hyperconcentrated flows risk management, up to civil protection purposes. For a quantitative analysis, it is clear that physically-based approaches are absolutely required. But while the needs are obvious, it is still problematic to tackle this issue due to either the complexity of the rainsplash-related mechanisms or to the lack of methods applied and validated to provide quantitative estimates of the solids detached.

Starting from the available literature, this paper aims to provide a novel contribution to the topic proposing the application of the Discrete Element Method (DEM) to the numerical simulation of a sequence of droplets falling at the ground surface in a reference test area along a slope. This would be the first time that such kind of approach, usually...
referred as “micromechanical”, is tested to the numerical simulation of splash erosion (Della Sala, 2014). The novelty is that the effects of each raindrop on each solid grain impacted are simulated, and this is reasonable as the erosion is a dynamic and spatial-dependent process acting on discrete portions of the ground surface, while the previous literature treated the erosion process as a continuous process both in space and time. In the paper, a parametric analysis is performed and the numerical results are compared to experimental evidences reported in the literature and the possible applications of this approach are discussed as well.

2. Literature review

Rainsplash erosion involves a series of complex processes mainly classifiable into three stages (Kinnell, 2005): i) collision and deformation of a falling raindrop at the ground surface; ii) rupture and collapse of the drop into a thin disk of fluid spraying radially outwards from the point of impact; iii) jetting of daughter ejection droplets in parabolic-like trajectories away from the original point of impact.

To date, the methods available in the literature for the rainsplash erosion analysis are mostly based on the experimental evidence. It is remarkable that the understanding of rainsplash process has been considerably improved in the last decades by laboratory testing (Poesen and Savat, 1981; Nearing and Bradford, 1985; Ghadiri and Payne, 1986, 1988; Poesen and Torri, 1988; Sharma and Gupta, 1989; Salles et al., 2000; Mouzai and Bouhadef, 2003; Ma et al., 2008; Long et al., 2011), and field experiments (Morgan, 1981; Parlak and Parlak, 2010; Ghahramani et al., 2012; Geißler et al., 2012; Angulo-Martinez et al., 2012).

In particular, the raindrop detachment and transport has been measured using a variety of techniques, including trays and transporters (Van Dijk et al., 2002, 2003) and splash cups (Ghahramani et al., 2012; Geißler et al., 2012). To date, the classical method for quantifying the splash erosion relies on the use of splash cups, or small traps that collect the soil particles detached and transported by splash (Ellison, 1947; Morgan, 1978; Poesen and Torri, 1988; Salles and Poesen, 1999; Van Dijk et al., 2003; Legout et al., 2005).

Most of the experimental studies show that the mobilization rate of soil particles ($D_s$, kg/m²/s) on bare soil – defined as the weight of solids mobilized by rainfall at a unitary area of the ground surface per unit time (Ma et al., 2008) – can be expressed by one of the following equations of:

$$D_s = \beta I^a s^b$$

(1)

$$D_s = KE^a s^b e^{-\alpha h}$$

(2)

where $I$ is the rainfall intensity (mm/h), $s$ is the slope expressed in m/m or as a sine of the slope angle, $KE$ is the kinetic energy of the rain (J/m²) and $h$ is the depth of the water table (m), while $a$, $b$ and $c$ are empirical parameters to be fitted from experimental evidences from the field or laboratory.

Based on a great amount of experimental evidences, mathematical erosion models were set up and applied to real cases. For instance, Jayawardena and Bhuiyan (1999) provided an empirical correlation between rainfall intensity and the erosion rate. Alternatively, starting from the experimental evidence of splash tests, in the physically-based model LISEM (Jetten, 2002) the rate of splash erosion was related to: i) the so-called soil aggregate stability (median number of drops to decrease the aggregate by 50%); ii) the rainfall kinetic energy; iii) the depth of the surface water layer; and iv) the amount of rainfall and the surface over which the splash takes place. In addition, the amount of solid particles detached by raindrop impact and leaf drip were related to rainfall intensity, vegetation cover and soil texture in the so-called physically-based model SHESED (Wicks and Bathurst, 1996).

As suggested by the above equations, the erosion of soil particles due to raindrop impact is related to the rainfall characteristics. Generally speaking, a rainfall can be defined by the intensity and the drop size distribution. In turns, each drop size corresponds to a different terminal velocity (van Dijk et al., 2002) at the ground surface.

The literature provides power law relationships between the median drop diameter $D_s$ (mm) and the rainfall intensity $I$ (mm/h), which can be expressed in the general form of Eq. (3):

$$D_s = a I^b$$

(3)

where the coefficients $\alpha$ (in h) and $\beta$ are available from several studies (Laws and Parsons, 1943; Atlas, 1953; Brandt, 1988; Kelkar, 1959; Zanchi and Torri, 1980; van Dijk et al., 2002). For instance, Zanchi and Torri (1980) obtained $\alpha$ equal to 0.98 (considering an air temperature equal to 20 °C) and $\beta$ equal to 0.292 for a rainfall intensity variable between 1 and 140 mm/h in a Florence site (Central Italy).

As pointed out by Atlas and Ulbrich (1977), a raindrop of a given diameter $D$ impacts the ground surface at a terminal velocity ($v$), usually expressed by exponential or power law equations requiring estimate of Reynolds number, which depends, in turn, on air and fluid densities, dynamic viscosity and surface tension. Van Dijk et al. (2002) proposed a simplified third-order-polynomial equation (Eq. (4)) under standard conditions of air pressure (1 bar) and air temperature (20 °C) and for raindrop sizes variable between 0.1 and 7 mm, as follows:

$$v = 0.0561D^3 - 0.912D^2 + 5.03D - 0.2541$$

(4)

According to Mouzai and Bouhadef (2003), the rainsplash erosion is related to raindrop force and raindrop pressure applied on the ground surface, that are strictly dependent on density, diameter, fall height, velocity of the raindrop and impact area. In particular, the authors proposed that the raindrop impact force ($F$) is expressed as follows:

$$F = \frac{m v^2}{D^2}$$

(5)

where $m$, $D$ and $v$ are the mass, the diameter and the terminal velocity of the raindrop, respectively.

With reference to the displacement of the detached particles, recent investigations with multiple and high-speed cameras, were performed by Long et al. (2011) in order to investigate the 3D particle trajectory and velocity during both the impact, detachment, transport and deposition processes. In addition to these ballistic measurements, the authors used photogrammetric techniques to analyse the change in the surface morphology caused by a single droplet impact. Through these measurements, both the particles travel distances and the total amount of eroded solids were investigated, providing valuable insights into the raindrop erosion processes. Particularly, the experimental results demonstrated the influence of the interactions of particle size and droplet characteristics on detachment and transport over different slope angles.

3. Discrete Element Method (DEM) applied to rainsplash erosion analysis

3.1. Theoretical basis

This paper proposes an application of a particle-scale numerical model for the analysis of the rainsplash erosion process. This is a novel attempt, which cannot be found in the current literature.

The Discrete Element Method (DEM) was firstly introduced by Cundall and Strack (1979). It is based on the use of an explicit numerical scheme in which the interaction of the soil particles is monitored contact by contact and the motion of the particles modelled by particle.
The DEM approach allows representing the discontinuous nature of granular materials by a set of discrete elements and allows computing the motion of a large number of particles. The approach is fully micromechanical, i.e. the solid phase is modelled by defining the mechanical properties of the interaction between the grains that compose it. The grain’s shape is assumed spherical in this study. The basis of DEM is micromechanical, i.e. the solid phase is modelled by de

The grain's shape is assumed spherical in this study. The basis of DEM modelling the interaction between the grains that compose granular materials by a set of discrete elements and allows computing boundary conditions at the ground surface. Doing so, the sample is mechanically stable under vertical gravity forces. The same occurs when the gravity forces are tilted according to different slope angles to reproduce the geometry of an ideal “infinite slope” (Fig. 1). In both cases, a uniform soil thickness is obtained in the whole domain.

As for the soil mechanical properties in a DEM analysis, they are referred to the particles or to the contact points among the particles and in this paper the set of mechanical parameters were selected to reproduce realistic boundary value problems.

Finally, the definition of the boundary conditions at the ground surface and the analysis of the impacts consequence was tackled through a novel six-steps procedure (Fig. 2) based on: 1) computation of the raindrop impact force; 2) definition of the application point for each impact force; 3) assessment of the particles impacted by each raindrop; 4) distribution of the raindrop impact forces among the grains impacted; 5) computation of the time sequence for the raindrop impacts; 6) computation of both the volume of the particles “eroded” from the ground surface and the average eroded thickness. The step “1” was tackled referring to the Eqs. (3–5). It entails that for a given rainfall intensity (I), diameter (D) and velocity (V) of each droplet can be computed, and hence the impact force (F) of each droplet. The step

3.2. The adopted procedure

The application of DEM to the numerical simulation of the rainsplash erosion process requires: i) the creation of the computation domain; ii) the definition of the soil particle properties; iii) the definition of the boundary conditions at the ground surface. The definition of the particles sample is an important and complex task in DEM simulations. The representativeness of the sample is related to the number of particles. If the number of particles increases, the reliability of the considered macroscopic properties increases. In this paper, the size of the sample was chosen in relation to the grains dimension. Referring to shape of soil particles, they are assumed as spheres characterized by different diameters belong to the class of “sand”. The particles have a simplified linear grain size distribution, which counterbalances the need to have grains of different sizes arranged in clusters and the higher computational costs due different grains because of small particles moving among greater particles. In the DEM model, a combination of a small eroding surface and periodic boundary conditions applied to the vertical external walls of the domain is proposed (Fig. 1). The deposition of the particles under the effect of gravity was reproduced, assuming a fixed impervious bottom of the domain. Periodic boundary conditions are used, as if an infinite slope was made of duplicates of a single reference domain. It entails that any particle exiting at a lateral boundary is reintroduced in the computational domain at the opposite side, so reproducing an ideal infinite soil deposit and eliminating any boundary effect. Such a modelling choice allows an optimization of the features of the computational domain as: i) the eroding surface is big enough compared to the size of grains, ii) the use of lateral periodic boundary conditions allows the repetition of an identical domain beside the eroding surface, maximizing the homogeneity of the eroding surface. Doing so, the sample is mechanically stable under vertical gravity forces. The same occurs when the gravity forces are tilted according to different slope angles to reproduce the geometry of an ideal “infinite slope” (Fig. 1). In both cases, a uniform soil thickness is obtained in the whole domain.

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![Fig. 1. Computational scheme.](image)

![Fig. 2. Flow chart of the procedure for numerical modelling.](image)
“2” was based on the random selection of a pair of coordinates \((x, z)\) corresponding to the location of the impact centre point. The step “3”, i.e. assessment of the particles impacted by each raindrop, was based on: i) a circular shape for the impacted zone assumed as large as the droplet diameter \((D)\); ii) a thickness of influence equal to \(D\); iii) the division of the uppermost particles \((n_D)\) in the volume of influence \((D^2)\), defined by the impacted area \((D^2)\) and the influence thickness \((D)\). The step “4” was simply based on the equalitarian repartition of the raindrop impact force \((F, Eq. (5))\) among the \(n\) uppermost particles located in the volume of influence. In the step “5”, the assessment of the impact time duration \(t_{imp}\) was computed as the time necessary for the water to cover a distance equal to the drop diameter \((D, from Eq. (3))\) at the velocity of Eq. (4), and it reads: \(t_{imp} = D / v_0\). From the rainfall intensity \((I, m^3/s)\), it is also simple to derive the number of droplets \((n_D, s^{-1})\) impacting a unitary area in time as: \(n_D = 6 \cdot I / \pi \cdot D^2\). The time span between two next impacts \(\Delta t\) was obtained in relation to the expected number of droplet \((n_D)\) in a given reference area of the ground surface \((A_{ref})\). To reduce the computational costs, \(\Delta t\) was reduced 10 times \(t_{imp}\) assuming that at this stage the disturbance effects from subsequent impacts were over. Finally, in the step “6” the particles which travelled a distance larger than the size of the computational domain are labelled and their cumulative solid volume is computed \((V_{er}, “volume eroded” later on); in addition, from this solid volume a corresponding total volume – solids and voids – can be computed referring to the soil porosity \((\eta)\), and from here the average “eroded thickness” \((h_{er})\) as follows: \(h_{er} = V_{er} / (\eta \cdot A_{ref})\). It is worth noting that the simulation procedure refers to the very early stage of the rainsplash erosion mechanism, when it can be reasonably assumed that soil suction and water content are not modified by raindrop impacts. Moreover, rainfall impact induces saltation process and formation of particles cloud\((Kinnell, 2006)\); in the paper there is no model for such phenomena (hence no assumptions either), we compute the movement of every single particle, and collective behaviour like cloud and interactions between coarse and fine particles come out as results.

4. Parametric DEM analysis

4.1. Schemes and input data

A sensitivity analysis is conducted, simulating the evolution of a slope under different rainfalls and to evaluate the solid particle mobilization due to the raindrops impact. Specifically a parametric analysis of rainsplash erosion was performed to evaluate the eroded volume in relation to important geotechnical parameters (e.g. capillary pressure) over different slope angles and for different rainfall intensities. The presence of the capillarity forces in unsaturated conditions is a key factor for slope stability.

The computational domain was fixed as large as possible to include a significant number of solid particles in the analysis and as small as possible to reduce the computational efforts to reasonable values. Thus, from this counterbalance the grain size distribution was assumed linear between 1.2 mm and 1.8 mm (i.e. coarse sand), the domain was assumed 70 mm wide and large (with a thickness equal to 25 mm), with the special periodic boundary conditions above mentioned at the lateral walls. The number of grains was equal to 15,000. The computational domain was kept fixed for all the computations, while the gravity acceleration \((g)\) was split in two components \((g_x, g_z)\) related to the steepness of the slope.

A range of slope steepness was considered, i.e. 20°, 30°, 36° and 40°. These specific values were set in relation to the mechanical properties of the soil which were: friction angle \((\phi')\) equal to 36° and effective cohesion \((c')\) nil. It entails that: i) the gentler slopes (20° and 30° steep) are stable independent of the soil suction; ii) the intermediate slope (36° steep) is a limit stability condition if soil suction is nil while stable if soil suction exists; iii) the steep slope (40°) can be stable only if a soil suction exists. As further grain properties, the sphere density \((\rho, N/m^3)\) was 1600, the grain Young’s module \((E, MPa)\) was 150,000, the grain Poisson’s module \((\nu)\) was 0.5.

The capillary pressure was set equal to 0, 20 or 30 kPa. The former case corresponds to a dry slope (poorly realistic case in nature) or a to fully saturated slope with a vertical downwards flow net; while, the latter two cases are typical of many shallow deposits of soils originated by air-fall deposition \((Cascini et al., 2014)\) or degradation of under beneath bedrock \((Cascini et al., 2010)\). For the sake of simplicity, the capillary forces are assumed constant during and after the impacts. It is worth noting that previous insight has been obtained through splash-cup experiments on a plane and for small capillarity pressure such 25 mm, i.e. 0.25 kPa \((Kinnell, 1974, 1976)\), while our main concern is for cases of low water content and high suction, that are those experienced by steep slopes in Mediterranean Countries after Summer \((Cascini et al., 2014)\).

A series of numerical tests were performed and a selection of those most significant will be discussed herein, and are listed in Table 1. Rainfall intensity \((I)\) is changed from moderate \((20 mm/h)\) to heavy storm \((150 mm/h)\), which is a range realistic for many areas in the Mediterranean Countries and/or in semi-arid climates. Depending of rainfall intensity, Raindrop size distribution is assumed to change as suggested by van Dijk et al. (2002), and reported in Eq. (3). Based on the procedure of Section 3.2, the raindrop velocity and impact force were computed as a non-linear function of the rainfall intensity \((Eqs. (4, 5))\). In this paper, raindrop size ranges from about 2 mm to 4 mm, which are similar to those used in Kinnell (1974, 1976). In addition, the random selection of impact zones included in the model makes the results user-independent. Trial numerical tests were performed to check the consistency of the proposed procedure and the duration of the simulated rainfall. Starting from the initially homogeneous periodic slope, the particles at the ground surface were coloured if impacted by any droplet and computed as eroded only in case they overcome the lateral boundaries of the computational domain, thus contributing to increase the “volume eroded” \((V_{er})\). As far as the initial smooth surface which becomes pitted as raindrops impact the surface, we underline that a micromechanical approach like DEM can properly take into account the local modifications of topography and particles rearrangements due to the mobilization of individual particles or clusters. The impact can trigger further particle displacements if the impacted particles move and collide other particles, resulting in a cascade of instabilities.

4.2. Numerical results and discussion

The role of each factor was specifically evaluated comparing the rainsplash erosion scenarios obtained through the DEM analysis.

The first comparison is aimed to outline the role of capillarity forces \((u_c)\) and refers to a slope 36° steep and subjected to rainfall intensity equal to 100 mm/h (case c of Table 1), under two different soil suctions, 0 or 20 kPa (Fig. 3). In both the cases, the rainfall splash erosion is simulated but with an order of magnitude of difference; the higher the soil suction the smaller is the eroded volume, as expected. It is interesting noting that the computed eroded volumes, ranging from \(10^{-6}\) to \(10^{-5}\) m³ in a \(70 \times 70\) mm² reference area, roughly correspond to an eroded height from 0.4 to 4 mm, if a soil porosity \((\eta)\) equal to 0.5 is

| Table 1 |
| Boundary conditions and details of numerical simulations.

<table>
<thead>
<tr>
<th>Case</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (mm/h)</td>
<td>20</td>
<td>50</td>
<td>100</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>D (mm)</td>
<td>2.35</td>
<td>3.07</td>
<td>3.76</td>
<td>3.97</td>
<td>4.23</td>
</tr>
<tr>
<td>F (N)</td>
<td>0.016</td>
<td>0.034</td>
<td>0.058</td>
<td>0.066</td>
<td>0.077</td>
</tr>
<tr>
<td>t_{imp} (s)</td>
<td>3.24e^{-4}</td>
<td>3.74e^{-4}</td>
<td>4.30e^{-4}</td>
<td>4.48e^{-4}</td>
<td>4.73e^{-4}</td>
</tr>
<tr>
<td>Δt (s)</td>
<td>3.24e^{-4}</td>
<td>3.74e^{-4}</td>
<td>4.30e^{-4}</td>
<td>4.48e^{-4}</td>
<td>4.73e^{-4}</td>
</tr>
<tr>
<td>T (s)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Notes: I: rainfall intensity, D: median diameter of raindrops, F: raindrop impact force, t_{imp}: impact time duration, Δt: time span between two impacts, T: rainfall duration.
assumed. This order of magnitude for the eroded height is of twofold interest, because it agrees with the literature evidences and it also confirms that the effects of rainsplash are observable only at the particle-scale level.

The second insight refers to the role of the slope angle ($s$); it is expected that the higher is the steepness, the higher should be the eroded volume, because the general stability conditions of the particles are weaker as the steepness increases and the impacted forces have a greater component along the x-axis that is the preferential direction for the grains’ motion along the slope. The numerical results confirm these expectations and provide a quantitative measure of the differences for the scenarios depicted in Fig. 4. It is interesting noting that all of the plots have a regular time trend but for the 40° steep slope, some steps and plateaus can be also observed in the plot; this finding is related to the severe geometrical configuration, which enhances the role of very local specific arrangements of the particles along the ground surface of the domain.

The importance of the rainfall intensity ($I$) is discussed in relation to the value of both the impact forces and the eroded volume. Fig. 5 shows that the higher is the rainfall intensity, the greater is the droplets median diameter ($D_{50}$) and the less are the impacts, whose force ($F$) increases with $I$. Due to these boundary conditions applied at the ground surface, the computed eroded volume increases with rainfall intensity ($I$), as observed in the field and in the literature experiments quoted in the Section 2.

Fig. 3. Eroded volume for different soil capillary forces in a slope 36° steep subjected to 100 mm/h rainfall intensity.

Fig. 4. Eroded volume for different slope angles (20°, 30°, 36° and 40°) for a rainfall intensity equal to 100 mm/h, and soil capillary equal to 20 kPa.

Fig. 5. Number of raindrops in 20 s, diameter and impact forces applied at the ground surface in relation to the rainfall intensity.

Fig. 6. Eroded volume for different rainfall intensities and a soil capillary equal to 20 kPa after 20 s.
The corresponding best-fitting power law relationships are given by the Eqs. (6) and (7):

\[ D_r = 1.1034I^{0.1228} \]  
\[ D_r = 1.4142I^{0.0639} \]

where \( D_r \) (g/m²/s) is the erosion rate and \( I \) (mm/h) is the rainfall intensity.

The Eqs. (6) and (7) are characterized by a different level of uncertainty, being \( R^2 \) equal to 0.91 and 0.65, for a capillarity force equal to 30 kPa or 20 kPa, respectively. Such a difference could be explained referring to the fact that the lower is the capillarity force, the worse are the general stability conditions of the solid grains and hence the simulated erosion scenarios are more easily “disturbed” by local peculiarities of either the grains arrangements or the impact effects. Nevertheless, those equations have a twofold value: i) to be mechanically-based as they derive from DEM computations, ii) to correctly interpret the empirical evidences, which evidence \( D_r \) as an increasing power law function of \( I \).

From an engineering point of view, both the Eqs. (6) and (7) indicate that 1.5–2.0 g/m²/s is the average order of magnitude for \( D_r \) in the analysed cases of a 20–40° steep slope made of unsaturated coarse sands.

Aimed to compare these findings with the existing literature, a series of literature empirical correlations between \( D_r \) and \( I \) were plotted in Fig. 9. It is appreciable that the DEM numerical results are fully consistent with the literature results Wicks and Bathurst (1996); Jayawardena and Bhuian (1999) and Jetten (2002).

As general comment, we underline that a DEM modelling was proposed for rainsplash erosion analysis as a novel contribution to the literature as DEM can take into account the features and processes typical of the particle scale, such as formation of cluster of grains with different sizes, inhomogeneities induced by raindrops impacts, and modifications of roughness of ground surface in time. We are aware of the current limitations of proposed DEM modelling, which are mostly related to the simplifications assumed to describe the impact of a droplet, e.g.: i) the equilibrant distribution of the forces among the impacted particles, ii) the capillarity force kept constant during the impact, iii) soil the water content is not changed after each impact. Thus, improvements of the proposed approach are desirable especially in the light of the encouraging results obtained in this paper. Due to these limitations, the numerical simulations were limited to the very early stage of the rainsplash erosion process, after that the assumption that soil suction and water content are not changed become less realistic. Apart from this, improved versions of the model should address better soil texture composition and the effect of rainsplash on soil aggregates, but certainly are out of the scope of the present article.

5. Conclusions

Rainsplash erosion is one important rainfall-induced mechanism acting on steep slopes, which contribute to the mobilization of solid grains later conveyed at the outlet of mountain basins. In the literature, the erosion of grains from the ground surface due to rainsplash is investigated through the empirical analysis of the field evidence or experimental laboratory measurements. To date, it is known that the rainsplash erosion rate is an increasing power law function of the rainfall intensity and a variety of relationships exist.

The novelty of this paper is that the effects of each raindrop on each impacted solid grain are simulated, and this is reasonable as the erosion is unsteady process acting at particle-scale on the ground surface, while the previous literature treated the erosion process as a continuous process both in space and time.

To this aim, the Discrete Element Method (DEM) was firstly applied to the numerical (micromechanical) simulation of a sequence of droplets falling at the ground surface in a reference test area along a slope. A parametric analysis was performed, assuming realistic rainfall
intensities, and a range of both slope steepness and capillary forces. An existing DEM code was used (Yade), while it was necessary to implement a new methodology and a specific procedure to compute the input data and to perform the analysis.

The DEM numerical results highlight the specific role of the slope steepness, capillary force, and rainfall intensity towards the final value of the solid volume eroded from the ground surface at the computational domain. It is also valuable that the numerical results are in agreement with the literature formulations, and increasing power law functions were found to well correlate the eroded volume and the rainfall intensity. Some limitations of the work must be also admitted such as the equalitarian distribution of the forces among the impacted particles, the capillary forces kept constant during the impact, and that the soil water content is not changed after each impact. With these assumptions, only the very early stage of the rainsplash erosion process was consistently simulated. Therefore, improvements of the proposed approach are needed, and future research will add new insight to the encouraging results obtained in this paper.

References