Particle based method for shallow landslides: theoretical effect of sliding surface lubrification by rainfall

G. Martelloni, E. Massaro and F. Bagnoli

University of Firenze, Dipartimento di Energetica (CSDC – Center of the Study of Complex System), Via Santa Marta 3, 50139 Firenze, Italy.

University of Firenze, Earth Sciences Department, Via La Pira 4, 50121 Firenze, Italy.

Email: gianluca.martelloni@unifi.it

Dipartimento di Energetica "Sergio Stecco"

CSDC Centro Studi Dinamiche Complesse

Università degli Studi di Firenze

DEPARTMENT OF EARTH SCIENCES

CENTRE OF COMPETENCE OF THE CIVIL PROTECTION DEPARTMENT

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1) INTRODUCTION

Predicting natural hazards such as landslides, floods or earthquakes is one of the challenging problems in earthscience. With the rapid development of computers and advanced numerical methods, detailed mathematical models are increasingly being applied to investigate complex process dynamics such as flow-like landslides or debris flows. The term landslide has been defined in the literature as a movement of a mass of rock, debris or earth down a slope under the force of gravity. Landslides occur in nature in very different ways. It possible to distinguish landslides through two main parameters: material involved and type of movement. Landslides can be triggered by different factors but in most cases the trigger is an intense or long rain. Rainfall induced landslides deserved a large interest in the international literature in the last decades with contributions from different fields, such as engineering geology, soil mechanics, hydrology and geomorphology. In the literature, two approaches have been proposed to evaluate the dependence of landslide occurrence on rainfall measurements. The first approach is based on physics-based models and the second approach relies on the definition of empirical thresholds. For what concerns the simulation of the landslide propagation, most of the numerical methods are based on Eulerian continuous models, with an implicit representation of the discontinuities, where only the influence of some physical elements, such as deformability or strength, are considered through constitutive laws. An alternative to these continuous approaches is to use Lagrangian discrete-particle methods which represent the material as an ensemble of interacting elements (also called units, particles or grains). The model then explicitly reproduces the discrete nature of the discontinuities, which are represented as the boundary of each element. These methods are inspired by models of granular material, for which a discrete Lagrangian models is very near to their physical description. The resulting numerical method is similar to that of molecular dynamics. This approach is particularly suited for the inclusion of nonlinear elements such are instantaneous change of velocities, constitutive relations among different quantities, chemical reactions, etc. This flexibility was also exploited in the modelization of continuous material by means of "mesoscale" models (smoothed particle hydrodynamics or the mesoscopic lattice gas). A method widely used in the simulation of granular material dynamics is the so-called Discrete Element Method (DEM). DEM is very closely related to Molecular Dynamics (MD): the first method is generally distinguished by its inclusion of rotational degrees-of-freedom as well as stateful contact and often complicated geometries, while the second uses an interaction potential (for example Lennard-Jones potential). In this paper we present a model, based on MD theory, applied to the study of the starting and progression of shallow landslides, whose displacement is induced by rainfall. The main hypothesis of the model is that the static friction decrease as result of the rain: in this way the rain acts as a lubricant. Although the model is still schematic, missing known constitutive relations, its emerging behavior is quite promising. The results are consistent with the behavior of real landslides: the proposed model is particularly effective to modeling the evolution of the slow shallow landslides induced by rainfall. In our simulations can be observed emerging phenomena such as fractures and detachments. In particular, the model reproduces well the energy and time distribution of avalanches, analogous to the observed Gutenberg-Richter and Omori distributions for earthquakes. These power laws are in general considered the signature of self-organizing phenomena. As in other models, this self organization is linked to a large separation of time scales. The main advantage of these particle methods is given by the capability of following the trajectory of a single particle, possibly identifying its dynamical properties.

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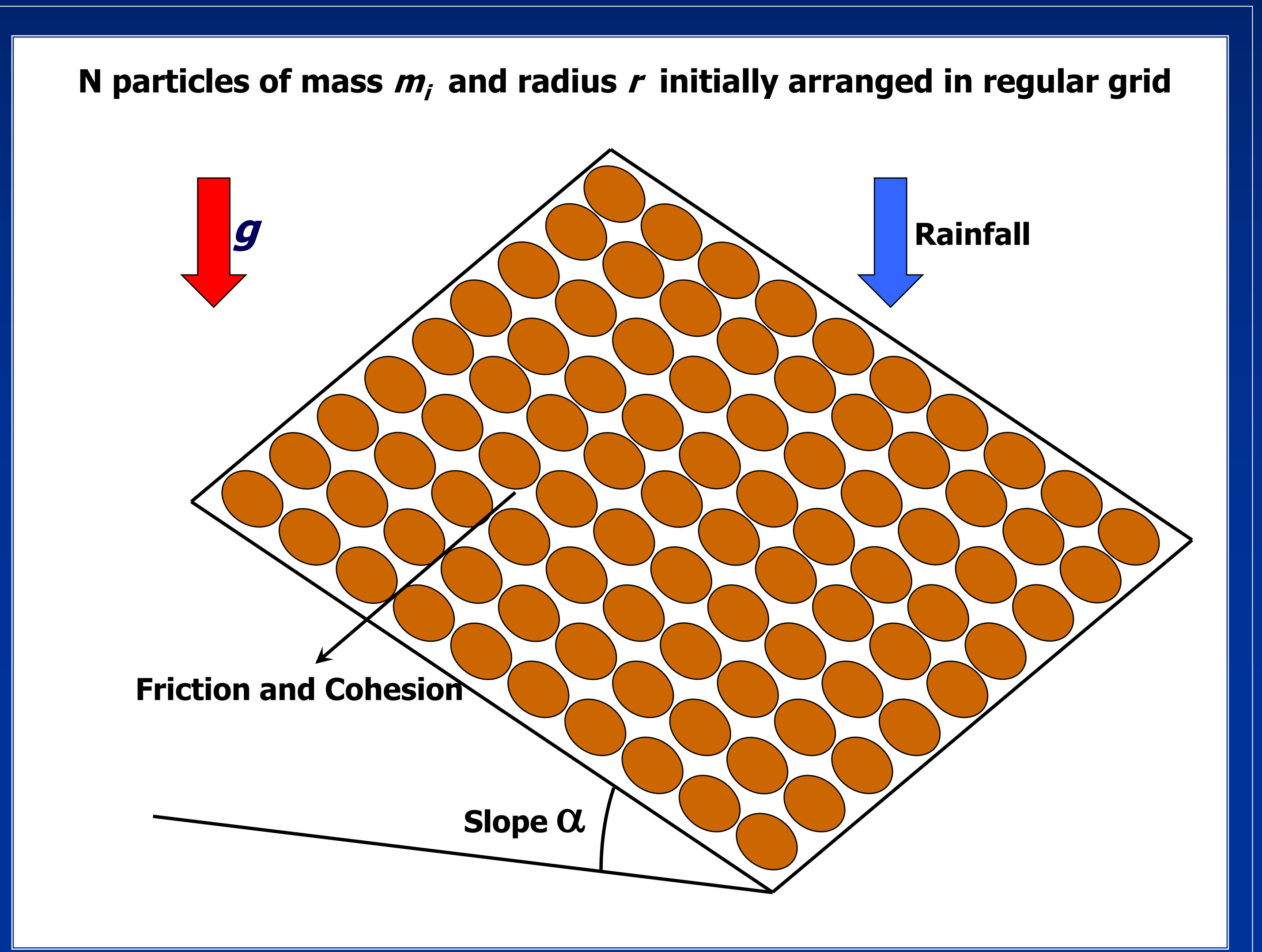
2) THE MODEL AND SIMULATION METHODOLOGY

In this work we limit the study to two-dimensional simulations along a slope, modeling shallow landslides. We consider *N* particles, initially arranged in a regular grid, all of radius r and mass m_i.

The idea is to simulate the dynamics of these particles during and after a rainfall. In the model the rain has two effects: the first causes an increase in the mass of particles, while the second involves a reduction in static friction between the particle and the surface below.

In the our model we want to find a trigger condition of the particle that is based on the law of Mohr-Coulomb in terms of effective stresses:

$$\tau_f = \sigma'_n \tan\phi' + c'$$



The Mohr-Coulomb equation is modeled considering the active forces (gravity forces along the slope plus contact forces in case of motion) as tangential stress, a theoretical force of static friction F_{si} as term of friction, while the cohesion is modeled by a random coefficient that depends on the position of the surface.

The irregularities of the surface are modeled by means of the friction coefficients, which depends stochastically on the position (quenched disorder).

$$\left|F_i\right| < F_{si} + C'_i$$
$$\left|v_i\right| < v_{static\_threshold}$$
$$v_{static\_threshold} \cong 0$$

Triggering static conditions on forces and velocities

$$F_{si} = (m_i + w_i(t)) \cdot g \cdot \cos(\alpha) \cdot (\mu_s \cdot \exp(-w_0 \cdot t) + \mu_{slow} \cdot (1 - \exp(-w_0 \cdot t)))$$
$$\mu_s(x,y) = \mu_0 + \frac{\mu_0}{\Delta} \cdot \sigma_\mu(x,y)$$
$$\sigma_\mu(x,y) = \sqrt{-2 \cdot \log(\sigma_1(x,y))} \cdot \sin(2\pi \cdot \sigma_1(x,y))$$

The time of landslides-triggering T_{primer} can be defined, for instance the time of the first moving block. In case of mass constant it is simple to obtain the trigger time theoretically.

$$T_{primer} = -\frac{1}{w_0} \cdot \log\left(\frac{\tan(\alpha) - \frac{C'}{m^* \cdot g \cdot \cos(\alpha)} - \mu_{slow}}{\mu_s - \mu_{slow}} \right)$$

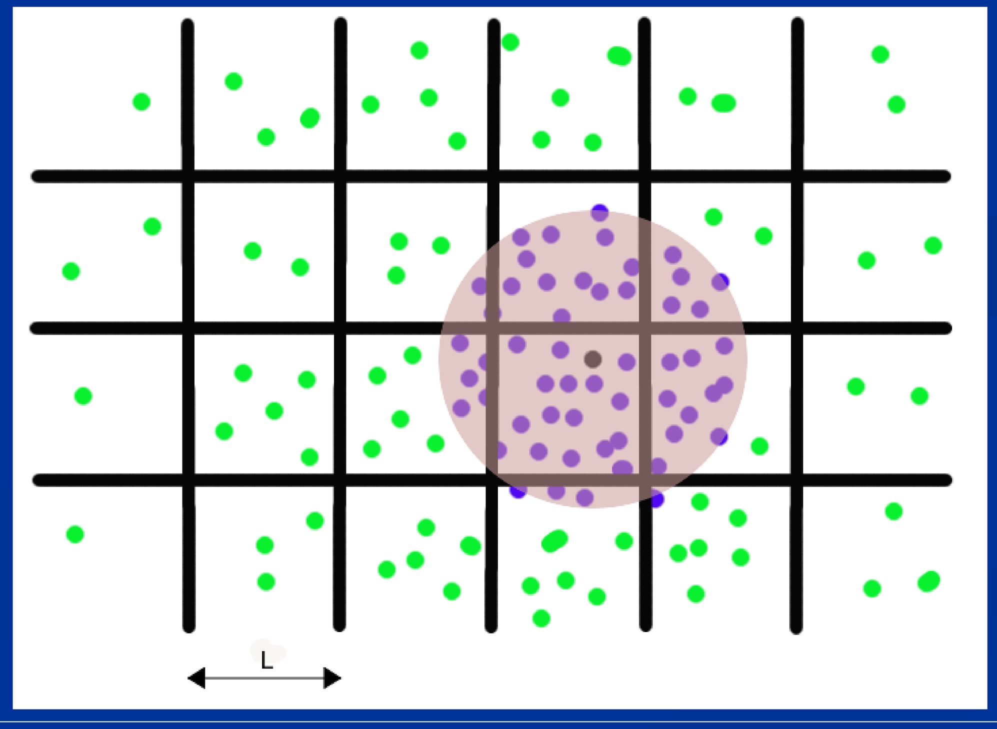
$$0 < \frac{\tan(\alpha) - \frac{C'}{m^* \cdot g \cdot \cos(\alpha)} - \mu_{slow}}{\mu_s - \mu_{slow}} \le 1$$

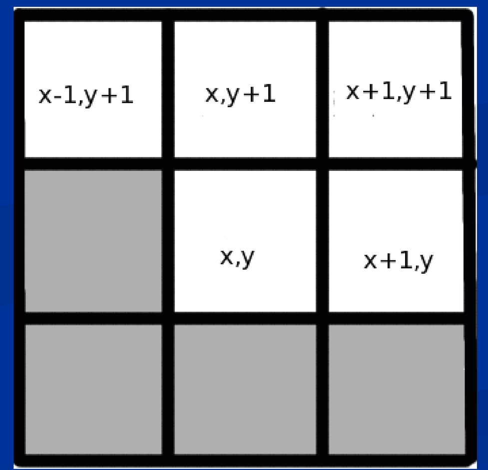
Dynamic conditions and computation technique

$$F_{ij} = -F_{ji} = -\nabla\left[\left(\frac{r}{L}\right)^{-12} - \left(\frac{r}{L}\right)^{-6}\right]$$
$$r = \left|r_{ij}\right| = \sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2}$$

The interaction force between two particles is defined trough a potential that, in the absence of experimental data, we modeled after the Lennard-Jones one.

Particles in the computational domain: the maximum radius of iteration defined in the algorithm is equal to the side L of the cell.

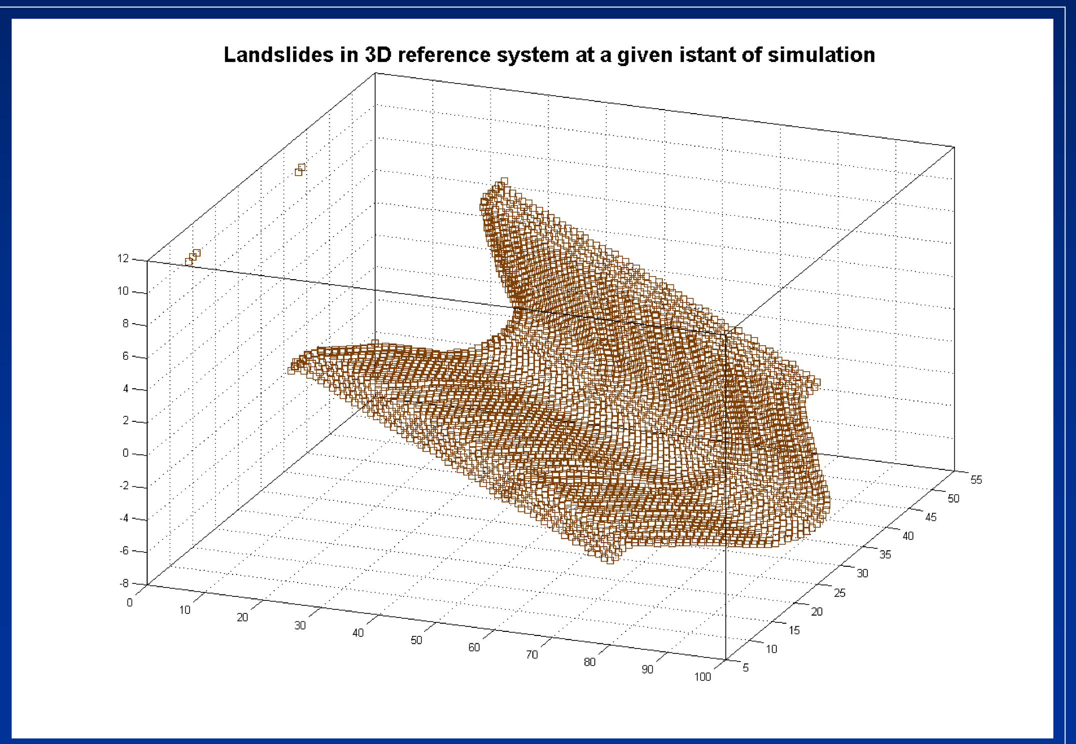




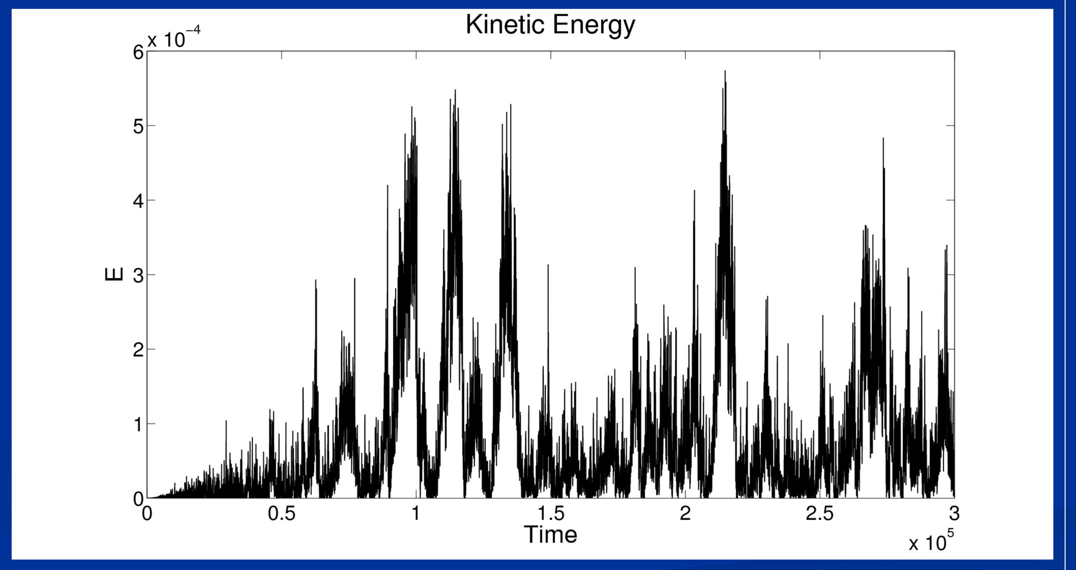
Cells considered when calculating the forces: if a particle is in cell (x; y),the interaction forces will be calculated considering only the particles located in white cells. This method halves the number of interactions because it calculates 4 cells instead of 8.

3) RESULTS

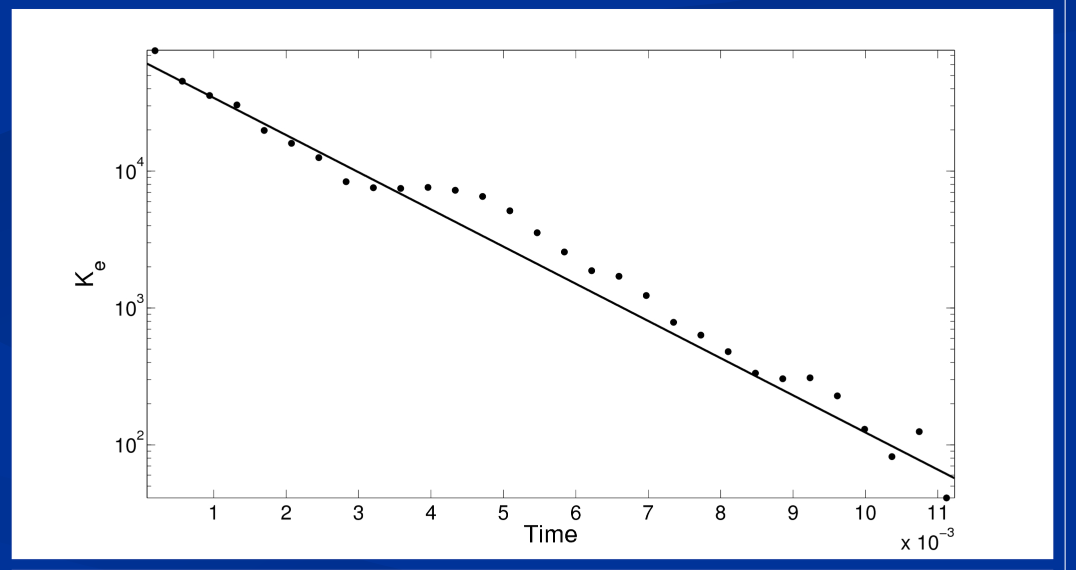
In our simulations, depending on the values of chosen parameters, we can observed deformations and fractures. The model is suitable for modeling the shallow landslides.



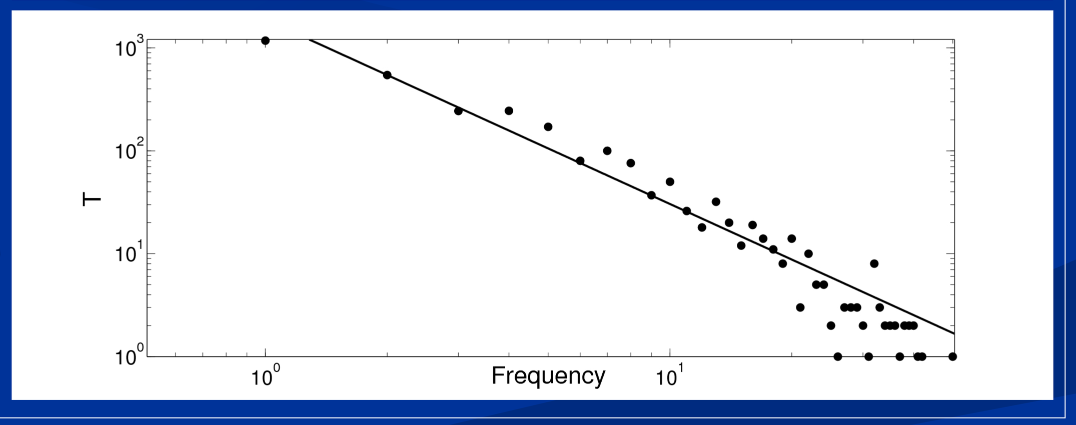
The observed kinetic energy in time shows a "stick-slip" dynamic: we suppose that the speed of the landslides is much bigger than the rain flux, so that the computation of sliding is performed without the rain contribution (i.e., instantaneously).



The distribution of the kinetics energy is well approximated by an exponential (*f(x)=a·exp(b·x)*, with *a*≈3.2 ·10⁴ and *b*≈-0.1042).



The statistical distribution of the intervals between single trigger times is well fitted by a power low (*f(x)=a·x^b*, with *a*≈691.1 and *b*≈-0.4295). Severeal authors have observed that some natural hazards exhibit a power low distribution



4) CONCLUSION

In this work the main hypothesis is that the rain acts as a lubricant between the sliding surface and the granular: this effect has been modeled by a preliminary study that includes the reduction of static (or dynamic) friction when we simulate the rainfall. The reduction in friction allows to follow the evolution and change in the position of the particles during and after a rainfall. The results obtained are very encouraging as regards both the displacement and evolution of the particles and in the statistical properties of the system. The next step will be to develop an experimental setup where granular material (sand or gravel) will be placed on a sloping surface: through liquid lubricant (soap and water) we will study the dynamics of these particles. The comparison of experimental and computational model will be very useful for the analysis of the effect of lubrication of the soil caused by rainfall.