Experimental and numerical analysis of impact forces on structures due to a granular flow

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Abstract

The paper presents the results of an experimental and numerical analysis aimed to clarify some aspects regarding the impact of a granular flow on structures. The experimental set-up comprises a flume equipped with a system of differently sized model obstacles, which are placed along the run-out trajectory to measure the impact force. The soil used for the small-scale model is a mono-granular medium sand, which was revealed to be particularly suitable the simulation of flows like debris or rock avalanches. The numerical analysis deals with the capability of a DEM code of predicting the experimental evidences. The most significant results of the measured impact forces versus time have been numerically reproduced by a Distinct Element Model (DEM), after the numerical model of the granular flow had been calibrated on the basis of the displacement measurements, obtained through a photogrammetric technique.

1 Introduction

The evaluation of the run-out distance of the slide material and of the impact force on structures during the occurrence of fast slope movements, such as rock avalanches or debris flows, still remains a problem of difficult solution. This is due to the inherent complexities of the nature of the material involved, the presence of water and the dynamic character of the process.

Reliable methods of prediction of such effects and prevention against natural phenomena are then in great need. For a successful risk analysis in this field, the use of numerical codes as predictive tools is assuming a growing importance. Recent advances in the use of numerical methods based on discontinuum modelling make the simulation of rock slope failure mechanisms and evolutions very appealing and promising. In particular, the Distinct Element Method (DEM)

proposed by Cundall and Strack [1], through the implementation in the PFC^{2D} code, has been demonstrated to be of great interest for the study of fast slope movements in terms of back analysis of past events [2][3].

The study of the evolution phase of a rock avalanche or a debris flow, if performed by using a DEM code, needs the calibration of some numerical parameters. The process of calibration can be successfully carried out only on the basis of experimental data and measurements [2], because of the difficulty in correlating such numerical parameters to any physical quantity.

For this reason, systematic laboratory experiments involving the motion of a finite mass of dry sand, flowing down an inclined plane, have been carried out. During each test the three-dimensional geometry of the mass profile has been recorded; displacements, velocities and impact forces against an obstacle, positioned along the run-out trajectory, have been measured. The observations and the derived data showed very useful for a direct quantitative comparison between an ideal experiment and the numerical simulation by the DEM.

2   Experimental tests

Laboratory experiments were carried out by using a small-scale physical model, which was intended to be an idealised scaled-down representation of typical large rock avalanches. In line with previous studies performed by some Authors, the material used in the model was chosen to be a sand, assuming that its behaviour is similar to that of a rock-avalanche [4].

The particulate medium employed was the Ticino sand, a mono-granular sand (d_{50} = 0.6mm) well characterized from a geotechnical point of view and previously adopted in a number of modelling studies. The sand bed, characterized by a relative density ranging from 40% to 80%, has been obtained by using the pluvial deposition technique.

2.1 Laboratory set-up

The experiments were performed in a 4 m long, 0.5 m wide Plexiglas-sided flume, which was made of two straight portions variably inclined to obtain different geometrical configurations. The sand was positioned in the upper part of the flume for 0.75 m in length and 0.1m in height. The granular mass was confined by a retaining shutter, consisting of an aluminium blade, which was able to rotate at a speed of about 12 rad/s around a rigid axle after removing a bolt, to give rise to an instantaneous trigger mechanism. Figure 1 shows the arrangement of the set-up. The roughness of the slowing surface was obtained by glueing a thin layer of sand of the same kind on a rubber sheet. The sidewall smoothness was kept small in an attempt to maintain the two-dimensional conditions as far as possible.

During each test, the initial and final geometrical configurations of the granular mass were well known and could be represented along a longitudinal middle section of the flume. The entire process was recorded also by a video-camera positioned on the side of the flume.
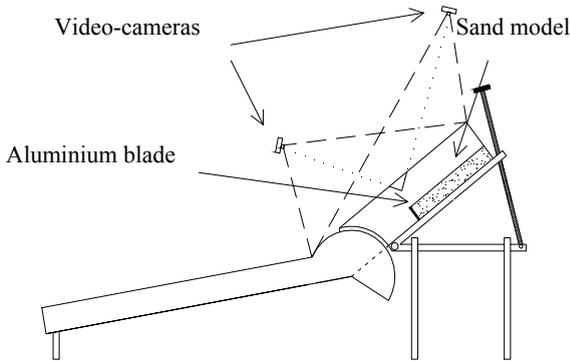
Figure 1:   Experimental set-up.

2.2 Measurement of impact forces

In order to investigate the impact behaviour of the material, two differently sized obstacles were constructed: the first one was a 7x5x5cm wooden parallelepiped [Figure 2a]; the second one was made of an aluminium thin plate, which occupied the entire flume section [Figure 2b]. In both cases the obstacle was fixed to a rigid small beam through a flexible aluminium strip, which was equipped with four strain-gauges. The instruments had been previously calibrated in order to correlate the force to the strip deformation, given by the corresponding difference of electric potential (voltage). The measurements were then determined with a frequency of 100Hz.
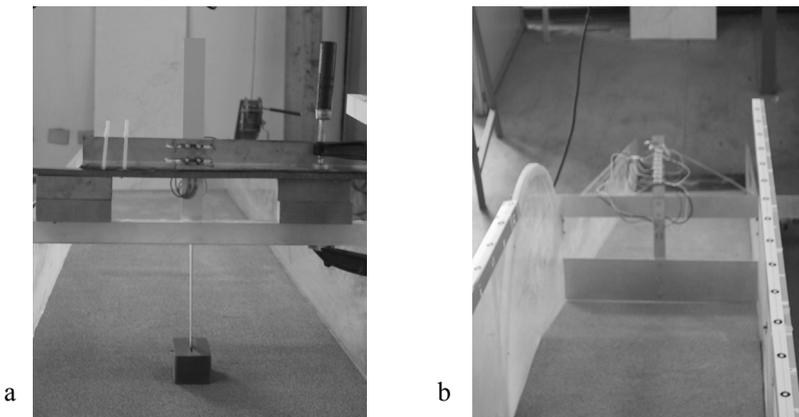

Figure 2:   Instrumented obstacles in the physical model.

A series of experiments were carried out by varying the slope of the flume and the relative density of the sand.
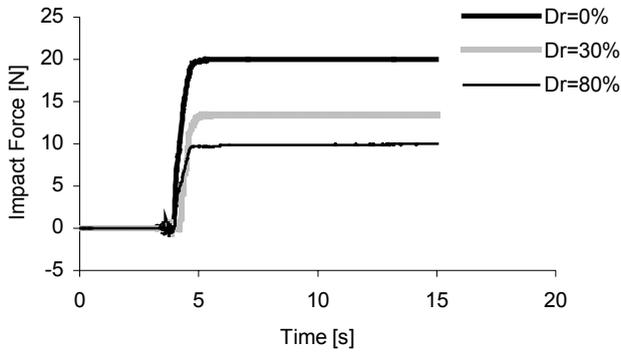
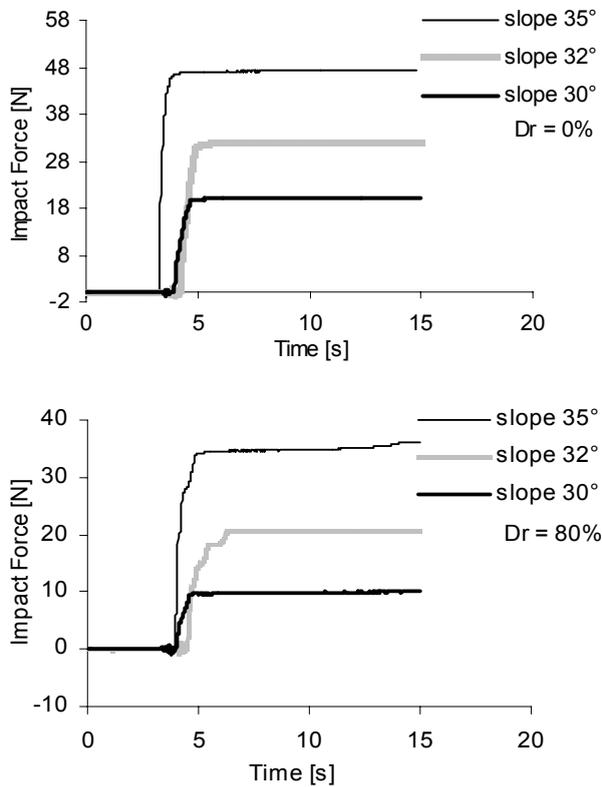Figure 3:   Impact force versus time for different values of D_r.

Figure 4:   Impact force versus time for different slopes, with fixed values of D_r.

The most significant results of the measured impact forces versus time, for an inclination of the flume equal to 30° and different relative densities of the sand, are reported in Figure 3. Figure 4 shows experimental results for different slopes of the flume, at fixed D_r values of the sand.

2.3 Measurement of displacements

Some tests were carried out to obtain measurements of displacements and velocities for the granular mass during the fast movement. To this purpose a photogrammetric technique has been set up: digital images, acquired during the flow experiment, allowed one to map the displacements of a great number of reference points in a precise and automated way.

The reconstruction of the displacement field of the flowing sand is obtained by identifying points belonging to different images. 176 plastic white spheres (targets) were positioned in an orderly way on the model surface by using a grid [Figure 5]. Each sphere, which was 6 mm in diameter, was grounded to the sand by means of a 10 mm long pin, in order to be integrated with the sand during the movement. A sharp colour contrast between the targets and the background was obtained by colouring the shallow sand with a black ink.
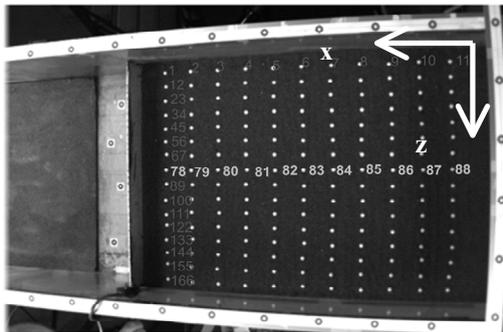

Figure 5:   Reference particles on the sand surface.

The target displacements were obtained by processing a series of frames acquired at a well-timed frequency. The reconstruction of their position was possible by using a couple of frames: the same view was caught at the same time by two video-cameras (Basler A101f – 1200x550 pixel – frame rate 22 fps), positioned above the flume to form an angle of about 90° [Figure 1].

The evaluation of the object coordinates corresponding to the target positions was based on a first analytical phase of video-camera calibration (interior and exterior orientation) and on a second phase of prediction and "least square matching", conducted for all the frames. To obtain the complete particle tracking, it was necessary to operate separately, but in the same way, on the two frame sequences [5].

The idealized tests have been carried out by using the flume inclined up to 25° with respect to the horizontal. Each test was repeated four times in order to evaluate its repeatability and to assess the validity of the corresponding measurements.

An example of three dimensional displacement measurements, obtained for targets n. 79 and n. 83 [Figure 5] is given in Figure 7, together with the numerical results. For each target, the object coordinates (x, y, z) referred to the system shown in Figure 2 (y is orthogonal to the flume bed) have been calculated: in this way, it was possible to draw velocity and acceleration, simply by applying classic kinematics relations.

3 Numerical modelling

To simulate the laboratory tests, the material parameters of the physical model have been transferred to the plane strain conditions, typical for the numerical model, with consideration given to the middle longitudinal section of the granular mass. A particular attention was given to the shape, dimension, number and mass of numerical particles. To represent the rough grains of the Ticino sand and the roughness of the flume bed, the numerical particles were modeled by using the clump logic available with PFC^{2D}. Also, due to the limited computing capacity available, the total number of particles that could be realistically used in a PFC^{2D} simulation was small in comparison with the actual number of particles in the physical model. The total number of single numerical particles has been derived on the basis of the known D_r value of the sand positioned in the flume, by considering the correspondence between the porosity of the Ticino sand and the porosity of the numerical material in the 2D model [5].

To obtain an overall unaffected mechanical behaviour, representative of the conditions holding true for the physical model, the mean radius of each numerical particle (r_m) was calculated to fulfil the relation $H/r_m > 40$, by assuming the thickness of the sand layer (H) to be the reference dimension of the problem. To reproduce numerically the granular flow under the effect of gravity, the equality between the mass and the potential energy in the physical model and the same quantities in the numerical model, has been obtained.

3.1 Mechanical and dynamic parameters

The appropriate values for the mechanical parameters of particle-particle and particle-wall contacts, such as spring stiffnesses ($k_n = k_s = 10^5$ N/m), have been determined by carrying out numerical biaxial tests on a unit volume element sized 10x10cm, composed of the same kind of particles. By applying four confinement stresses (0.5, 1, 2 and 3 kPa) of the same order of magnitude as those present in the physical model, the results led to a maximum stress ratio $\eta_{max} = 0.53$. This value, which is linked to the friction angle by the equation $\eta_{max} = \text{sen}\phi$, allowed to obtain $\phi = 32°$, i.e. the angle of the natural slopes of the Ticino sand that was experimentally observed and measured. The friction

coefficient μ (dimensionless) between particles is taken to be equal to 0.5 (i.e. the friction coefficient between two quartz surfaces).

A further element that revealed very useful to obtain a well calibrated numerical model was the comparison between two-dimensional images of the physical test and its numerical simulation, corresponding to the same time instant. As depicted in Figure 6, the geometrical configurations at the end of the test, in the two cases, compare remarkably well.
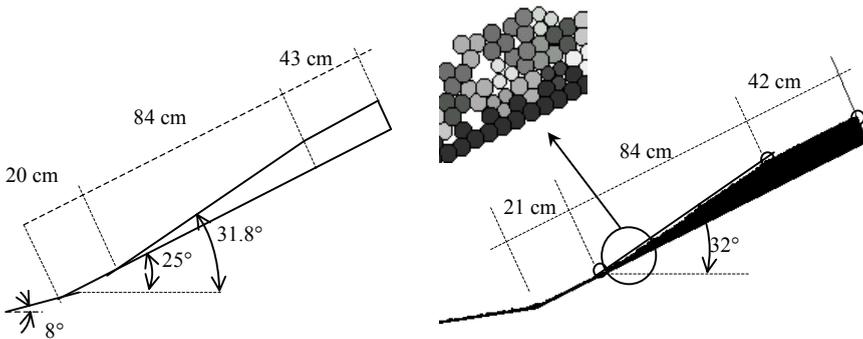

Figure 6:   Comparison between physical (a) and numerical model (b).

3.2 Numerical simulation of flume tests

The numerical simulation was carried out by starting with the initial model configuration as close as possible to that of the physical model. An equilibrium condition in the numerical model was reached with particle velocities of the order of 10^{-5}m/s. A total of 19500 elementary particles, bounded together to form 6500 clumps, were used. The mean radius of each elementary particle (r_m) was equal to 1.2 mm, ranging between 1.1 mm and 1.3 mm. The equivalent thickness of cylindrical particles was calculated to be equal to 0.34 m. In order to determine the radius and the number of particles, a two-dimensional porosity n=0.15 was assumed, which corresponded to a relative density of the sand equal to 50%.

The results of physical tests were compared with those obtained by the numerical model, also to be able to validate the procedures adopted and the parameters used.

This led to the calibration of the numerical damping (δ) which was finally assumed to be equal to 0.05. With this value holding true, the kinetic energy of the system resulted to be equal to zero 5s after the beginning of the event, as in the physical test.

3.3 Comparison between physical and numerical results

With the numerical model being two dimensional, only the targets positioned along the middle line in the physical model were considered. For clumps in the same position of the targets, the displacements referred to a fixed reference system and the corresponding velocities were calculated. The results obtained for

targets n. 79 and n. 83 only [Figure 2] are shown in Figure 7 (a, b) for displacements and in Figures 8 and 9 for velocities.
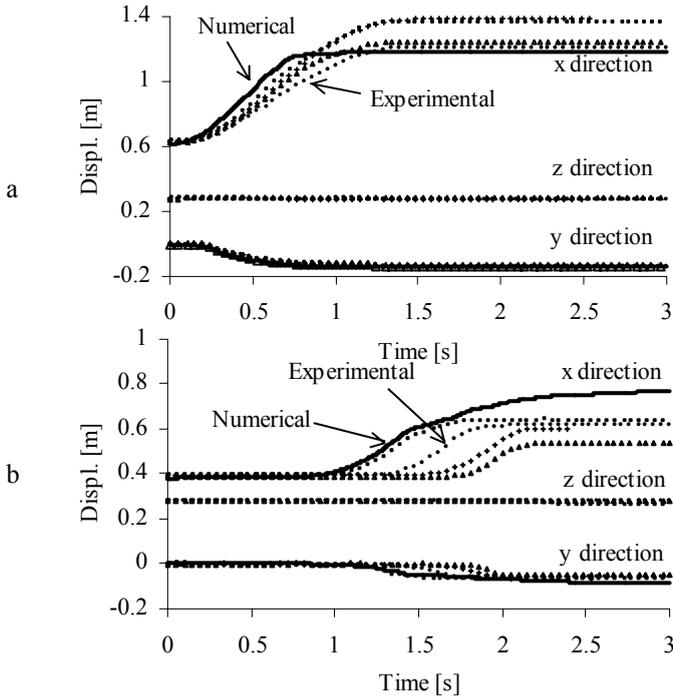

Figure 7:   Comparison between experimental and numerical displacements for target n. 79 (a) and target n. 83 (b).
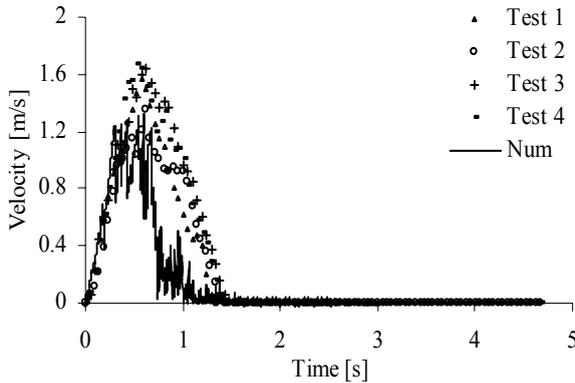

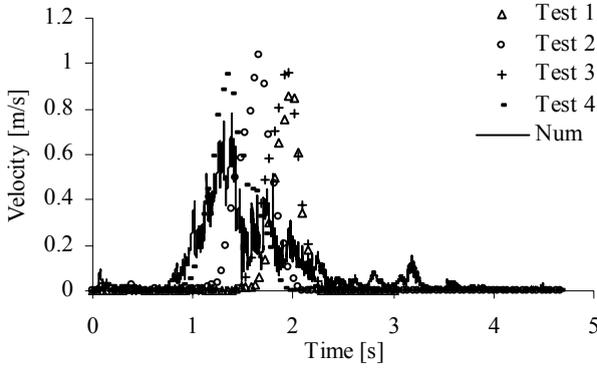Figure 8:   Comparison between experimental and numerical velocity for target n. 79.

Figure 9:   Comparison between experimental and numerical velocity for target n. 83.
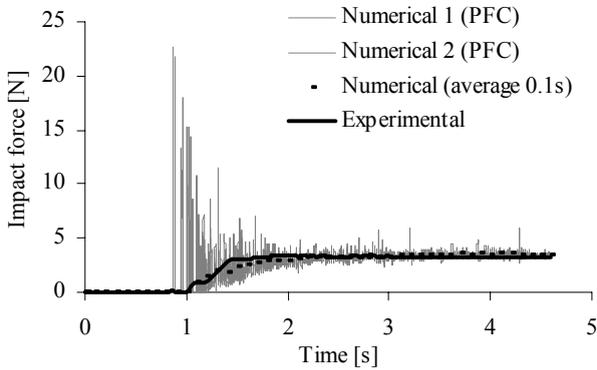

Figure 10:   Comparison between experimental and numerical impact force for the small obstacle.
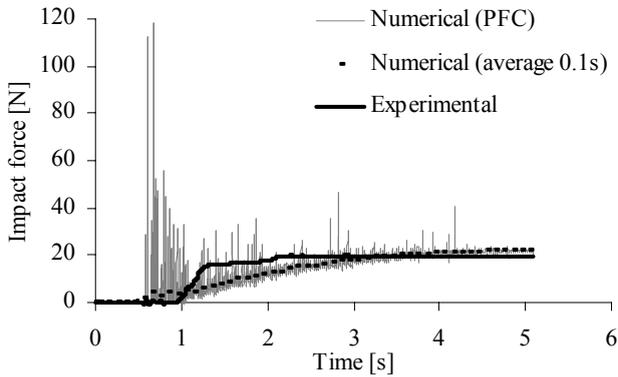

Figure 11:   Comparison between experimental and numerical impact force for the big obstacle.

Once the numerical parameters had been calibrated, a new numerical model reproducing the geometry of an impact test was created. In this case the flume was inclined up to 37° in the upper part and 8° in the lower one. Two tests were finally simulated and the impact force predicted. Figures 10 and 11 show the interesting comparison between the numerical and the experimental impact forces respectively on the small obstacle and on the bigger one.

The peaks of the numerical simulations are due to the distinct element behaviour and to the measurement of each single impact against the obstacle. It is sufficient to consider mean values of the impact force into time intervals equal to 0.1s to verify that a substantial agreement is achieved between the numerical and the experimental results.

4   Concluding remarks

Fast slope movements and impact forces on structures have been analysed by the Distinct Element Method (DEM). The difficulties in doing this deal with the determination of the parameters, which have to be introduced in the numerical model. Some indications on the link between experimental evidence and the numerical parameters can be obtained by comparing the results of numerical models with 1g model tests performed on dry sand, which is intended to simulate the granular flow in laboratory flume tests. This process of validation represents a start point for a successful numerical prediction of impact forces on structures, through DEM analyses, for a good design and for risk assessment.

References

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[4]   Davies, T.R. & McSaveney, M.J., Runout of dry granular avalanches. *Can. Geotech. J.* 36, pp. 313-320, 1999.
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