Experimental study of dam-break dry granular flows

STEFANIA EVANGELISTA, GIOVANNI DE MARINIS, CRISTIANA DI CRISTO, ANGELO LEOPARDI & LUCA GRIMALDI
Dipartimento di Ingegneria Civile e Meccanica
Università di Cassino e del Lazio Meridionale
via G. Di Biasio, 43, 03043 Cassino (FR)
ITALY
s.evangelista@unicas.it    http://www.docente.unicas.it/stefania_evangelista

Abstract: - This work presents some experimental results of dry granular flows produced by dam breaks. Granular flows have been the subject of several researches in the last years, not only in fluvial hydraulics and risk assessment and management but also in many other engineering applications (material stockpiling and freights, food manufacturing and industrial processes). It is interesting, for example, to investigate the fluid-like behavior of a granular material flow.

This research is aimed at giving a contribution in the comprehension of such phenomena through a campaign of small-scale laboratory experiments conducted in the Laboratory of Water Engineering (LIA) at University of Cassino and Southern Lazio, Italy. Tests have been performed with different initial sand heights and two different sands. They provided data available for the validation of numerical models, not only those describing granular flows, but also morphodynamic models adopted for the simulation of fluvial hydraulic processes by analyzing the behavior of the only solid phase.

Key-Words: - Granular Flows, Dam Break, Laboratory Experiments, Image Analysis, Debris Flows

1 Introduction

Dam-break flows have been widely investigated, from theoretical, numerical and experimental standpoints ([11], [2], [3]) especially in the clear water case ([4], [5]) but also in the presence of erodible bottoms, when sediment transport and bed evolution deeply affect the phenomena (e.g. [3], [6]). Dam breaks considering different fluids, sediment mixtures or granular materials have also been investigated (e.g. [7], [8]).

Granular flows have been the subject of several researches in the last years, since they are related to many engineering applications. Besides the classic interest in landslides and debris flows, natural large-scale events investigated in the fields of disaster prevention and risk assessment and management, granular flows constitute an interesting issue also in material stockpiling and freights, food manufacturing and industrial processes. Research on this topic is justified by a deep interest in better understanding lots of natural and men-induced phenomena. The dynamic behavior of a granular cluster depends on the peculiar characteristics of the moving material. Different rheological models have been adopted in order to reproduce the experimental evidences for different materials ([9], [10]).

It is interesting, however, to investigate the analogies in the evolution of waves arising from the fast opening of a gate trapping a fluid or granular material, and the possibility of applying the modeling approach adopted in the clear-water case to granular flows [11]. This aim motivates the present research.

Granular materials exhibit, in several physical phenomena, a fluid-like behavior, which is strongly dissipative due to friction and inelastic collisions. A first study in this field was conducted by [12], who investigated the behavior of spherical particles, in laminar, homogeneous and steady conditions, by means of a simplified conceptual model completed with experimental analyses.

Significant progresses in understanding the dynamics of granular flows have been made through the study of steady granular flows down a slope using depth-averaged equations and reproducing in different ways the effect of friction ([13], [14], [15]). As for transient cases, some experiments have been conducted with the instantaneous release of a stationary cylindrical column of dry granular
material on a horizontal plane ([16], [17]). Despite the complexity of the dynamics, simple scaling laws have been found to describe the final deposit configurations. Experimental investigations on two-dimensional dam breaks are reported in [18], [19] and [20] with different dry granular materials. [21] compared dam-break experiments realized with water, fluidized and dry granular flows, showing a water-like behavior of initially fluidized granular flows, with meaningful differences respect to the dry material.

Several attempts of modeling dry granular dam breaks, in which the main problem is related to the expression of resistances, have also been performed. In dry granular flows particle interactions, such as friction and collisions, are the dominant source of energy dissipation. [22] proposed a shallow-water model with a Coulomb-base friction stress and a pressure coefficient, which incorporates the effect of the internal material friction. [23] also proposed a shallow granular-flow model, in which resistance are assumed to derive from a Coulomb-like friction and a collisional stress.

In the present work, the behavior of a granular material in a transient situation on an horizontal surface is analyzed experimentally. In particular, cohesionless dry grains, without interstitial fluid effect, are considered.

A specific experimental campaign has been conducted in the Laboratory of Water Engineering (LIA) at University of Cassino and Southern Lazio, Italy. Small-scale laboratory experiments of dry granular dam breaks have been performed reproducing the sudden collapse by abruptly removing the retaining wall of the sand grains in a rectangular channel.

Different tests have been performed starting from different initial sand heights and using two different almost-uniform sands. The provided data will be available for the validation of numerical models, not only those describing granular flows, but also morphodynamic models adopted for the simulation of fluvial hydraulic processes by analyzing the behavior of the only solid phase. In fact, multi-phase flow modeling is a difficult task and several numerical models have been developed, for example, for sediment transport and bed evolution in unsteady river flows (e.g. [24], [25]). The robustness of such models is usually verified in clear-water conditions; conversely, in this article only the solid fraction is considered.

2 Laboratory device and test procedure
A set of small-scale laboratory experiments on dam-break of dry granular flows have been carried out in the LIA Lab in a horizontal rectangular channel with transparent walls. The granular material is trapped by a vertical fast-opening sluice gate, thus forming a 0.40-m wide and 0.50-m long reservoir (Figure 1). The sudden removal of the gate produces the dam break flow (Figure 2).

Two computer controlled cameras (with an acquisition frequency of 30 fps) are positioned frontally and at the top of the channel, respectively, in order to record the evolution of the phenomenon during each test. For each frame the flow depth profile along the channel and the front position are evaluated through a specifically developed image analysis technique [26].

![Figure 1: Sketch of the experimental equipment](image1)

![Figure 2: Sketch of the considered dam-break scheme](image2)
second one ("coarse sand" or "sand B") has a particle mean diameter of 1.60 mm, a solid density $\rho_s = 2560 \text{ Kg/m}^3$, and an internal friction angle of 41°.

More details about the experimental setup and procedure are reported in [23] and [27], in which, however, only the "fine sand" is considered.

Four tests for each sand are here examined, with an initial height $H_0$ in the reservoir varying from 0.20 m to 0.50 m, so that the reservoir height-to-base aspect ratio $r = H_0 / L$ is in the range 0.3-1.0 (Table 1).

<table>
<thead>
<tr>
<th>TEST</th>
<th>Sand</th>
<th>$H_0$ [m]</th>
<th>$L$ [m]</th>
<th>$r$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>A</td>
<td>0.20</td>
<td>0.50</td>
<td>0.4</td>
</tr>
<tr>
<td>A2</td>
<td>A</td>
<td>0.30</td>
<td>0.50</td>
<td>0.6</td>
</tr>
<tr>
<td>A3</td>
<td>A</td>
<td>0.40</td>
<td>0.50</td>
<td>0.8</td>
</tr>
<tr>
<td>A4</td>
<td>A</td>
<td>0.50</td>
<td>0.50</td>
<td>1.0</td>
</tr>
<tr>
<td>B1</td>
<td>B</td>
<td>0.20</td>
<td>0.60</td>
<td>0.333</td>
</tr>
<tr>
<td>B2</td>
<td>B</td>
<td>0.30</td>
<td>0.60</td>
<td>0.5</td>
</tr>
<tr>
<td>B3</td>
<td>B</td>
<td>0.40</td>
<td>0.60</td>
<td>0.667</td>
</tr>
<tr>
<td>B4</td>
<td>B</td>
<td>0.50</td>
<td>0.60</td>
<td>0.833</td>
</tr>
</tbody>
</table>

Each test has been repeated three times in order to verify the reproducibility of the experiments.

The front position is detected from the analysis of the images recorded from the top of the channel (Figure 3). The longitudinal depth profile is reconstructed from the frontal camera.

An automatic procedure making use of preprocessing and edge-detection tool software, for the fast and objective process of a great number of images, has been set up.

Numbered regular grids are attached on the frontal wall and on the channel bottom, in order to permit proper rectification and scaling of the recorded images and, consequently, a correct measurement operation.

In this way the evolution of the time- and space-dependent processes can be properly evaluated.

For all tests, images reveal also no significant wall effects on the depth, which is rather constant in the cross section, thus confirming that the flows are fairly two-dimensional and the assumption of a 1-D framework is acceptable: the longitudinal section detected from the images on the transparent front sidewall can be assumed as representative of any other longitudinal section in the flow.

3 Experimental evidence

For all the performed tests, the column of sand collapses with a gradual transition from relatively-slow fracture planes, along which the grains slide down. A surface wave propagates backward in the reservoir and the backward front stops before reaching the reservoir upstream boundary, leaving a portion of mass that does not move. The wave propagating downstream stops when, at some point, a sand layer at contact with the bottom comes to a halt due to friction. As also observed by other authors (e.g. [15]), shock waves form, which bring the granular material to rest. The downward propagating wave is similar to the one that can be observed in a fluid dam break; however, in that case, the fluid keeps flowing towards the flume outlet, while for the sand the avalanche stops by friction when it reaches the bottom (or, more generally, a solid wall). In this moment, another wave is initiated, which propagates upslope, in a way that the material below the shock is at or near rest, whilst the grains above the shock flow rapidly downslope.

The flow always forms a final deposit whose longitudinal extent is lower than the channel length. While the final front position is clearly defined, the final runoff is more ambiguous. In fact, it is observed that after the collapse, when the slump comes to rest at the upward front, the backward wave still propagates in the channel. Material continues to adjust by avalanche of superficial layers (secondary movement), which decrease the upper surface slope until equilibrium is reached.

The final upward front positions $x_{sf}$ and its stopping time $t_{sf}$, as well as the total time $t$, at which also the secondary movement is concluded, are reported in Table 2 for all the tests. The front...
position is evaluated starting from the gate position, assumed as the origin of the abscissa \( x \).

**Table 2:** Experimental data for the final configurations: front position \( x_{sf} \), stopping time \( t_f \) and total time \( t_t \) for all tests

<table>
<thead>
<tr>
<th>TEST</th>
<th>( x_{sf} ) [m]</th>
<th>( t_f ) [s]</th>
<th>( t_t ) [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.263</td>
<td>0.600</td>
<td>1.933</td>
</tr>
<tr>
<td>A2</td>
<td>0.388</td>
<td>0.733</td>
<td>3.133</td>
</tr>
<tr>
<td>A3</td>
<td>0.518</td>
<td>0.900</td>
<td>3.666</td>
</tr>
<tr>
<td>A4</td>
<td>0.608</td>
<td>1.033</td>
<td>4.000</td>
</tr>
<tr>
<td>B1</td>
<td>0.278</td>
<td>0.633</td>
<td>1.067</td>
</tr>
<tr>
<td>B2</td>
<td>0.388</td>
<td>0.767</td>
<td>1.267</td>
</tr>
<tr>
<td>B3</td>
<td>0.518</td>
<td>0.867</td>
<td>1.567</td>
</tr>
<tr>
<td>B4</td>
<td>0.631</td>
<td>1.067</td>
<td>1.867</td>
</tr>
</tbody>
</table>

Figure 4 shows for both sands and an initial depth \( H_0 \) equal to 40 cm (tests A3 and B3) the longitudinal profiles of the sand, respectively, at the front stopping time \( t_f \) and in the final configuration, i.e. at time \( t_t \), which is the total duration of the phenomenon. It can be noticed that the difference between the two profiles is more evident for sand A, for which the above-described effects of the secondary movement are more important.

A more detailed analysis of the experimental data for sand A, also using scaling results, is reported in [23], [27] and [28].

Figure 5 reports the same comparison between the longitudinal profiles of both sands, respectively at the front stopping time \( t_f \) and at the final time \( t_t \), for all the values of initial sand height \( H_0 \). It can be noticed that generally the coarse sand front is slightly advanced respect to the fine sand one. In addition, the difference between curves corresponding to different sands at equal values of \( H_0 \) is smaller in the final configuration respect to the one observed at front stopping time \( t_f \). At time \( t_t \) the two curves are almost coincident.

It is also worth of noting that, for each test, in the final configuration three different profile zones can be identified (Figure 6), differing from each other on the different values of the slope angle. Specifically, the final part presents a clear reduction of the slope value downstream of the gate respect to the repose angle value. This observation shows that the final configuration is not the equilibrium bank profile, but it depends on the dynamics of the phenomenon.

**Fig. 5.** Comparison between profiles for sands A and B at stop front and final configuration, respectively, for the entire set of tests.

Table 3 reports the different slope values measured for the three zones, starting from upstream, for each sand. The slope average is lower than the internal friction angle of the material for both sands, as a consequence of the dynamic effects of the phenomenon.
Table 3: Measured longitudinal slope angles for each test

<table>
<thead>
<tr>
<th>TEST</th>
<th>$\phi_1$ [°]</th>
<th>$\phi_2$ [°]</th>
<th>$\phi_3$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>28</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>A2</td>
<td>31</td>
<td>23</td>
<td>12</td>
</tr>
<tr>
<td>A3</td>
<td>29</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>A4</td>
<td>30</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>B1</td>
<td>31</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>B2</td>
<td>32</td>
<td>26</td>
<td>11</td>
</tr>
<tr>
<td>B3</td>
<td>31</td>
<td>26</td>
<td>9</td>
</tr>
<tr>
<td>B4</td>
<td>30</td>
<td>26</td>
<td>11</td>
</tr>
</tbody>
</table>

For a better interpretation of the results, the main characterizing quantities may be considered in a dimensionless form. In particular, the following dimensionless variables are defined:

\[
X = \frac{x}{H_0} \\
H = \frac{h}{H_0} \\
T = \frac{t\sqrt{g}}{H_0}
\]

In Figure 7 dimensionless front position $X_{f0}$ is plotted as a function of dimensionless time $T$.

The trend of front position to progress faster for sand B than for sand A, especially at the beginning of the process is highlighted.

Dimensionless longitudinal profiles ($H$ versus $X$) are plotted separately for sand A and B, respectively, first at time $t_f$ (Figure 8) and then at time $t_t$ (Figure 9).
In these diagrams curves appear to collapse into the same curve. The final values of dimensionless wave front position is almost the same for all tests and can be estimated equal to about $X_d = 1.25$. The values of the final upstream front positions are also the same and about equal to $X_u = -0.84$. In addition, time at which the process ends in almost the same for all tests and can be assumed equal to $T = 4.3$, although this is more an average value, being quite evident the difference between the various tests.

Figure 8 also highlights the self-similarity of longitudinal profiles at the front stopping time and at the end of the phenomenon. This self-similarity is better achieved for sand B. This is in agreement with the physical intuition that, if solid particles are big and smooth enough, the granular matter exhibits a fluid-like behavior.

4 Conclusions
In this work small-scale experimental results of dry granular flows produced by dam breaks have been presented. Tests have been conducted on two different kinds of almost-uniform sands, starting from different initial sand levels in the reservoir. Longitudinal sand profile and wave front positions have been evaluated for each tests at different times through an ad-hoc image-analysis procedure. Results highlighted the existence of a secondary movement which affects the phenomenon evolution. It is more evident for the finer sand. The longitudinal profile slope is on the average smaller than the sand internal friction angle for both materials, due to the dynamical effects characterizing the process. The coarser sand, for the same initial depth in the reservoir, shows a faster progress with time. A self-similarity of final longitudinal profiles is also observed, especially for the coarser sand. Moreover obtained experimental results dataset could be used for validation of numerical models of granular matter flows.

References:
[17] Lajeunesse E., Mangeney-Castelnau A., & Vilotte J.P., Spreading of a granular mass on a


