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Stick–slip motion and high speed ejecta in granular avalanches detected through a multi-sensors flume

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ABSTRACT

An oscillatory motion of dense, dry granular flows is experimentally observed by means of a 5.5 m-long densely instrumented flume. An array of 35 sensing devices allowed recording kinematic and dynamic data of the entire flow with high spatial and temporal resolution. Dynamic data, in addition to the kinematics, provide valuable information to unveil stick–slip motion that is proposed as the triggering mechanism for the appearance of periodic changes in compaction of the granular material called density waves. Periodic reverse graded strata after deposition of the flow accounts for such density waves. Besides, internal interactions between different parts of the avalanche, lead to the ejection of material and a high peak of the avalanche front velocity — or an "abnormal acceleration" — at the break slope and ejection of rocks from the flow was systematically observed, evidencing internal interactions among different parts of the avalanche body while descending the inclined plane. The velocity peak registered at the break in slope is interpreted as complementary evidence of these internal collisions and a non perfect inelastic-collision simple model is assumed in order to explain the counter-intuitive acceleration observed during the ejection process. High speed ejection at the break in slope, stick–slip, and expulsion from the flow are robust, ubiquitous phenomena which do not strongly depend on the granulometric distribution used.

1. Introduction

Granular flows differ significantly, both from the experimental and theoretical point of view, from the flow of a viscous liquid (Jaeger et al., 1996). In spite of continuous models widely used in simulations, a set of equations (analogous to Navier–Stokes equations) that can fully describe the behavior of a dense granulate flowing down an inclined plane is still lacking (Oda and Iwashita, 1999 pp 86–132). The behavior of a granular flow depends on energy dissipation rates due to the particle–particle interaction, which is dominated by friction, particle shape, density, size, hardness and roughness. Other important factors include the local geometry of channels through which they flow, such as surface roughness, slope and topography (Forterre and Pouliquen, 2008; Pouliquen et al., 2006). Moreover, flow changes dramatically, due to the presence of some interstitial fluid (gas, water), inherent segregation processes (Ottino and Khakhar, 2000), particle fragmentation or abrasion (Davies et al., 1999) or the presence of obstacles (Amarouchene et al., 2001). Furthermore, Coulomb friction, which is responsible for large energy looses, can affect the flow due to arch formation, clogging or local Reynolds dilatancy, among other important phenomena. Coulomb friction between two grains pushing against each other produces elastic deformation of particles (accumulating potential energy in the process), until a critical stress is reached, static friction yields and particles surfaces slide. Thus, potential energy is liberated as kinetic energy, which in turn will be dissipated due to dynamic friction, bringing the motion to a stop and producing an intermittent motion when this cycle starts again. This general behavior, produced when two internal parts of a discrete system interact with each other, is called stick–slip motion and can be found at very small scales in the squeaking of a door's hinge (high frequency) or at very large scales in an earthquake (low frequency), when two tectonic plates slide on each other (Scholz, 2002). Since internal interactions among grains within a dense granular flow are complex and difficult to observe, there is still an open question on how these internal interactions affect the flow. Likewise, kinematics and dynamics of the center of mass of the avalanche do not obey a simple model of a solid block sliding down with Coulomb friction, sometimes used to estimate an avalanche run out. On the other hand, in geological and planetary sciences, accumulation of gas pressure in volcanic eruptions or sudden momentum transfer in impact cratering, leads to matter ejection. In granular materials, the ejection of jets traveling at speeds higher than the object that produce them has been reported due to a sudden collapse of the void formed during the penetration of a hard object into a very loosely compacted sand (Lohse et al., 2004). In this way, internal collective

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motions within a granular medium can produce acceleration on part of the medium at expenses of the momentum of some other regions (van Gassen and Cruden, 1990).

Dense granular flows, such as landslides, avalanches, pyroclastic flows, and other mass waste processes, are ubiquitous geological phenomena that represent important hazards to populations around the globe and, nevertheless, remain poorly understood. In this context, a still open debate on the origin of a runout of natural rock avalanches larger than predicted by Coulomb frictional models had put forward several theories in order to explain such discrepancies (Manzella and Labiouse, 2009; Yang et al., 2011 and references therein). Internal interactions among constituent particles of the flow have been described theoretically by van Gassen and Cruden (1990) and could lead to anomalous acceleration of the avalanche front described in this work and also detected by Manzella and Labiouse (2009). However, broadening the current knowledge on the development and deposition of granular flows requires gathering complete kinematic and dynamic data, together with extended imaging along the whole experimental runway, using flume lengths that allow dilation, segregation, formation of density waves, defined as periodic changes on the packing fraction of the grains (e.g. Baxter et al., 1989; Jaeger et al., 1996), and stratification processes. In this context, several experimental flumes have been reported in literature, each one with different mechanical structure and dimensions (channel or open frame) with fixed or variable slope, number and type of available sensing devices, etc. The largest of such setups is a channel measuring 90 m long and 2 m wide with a fixed slope (Iverson, 2003) that worked with wet flows allowing the comparison against continuous theoretical models of the global flow behavior. Many other groups developed a few meters long and variable slope flumes, whose experimental results revealed velocity gradients of the granular flow (e.g., Forterre and Pouliquen, 2008; Sulpizio et al., 2014), the effect of erosion (e.g. Chen et al., 2006), the role of different grain size mixtures on the runout (e.g. Kokelaar et al., 2014), pore pressure variations (e.g. Okada and Ochiai, 2008), different friction coefficients and shear stresses (e.g. Pouliquen and Forterre, 2002; Rowley et al., 2011) or flow velocity (Yang et al., 2011) and initial structure of the granular pile as consequences on the flow development and deposition (e.g. Manzella and Labiouse, 2013). In all cases, experimental data, numerical models and natural phenomena show good agreement (e.g. Bursik et al., 2005; Crosta et al., 2003; McClung, 1990). All this experimental efforts focus on the global behavior of the moving avalanche body as if it were a continuous fluid. However, the discrete nature of the flow produces very different phenomena at the length scales on the same order of grains (microscopic) and triggers different events at the whole flow scales (macroscopic).

In order to evaluate real risks associated to geophysical granular flows, we need to better understand the subtle internal interactions between grains inside the flow, which have large consequences on the global flow behavior from experimental, numerical and theoretical perspectives.

The purpose of this paper is to analyze experimentally the development of the avalanche and the intermittent behavior of the granular flow, which leads to segregation, pulsed deposition and rock ejection events by means of high spatial and temporal resolution measurements in a densely instrumented flume.

2. Description of the experimental flume

The instrument was developed at Universidad Autónoma de San Luis Potosí, "Laboratory of Image Analysis and Analog Modelling", to simulate geologic granular flows, both dry and wet. Its aim is to fully describe the formation, development and deposition of the granular flow, from kinematic, dynamic and particle interaction parameters. This experimental facility allowed us to address some limitations of previous laboratory-scale experiments due to a conspicuous amount of sensors of different type installed, the ability to continuously adjust the slope of the flume and deposition area (mimicking in a more realistic way a natural landscape), and the usage of a great quantity (up to 50 kg) of both natural or artificial particles. Maintaining all the variables under strict laboratory control, we can provide good insight into the physical phenomena involved during the development and deposition of the avalanche.

An overview of the system is shown in Fig. 1. It consists of a supporting tower, a hopper, a flume, and a deposition unit. The flume is 5.5 m long and 0.3 m wide and fully waterproof, with transparent tempered glass walls. The flume slope can be adjusted, continuously, from 0° to 40°. The granular material is loaded into a PVC hopper, 20 cm × 20 cm × 90 cm, capable to contain up to 50 kg of material, depending on its density and packing fraction. The material travels along the flume until it finally deposits on a plane-floor, transparent-wall sedimentation unit, 1.2 m wide and 2.4 m long. Depending on the type of experiments, it is possible to confine the deposit between glass walls. The sedimentation unit can also be inclined at different slopes from 0° to 20°.

The electronic system, specifically designed, comprises 15 programmable instrumentation amplifiers connected, as needed, to 5 load cells (called LC1 to LC5, hereafter), in order to measure load and pressure exerted by the granular material, and 14 laser optical interrupters (called D1 to D14, hereafter), which allow to measure kinematic parameters of the flowing material. In addition, there are 3 microphones and 8 piezoelectric sensors to record sound and vibrations related to collisions between grains, these sensors are not used in the experiments reported in this paper because they do not give useful information about the kinematics of the granular flow. Sensor data is collected by means of two 16-channels, analog acquisition cards (Measurement Computing model USB-1608GX-2AO and National Instruments model NI USB-6211), with a resolution of 16 bits and a sampling rate up to 15,625 samples per second per channel. Data transfer and acquisition cards control

Fig. 1. General view of the flume installed on the roof of the Geology Institute of the UASLP.