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Shaking of pyroclastic cones and the formation of granular flows on their flanks: Results from laboratory experiments

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ABSTRACT

We have carried out laboratory experiments to study the generation of granular flows on the slopes of pyroclastic cones that are experiencing volcanic tremor or tectonic earthquakes. These experiments are inspired by the occurrence of granular flows on the flanks of Mount Vesuvius during its 1944 eruption. Our laboratory model consists of sand cones built around a vibrating tube which represents a volcanic conduit with erupting magma inside. A video camera allows the study of the granular flow inception, movement and deposition. Although the collapse of the entire cone is obtained at a specific resonance frequency, single granular flows can be generated by all the vibration frequencies (1–16 Hz) and all the vibration amplitudes (0.5–1.5 mm) that our experimental apparatus has allowed us to adopt. We believe that this is due to the fact that the energy threshold to trigger the flows is small in value. Therefore, if this is true in nature as well, shaken pyroclastic cones are always potentially dangerous because they can easily generate flows that can strike the surrounding areas.

1. Introduction

Volcanoes are well known to be structures that are inherently unstable because they are built by rapid accumulation of rock material which can develop into rock avalanches and debris flows (e.g., Siebert et al., 1987; Scott et al., 2001) as well as small-scale grain flows (e.g., Sohn and Chough, 1993). The instability of volcanoes is increased by the fact that they are usually chemically altered and dissected by faults (Merle et al., 2008). In this paper, however, we show that also unaltered pyroclastic cones which are not weakened by faults or fractures can generate instabilities when shaken by volcanic tremor or tectonic earthquakes. These instabilities consist of dry granular flows (whose mechanics is therefore dominated by particle interactions of collisional and frictional nature) which travel on the surfaces of the cones. These flows are not due to volcanic dome explosions or eruptive column collapses such as the pyroclastic flows (e.g., Cas and Wright, 1988) which draw most of the attention in volcanology.

Dry granular flows have been generated, for example, on the flanks of Mount Vesuvius (Italy) during the cone formation in 1944 as a result of syn-eruptive seismicity (Hazlett et al., 1991). Syn-eruptive ground shaking is caused by magma activity within the volcanic conduit and it is usually characterized by a relatively narrow band of frequencies with values smaller than 10 Hz and amplitudes that can span seven orders of magnitude (McNutt, 1992). On Vesuvius, in 1944, the tremor is known to have increased during the lava fountain phase of the eruption with the increase of the gas discharge rate (Pappalardo et al., 2014). Usually, as the violence of the eruption increases, the amplitude of the vibrations becomes larger (McNutt, 1992). The Vesuvius cone is ~300 m high and it is located at the top of the much taller Mount Somma, Italy (Santacroce and Sbrana, 2003). Fig. 1 shows that virtually all flanks were affected by granular flows. These flows are not deep sector collapses because they travelled on the cone surface without dissecting the internal structures of the cone. They have left long finger-like deposits at the base of Vesuvius and erosive scarps at the top (Fig. 1).

Hazlett et al. (1991) describe the two types of flows on Vesuvius that are shown in Fig. 1: they are ash flows which consist of ash with comminuted scoria and block-and-ash flows with up to ~20% of blocks dispersed in ash. By definition, ash is <2 mm in grain size and blocks are >64 mm in grain size. In Fig. 1, the longest flow deposit is 1.3 km in length, but most are less than half this long. Lobe widths range from a few tens of metres to several hundred metres. The thickness is larger at the front of the deposits with typical values between 20 and 30 m. Levees are present. Fig. 2 shows the front of a flow deposit where block-size rock fragments are clearly visible.

Similar granular flows are not a rare occurrence in nature. For instance, a flank failure originated a hot granular flow (resembling a pyroclastic flow) at the top of Mount Etna (Italy) on February 11, 2014 (www.ct.ingv.it). This phenomenon took place during a Strombolian activity with

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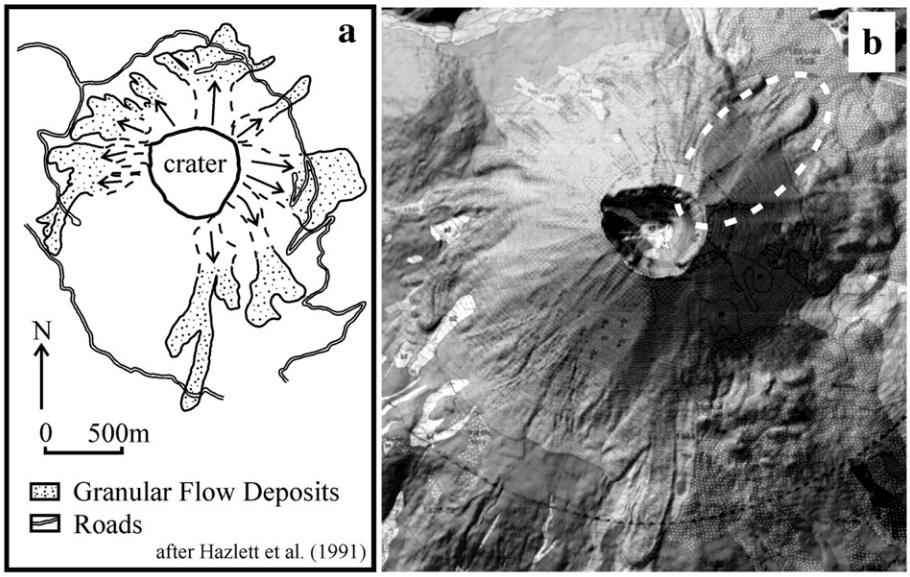

Fig. 1. Granular flows on Mount Vesuvius: (a) after Hazlett et al. (1991) and (b) as shown by a digital elevation model. The dashed ellipse highlights the hourglass shape of the combined outlines of an erosive scarp and the associated flow deposit.

ongoing volcanic tremor and it was due to the instability of accumulated scoria fragments. In 1930, also Stromboli volcano (Aeolian Islands, Italy) generated hot density currents that were the consequence of syn-eruptive failures of rapidly accumulated pyroclasts (Di Roberto et al., 2014). This example is noteworthy for future hazard assessments on Stromboli because the 1930 flows travelled within valleys distinct from the Sciara del Fuoco collapse scar that is the usual uninhabited path (e.g., Tommasi et al., 2008) for landslides and lava flows on the island. Flows on an island can also trigger tsunamis when they enter the sea.

In this study we explore experimentally the effect of vibrations on the generation of superficial granular flows on the flanks of laboratory sand cones that model natural pyroclastic cones. We are not aware of other experiments in the literature which focus on the geological meaning of similar granular flows. For example, Tibaldi (1995), in his laboratory experiments, was interested in pyroclastic cone formation and the interaction of the cones with faults. Merle and Borgia (1996) carried out experiments with sand cones where their instability is induced by the deformation of the substratum. Acocella (2005) studied deep sector collapses of laboratory sand cones due to faults, erosion, rapid accumulation of material and volcanic intrusions. The stability of vibrated granular slopes in the laboratory has been investigated, for example, by Katz and Aharonov (2006), but the geometry of their slopes (planar) and that of their instabilities (deep slope deformations) are significantly different from those in our system.

Our laboratory model consists of sand cones built around a vibrating tube which is located along the cone vertical axis. The sand cone represents a pyroclastic cone whereas the vibrating tube represents the volcanic conduit with pulsating magma inside. Here, we explore the inception, movement and deposition mechanisms of granular flows that travel on the surfaces of granular cones and that are generated by shaking. These flows of granular material, thus, do not travel within pre-existent channels.

Fig. 2. Front of the flow deposit highlighted by the ellipse in Fig. 1. Block-size fragments can be seen protruding from the deposit.

2. Method

2.1. Experimental apparatus

The experimental apparatus consists of a sand cone placed on a large table top (Fig. 3). The cone is 20 cm tall and it is built around an aluminium tube (3 cm in diameter) located along its axis. The tube is rigidly connected to the top surface of a vibrating table that is positioned underneath the large table. The tube does not touch the large table because its diameter is smaller than that of the hole through which the tube protrudes (Fig. 3). The vibrating table is rigidly joined to a

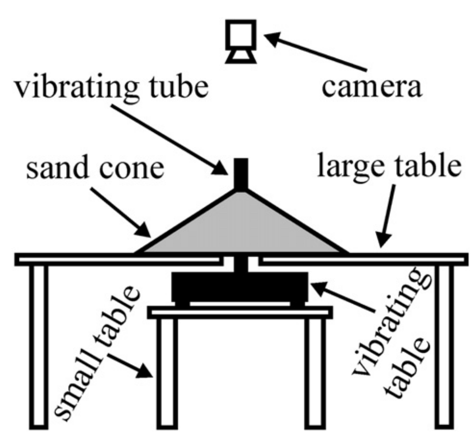

Fig. 3. Diagram of the experimental apparatus and position of the video camera.