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Invited review

From hot rocks to glowing avalanches: Numerical modelling of gravity-induced pyroclastic density currents and hazard maps at the Stromboli volcano (Italy)

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A B S T R A C T

Gravity-induced pyroclastic density currents (PDCs) can be produced by the collapse of volcanic crater rims or due to the gravitational instability of materials deposited in proximal areas during explosive activity. These types of PDCs, which are also known as "glowing avalanches", have been directly observed, and their deposits have been widely identified on the flanks of several volcanoes that are fed by mafic to intermediate magmas. In this research, the suitability of landslide numerical models for simulating gravity-induced PDCs to provide hazard assessments was tested. This work also presents the results of a back-analysis of three events that occurred in 1906, 1930 and 1944 at the Stromboli volcano by applying a depth-averaged 3D numerical code named DAN-3D. The model assumes a frictional internal rheology and a variable basal rheology (i.e., frictional, Voellmy and plastic). The numerical modelling was able to reproduce the gravity-induced PDCs' extension and deposit thicknesses to an order of magnitude of that reported in the literature. The best results when compared with field data were obtained using a Voellmy model with a frictional coefficient of $f = 0.19$ and a turbulence parameter $\xi = 1000$ m s^{-1}. The results highlight the suitability of this numerical code, which is generally used for landslides, to reproduce the destructive potential of these events in volcanic environments and to obtain information on hazards connected with explosive-related, mass-wasting phenomena in Stromboli Island and at volcanic systems characterized by similar phenomena.

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1. Introduction

Glowing avalanches generated from the collapse of the unstable portion of a volcanic crater's rim or the gravitational instability of materials deposited during explosive activity can be defined as gravity-induced pyroclastic density currents (PDCs). They have been directly observed and their deposits have been identified on the flanks of several volcanoes fed by mafic to intermediate magmas (Davies et al., 1978; Nairn and Self, 1978; Hazlett et al., 1991; Arrighi et al., 2001; Alvarado and Soto, 2002; Calvari and Pinkerton, 2002; Cole et al., 2005; Yasui and Koyaguchi, 2004; Yamamoto et al., 2005; Miyabuchi et al., 2006; Behncke et al., 2008; Di Roberto et al., 2014; Di Traglia et al., 2014; Calvari et al., 2016). Such gravity-induced PDCs have small volumes (10^4–10^7 m^3) but are emplaced at very high temperatures and can travel far from the source (Davies et al., 1978; Nairn and Self, 1978; Hazlett et al., 1991; Yamamoto et al., 2005; Miyabuchi et al., 2006; Di Roberto et al., 2014). Small volume PDCs are potentially dangerous for communities close to the volcanoes and tourists. Runouts longer than 8 km from the source have been reported for gravity-induced PDCs that presumably resulted from the avalanching of pyroclastic materials accumulated on slopes steeper than the angle of repose at Shin-Fuji volcano, Japan (Yamamoto et al., 2005) and for those that emerged from notches in the crater rim during the 1974 eruption of the Fuego volcano, Guatemala (Davies et al., 1978). Similar “gravity-induced” processes have been hypothesized for the formation of the glowing avalanches generated during the 1975 eruption at Ngauruhoe volcano, New Zealand (Nairn and Self, 1978; Lube et al., 2007) and for the PDCs of Asama volcano, Japan (Aramaki and Takahashi, 1992; Yasui and Koyaguchi, 2004) and Tungurahua volcano, Ecuador (Kelfoun et al., 2009). On 11 February 2014, a large volume of unstable and hot rocks detached from the lower-eastern flank of Etna's New Southeast Crater, Italy, and caused a PDC, travelling approximately 3 km on the eastern flank of the volcano and reaching the bottom of Valle del Bove at an average speed of >60 km h^{-1} (Bonforte and Guglielmino, 2015; De Beni et al., 2015). In addition, there are more hazards connected with small-volume gravity-induced PDCs. To improve hazard assessments from all types of PDCs, it is necessary to expand the understanding of PDCs and evaluate their possible impacts on human activities.

In this research, the suitability of landslide numerical models for simulating and assessing hazards related to gravity-induced PDCs was tested. The results of a back-analysis of three events of “glowing avalanches” at the Stromboli volcano are presented. The DAN-3D depth-averaged 3D numerical code, developed by McDougall and Hungr (2004) and Hungr and McDougall (2009), was applied. As case studies, three gravity-induced PDCs in 1906, 1930 and 1944 were selected. In relation to the 1930 event, detailed descriptions were compiled by Rittmann (1931) and Abbruzzese (1935) shortly after the eruption, from which crucial parameters such as the total runout distance, velocity, thickness and distribution of the deposits were deduced. Additional data on the flow dynamics and distributions of the deposits have been reported by Di Roberto et al. (2014).

The findings were also used to assess whether the inhabited areas of Stromboli (Stromboli and Ginostra villages) could be affected if one of the events is repeated in the future with dynamics similar to that in historical times and to evaluate the potential associated damage. The methodology used here may be applied to other volcanoes and, perhaps to other geological contexts, giving implications for hazard assessments in areas prone to mass-flows.

2. Eruptive activity and pyroclastic flows at the Stromboli volcano

Stromboli is the northernmost volcanic island of the Aeolian archipelago, in the southern Tyrrhenian Sea (Fig. 1). The island is the subaerial part of a rather regular volcanic edifice that rises to 924 m above sea level (a.s.l.) from a base that lies at a water depth between 1300 and 2300 m. Volcanic activity on Stromboli has been continuous since the III–VII centuries A.D. and consists of mild- to low-energy intermittent explosions (Strombolian activity), which are occasionally interrupted by effusive events and violent explosions that are commonly called paroxysms (Barberi et al., 1993; Rosi et al., 2000). The active vents are located in the crater terrace at approximately 750 m a.s.l. on the upper part of the Sciara del Fuoco (SdF), which is a horseshoe-shaped depression on the NW uninhabited flank of the volcano (Fig. 1).

At the Stromboli volcano, the formation of mass flows of hot pyroclasts has been reported several times. The flows occurred as a direct result of explosive and effusive volcanic activities such as those on 6 December 1985, (De Fino et al., 1988), 5 April 2003, (Rosi et al., 2006, accepted for publication; Pistolesi et al., 2008) and 12 January 2013 (Di Traglia et al., 2014; Calvari et al., 2016) or of the sliding of incandescent pyroclastic fall deposits accumulated over steep slopes such as during the 1930 and 1944 paroxysms (Di Roberto et al., 2014) and the eruptive activity of 28 and 29 December 2002 (Pioli et al., 2008). Gravity-induced PDCs usually occur in the SdF depression and therefore do not represent a serious threat to the population of Stromboli (Barberi et al., 1993; Rosi et al., accepted for publication). However, in 1906, 1930 and 1944, gravity-induced PDCs occurred outside the SdF, and in the latter two cases they reached the coast of the island. In particular, the 1930 PDCs reached the village of Stromboli on the NE part of the island, causing extensive damage and four casualties (Rittmann, 1931).

2.1. Gravity-induced PDCs in 1906, 1930 and 1944

Little information was reported on the PDCs on 15 July 1906 and 20 August 1944. Riccò (1907) reported that during the late afternoon of 15 July 1906 a very large eruption of incandescent material hit the area of Forgia Vecchia on the ESE side of the island (Fig. 1) and was preceded by a loud and long-lasting rumble. A column of incandescent material flowed in the direction of the village of Ginostra, WSW from the vent, burning the vegetation. Similarly, Ponte (1948) described that on 20 August 1944 a large amount of incandescent material consisting of large blocks and ash that had accumulated on the summit of the volcano and on the Forgia Vecchia flowed downslope, reached the shore and formed a ca. 100-m-long delta in the sea. The delta was rapidly eroded by the action of sea waves.

The event during the 1930 paroxysm is the best described. It was triggered by the sliding of an approximately 1 m-thick source deposit with an estimated volume of at least 45,000 m^3 and consisting of metre-sized spatters, decimetre-sized bombs, lapilli, and ash (Rittmann, 1931; Abbruzzese, 1935). That deposit had accumulated over an area of >60,000 m^2 on the steep cliff side of Chiappe Lisce (Fig. 1) approximately 1 h before the initiation of the gravity-induced PDC event (Rittmann, 1931) during an extremely violent paroxysm; this paroxysm was possibly the most violent event known to date in the recent history of Stromboli (Bertagnini et al., 2011). The initiation mechanism can be classified as a “rock irregular slide”, which is defined as the “sliding of a rock mass on an irregular rupture surface consisting of a number of randomly oriented joints, separated by segments of intact rock” (Hungr et al., 2014). The failure mechanism of this type of landslide is generally complex and difficult to describe and often includes elements of toppling (Hungr et al., 2014). At Stromboli, the inclination of some slopes exceeds the internal friction angle of the pyroclastic materials, but this condition is not sufficient to induce “rock irregular slide” events (Nolesini et al., 2013). Instead, the sliding processes are induced by the accumulation of pyroclastic materials, which produces a loading effect (overloading) on the summit of the volcano (Nolesini et al., 2013). This mechanism was also proposed for the generation of the glowing avalanches at Mt. Vesuvius during the 1944 eruption (Hazlett et al., 1991). Analogue modelling by Nolesini et al. (2013) revealed that the accumulation of material (representing either lava or spatter