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Mitigation of lava flow invasion hazard through optimized barrier configuration aided by numerical simulation: The case of the 2001 Etna eruption

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ABSTRACT

Lava flow spreading along the flanks of Etna volcano often produces damages to the land and proprieties. The impact of these eruptions could be mitigated by building artificial barriers for controlling and slowing down the lava, as recently experienced in 1983, 1991–1993, 2001 and 2002. This study investigates how numerical simulations can be adopted for evaluating the effectiveness of barrier construction and for optimizing their geometry, considering as test case the lava flows emplaced on Etna's south flank during 2001. The flow temporal evolutions were reconstructed deriving the effusion rate trends, together with the pre-eruption topography were adopted as input data of the MAGFLOW simulation code. Three simulations were then conducted to simulate lava flow with and without barriers. The first aimed at verifying the reconstruction of the effusion rate trends, while the others at assessing the performance of the barrier system realized during the eruption in comparison with an alternative solution here proposed. A quantitative analysis carried out on the first simulation confirms the suitability of the selected test case. The comparison of the three simulated thickness distributions showed both the effectiveness of the barriers in slowing down the lava flow and the sensitivity of the MAGFLOW code to the topographical variations represented by the barriers. Finally, for reducing both the time necessary to erect the barrier and the barrier environmental impact, the gabion's barrier construction was analyzed. The implemented and tested procedure enforces the capability of using numerical simulations for designing optimized lava flow barriers aimed at making swifter mitigatory actions upon lava flows and improving the effectiveness of civil protection interventions during emergencies.

1. Introduction

Volcanic risk is the combination of hazards associated with dangerous and/or destructive volcanic phenomena and exposure of the people living and/or properties located in the involved areas. The assessment of volcanic hazards, that is the probability that given areas will be affected by potentially destructive volcanic processes, represents one of the most important goals of current volcanology with an immediate and practical impact on society.

Lava flow eruptions are among the most common volcanic phenomena since they represent the typical outpouring process on the earth surface of basaltic magma generated in the earth mantle. Although these eruptions do not normally result in a loss of human life, they can potentially cause enormous damages to land and properties. Several examples of lava flows, which severely impacted on a densely populated area, come from Etna volcano, due to its frequent effusive eruptions. In order to mitigate the destructive effects of lava flows on inhabited volcanic slopes, lava flow diversions and building of artificial barriers are fundamental measures for slowing down the lava flow advance and limiting its expansion. The past experiences, in particularly those related to a few Etna historical eruptions described in the subsequent chapter, highlight that for the successful building of earthen barriers it is very important to plan how fast to execute the works in the field. Thus, in order to define a more detailed construction plan it is necessary to improve the knowledge on the lava flow emplacement process. At present, numerical simulation codes provide a powerful tool in testing the effectiveness of these mitigation actions, as a matter of fact the simulated lava path can be used to define an optimize project to locate the work. Simulation codes were applied in few cases to understand the effect on lava flow path of artificial barriers for hazard mitigation. The first phase of the 1991–1993 Etna lava flow, has been simulated using a probabilistic code (Dobran and Macedonio, 1992). The results of human interventions, such as the construction of a barrier at Portella Calanna and lava flow diversion by obstructing the lava tunnel in Valle del Bove, were evaluated. During the 2001 Etna eruption, simulations by the SCIARA code (Barca et al., 2004) were carried out to reproduce the main flow propagation and, varying the flow rates, to forecast possible scenarios. When simulations showed that lava flows threatened inhabited areas, morphology alterations were introduced to reproduce possible operations to deviate the lava flow (Crisci et al., 2004). The LavaSIM code

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(Hidaka et al., 2005) was adopted to evaluate the effects of artificial barriers, water-cooling and guiding channels on 1986 Izu-Oshima lava flow, providing quantitative results useful for real-time crisis management (Fujita et al., 2008). Finally, the DOWNFLOW code was adopted to investigate the possibility of reducing the lava flow hazard at Nyiragongo volcano, particularly for the neighboring towns of Goma (DRC) and Gisenyi (Rwanda), by modifying the pre-eruption topography for simulating the construction of protective barriers (Chirico et al., 2008; Favalli et al., 2005; Favalli et al., 2008).

In this study we investigate how the numerical simulations can be adopted for evaluating the effectiveness of a barrier construction as a mitigation action and for supporting their optimal design. The barriers built during the 2001 Etna eruption to protect zones under significant threat were selected as test case. We adopted the MAGFLOW code, developed at INGV Sezione di Catania, which is a Cellular Automata (CA) model for simulating the lava flow emplacement (Del Negro et al., 2007; Vicari et al., 2007). In MAGFLOW the state of the cells is defined by the lava thickness and the quantity of heat. Its evolution function is the steady-state solution of Navier–Stokes's equation for the motion of a Bingham fluid, subjected to pressure force, on an inclined plane (Dragoni et al., 1986). In order to reduce the impact of the cell geometry, a Monte Carlo approach was adopted to improve the solution (Vicari et al., 2007). The simulation starts discharging lava at a certain rate from one or more vent cells as a function of the flow rate that can change over time, thus increasing the lava thickness at the vents. When such thickness reaches a critical level, the lava spreads over the neighboring cells. Next, whenever the thickness at any cell exceeds the critical thickness, the lava flows into its neighbors. At the same time, the heat content of the lava in each cell is modified in accordance with the flow motion and by considering the heat loss by radiation from the flow surface; solidification effects are also modeled. The code was quantitatively validated by simulating the whole emplacement of the main 2001 Etna lava flow (Coltelli et al., 2007; Vicari et al., 2007). It was also applied to the 2006 Etna lava flow allowing to investigate different viscosity laws to be implemented in the code, and a methodology for satellite estimation of the effusion rate (Del Negro et al., 2007; Vicari et al., 2007).

This work shows as the lava flow simulations can provide a fundamental support for deciding the position of a protective barrier relatively to the simulated lava path. However building an earth barrier implies complex operational constraints and logistical problems as it would entail a large amount of materials being transported. As a consequence, many working hours, heavy trucks and engineering vehicles would also be necessary for the transportation of large quantities of rock and earth. Furthermore the issue of identifying a site, from which digging up the materials, poses additional limitations in a protected natural area such as Mount Etna. Thus, in order to reduce the time necessary to erect the barrier and its environmental impact, we analyzed a different type of engineering work, the gabion building filled with blocks of lava. This solution can improve the efficiency of the protective measures and reduce the construction time. Therefore, the building of a gabion barrier was, here, quantitatively analyzed to establish the technical and operational advantages compared to the classical earth barriers.

2. Case history of mitigation actions on lava flow invasion at Etna

Diversion barriers have been created to slow or divert lava flow paths. Barrier construction represents the first step that should be undertaken in order to delay the lava advance, especially as regards to the most dangerous eruptions, such as those originating from low altitude vents and in proximity of inhabited areas (Maugeri and Romano, 1980–1981). These activities should be combined with other types of mitigation actions, including population evacuation. The concept of slowing and diverting lava flows by means of artificial barriers for guiding their paths arose from the observation of lava encountering natural morphological obstacles or pre-existing barriers. These cases were experienced when the lava flow approached Catania's city walls in 1669 (Lyell, 1875) and when lava reached the railway embankment near the village of Kapoho, Hawaii, in 1955 (MacDonald, 1958). Up today, very few interventions of barrier construction were carried out during emergency phases: examples include the barriers erected on Hawaii in 1955 and 1960 (MacDonald, 1962) and the earthen barriers built during the Etna eruptions of 1983, 1991–1992, 2001 and 2002 (Colombrita, 1984; Barberi et al., 1993; Barberi and Carapezza, 2004).

The 1983 lava flow, emplaced on the Etna's South flank between 28 March and 6 August, was fed from a 750-m long fissure, extending from 3000 m down to 2250 m a.s.l., though the main lava discharge occurred from vents opened between 2320 and 2265 m a.s.l. The low effusion rate resulted in the emplacement of a compound lava flow made of bifurcating and overlapping short-lived flows (Guest et al., 1987). The interventions on the 1983 lava flow were aimed to deviate the flow path in an artificial channel, excavated parallel to the natural one. Earthen barrier were also built to guide the path of the diverted lava by impeding lateral expansion in built-up or farmed areas. Explosives were utilized to create an opening in the solid levee of the lava channel at the junction with the artificial one. A number of difficulties prevented the placing of charges in the deepest part of the lava levee, thus a modest diversion was created and it was supplied only a couple of days (Abersten, 1984). As a matter of fact the little slope of the artificial channel and the exposition of fresh lava to the atmosphere facilitated the lava cooling and consequently the artificial channel was obstructed soon. However, the dumping of a large amount of big solid fragments produced by the explosion into the lava channel plugged the tunnel located just downhill from the point of intervention, forcing nearly all the lava to overflow out of the tunnel (Barberi et al., 1993). This intervention was a partial success but demonstrated that man can effectively control the development of a lava flow.

During the 1991–1993 eruption (Calvari et al., 1994), the lava flow approached Zafferana, 8 km away from the vent, and through a simple computer simulation, the identified lava flow path showed that the town was likely to be inundated (Dobran and Macedonio, 1992). The measures to protect Zafferana included the building of four lava-containment earth barriers and several attempts at plugging the lava tube by throwing concrete blocks, steel hedgehogs and large fragments of solid lava into a skylight close to the vent. Downhill, the earth barriers, oriented orthogonally to the direction of the lava flow, slowed the front propagation down for a few weeks although they were not able to stop it altogether. Lava overflowed on the earth barriers, thus inducing the Civil Protection authorities to carry out a drastic lava flow diversion near the vent. Finally, the lava flow was totally diverted into an artificial channel by blasting the wall separating it from the natural channel and obstructing downstream the natural tunnel (Barberi et al., 1993).

During the 2001 eruption, lava flows emitted by seven vents propagated mainly on the southern flanks of Etna (Coltelli et al., 2007). The lava flows emitted from the 2700 and 2550 m a.s.l. vents threatened the tourist facilities on the Rifugio Sapienza area. Thirteen earth barriers were built up to protect the area, initially delaying the advance of the flows and then diverting it toward SE, away from the aforementioned facilities. The first five upper barriers were almost totally buried by the lava flowing down the slope, whereas the four barriers erected close to Rifugio Sapienza for diverting the approaching flow were successful partially thanks to the decreasing effusion rate (Barberi and Carapezza, 2004).

The 2002–2003 eruption produced two lava flows which covered both the northeastern and the southern Etna flanks (Andronico et al., 2005). On the northeastern side a flow, active between 26 October and 7 November 2002, partially covered the tourist facilities of Piano Provenzana. On the South flank the effusion lasted until 28 January 2003 threatening once again the Rifugio Sapienza area. A great effort was devoted to the construction of earthen barriers: six barriers (five on the south and one on the north-east flank), oriented about 30° with respect to the main direction of the flow, were erected to contain the flow in correspondence of the touristic facilities. These actions, taken in accordance with the local authorities including the Park of Etna, contributed to mitigate the effect of the lava flows advance considering