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Insights from analogue modelling into the deformation mechanism of the Vaiont landslide

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A B S T R A C T

The Vaiont landslide (Southern Alps, Italy) represents one of the most catastrophic landslides in the world recorded in the modern history. The landslide, occurred on 9th October 1963, involved about 3×10^8 m^3 of rock that collapsed in an artificial lake: more than 1900 people died as a consequence of the tsunami produced by the sudden fall of the mass in the water.

Despite the importance of this event, many aspects of the Vaiont rockslide still remain unexplained, particularly its fast emplacement. In order to obtain a better understanding of the Vaiont disaster, this paper focuses on the results of analogue models designed to get insights into the internal and surficial deformation patterns that characterized the sliding rock mass. Plan view reconstructions of surface model displacement reveal that the rock mass is subdivided into compartments with different relative movements and differential rotations, believed to have played a significant role in causing the fast collapse. The deformation of the analogue models, compared with geological cross sections and in-situ data, suggests that sliding of the rock mass was accomplished by the development of some new (or the reactivation of pre-existing) fractures into the rock mass.

1. Introduction

Understanding the mechanism of landslides is fundamental when evaluating their hazard and to predict the energy release during the principal failure phase, the associated velocity and the runout distance. Furthermore, detecting the magnitude of landslides represents the main step to understanding the hazard scenario. Sometimes the behaviour of a landslide in terms of mass acceleration, velocity or runout distance is much more intense than expected (Hutchinson, 1987). These phenomena have strong civil protection implications, and their deep understanding is fundamental to be extended to similar events.

The Vaiont landslide developed on the northern slope of Mt. Toc, in the Vaiont Valley, a deep and narrow canyon located in the Pre-Alpine Belt about 90 km north of Venice (Fig. 1). The instability of whose slope was known for at least 400 years (Kilburn and Pasuto, 2003). The landslide collapse was preceded by numerous episodes that lead to define the 9th October 1963 event as a tragedy waiting to happen.

The peculiar morphology of the Vaiont valley, characterized by very narrow and steep slopes, was identified as an ideal site where building a hydroelectric reservoir. The preliminary design of a 200 metre high dam back dates to 1920 but the building started only in 1957 (Genevois and Tecca, 2013). In 1957 a variation to the original project raised the height of the dam to 266 m; in this way the reservoir volume was increased from 5.8×10^7 m^3 to 1.5×10^8 m^3. As a consequence of a landslide that occurred in 1959 at the Pontesei dam, where an earthslump fell into a reservoir causing a tsunami with a 20 m high wave, a study of the whole Vaiont basin was carried out and revealed the presence of a palaeolandslide in the Mt. Toc slope (Giudici and Semenza, 1960). In September 1960 the dam was completed and the progressive filling of the reservoir started; the month after, probably also in relation to intense rainfall, a 2 km long continuous peripheral crack developed in the northern slop of Mt. Toc. A first important landslide occurred there on November 4th, and involved more than 7×10^5 m^3 of rock causing a 2 m high wave in the lake. After this event a series of surface markers were installed to monitor the slope deformation and the construction of a bypass started, in order to manage the hydraulic consequences of a possible future bigger landslide.

In the period 1960–1962 the reservoir was partially filled and emptied, and the deformation recorded seemed to be related to increasing/decreasing in the reservoir water level. During 1963 the reservoir was gradually filled until September 1963 when it reached its maximum value (710 m asl; Kilburn and Petley, 2003). In this period the recorded deformation was about 3.5 cm day^{-1}. To confine this deformation the reservoir was progressively emptied, but on 9 October 1963 about

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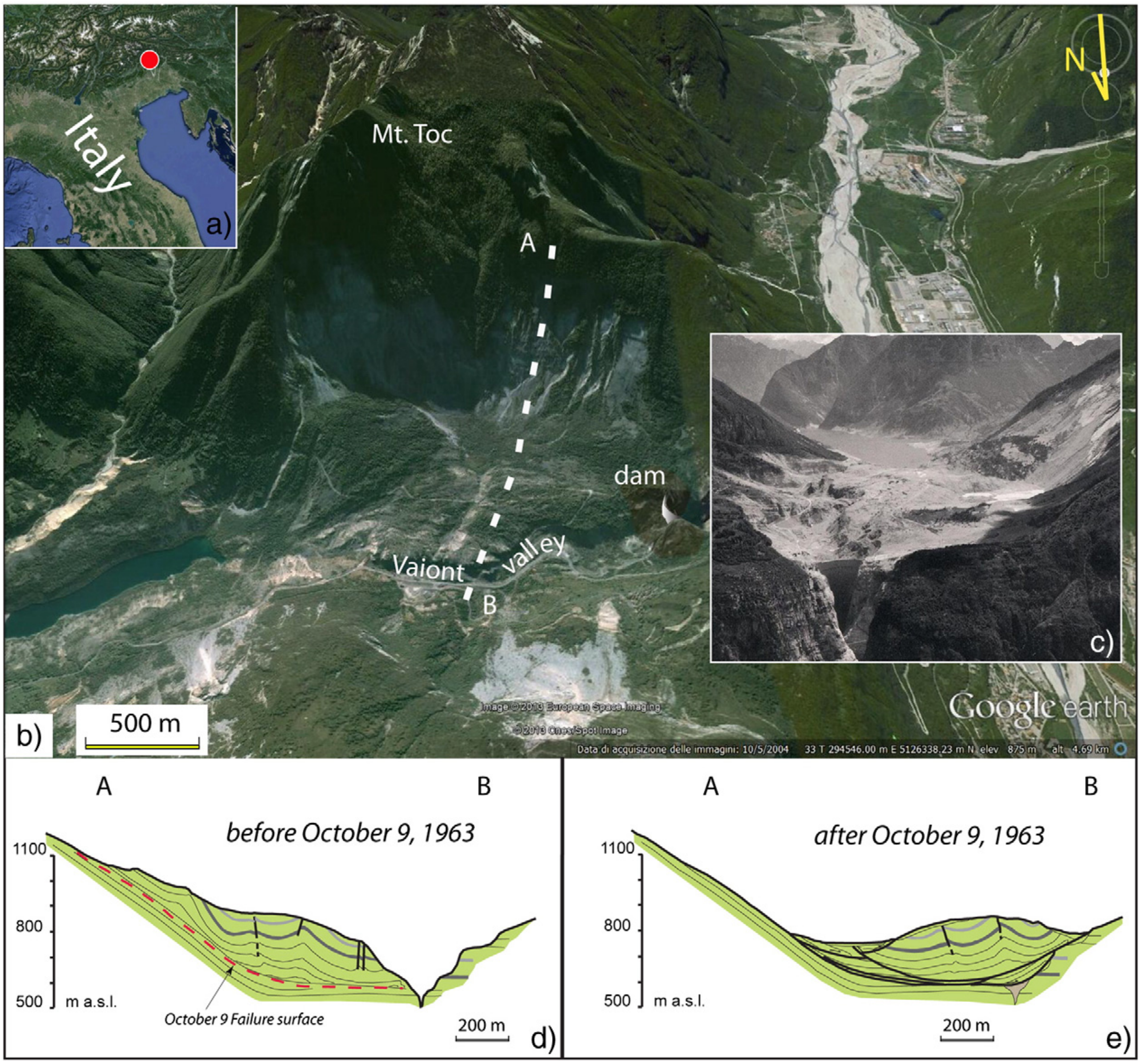

Fig. 1. Overview of the study area. (a) Location of the study area in northern Italy. (b) Google earth image of the Vaiont landslide. (c) Photo of the Vaiont valley immediately after the catastrophic event of 9 October 1963. (d) and (e) Geological cross sections (d) before and (e) after the landslide (modified after Rossi and Semenza, 1965).

3×10^8 m^3 of rocks slid into the reservoir from Mount Toc at an estimated mean velocity of 30 m s^{-1} (Hendron and Patton, 1985).

The geological, geomorphological, hydrogeological, geo-structural and geo-mechanical characteristics of the failed slope have been studied and continuously re-analysed since 1960 when a palaeolandslide affecting the future reservoir was recognized (Giudici and Semenza, 1960; Hendron and Patton, 1985; Mantovani and Vita-Finzi, 2003; Genevois and Ghirotti, 2005; Paronuzzi and Bolla, 2012; Hungr and Aaron, 2013). Nevertheless, many aspects of the Vaiont rockslide remain unexplained (Sitar et al., 2005; Paronuzzi and Bolla, 2012) still after the 50th anniversary of the Vaiont tragedy. To address this issue, this paper presents a series of experimental models performed to get insights into the dynamics of the Vaiont landslide and to reconstruct the internal and surficial deformation pattern of the sliding rock mass. The analogue models were performed at the Tectonic Modelling Lab of the CNR-IGG and of the Department of Earth Sciences of Florence.

2. Open issues on Vaiont landslide dynamics

Although the Vaiont landslide has been the subject of numerous studies, many questions remain unresolved, especially regarding its unexpected behaviour in terms of (i) causes of the failure, (ii) the origin of the anomalous velocities, and (iii) how did the reservoir level influence the slope stability.

The most debated aspect is certainly the extremely high velocity of the landslide, which is estimated to be 20 to 50 m s^{-1} (Hendron and Patton 1985; Sitar et al., 2005). To explain such an extremely high velocity of the rockslide, some hypotheses have been proposed. In particular, Hendron and Patton (1985), Nonveiller (1986) and Hutchinson (1987, 1988) postulate that the sudden breakage of the marly-calareous rock within the landslide mass was responsible for its paroxystic acceleration; the rockslide velocity was consequently maintained high by: 1) the extremely high heat-generated pore pressure (Romero and Molina, 1974; Habib, 1975; Hendron and Patton, 1985; Nonveiller, 1986); and 2) the very low dynamic friction angle of the clayey interbeds along the sliding surface (Tika and Hutchinson, 1999). Temperature increase along the sliding surface, due to sliding on a low permeability and high plasticity basal surface, could have triggered pore pressure increase leading to very high sliding velocity (about 25 m s^{-1}, Hendron and Patton, 1985) although this alone is insufficient to understanding the Vaiont dynamics (Alonso and Pinyol 2010; Pinyol and Alonso, 2010). Given its extremely high velocity, the Vajont rockslide can also be classified as sturzstrom; these were defined by Hsü (1975) based on Heim's (1932) description as a stream of very