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

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ABSTRACT

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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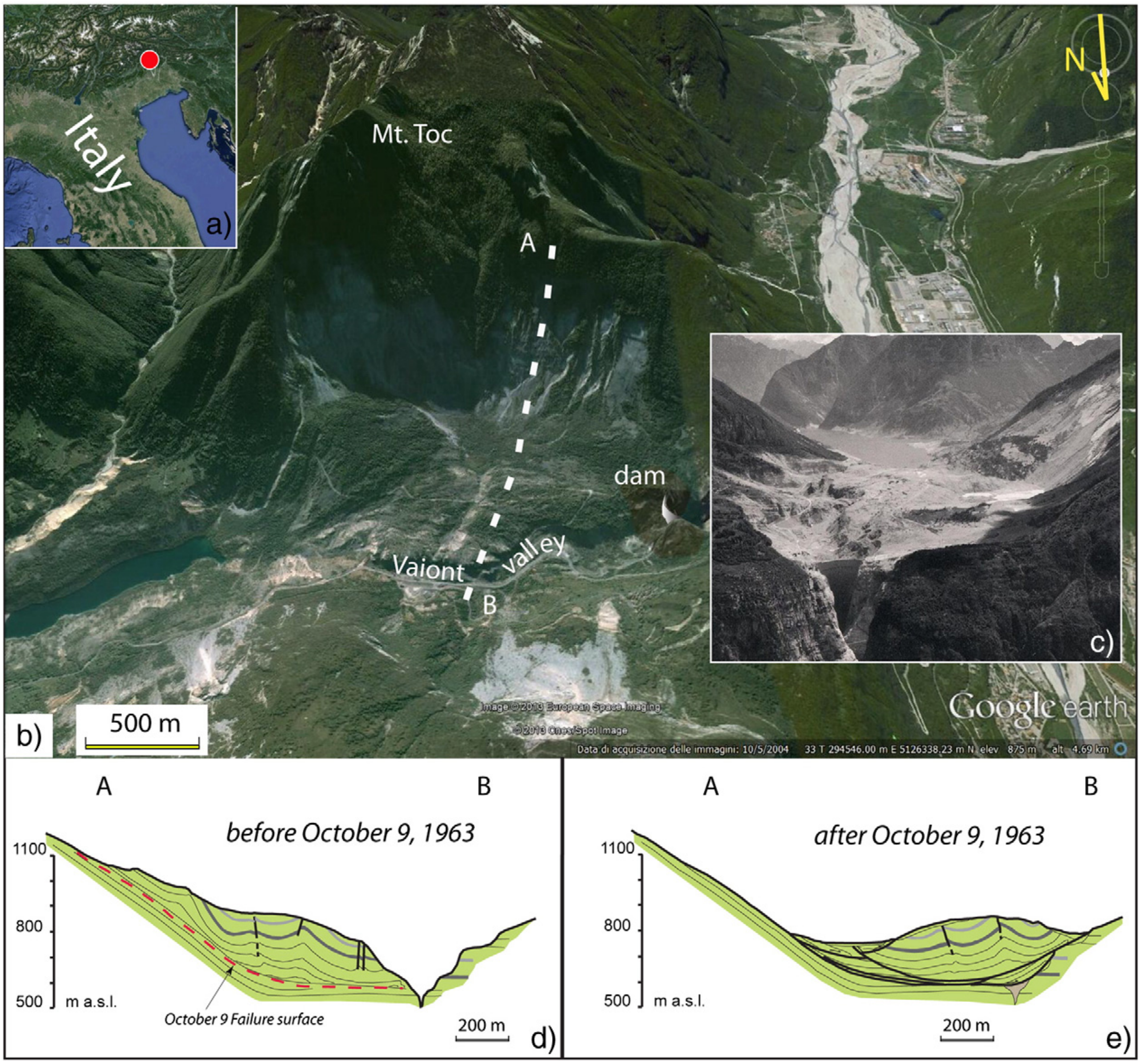

Fig. 1. Overview of the study area. (a) Location of the study area in northern Italy. (b) Google earth image of the Vaiont landslide. (c) Photo of the Vaiont valley immediately after the catastrophic event of 9 October 1963. (d) and (e) Geological cross sections (d) before and (e) after the landslide (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 rapidly moving debris derived from the disintegration of a fallen rock mass of very large size; they can move along a flat course for unexpectedly large distances. The Vajont rockslide, however, constitutes an example of incomplete sturzstrom, as the runout (and consequently the rock mass disintegration) was limited by the opposite slope of the narrow valley, which forced the mass to surge upward by the power of its momentum.

The influence of reservoir operations (filling and drawdown) on Mt. Toc slope stability was recognized immediately and recently confirmed (Paronuzzi et al., 2013), considering the local hydrology on the basis of new engineering geological surveys and on re-interpretation of bibliographical data. The new data have led to the conclusion that, in partial contrast with previous hypotheses (Hendron and Patton, 1985; Kilburn and Petley, 2003), the natural hydrogeological context was deeply modified by filling–drawdown cycles of the Vaiont reservoir, leading to variations of pore water pressure inside the rock mass. However, the mechanisms that have been proposed to explain the peculiarity of the Vaiont landslide are far from being framed into a single evolutionary model.

3. Analogue modelling

The analogue modelling is demonstrably a useful tool for understanding the dynamics of a wide range of geological and tectonic processes such as extensional, compressional, strike-slip and inversion tectonics (e.g. Brun and Nalpas, 1996; Corti et al., 2003; Del Ventisette et al., 2005, 2006, 2007; Cerrina Feroni et al., 2006; Bonini et al., 2007; Montanari et al., 2007; Sani et al., 2007; Corti, 2012; Graveleau et al., 2012), including fluid/magma migration and emplacement (e.g. Koyi, 1997, Román-Berdiel et al., 1997, Ranalli, 2001; Montanari et al., 2010; Ferré et al., 2012). Analogue modelling studies have also addressed surface deformation due to gravitational instability (e.g. Lajeunesse et al., 2005; Bois and Bouissou, 2010; Yamada et al., 2010; Le Cossec et al., 2011; Lacoste et al., 2012; Liu et al., 2013; Nolesini et al., 2013). Among the latter, previous laboratory experiments mainly investigated collapses of granular materials and the role of fluid overpressure on slope instability. As regards to the Vaiont landslide, many models attempting to reproduce both landslide dynamics and the effect of the landslide fall into the reservoir have been carried out since the 1960s (Roubault, 1967; Müller, 1968). Mencl (1966) presented the first model addressing the internal deformation of the landslide using different mixture of granular materials. During the 1970s and 80s physical modelling studies that focused on the explanation of failure mechanisms were also proposed (Rybar, 1974; Trollope 1979, 1980; Dunbavan, 1980; Trollope and Burman, 1980; Fig. 2). Similar to the previous ones, the latter experiments were carried out simulating only a planar sliding surface, without reproducing the natural staircase geometries. As far as we know, this study is the first attempt to investigate the internal and surficial deformation patterns of the Vaiont landslide by reproducing the initial geometries as reconstructed from field data before and after the event.

3.1. Model construction, deformation and scaling

Our modelling approach was based on available constraints on the basal sliding surface of the rock mass whose geometry was reconstructed using detailed geological data (Rossi and Semenza, 1965). The sliding surface mostly corresponds to a pre-existing thrust surface, which was already reactivated during a previous sliding event (Rossi and Semenza, 1965). Sliding was facilitated by a basal low-strength layer, which has been reproduced in our experiments with weak silicone.

The substratum of the analogue models was built on the basis of pre- and post-sliding topographic and geologic maps of the Vaiont Valley. A scaled model (1:5000) was built based on a detailed topographic map surveyed before 9th October 1963 (Rossi and Semenza, 1965). A flat-ramp geometry of the sliding surface was reconstructed from the interpolation of five cross sections through the landslide provided by Rossi and Semenza (1965, 1985) and Hendron and Patton (1985).

To allow the exposure of two transverse sections, the model base was built by juxtaposing of layered plywood panels and successively covered by plasticine that was modelled to reproduce a realistic replica of the natural sliding surface (Fig. 3) and adjacent morphology. In particular, the model consisted of three distinct parts (joined subsequently). The two surfaces separating the three bodies of the model (Fig. 3) correspond to sections 2 and 10A in Rossi and Semenza (1965; Fig. 1), which have been considered to be representative of the two extreme conditions of the sliding surface.

In the analogue modelling, the sliding rock mass was represented by means of quartz sand sieved above the reconstructed sliding surface, which was simulated with a low-viscosity décollement mixture of silicone and oleic acid. During construction, the model was rotated to obtain a stable position of the landslide body. After sieving the sand, the model was tilted to reach the natural slope, after which the landslide started to move under the sole effect of gravity. Coloured sand layers were sieved as passive markers in the modelled landslides to visualize the internal deformation after the sliding. A passive reference grid was drawn with white dry quartz sand above the model surface. To understand the role of the different rheology of the slip surface and sliding mass, a series of experiments were performed. The models were run until deformation stopped completely. For example, the model was chosen as representative of the Vaiont landslide evolution and described below, for 29 min and 30 s.

Although several original reports did not consider the clay interbeds along the failure surface of the Vaiont rockslide (i.e. Müller 1968), many authors acknowledged their importance in controlling the kinematics

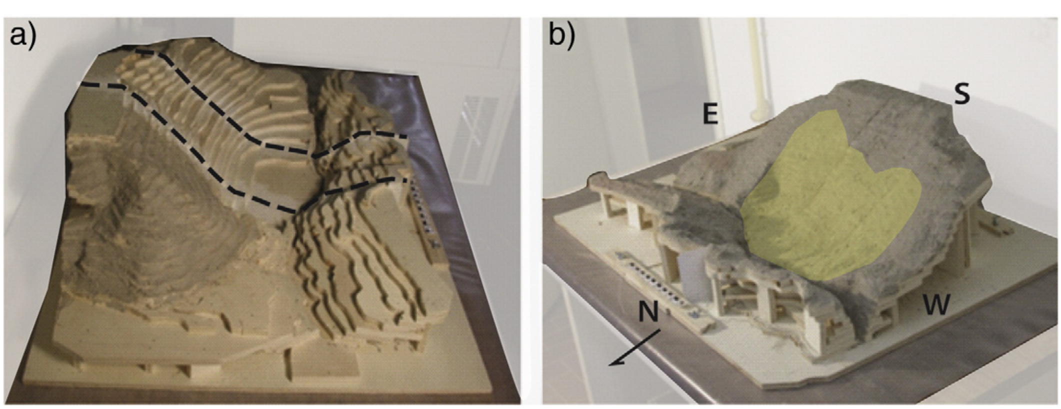

Fig. 2. Reconstructed topography of the sliding surface of the Vaiont landslide, and valley topography. The model scale is 1:5000. (a) Woody model skeleton. (b) Plastered model topography. The dotted lines correspond to the cross sections (sections 2 and 10A in Rossi and Semenza, 1965). The yellow area in (b) corresponds to the reconstructed sliding surface. Cardinal points corresponding to the natural analogue are also reported.

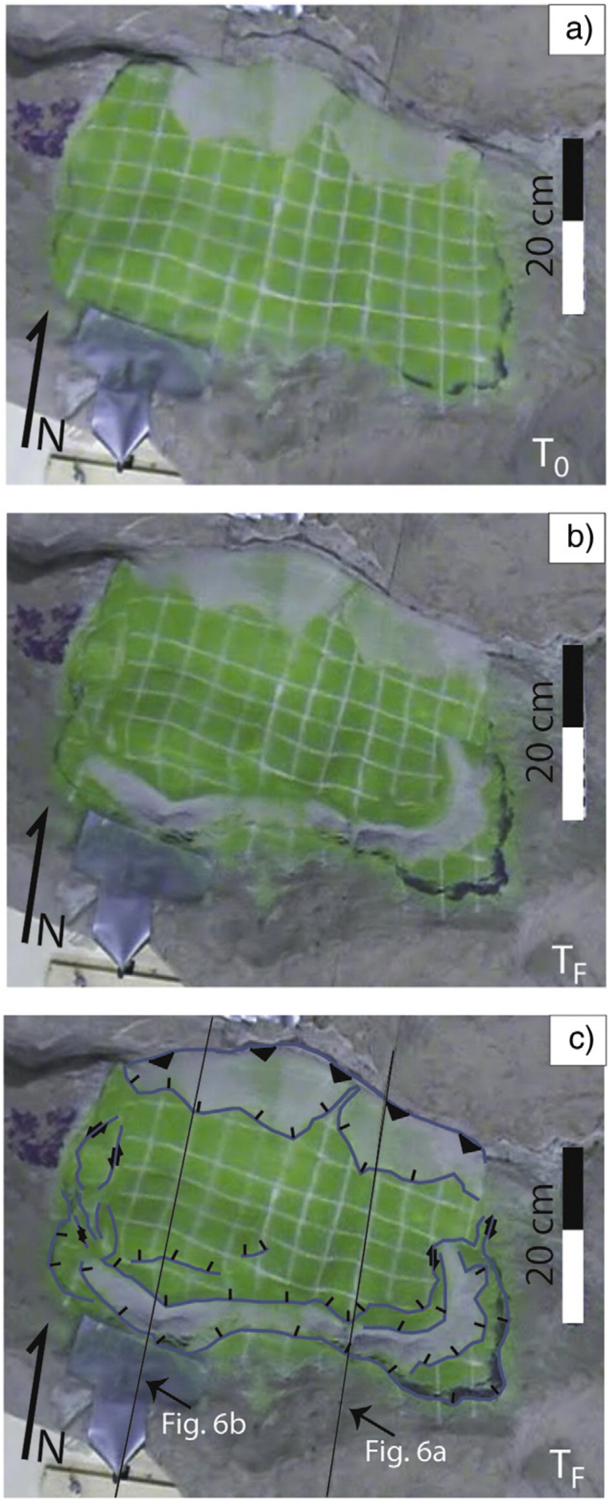

Fig. 3. Comparison between model surface at the (a) beginning and (b) end of deformation. (c) Line drawing of features developed on the model surface.

and dynamics of the movement. However only Hendron and Patton (1985), Tika and Hutchinson (1999), and Ferri et al. (2011) carried out laboratory analyses to determine their mechanical properties. In the models we assumed that these interbeds are concentrated in a narrow band at the base of the landslide body.

The rock mass has a cohesive resistance sensibly lower than the surrounding substratum, due to fracturing achieved during previous thrusting and sliding. The mechanical properties of the rock mass have been properly scaled to nature which is a necessary condition to obtain a realistic replica of the natural processes under investigation.

The model to nature stress ratio (σ^*) can be computed as

$$\sigma^*(=\sigma_m/\sigma_n) = \rho^* g^* l^* \approx 0.6 l^* \quad (1)$$

where the superscript * means a ratio, subscripts m and n refer to model and nature, respectively, σ is stress, ρ is density, g is gravity, and l is length (Table 1). The models were conveniently scaled with 1 cm in the model corresponding to 50 m in nature, which implies a length ratio (l^*) of 2×10^{-4}. Typical cohesive strength of slide rock mass varies between 1 and 3.5 MPa (Hoek, 1990). In order to maintain the stress ratio, i.e. dynamic similarity between models and nature, the cohesion of sand should range between 120 and 420 Pa. We tested different brittle materials with variable mechanical properties, particularly cohesion and density by using different sand types. We found that the best fit to the natural conditions is achieved with dry quartz sand with low cohesion that best simulates the relatively low cohesive strength of the slid rock mass (Table 1). The main difference between the experimental system and the natural prototype concerns the mechanical properties of the low-viscosity analogue material that do not exactly reproduce those of the natural shales along the sliding surface. However, the low-viscosity layer was introduced merely to trigger the landslide movement: silicone has the ability to effectively reproduce weak zones such as that above which the model landslide body deforms by developing internal and surficial structures. This rheological limitation together with the observation that the models deformed at relatively high velocity under a normal gravity field implies that the modelling results cannot be used to scale down model velocity to nature (e.g., Ramberg, 1981). On the other hand, the aim of this modelling was to understand the deformation mechanisms of the sliding mass in relation the 3D geometry of the underlying sliding surface. The landslide body was simulated by sand, a time and strain rate-independent brittle material, and therefore the influence of the time factor can be neglected in the analysis of model results.

4. Experimental results

Taking the passive grid markers constructed above the model surface as a reference, it was possible to reconstruct the deformation of the model through time and the dynamics of the analogue landslide in each sector (Fig. 4). In particular, deformations of the models were analysed with two different approaches. The first consisted in monitoring the surficial deformation by detecting the grid position at the beginning and at the end of the model (Fig. 4a); this provides information on any dissimilarity in the diverse sectors of the model. Understanding of the deformation dynamics is based on the monitoring through time of the position of nine selected points (Fig. 4b). The second approach is the analysis of internal deformation by exploring cross sections cut at the end of the deformation. To gain a description of model results, the cardinal points (N, S, E, and W) are shown to refer to the different sectors of the model using the same orientations of the natural case reproduced by the model (Fig. 2). To simplify the comparison with the natural prototype, we describe the results of the most representative model. After sliding, the surface deformation is concentrated in the southern sector (Figs. 3B,C and 4) where extensional fractures were

Table 1
Analogue modelling scaling parameters.

	Nature	Model	m/n = *
Density (ρ)	2500 kg m^{-3}	1500 kg m^{-3}	0.6
Internal friction angle (ϕ)	30–32°	30–32°	1
Length (l)	50 m	1 cm	2×10^{-4}
Gravity (g)	9.81 m s^{-2}	9.81 m s^{-2}	1
Stress (σ)	–	–	1.2×10^{-4}
Cohesion (c)	1–3.5 MPa	120–240 Pa	1.2×10^{-4}

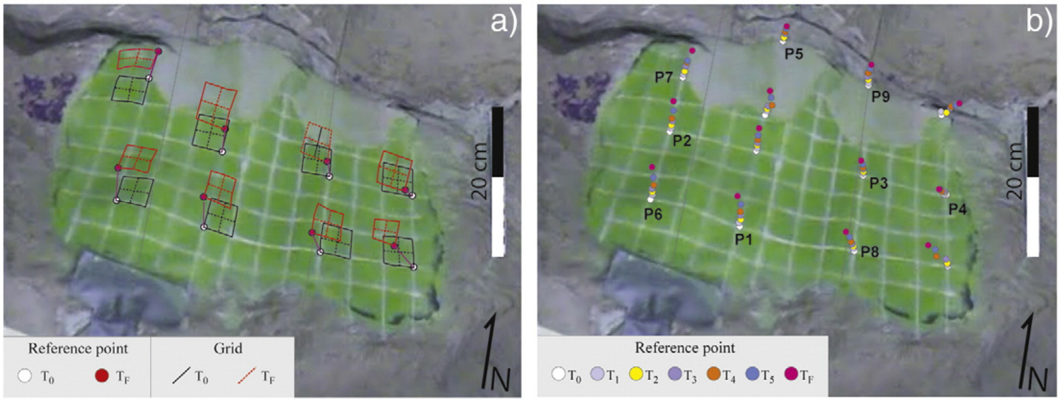

Fig. 4. Surficial deformation of the model. (a) The position of selected nodal planes at the beginning of the model deformation is indicated in black; the position of the same nodes at the end of the model deformation is indicated in red. (b) Sequential position of selected reference points through time.

well developed and corresponded to the main scarp of the landslide. Strike-slip shear zones developed on the eastern and western sectors of the model bounding the landslide and acting as tear zones accommodating the movement. In the northern sector, the zone of accumulation was well developed with the landslide toe that filled and bypassed the Vaiont creek incision. No evident deformation was recognizable in other parts of the model.

Displacement vs. time analysis of nine reference points located on the model surface (Fig. 5) indicates that the movement of each landslide sector was characterized by a high velocity during the first steps of movement, with higher speeds displayed by the reference points located on the western side (P1, P2, P6, and P7), suggesting a general clockwise rotation of the sliding mass. During the second part of the experiments the measured velocities evidenced a gradual deceleration (Fig. 5). At the end of the experiments, the deformation was prevalently accommodated by the development of transverse faults that compartmentalized the sliding mass into different sectors characterized by different main directions of movement and that were rotated in a differential way (see Section 5 for further details). The maximum recorded rotation was about 5.5°.

Model cross sections (Fig. 6) show that sub-vertical faults fractures, prevalently with normal displacement, developed in the central part of the model. Specifically, these faults/fractures developed at depth

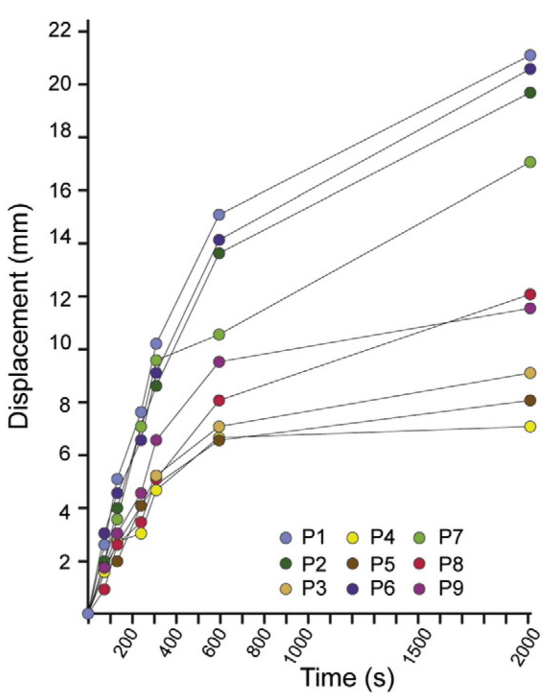

Fig. 5. Displacement vs. time of nine reference points located on the model surface. The points correspond to those shown in Fig. 4b.

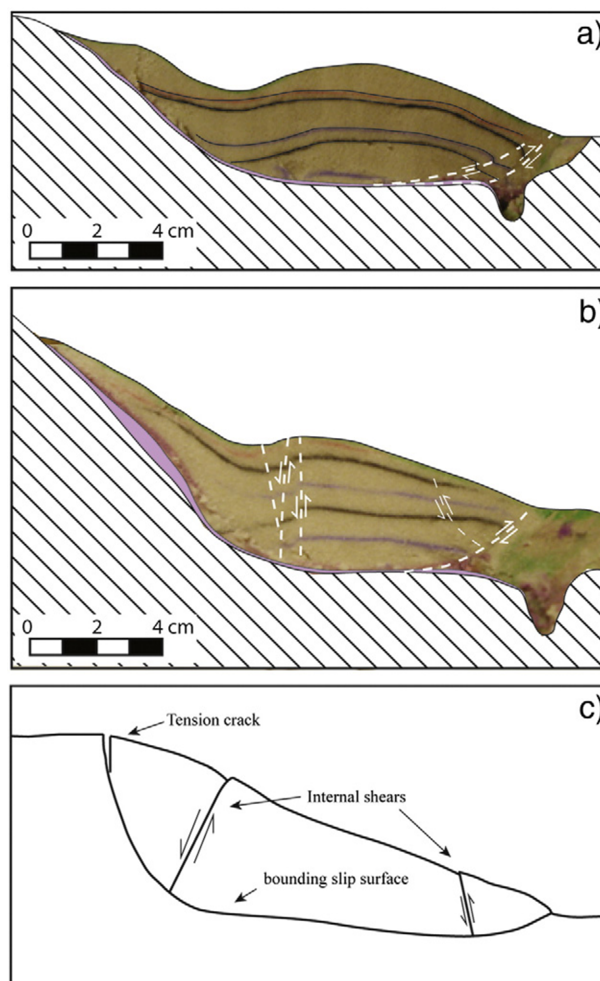

Fig. 6. Cross sections. a) Interpretative line drawing of the eastern model cross section (location in Fig. 3c). b) Interpretative line drawing of the western model cross section (location in Fig. 3c). c) Theoretical internal structures developed in a flat-ramp complex landslide body (modified Hutchinson, 1987).

around the flat-ramp boundary of the main sliding plane. Thrusts and secondary back-thrusts developed instead at the toe of the landslide.

5. Discussion and comparison with nature

During the analogue model construction, minor surficial landslides developed in the northern sector of the model (Fig. 4a). This deformation is related to a limit of the construction procedure; the local slope was higher than the repose angle of employed quartz sand. This phase however may have a direct correspondence with the natural prototype.

Unfortunately we do not have a sufficiently detailed quantitative documentation of surface deformation after the Vaiont landslide. The only data available are related to the interpretation on terrestrial photogrammetry (Wolter et al., 2014). The benchmark monitoring points have been lost after the landslide, making it impossible to reconstruct the post-event displacement field. However, the good correspondence between the analogue model movements at surface and the pre-event measures carried out by Müller (1968) allows us to consider the comparison between the experimental displacement field and the pre-kinematic one of the natural prototype to be acceptable. In particular our model shows a compartmentalization of the landslide into four different sectors as reported by Müller (1968; Fig. 7). The surface deformation of the models indicates that sectors 1–3 have a prevalently northward movement, with a minor rotational component both clockwise and counter clockwise for sectors 2 and 3, respectively. Sector 4 had a direction of movement mainly towards the NW, probably due to the development of main fractures during deformation related to the sliding surface morphology.

The comparison of the model surface deformation with the evolution of the surface movements of the landslide, from the available pre-rupture motion of benchmarks immediately before the landslide of 9 October 1963, indicates a match in the direction of movement, and in particular the tendency of the mass to rotate clockwise with pivot point in the southeastern corner. Furthermore, the sliding kinematics deduced from morpho-structural analysis (Broili, 1967; Wolter et al., 2014) agrees well with the kinematics inferred from our models (Fig. 7).

The map-view of the analogue models shows a very complex structural pattern characterized by the development of new (or the reactivation of pre-existing) internal faults, which is comparable, at a first approximation, with the results of the pervious field surveys. The geometry of the internal faults is strikingly similar to those resulting from the detailed mapping of the slide body, and supports the previous hypothesis that brittle failure took place into the rock mass to accommodate sliding above the kink(s) of the sliding surface (e.g., Hutchinson, 1987). Notably, the rotation of the rockslide mass could have generated an abrupt friction decrease along the step fault plane that separated the sliding mass from the stable substratum to the east (i.e., the left side in Fig. 7). As a result, the rotation and the sudden lateral friction loss could have contributed significantly to the achievement of such an elevated landslide velocity.

The analogue modelling also agrees with a numerical model built for investigating the failure mechanism of the Vaiont rockslide (Gigli, 2004). According to Hutchinson (1988, 1987) hypotheses the numerical model demonstrates that by neglecting the rock mass internal strength, the factor of safety of the northern slope of Mount Toc was less than 1. Under these conditions the slope was indeed kept stable thanks to the sliding mass internal strength, and the paroxystic phase, with its extraordinary violence, which could only have taken place after internal breakage of the rock mass itself (Fig. 8). This very important aspect that can be extended to similar phenomena is that, even pre-existing landslides, possibly in conditions of residual strength, may experience sudden accelerations of paroxysmal type.

By comparing the cross sections on the theoretical model of the complex landslide (Hutchinson, 1987) and the landslide cross sections developed by Rossi and Semenza (1965) with the results obtained by the current analogue models, it is evident that the model faithfully reproduces the internal geometry of the landslide (Fig. 6). The latter is characterized by sub-vertical faults that nucleated where the sliding surface changes inclination from steep to flat, and by an anticline structure developed at the front of the landslide. In the model landslide toe, minor back-thrust developed similarly to the theoretical model. In the model cross section the anticline is however less developed than in the nature, probably due to the initial accumulation of analogue material at the front of the developing landslide.

6. Concluding remarks

The results of this experimental study suggest the following main conclusions.

– The surficial deformation pattern and velocity field of analogue models show the development of different sectors characterized by different evolution and distinct direction of sliding.
– Internal, and prevalently sub-vertical structures developed within the sliding mass, in a position strongly controlled by the geometry of the sliding surface (ramp-flat surface).
– The development of internal structures, the geometry of which is well comparable with that of the theoretical models of complex landslides, is probably the main controlling factor that induced the compartmentalization of the sliding mass.

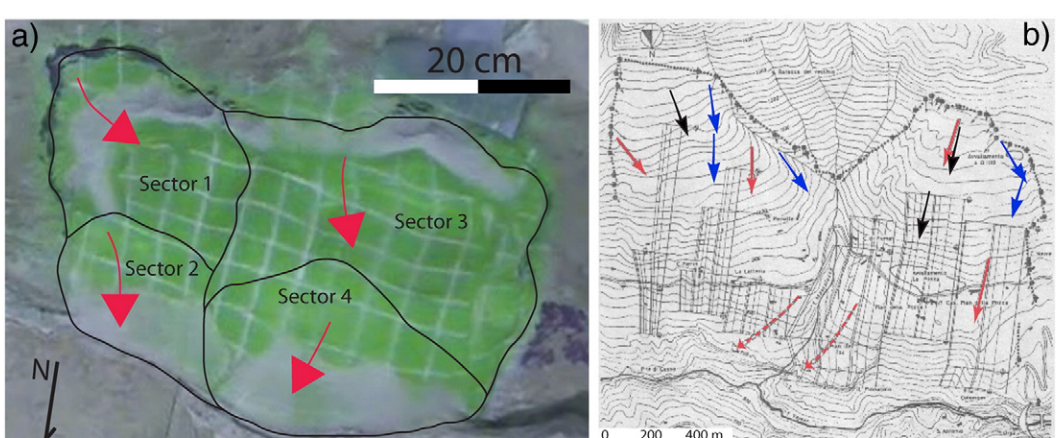

Fig. 7. Comparison between (a) the surficial deformation of the analogue model and (b) the movement directions measured on the Vaiont landslide. Red arrows and the reference map are after Müller (1968); green arrows after Broili (1967), and blue arrows after Wolter et al. (2014).

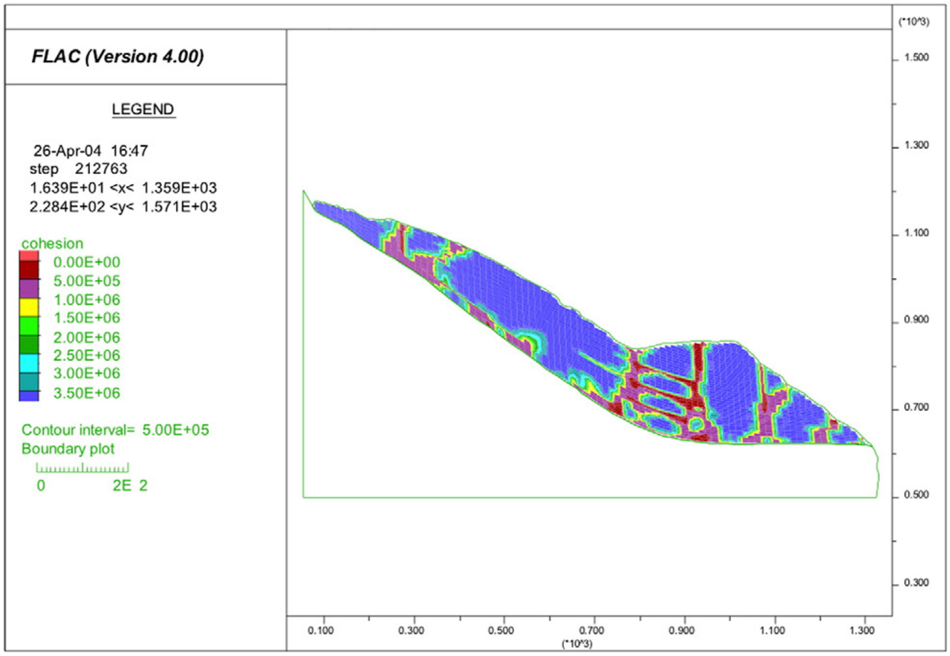

Fig. 8. Numerical modelling of section no. 2, showing cohesion values of the strain-softening model during the landslide trigger.

– The rotation of the blocks and the consequent decrease of the lateral friction may have played a key role in triggering the unexpected acceleration of the Vaiont landslide.

Finally, from a more general point of view, this work shows that analogue modelling may represent a powerful tool in analysing internal deformation, role of sliding surfaces and sliding dynamics of landslides.

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