Rock Mech Rock Eng (2013) 46:1267–1270
DOI 10.1007/s00603-013-0483-7

EDITORIAL

The 1963 Vajont Landslide: 50th Anniversary

Giovanni Barla · Paolo Paronuzzi

Published online: 26 September 2013

1 Introduction

This editorial is intended to bring to our minds the 50th Anniversary of the Vajont Landslide occurred on 9 October 1963 at 10.39 pm in Italy, in the Dolomites of Friuli, on the borders of the Veneto Region and about 100 km north of Venice. A mass of approximately 270–300 million m^3 of rock and debris collapsed into the reservoir generating a wave that over-topped the 261.6 m high double curved arch dam built across a V-shaped gorge (Fig. 1). The flood wave dropped into the Piave Valley destroying the town of Longarone and other villages nearby. More than 2,000 people (the real number is not known) were killed.

The Vajont landslide is considered to be one of the most catastrophic slope failures and is an outstanding and valuable reference case history for the study and back analysis of the complex instability mechanisms which generally characterize deep-seated landslides and rock slopes. This dramatic event is also of particular importance for the understanding of the influence of mountainside reservoirs on the stability of the adjacent slopes, when deep-seated landslides are present which were not disclosed or fully investigated at the design stage.

At the same time, interest stems from the need to find the most appropriate investigation techniques to be adopted at the design stage, including suitable numerical modelling methods to be used for the analysis of instability modes and simulation of the interaction between the rock mass and the new infrastructures to be built. Also the re-analysis of the available database on the triggering and subsequent propagation of the landslide may shed light on monitoring methods—with conventional and advanced technologies—used as key components of hazard assessment. This is of particular relevance for those countries where the need for energy and development leads to the construction of new infrastructures, including dams, of unprecedented sizes.

It is noted that this editorial is only intended to remind us what is considered to be the starting point for the development of modern Rock Mechanics and Rock Engineering, when in rock as well as in soil, according to Terzaghi '*we were over-stepping the limits of our ability to predict the consequences of our actions*' (Hoek 2007). With the intent to account for the most recent and updated studies on the Vajont landslide, the Editor has asked the help of Professor Paolo Paronuzzi from the University of Udine who, together with his research group, has been and is carrying out a comprehensive research project on different aspects and debated questions still posed on the Vajont catastrophic landslide.

2 Geological and Geomechanical Problems

Considerable work has been carried out on the Vajont landslide. A special mention should be made of the technical report by Giudici and Semenza (1960), at the time of the construction of the dam, the studies of Professor Leopold Müller on the failure mechanisms, published in our journal in 1964 and 1968 (Müller 1964, 1968), and the most comprehensive work by Hendron and Patton (1985). A geo-database of published and unpublished data is available which currently includes more than 120 scientific papers and technical reports (Superchi et al. 2010).

G. Barla (✉)
Politecnico di Torino, Turin, Italy
e-mail: giovanni.barla@polito.it

P. Paronuzzi
Udine University, Udine, Italy

Fig. 1 Panoramic view of the slip surface of the Vajont landslide and of the double curved arch dam

For many years after the landslide failure, the geology and geomechanics of the 1963 landslide and the influence of the alternated filling–drawdown cycles performed on the reservoir have been matter for debate. In fact, the understanding of the geological–geomechanical model and failure mechanisms is decisive to interpret the structure of Alpine valleys correctly, where large deep-seated landslides and rockslides are present, and to avoid erroneous decisions on the positioning of new dams and hydraulic management of the reservoir levels (design level of the man-made lake, filling and drawdown rates and procedures, etc.).

It is important to keep in mind that Alpine reservoirs always determine a change in pore water pressure distribution within the slope with a new fluctuating water table, directly influenced by the reservoir level and rock mass permeability. The change in the effective stress state can cause the collapse of slopes which, without the reservoir, are in limit equilibrium conditions. For this reason the geological, geomorphological, geostructural, hydrogeological and geomechanical features need to be investigated in great detail, to identify and characterize previously failed rock or soil masses (prehistoric landslides).

One of the main scientific controversial aspects of the 1963 Vajont landslide regards the existence of a prehistoric landslide on the southern valley side (the Mount Toc prehistoric rockslide with a volume of 270–300 million m^3) and the presence of clay beds along the basal failure surface and within the lower limestone sequence (the Fonzaso Formation: middle-upper Jurassic). In all cases, it is agreed today that the 1963 landslide was effectively a reactivation of a huge rock mass which had already failed in the past and involved different materials including limestone layers, angular gravel and lenses of clay (Ca-montmorillonitic clays, in most cases).

Based on a comprehensive survey of both the 1963 failed rock mass and the detachment surface (with field mapping and laboratory characterization studies), a new geological–geomechanical model of the Vajont landslide has recently been proposed, as shown in Fig. 2 (Paronuzzi and Bolla 2012; Paronuzzi et al. 2013). A 30–60 m thick shear zone at the base of the prehistoric Mount Toc landslide has been described. This shear zone, composed of chaotic material including folded rock masses, limestone gravel and clay beds, is considered decisive in explaining the slope toe response during the filling and drawdown procedures, including the third drawdown which culminated in the catastrophic collapse on 9 October 1963 (Fig. 3).

3 Open Issues

The Vajont landslide is characterized by many geological and geomechanical aspects that have been interpreted differently such as the occurrence of clay layers and a basal sliding surface. Of particular relevance is the uncertainty of the geometrical and structural features of the landslide body, including the karstic features. Also, to be mentioned, is the behaviour of groundwater as well as the different slope responses during the filling stages of the reservoir. Finally, the “en masse” motion with a preservation of the entire rock mass structure deserves attention, together with the extraordinary translational velocity observed in the 9 October 1963 landslide.

The most significant need is to explain the evolution of the landslide over time, including the transition from

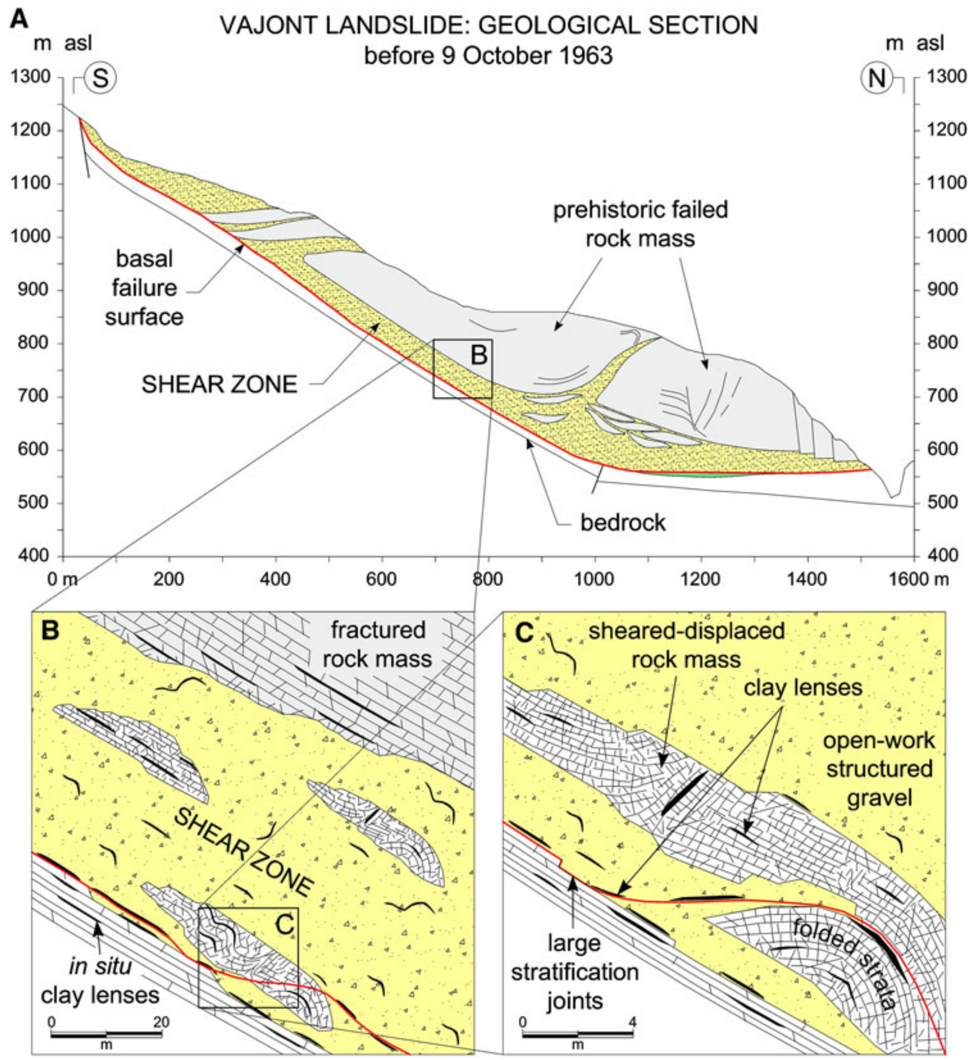

Fig. 2 **a** Geological section of the Vajont landside before 9 October 1963 showing the presence of the thick shear zone. **b**, **c** Details of the shear zone (Paronuzzi et al. 2013)

triggering of the instability, to the development of large slope deformation, up to the final brittle collapse which characterized the rock mass response. In fact, one envisages the need for a better understanding of intact rock fracturing and shear strength of rock discontinuities filled with clay. At the same time, it is to be clarified how the initial rock slide can evolve into a complex-structured landslide with mechanical and hydrological behaviour fundamentally controlled by the basal shear zone.

The landslide complexities of a mass resting on a thick shear zone make it difficult to interpret monitoring results (and this is particularly evident in the Vajont case) as well as the simulation of slope responses to provide insights into the expected displacement history and hazard scenarios. It is clear that traditional 2D stability analyses based on the limit equilibrium methods have obvious limitations and more sophisticated 3D numerical modelling methods are required to reproduce slope behaviour.

Specific effort should be made in the future to analyse internal deformation phenomena affecting an unstable rock mass characterized by soft inter-strata and to investigate the appearance of localized high stress states inducing the heavy fracturing of the limestone. However, the study of these issues requires a more sophisticated numerical modelling approach considering the real multi-layered nature of the rock mass, the different materials involved, any possible sliding along joints, rock bridge fracturing and shear strength softening.

The case of the Vajont slope failure emphasizes that very different materials are involved in large deep-seated landslides and this leads to difficult choices concerning the appropriate constitutive laws and failure criteria to be adopted given that the shear strength is mobilized in very different conditions along the sliding surface. On the other hand, the modelling of well-stratified rock masses characterized by frequent variations in stiffness and strength properties, including anisotropy, is not simple. It is, however, a very attractive research topic which may shed light on the transition from ductile to brittle behaviour of large unstable rock slopes.

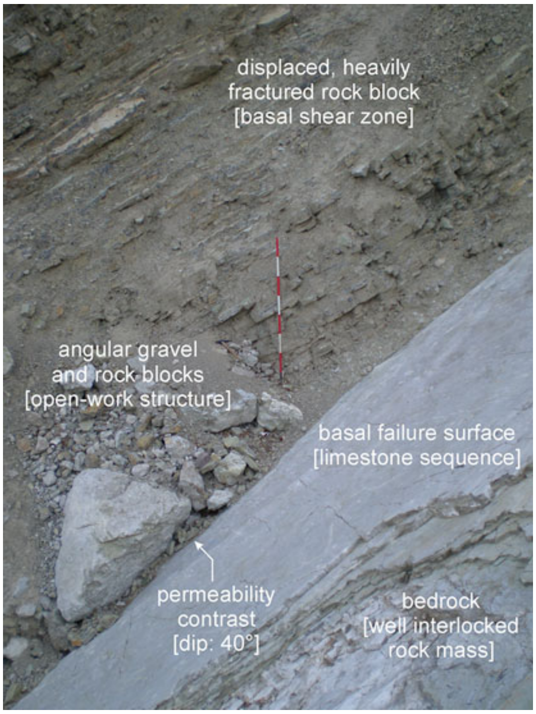

Fig. 3 Detail of the basal contact between the prehistoric shear zone and the underlying bedrock (Paronuzzi et al. 2013)

It is understood that the Vajont prehistoric failure involved a large rock wedge resting on a well-extended lateral surface (eastern boundary of the unstable mass) and that block movement can be described as a constrained sliding following an initial wedge-type failure. For this reason, the 3D geometrical features cannot be neglected when examining the stability conditions of the prehistoric landslide. Similar 3D effects also have to be considered when analysing the 1963 collapse because the prehistoric landslide impacted at the eastern extremity against the opposite valley flank, partially rising up onto it.

From a geological and geomechanical point of view, the first-time failure was a large rockslide that involved a sedimentary multilayer rock mass, characterized by thin limestone layers (1–10 cm) alternating with very thin clay inter-layers (0.1–2 cm, very often). In these conditions the mobilized shear strength is strongly influenced by the thickness of the soft infilling material interposed between the rock joints and by the many localized rock-to-rock contacts due to joint undulations. These may determine localized stress concentrations resulting in intact rock failure, stress redistribution and finally rock crushing.

These different mechanical features, changing over time and space, which characterize large deep-seated landslides with progressive failure phenomena, large surface displacement, and considerable rock mass deformation, including sliding along rock joints and re-blocking, localized failure of intact rock (rock bridges), and strain-softening behaviour can today be dealt with effectively. Up to date numerical modelling methods where the rock masses are represented as continuum, discontinuum and continuum–discontinuum media, including time dependence, are today available. Also, the simultaneous increase in computer power greatly facilitates the use of these methods.

What one should keep in mind, however, is that modelling should go hand in hand with the understanding of the geological and geomechanical conditions, physical investigations in the laboratory or in the field as well as observations and investigative landslide monitoring. As already noted in our previous editorial, responsible researchers realize that simulation and numerical modelling always require comparison with physical reality.

4 Conclusion and Invitation

It is understood that research work on the different aspects and open issues regarding the catastrophic Vajont landslide and large deep-seated landslides in general, as mentioned above, have been carried out or are being carried out by different people and research groups worldwide. The Editor would like to invite potential authors of papers dealing specifically with specialized topics in rock mechanics and rock engineering to write to him (giovanni.barla@polito.it) by submitting a title with a short abstract. It is envisaged to promote in the near future the publication of a special issue of the journal on "Rock mechanics and rock engineering of deep seated landslides" as a follow-up of the issue published in 2008.

References

Giudici F, Semenza E (1960) Studio geologico sul serbatoio del Vajont Unpublished report for SADE, Part A: text, Part B: photos with discussions, Venezia, Italy

Hendron AJ, Patton FD (1985) The Vaiont Slide, a geotechnical analysis based on new geologic observations of the failure surface I, II Technical Report GL-85-5, US Army Eng. Waterways Experiment Station, Vicksburg, MS

Hoek E (2007) Practical rock engineering. http://www.rocscience.com/educational/hoeks-corner

Müller L (1964) The rock slide in the Vajont valley. Rock Mech Eng Geol 2:148–212

Müller L (1968) New considerations on the Vaiont slide. Rock Mech Eng Geol 6:1–91

Paronuzzi P, Bolla A (2012) The prehistoric Vajont rockslide: an updated geological model. Geomorphology 169–170:165–191

Paronuzzi P, Rigo E, Bolla A (2013) Influence of filling-drawdown cycles of the Vajont reservoir on Mt. Toc slope stability. Geomorphology 191:75–93

Superchi L, Floris M, Ghirotti M, Genevois R, Jaboyedoff M, Stead D (2010) Technical note: implementation of a geodatabase of published and unpublished data on the catastrophic Vaiont landslide. Nat Hazards Earth Syst Sci 10:865–873