



## A Geomechanical Evaluation of the Rock Mass Involved in the 1963 Vajont Landslide (NE Italy)

Laura Superchi, Luca Zorzi, Fabio Ferri, Rinaldo Genevois, and Maria Lafelice

### Abstract

The Vajont landslide (NE Italy) occurred on the 9th October 1963, when approximately 270 million m<sup>3</sup> of rock slid down into the existing reservoir at 20–30 m/s. The movement involved limestones and marls of the Fonzaso and Socchér Formations and occurred along a chair-like sliding plane. The landslide has been object of numerous studies but a comprehensive explanation of its triggering and dynamics remains elusive. Here we report the results of new structural and geomechanical data from conventional mapping on 88 field stations within and outside the landslide. Each station includes joints orientation, spacing, persistence and roughness, Geological Strength Index and Schmidt Hammer tests. The characterization of the landslide deposit was completed by the description of seven boreholes drilled by RODIO Company in 1965 down to the sliding surface. Representative rock samples were collected for laboratory measurements of the unconfined compressive strength, Young modulus and Poisson's ratio. The new data represent an important tool to reconstruct a detailed 3D geological and geomechanical model of the landslide.

### Keywords

Vajont landslide • Geomechanics • Laboratory • Boreholes

### Introduction

The Vajont Landslide is one of the largest catastrophic slope failures of the past century. About 270 Mm<sup>3</sup> of limestone, mudstone, and marl slid into the Vajont Reservoir on the 9th October 1963, producing a displacement wave that overtopped the dam and killed over 2000 people in the valley below.

Although the slide has been intensively studied over almost half century, its kinematic and dynamic remains unclear. For a comprehensive review on the investigations in the Vaiont landslide see Genevois and Ghirotti (2005). A modern reevaluation of the geological, structural and

geomechanical aspects is required to characterize the rock mass conditions before the failure and to model the instability process.

The aim of this work is to provide a comprehensive structural and geomechanical dataset of the rock sequence involved in the slide before and after the 1963 event. The geomechanic features of the pre-slide condition were performed on the base of detailed field investigation on outcrops from outside the deposit (pre-slide conditions) and from laboratory test performed on selected samples.

The post-slide conditions were determined combining the field data on the deposit with the description of the seven boreholes drilled by RODIO Company down to the sliding surface. The boreholes offer a very good possibility to characterize the rock sequence involved in the sliding movement.

The new dataset will be useful to reconstruct a detailed 3D geological-technical model of the landslide and develop an exhaustive failure mechanism.

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## Geological Setting

The Vajont Valley was eroded along the axis of an eastwest trending, asymmetrical syncline plunging upstream to the East (Erto syncline) (Fig. 1). The abrupt monoclinical flexure on the southern limb of the syncline formed a peculiar and important aspect of the geology of the slide. The movement occurred along a chair-shaped failure surface in part corresponding to a pre-existing slip surface as indicated by the geological evidence recognized before 1963 (Semenza 1965). The failure surface was indicated to be largely confined within 0.5–18 cm thick clay-rich layers which were observed to be continuous over large areas of the failure surface (Hendron and Patton 1985).

The geological sequence of the area includes three main formations: (1) the oolitic limestones of Calcarea del Vajont (middle Jurassic); (2) the Fonzaso Fm, composed by calcareous marls with brownish chert nodules and local clayey layers (late Jurassic-early Cretaceous); (3) the Socchér Fm (early Cretaceous), including conglomerates in the lower part and different types of marly limestones on top (Fig. 2, details in Rossi and Semenza 1965).

The landslide involved Jurassic and Cretaceous rocks (limestones and marls mainly of the Socchér Formation) with varying degrees of fracturing; they slid down along the “chair-like” bedding planes, causing the outcrop of the Fonzaso Fm (Genevois and Ghirotti 2005).

As regarding the shape of the sliding surface, important morphological differences, moving from West to East have been detected. The western area is concave and much smoother than the central folded area: it is however marked by several steps, as well as by conjugate discontinuities. The failure surface is located in the same stratigraphic interval which contains clay-rich levels.

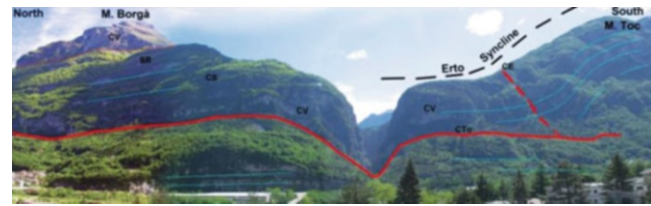
## Structural and Geomechanical Analysis

### Field Data

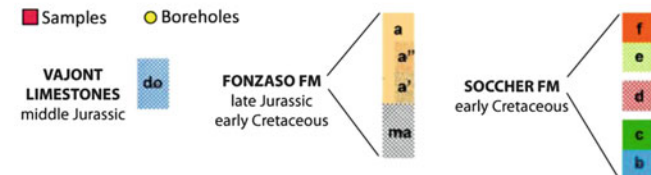
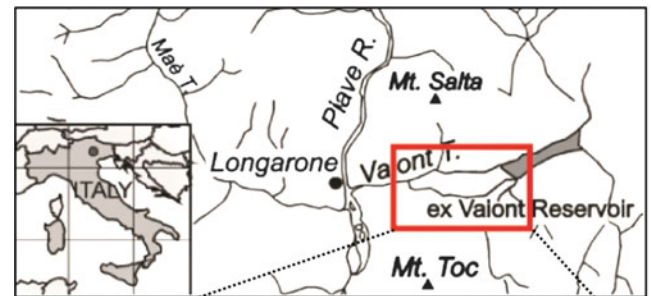
In order to reconstruct the structural and geomechanical setting that led to the 1963 landslide, a detailed fieldwork was carried out collecting data inside and outside of the Vajont landslide.

The morpho-structural setting was deeply investigated, in particular, in its discontinuity characteristics such as failure surface morphology (undulations, step-paths, rock bridges), persistence, block size, roughness and rock fracturing degree.

This study permitted to better clarify the structural pattern that led to 1963 movement and to individuate the best location for the geomechanical surveys. A sufficient number



**Fig. 1** Structural setting of the area involved in the Vajont landslide (view from west)



**Fig. 2** Location of the RODIO boreholes (R1 to R7) and of the samples collected for laboratory tests (Vj1 to Vj11). Stratigraphic units involved in the Vajont landslide are: (1) the Vajont Limestone, (2) the Fonzaso Formation, and (3) the Socchér Formation

of data have been collected in order to classify different areas from the geomechanical point of view.

The geomechanical in situ surveys were performed according to the ISRM standards (1978), to provide a description of the main geomechanical parameters of the area.

The Schmidt hammer and point load tests, the rock mass quality and the Geological Strength Index have been assessed along rock exposures on the failure surface, on and outside the accumulation area. Measurements by Schmidt hammer were carried out on different rock surfaces

and the mean value of the Schmidt rebound (R), together with the rock density, were used to estimate the value of the joint compressive strength (JCS). Point Load Tests were performed on intact rock samples, to define compressive/tensile strength of intact rock. The values of the evaluated Geological Strength Index reveal a big variability of the geomechanical properties distribution ranging from 25 for the eastern side landslide outcrops, to 50 for the rocks of the sliding surface. Higher values (up to 60) have been found outside the landslide mass.

## Geomechanical Description of the Boreholes

During the preliminary investigation activities, the Court of Belluno commissioned the RODIO Company and the ENEL Company a drilling survey in order to investigate the slip surface location as well as the structural and stratigraphic features of the landslide for a better evaluation of the phenomenon. Between August 1964 and May 1965, seven boreholes (named R1, R2, R3, R4, R5, R6, R7) were drilled by the RODIO Company. Except for the borehole R7, all the RODIO's boreholes are located on the landslide deposit (Fig. 2) and drilled to a depth ranging from 116.50 to 325.50 m (Martinis 1978). They are concentrated on the western portion of the landslide body (Fig. 2). The eastern portion of the landslide was not drilled by the RODIO Company because was under investigation by the ENEL Company (Martinis 1978).

After 50 year, only the RODIO boreholes are still examinable, and, thanks to the partnership and collaboration of the Fondazione Vajont Onlus and the ongarone Municipality, we gained access to them to (1) reevaluate the mechanical properties of the drilled materials and to (2) reconstruct the 3D geometry of the 9 October 1963 sliding surface.

All the boreholes were drilled using the continuous core technique, with a diameter ranging from 330 to 85 mm. The recovery of material was highly variable, and sometimes not determinable due to the intense fracturing and fragmentation of the collapsed mass (Martinis 1978).

Although 50 years have passed and the core boxes were first transported to the Court of L'Aquila and then moved back to Longarone, the drilled material is in an overall good condition. All the above mentioned transfer seems to have mainly induced some reworking of the drilled material, and, in some cases, also the loss of a few part (for example with R2 and R4). Our investigation were focused mainly on: (1) the mechanical properties of the collapsed mass, considering the grade of fragmentation and fracturing of the material especially nearby the sliding surface and, (2) sampling and on-site Schmidt Hammer tests on the cores with suitable shape. For the detailed stratigraphic description we mainly refer to the work of Martinis (1978).

All the drills, except R7, come through the landslide mass reaching and crossing the sliding surface, which can be found at variable depth ranging from 71.5 m in the R1 and 270.6 m in the R5. Approaching to the sliding surface, the recovered material is rather different showing a high fracturing degree (R1, R3, R4 or it is composed by angular debris, from coarse gravel to pebbles, with the lack of the finest terms (R5, R6).

In addition, in R6, R4 and R1, blocks of cemented breccias (from medium to fine gravel and coarse sand in grain size, belonging all to the Fonzaso and Socchér Formations) with a clayey matrix, were found. Even though a precise thickness of this level cannot be determined, due to the lack of continuity in the recovered cores, a thickness of about 1.5–2 m seems to be reasonable.

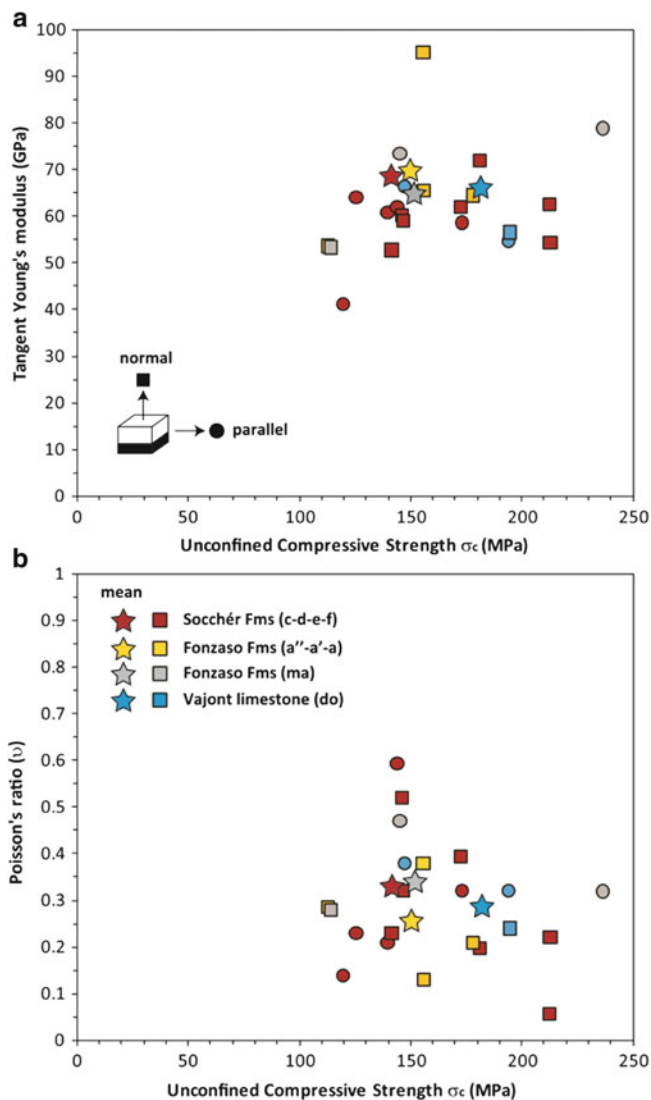
The R2 drill shows strong differences with respect to the others, because in the range of depth from 125.6 to 277.9 m the core is formed by a predominantly homogeneous debris made up of medium-coarse gravel with the lack of sand, silt and clays. The low percentages of recovery during the R2 drilling due to the high grade of fracturing of the collapsed mass, induced the drillers to fill the core boxes with the cutting material only for a stratigraphic purpose.

The high grade of fracturing of the landslide mass made very difficult and sometimes also impossible the complete fulfillment of the geomechanical analysis of the rock cores. In addition, any consideration about the spatial orientation of the detected discontinuities has been possible. Schmidt Hammer tests and RQD values evaluation were possible the bedrock of each drill, while inside the drills it was only possible to execute Schmidt Hammer tests on the few recovered cores (having an height of at least 10 cm). For each core, two series of measurements were collected: one with a test direction parallel to the principal axis and the second one perpendicular to that axis. The estimate mean values of the Uniaxial Compressive Strength (UCS) are:

- (a) Parallel direction tests:
  - Level “c” (Socchér Formation): 92.2 MPa;
  - Level “ma” (Socchér Formation): 43.2 MPa;
  - Vajont Limestones: 81.5 MPa.
- (b) Perpendicular direction tests:
  - Level “c” (Socchér Formation): 67.7 MPa;
  - Level “ma” (Socchér Formation): 45.6 MPa;
  - Vajont Limestones: 64.9 MPa.

## Laboratory Measurements

The Uniaxial Compressive Strength ( $\sigma_c$ ), the Young's modulus ( $E_{tan}$ ) and the Poisson's ratio ( $\nu$ ) were measured on selected samples collected from outcrops located outside the landslide deposit, and from the deposit (samples Vj1 to Vj11 in Fig. 2). The total number of the investigated samples is 23.



**Fig. 3** Variation of (a) tangent Young's Modulus ( $E_{tan}$ ) versus Unconfined Compressive Strength ( $\sigma_c$ ), and of (b) tangent Poisson's ratio ( $\nu$ ) versus Unconfined Compressive Strength ( $\sigma_c$ ). Squares and circles are directions normal and parallel to bedding respectively, stars are bulk average data

For every lithology, specimen were drilled in two directions, perpendicular and parallel to bedding planes, with about 38.0 mm diameter and length to diameter ratio between 2.0 and 2.5. The Young's modulus and the Poisson's ratio were obtained by using bonded linear electrical resistance strain gauges (TML). Tests were performed with the ADVANTEST9 apparatus (CONTROLS s.r.l.) by means of a 3000 kN capacity oil press and with a constant load velocity of 0.300 MPa/s. Unconfined compression tests were performed in accordance with the ASTM-D2938 suggested method.

In Fig. 3, the tangential Young's modulus and the Poisson's ratio are reported versus unconstrained compression strength ( $\sigma_c$ ). The Young's modulus  $E_{tan}$  was calculated

as tangential slope to the stress–strain curve corresponding to the 50 % of the  $\sigma_c$ . The results evidence that  $\sigma_c$ ,  $E_{tan}$  and  $\nu$  are highly variable:  $\sigma_c$  between 114.0 and 236.3 MPa;  $E_{tan}$  between 41.2 and 95.2 GPa, and  $\nu$  between 0.06 and 0.59. No systematic relations were observed in the stratigraphic sequence and, for every lithology, between the two sampling directions and this consideration could be related to the up to now small number of tests.

The averages values of  $\sigma_c$ ,  $E_{tan}$  and  $\nu$  for every stratigraphic unit (star symbols in Fig. 3) are comparable even not yet statistically significant.

## Conclusions

The present work gives new data for a detailed geological and geomechanical characterization of the Vajont landslide area. On the base of extensive field work it will be possible to develop a 3D model of the slided mas and determine the influence of the major joint sets on the instability phenomenon.

The geomechanical conditions of the rock masses before (areas outside the failed mass) and after the landslide (areas inside the failed mass), were defined for the different stratigraphic units on the base of conventional field surveys and laboratory tests on selected samples. The description of the RODIO boreholes down to the sliding surface offered the opportunity to characterize in detail geomechanical setting of the slide body after the collapse.

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