

A 3D GEOLOGICAL MODEL OF THE 1963 VAJONT LANDSLIDE

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ABSTRACT

The Vajont landslide has been the object of several studies because of its catastrophic consequences and particular evolution. Several qualitative or quantitative models have been presented in the last 50 years, but a complete explanation of all relevant geological and mechanical processes still remains elusive. In order to better understand the mechanics and dynamics of the 1963 event, we have reconstructed the first 3D geological model of the landslide, which allowed us to accurately investigate the landslide structure and kinematics. The input data for the model consisted in: pre- and post-landslide geological maps, pre- and post-landslide orthophotos, pre- and post-landslide digital elevation models, structural data, boreholes, and geophysical data. All these data have been integrated in a 3D geological model implemented in Gocad, using the implicit surface modelling method. Results of the 3D geological model include the depth and geometry of the sliding surface, the volume of the two lobes of the landslide accumulation, kinematics of the landslide in terms of the vector field of finite displacement, and high quality meshes useful for mechanical simulations. The latter can include information about the stratigraphy and internal structure of the rock masses and allow tracing the displacement of different material points in the landslide from the pre-1963-failure to the post-landslide state. As a general geological conclusion, we may say that the structural analysis and the 3D model allowed us to recognize very effectively a sliding surface, whose

non-planar geometry is affected by the interference pattern of two regional-scale fold systems. The landslide is partitioned into two distinct and internally continuous rock masses with a distinct kinematics, which are characterised by a very limited internal deformation during the slide. The continuity of these two large blocks points to a very localized deformation, occurring along a thin, continuous and weak cataclastic horizon.

KEY WORDS: *Vajont landslide, 3D geomodelling, Gocad, structural geology, landslide kinematics, Southern Alps*

INTRODUCTION

The Vajont Landslide is one of the most catastrophic slope failures of the past century and possibly of all times. About 240 Mm³ of the Jurassic-Cretaceous carbonatic sequence on the Monte Toc northern slope slid into the Vajont Reservoir on October 9th 1963, displacing the water in the reservoir and producing a huge wave that overtopped the dam and killed almost 2000 people in the Piave valley below. Both the pre-1963 and post-1963 geological configurations are very well characterized thanks to reliable geological and topographic data collected during the first phase of studies of the Vajont landslide, before the 1963 failure (ROSSI & SEMENZA, 1965). The availability of this dataset did not prevent the 1963 catastrophe (an historical account can be found in SEMENZA & GHIROTTI, 2005), but today allows a very detailed reconstruction of the landslide kinematics, which might be used to

gain a better understanding of landslides and the related hazard in general.

Although the landslide has been extensively studied, its structural controls, deformation mechanisms, triggering factors, and dynamics, are still not completely understood. The recent development of new technologies enables a better characterization and understanding of the landslide. Geological, structural, geomorphological, hydrogeological and geomechanical

features are being re-analysed using new field surveys, photogrammetric analyses, terrestrial and aerial laser scanning, topographic DEM analyses, rock-masses characterization, and a completely revised analysis of several boreholes drilled after 1963. Most of these new data are reviewed and discussed by MASSIRONI *et alii* (this volume), who propose a totally revised structural geology background for the landslide. Here we show how we have integrated all these new and historical

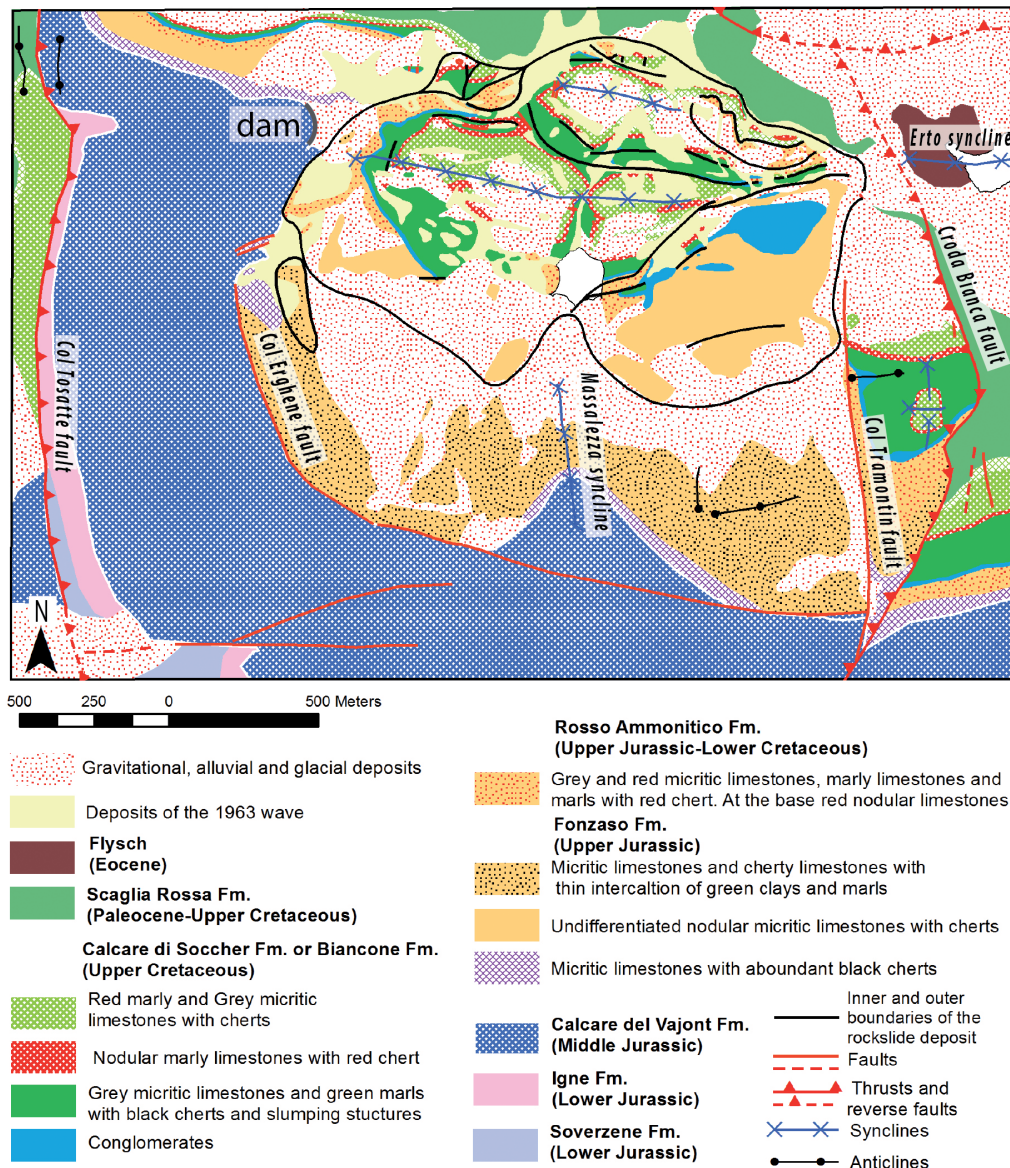


Fig. 1 - Geological sketch-map of the Vajont Landslide area (from MASSIRONI *et alii*, this volume)

data in a detailed 3D geological model of the landslide, how the 3D model has been reconstructed, which is its accuracy and reliability, and which is its importance as a basis for detailed numerical simulations of failure mechanisms. The 3D geological model allows to investigate the structural setting before and after failure, the landslide kinematics, and to compare all this with different kinds of numerical simulations.

GEOLOGICAL SETTING

The northern slope of Monte Toc, where the landslide developed in the Vajont Valley, is entirely carved within carbonatic Jurassic-Cretaceous sequences of the Venetian Southern Alps. The stratigraphy of these units has been described in detail by SEMENZA (1965) and MARTINIS (1978), in studies where the geology of the landslide (both at surface and in boreholes) has been compared with outcrops in the Vajont Valley, not far from the landslide itself. The units outcropping in the landslide accumulation and in its surrounding are, from bottom to top (Fig. 1):

- the Vajont Limestone (Dogger, 350-400 m): massive reworked oolitic limestone (e.g. ZEMPOLICH, 1995) outcropping in the Vajont Gorge, below the landslide;
- the Fonzaso Formation (Oxfordian-Callovian, 10-40 m): layered cherty limestone which in the upper part also show thin greenish clayey interlayerings, considered by HENDRON & PATTON (1985) the weak layers along which the sliding surface developed;
- the Rosso Ammonitico (Turonian-Kimmeridgian, 0-15 m): a thin and discontinuous fossiliferous nodular limestone unit which is not represented in most published maps;
- the Calcare di Soccher (Cretaceous, 150-250 m): massive limestones (lower member) grading to layered marly and cherty limestone (upper members); a large part of the landslide is constituted by this stratigraphic unit; the lower part of this unit is marked by a thin but characteristic conglomeratic layer which represents a very useful structural marker within the landslide and in its surroundings;
- the Scaglia Rossa (Upper Cretaceous-Eocene, ca. 300 m): layered marly limestones and marls with a penetrative scaly fabric, not outcropping in the landslide.

This sequence has been mapped at the 1:5.000 scale in the pre- and post-landslide setting by Rossi

& SEMENZA (1965), and constitutes the basis for the reconstruction of the geological structure within the landslide accumulation and substratum.

Regarding the structural setting, MASSIRONI *et alii* (this volume) have completed a thorough review of available data and a detailed new study, resulting in a complete reinterpretation of structures within the landslide, with consequences on any further development in terms of kinematic or dynamic models. Some of these observations, and particularly those performed at large scale, have been included in our 3D geological model.

Particularly important is the observation that most of the folds that can be recognized on the sliding surface, and the major folds occurring within the landslide accumulation, with N-S and E-W axes, predate the landslide and have a tectonic origin. This, which contrasts with assumptions made by many previous authors (e.g. PARONUZZI & BOLLA, 2012) is easily demonstrated since the same folding pattern is observed out of the landslide. The preservation of these structures within the landslide is so good that the largest folds can be traced to the corresponding structures in the immediate vicinity of the landslide (MASSIRONI *et alii*, this volume). Quite obviously, such a perfect preservation indicates that internal deformation of the landslide accumulation is very limited, and that landslide-related deformation occurred along localized fault-like horizons, as will be confirmed in the section on 3D kinematic analysis.

Considering just the large scale structures, MASSIRONI *et alii* (this volume) have also recognized that the overall geometry of the sliding surface is defined by the interference of two synclines, the E-W trending Erto Syncline and the (previously unknown) N-S trending Massalezza Syncline, defining a km-scale basin structure (Fig. 1). We will see in the following that this structure is very well represented in the 3D geological model, and has a strong influence on the kinematics and dynamics of the landslide (CASTELLANZA *et alii*, this volume).

3D MODELING

We have reconstructed a 3D geological model which represents both the pre-1963 and post-1963 configuration (Fig. 2). This was possible thanks to the reliable geological and topographic data collected during the geological surveys aimed at the design of the Vajont

Dam and particularly during the first phase of studies of the Vajont Landslide, before the October 9th 1963 failure (SEMENZA, 1965). Input data for the pre-1963 3D model consist in a 1:5000 pre-landslide geological map (ROSSI & SEMENZA, 1965), and in a digital elevation model obtained by interpolation of the contour lines (10 m equidistance) represented within this map. The post-1963 geology is well represented by the post-landslide geological map (ROSSI & SEMENZA, 1965), which after 50 years is still considered very reliable (see SEMENZA & GHIROTTI, 2000, and MASSIRONI *et alii*, this volume, for a review of the historic data). Stratigraphy and the characterization of boreholes drilled after the landslide is covered by MARTINIS (1978) and has been reviewed during this project. Post-landslide topography has been obtained from a recent aerial Lidar survey, and additional information have been collected on orthorectified aerial photos (both from irdat.regione.fvg.it/CTRNI/). Additional structural data and the overall geological setting are discussed in MASSIRONI *et alii* (this volume). The reliability of the pre-landslide geological map is ranked very high, by comparison with the post-landslide map by the same authors. Also the pre-landslide topography is considered quite reliable, by comparison with the recent Lidar survey in regions not affected by the landslide. In the last year a detailed geophysical survey, combining seismic and electric resistivity tomography, has been carried out by FRANCESE *et alii* (this volume), and also these data have been integrated in the post-landslide 3D model. In the first

phase of the project all these data have been georeferenced (Italian Gauss Boaga grid, east zone), converted to suitable file formats and imported in a Gocad project. In Figure 2 the pre- and post-landslide geological maps are shown, draped onto the pre- and post-landslide topography, readily evidencing the huge mass of the Vajont Landslide.

Due to the particular behaviour of the landslide - a rock slide where large coherent blocks glided along a very localized basal slipping surface (e.g. HENDRON & PATTON, 1985), the slide deposit is composed of two main lobes (eastern and western) internally separated into a few large blocks where the original stratigraphy is preserved. This is readily evident by comparing the pre- and post-landslide geological maps in the 3D rendering in Figure 2. These lobes are separated one from each other by localized discontinuities, and from the bedrock by the main sliding surface. This allowed us to reconstruct the stratigraphy within each block, which, in structural geology terms, could be considered as a relatively undistorted fault-bounded block, whilst the discontinuities can be considered as faults (actually they show the same geometries as low-angle normal faults). The basal sliding surface, extending everywhere below the landslide and separating it from the bedrock, is shared by both the pre- and post-1963 models. On the other hand, the topography and landslide structure show appreciable variations between the pre- and post-landslide models. In the following we will show how these variations have been used to

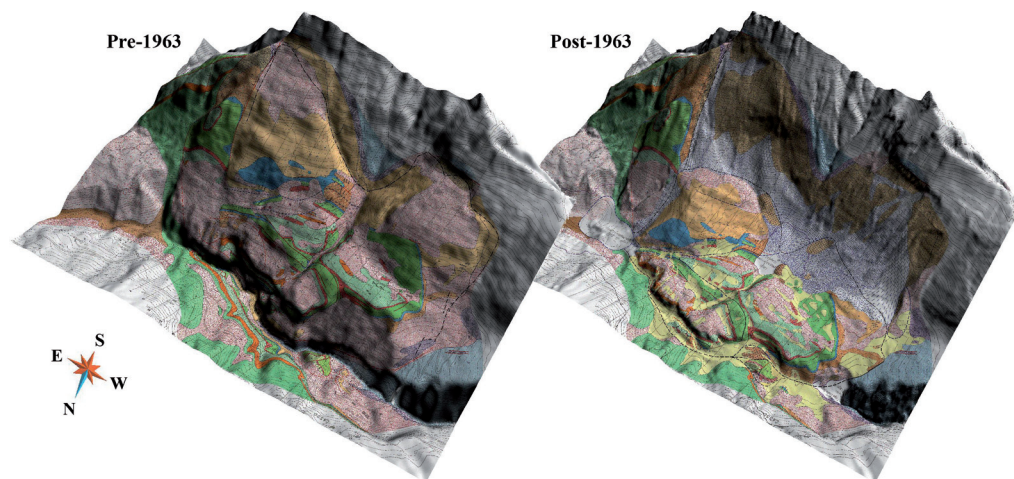


Fig. 2 - Pre- and post-landslide geological maps (-, 1965), draped on the pre- and post-slide topography. See legend in 252 Figure 1. The huge mass transfer (270 Mm³) from the steep northern slopes of Monte Toc, which filled the gorge, can be easily 253 recognized. Post-landslide boreholes, as deep as 300m, are shown as a reference in both images

reconstruct the landslide kinematics.

Both the pre- and post-1963 models have been reconstructed in two main steps. First the discontinuities have been interpolated in Gocad with conventional "explicit" interpolation techniques using the DSI algorithm (MALLET, 2002). Then the stratigraphy within each block has been modelled with an implicit approach, using the GRGPack plugin (CAUMON *et alii*, 2009; MASSIOT & CAUMON, 2010). This technique was found very effective in the integration of surface and subsurface geological data, both in the pre- and post-1963 setting.

In the case of the sliding surface, the data integrated in the model consist in (Fig. 3): (1) topography of the now-exposed upper portions of this surface (from Lidar point cloud), (2) surface geology (traces of faults and geological boundaries from pre- and post-landslide geological maps), and (3) boreholes (constraining at depth the sliding surface). In terms of 3D geomodelling techniques (MALLET, 2002), all these data have been added as control points to a surface pinned to the branch line (assumed perfectly known from geological maps), which marks the intersections between the sliding surface and the pre-1963 topography. The overall geometry of the sliding surface was then interpolated by means of the DSI algorithm in Gocad (MALLET, 2002).

Other discontinuities, such as those separating the two lobes, or different blocks within the two lobes, in the post-landslide 3D model (Fig.- 4), cannot be constrained so well, and basically are simply interpolated

between their branch lines. However, this is not considered a real concern, since the vertical extension of these discontinuities is limited.

Finally, implicit surface modelling was applied within blocks separated by discontinuities, allowing to independently model the stratigraphy within each block. The input data in this case are traces of stratigraphic contacts, structural data (including fold axes considered as in MASSIOT & CAUMON, 2010), bore-hole stratigraphy and geophysical data. The implicit surface modelling is carried out with the GRGPack plugin on an unstructured tetrahedral mesh generated within each block with the TetGen algorithm (MASSIOT & CAUMON, 2010). The result is a realistic reconstruction of the blocks' internal structure, with relevant ties to the pre-landslide structure, as discussed in MASSIRONI *et alii* (this volume).

Apart from a better definition of the internal structure of the landslide, the main improvements with respect to previous models of the landslide, based on dense networks of cross sections, are a more precise definition of the volumes involved and a more consistent and reliable reconstruction of the sliding surface. The volume of the landslide, calculated in the pre-1963 configuration, is 241.3 Mm³. The most significant differences in the shape of the sliding surface are (1) the presence of the Massalezza syncline, which results in a convergence of the western and eastern slopes of this surface (Fig. 3), and (2) a longitudinal shape which is partly different from the one assumed by previous authors.

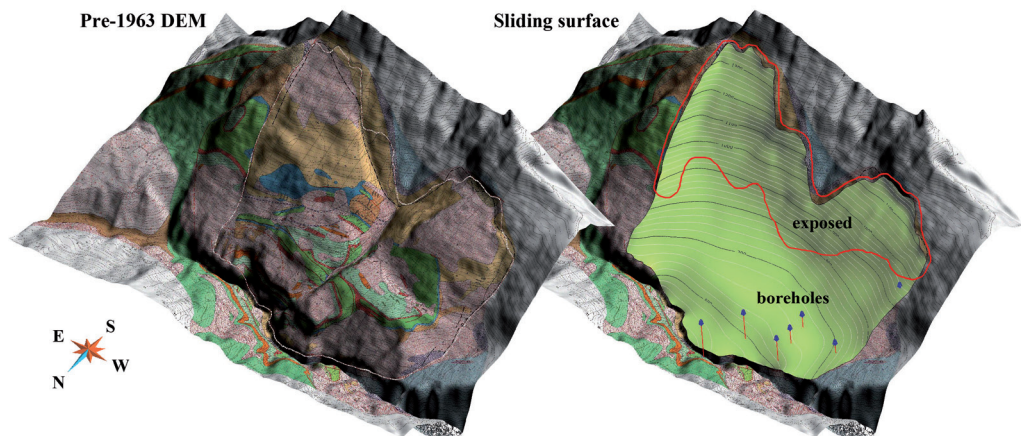


Fig. 3 - Pre-landslide model. The pre-landslide DEM (left) is removed as to reveal the sliding surface (right, in green with elevation contours). The red line marks the now-exposed portion of the sliding surface reconstructed from Lidar data. The boreholes in the western-lower area are highlighted

RELIABILITY AND ACCURACY OF THE MODEL

A general discussion on reliability criteria in 3D geological models reconstructed from surface and sub-surface geological data is provided by BISTACCHI *et alii* (2008). In that contribution, we proposed to consider an increasing level of uncertainty in our reconstructions depending on two parameters: (1) the distance from hard data points, where the 3D position of e.g. a geological boundary or a fault is directly observed and perfectly known (both in outcrop or in a borehole); and (2) the level of “geometrical complexity” of the structure, which is minimum for planar beds or faults, increases for regular curvilinear structures like cylindrical open folds, and reaches a maximum for convoluted structures like complex tight folds or intrusive contacts. Within this framework, we can rate the uncertainty level of the Vajont Landslide 3D model as follows.

The geometry of the sliding surface is very reliable in several key areas (Fig. 3): the upper portions, where it is exposed and mapped in the Lidar dataset; the lower edge, where it was mapped by E. Semenza before the 1963 landslide (ROSSI & SEMENZA, 1965); and the western half of the buried portion, where it has been recognized in several boreholes. On the other hand, the eastern part of the lower buried section of the sliding surface is not constrained by any hard data. Actually, some boreholes were drilled also in this part of the landslide, but these data are no more available. To converge to a reliable model of this part of the sliding surface we have used three criteria: (1) the depth to the sliding surface can be constrained by the

thickness of the Calcare di Soccher, also considering the pre-landslide folds which can be traced in the sub-surface in the geophysical dataset (FRANCESE *et alii*, this volume); (2) the geometry of the sliding surface should be consistent with the large scale folding patterns recognized by MASSIRONI *et alii* (this volume); and finally (3) in absence of contrasting evidences, the surface should be smooth and have a simple geometry. In the end we estimate that the geometry of the sliding surface is now well known, with uncertainty varying between ca. 1 m and less than 20 m.

The geometry of the folds recognized within the landslide accumulation blocks is defined with a more heterogeneous level of certainty. As a general rule, we may say that these geometries are very well defined in the vicinity, both in terms of stratigraphy and proximity to outcrops, to the conglomeratic horizon at the base of the Calcare di Soccher. This because this horizon is a very characteristic marker both in outcrops and in the geophysical dataset, where it is associated to an upsection increase in electric resistivity and seismic velocities (FRANCESE *et alii*, this volume). On the other hand, the structure is poorly defined where the landslide accumulation is covered by Quaternary deposits or in correspondence of the thicker upper members of the Calcare di Soccher.

FINITE DISPLACEMENT FIELD

The reconstruction of the pre- and post-landslide 3D model allowed to compare the 3D coordinates of several “tie points” that can be recognised both in the pre-1963 and post-1963 structure (Fig. 5). The

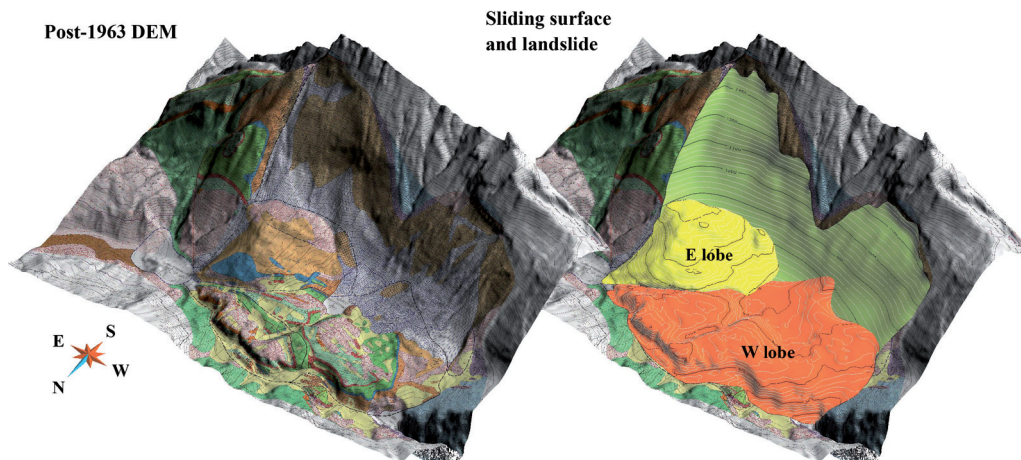


Fig. 4 - Post-landslide model. The western and eastern lobes are evidenced to the right

tie points have been connected with straight line segments, which represent the finite displacement vector accumulated between the pre- and post-landslide stages. The length and 3D direction of these vectors has been compared, and it was possible to recognize two distinct groups of vectors with a very limited internal variability. The two groups are represented in blue and red in Fig. 6, for the western and eastern groups, and correspond to tie points selected in the western and eastern lobe respectively. The western group of displacement vectors is characterized by a length of 361 ± 12 m, an azimuth of $8 \pm 2.5^\circ$, and a downward decrease in plunge, indicating a partly rotational kinematics (in cross section) for the western

lobe. The eastern group of displacement vectors is characterized by a length of 464 ± 12 m, an azimuth of $3 \pm 1^\circ$, and a rather constant plunge, indicating no rotational kinematics. Overall, the small standard deviations within each group indicates a very limited deformation within each block, consistently with structural geology observations by MASSIRONI *et alii* (this volume), and no rotations in a map view (in contrast with PARONUZZI & BOLLA, 2012). Moreover, it appears that the two lobes followed partly convergent paths (about 5° of convergence), which is consistent with the kinematic control - or “confinement” effect - exerted by the Massalezza syncline. In other words the western lobe was pushed to the

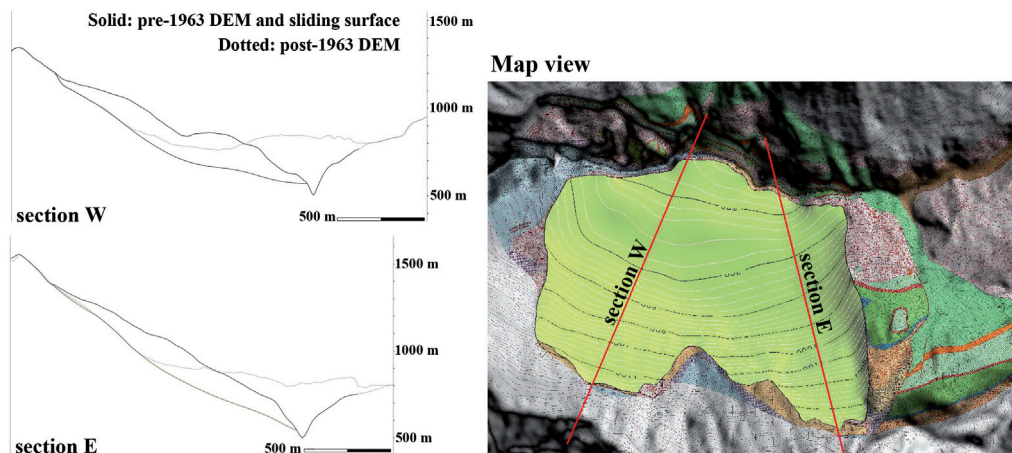


Fig. 5 - Cross sections across the western and eastern lobes and location of cross sections superposed on a map including the 259 sliding surface and the surrounding geology as in Figure 3

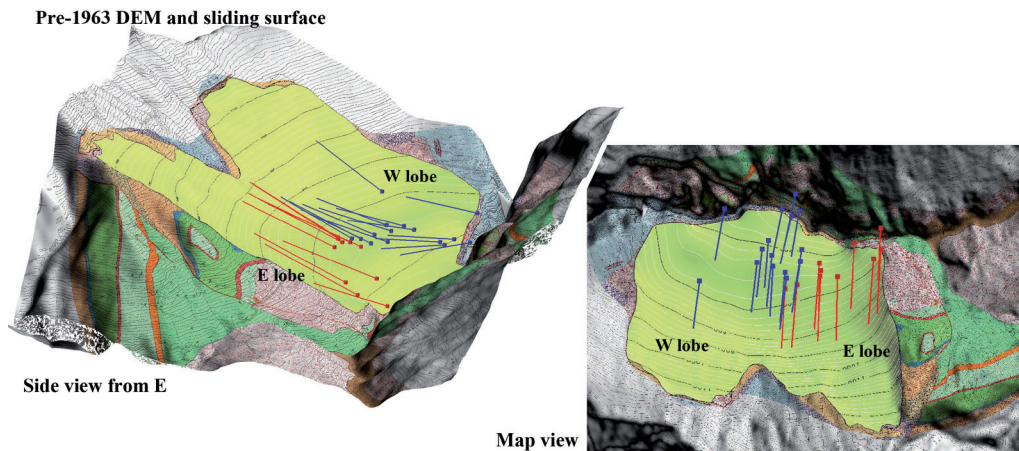


Fig. 6 - Finite displacement field. Reference points (“tie points”) recognized in the pre-1963 and post-1963 geology have been 261 connected by finite displacement vectors. The eastern and western lobes are represented by red and blue vectors respectively

NNE by the sliding surface dipping in that direction, and the eastern lobe suffered an opposite effect due to the eastern limb of the syncline dipping towards the NNW. Finally, the different lengths of displacement vectors is consistent with the eastern lobe being partly thrust on top of the western lobe for a distance of about 100 m, as already evidenced by SEMENZA (1965).

EXPORTING MODEL GEOMETRIES TOWARDS OTHER MODELING PACKAGES

One important goal of this 3D geological modelling project was to provide a common best-fit geometrical and geological basis for the development of numerical models dealing with various aspects of the landslide mechanics and hydrogeology. The geometries that we have obtained will be available in the future by request to the corresponding author. At the time of writing, these geometries have been exported in different file formats and made available to parallel projects mainly dealing with the mechanical simulation of the triggering phase. Different approaches have been used to export the Gocad geometries towards Midas/GTS (CASTELLANZA *et alii*, this volume), 3DEC, Slope Model, and UDEC.

Midas/GTS has an import tool particularly suited for sets of contour lines, which are used to constrain NURBS surfaces that in turn control the 3D finite element mesh. Thus, we exported (DXF format) a very high resolution set of contour lines from the sliding surface and topography, defined in Gocad as triangulated surfaces. We have also been able to import in Midas/GTS the tetrahedral mesh generated in Gocad with the TetGen algorithm, but in the end this mesh resulted very heavy, having a very high resolution, and was not used in simulations.

As regards 3DEC and SlopeModel, we have exported the Gocad triangulated surfaces to Rhino3D, using the intermediate OBJ exchange format. From this file format it is possible to generate 3DEC and FLAC3D geometries using KUBRIX Geo (www.itascacg.com).

Finally, two 2D sections have been exported in DXF format to be imported in different 2D modelling packages. These sections have been cut in the western and eastern lobes of the landslide, oriented parallel to the slope of the sliding surface.

CONCLUSION

The 3D geological modelling of large landslides is considered a very interesting, yet challenging task because of the very complex structures involved and of the lack of detailed subsurface data. In the case of the Vajont Landslide, these difficulties are less pronounced than in other cases, due to the particular kinematics, characterized by sliding of large coherent blocks along thin fault-like horizons. In addition a very complete topographic, geologic and geophysical dataset is available for both the pre- and post-landslide configuration.

The modelling approach chosen for this project, which includes a first step of conventional "explicit" modelling of large-scale discontinuities, and a second step of implicit surface modelling of the stratigraphy within each block, proved to be very effective. Particularly important is the possibility to include in the analysis data that are very heterogeneous and sparse.

Concluding, our approach allowed to reconstruct a reliable best-fit 3D geological model of the Vajont Landslide, which allows: (1) to measure the landslide volume, (2) to reconstruct its kinematics, and (3) to export the geometries and geological properties towards various geomechanical and hydrogeological modelling packages. A possible improvement in the model presented here would be the inclusion of geomechanical properties measured in outcrops or boreholes, which would allow for a very advanced geostatistical modelling of these fundamental parameters.

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