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THE VAJONT LANDSLIDE: STATE-OF-THE-ART

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INTRODUCTION

The next 9th of October 2013 is the 50th anniversary of the Vajont landslide. Many questions, legal, economic, social and scientific have accompanied the history of the dam and the management of the emergency concerning the Vajont reservoir slopes instability.

The dam was built by SADE-Società Adriatica di Elettricità (Adriatic Energy Corporation), the electricity supply and distribution monopolist in North-Eastern Italy at that time. The dam and the basin were intended to be at the center of a complex system of water management in which water would have been channeled from nearby valleys and artificial basins located at higher levels.

The long lasting story of Vajont dam begins at the dawn of the 20th century and ends abruptly on 9th October 1963 at 10:39 p.m. local time, in a 4-5 minutes of apocalypses. It is not only a story, as the journalist Tina Merlin wrote, of the "arrogance of strong power and subjection of humanity and science to economic reasons", but has to be regarded as a clear sign of the engineering geological knowledge existing at that time. At that time the dam was the tallest (265.5 m) concrete double arched dam in the world. After a three years long period of slow but on the whole accelerating movements on the morning of 9th October the situation was really critical, so that the engineer director of the construction site wrote to his head a dramatic letter: "*In these past few days translational speeds within the landslide have clearly increased. ……. Rupture on the slope and road, ..., the enlargement of the main landslide scarp,...., make me think the worst. Water level is lowering, ... It is my intention to reach the 695 level in order to have a safety margin in case of waves. ... May God help us!*"

On October 9, 1963 at 10:39 p.m. local time, about 270÷280 million m^3 of rocks slid into the Vajont reservoir creating a giant water wave that overflowed the dam, destroyed the many villages, killing about 2000 people.

On July 1965, a parliament Board of Inquiry stated that could not have been foreseen. On February 1968 three engineers of SADE, the firm charged of the dam construction, and of the department of public works were convicted; one of them was acquitted in appeal.

The mechanics of the final collapse, still poorly un-

Fig. 1 - The village of Longarone after the catastrophic water wave

derstood, has constituted and still constitutes a challenge to physicists, geologists and engineers over the last 50 years. The reasons why some catastrophic landslides move so fast and so far, cannot be fully explained yet, and the 1963 Vajont landslide is a tragic example of it. Owing to its intrinsic geological and geomechanical complexity, the Vajont rockslide has been considered as the starting point for the development of modern rock mechanics and rock engineering. Besides, the disaster exerted a great influence in the field of both engineering and geology, marking a turning point in the attention given in hydro-projects to the reservoir slopes, as was not the case before. Nowadays the impact of unstable slope must be evaluated and an implicit, if not explicit comparison is always made with the Vajont slopes.

For that, reports and scientific literature on the Vajont landslide are very numerous: no other slide in the world has been the subject of so many studies and researches.

The scientific community has never stopped the thorough study of the combined causes and the final mechanisms of this tragic event. But, despite the great scientific interest related to this catastrophic episode, most of the questions concerning the failure mechanism, the high velocity and the general characteristics of the slide should be considered not yet satisfactorily explained. Many geological, hydrogeological, and geotechnical aspects still remain unexplained, particularly as regards whether the 1963 slide was a new landslide or the reactivation of a prehistoric slide.

On the other hand, the event was unusual in that the flood was not caused by the dam collapse, but a catastrophic landslide from the slope of Monte Toc that pushed over the dam about 30 million m^3 of the water in the newly created reservoir. Nevertheless the dam resisted!

This keynote will be a short review of the events that preceded the Vajont disaster and of the studies and researches carried out both before and after the tragic landslide. It is structured in four main parts:

1) The chronicle of a disaster: it represents a temporal list of the events and the data gradually acquired up to the catastrophic landslide.
2) The studies before the failure: it represents the state-of-the-art of geological and engineering geological knowledge as they increased from the beginning to the ending failure.
3) The studies and researches after the failure: it is a summary of the worldwide researches on this event, embracing different disciplines from geology to engineering geology, hydrogeology, geomorphology, geomechanics and to hydraulics. It is not a review of all the papers written on this subject, but the main papers are reported.
4) The current studies: they refer only to the researches carried out in the range of the direct collaboration of the Geosciences Department of the University of Padova with the Simon Fraser (Canada), Milano La Biococca and Pavia Universities.

ἄριστον μὲν ὕδωρ
(Pindar - Greatest however [is] water)

THE VAJONT DAM HISTORY

THE DESIGN OF THE DAM: 1925 - JANUARY 1957

Preliminary studies for the Vajont dam construction began as early as in 1920 and in 1928 two possible cross sections were preliminarily individuated in

Fig. 2 - The Vajont gorge at Colomber bridge

the Vajont valley by SADE.

30th January 1929 - SADE asks for the permit to use the Vajont torrent waters (Eng. C. Semenza project).

4th August 1928 - Prof. Giorgio Dal Piaz, the geologist charged by SADE, suggests the dam location downstream of the Colomber bridge, where actually the dam will be built, rejecting the 1925 hypothesis of the Swiss geologist Prof. J. Hug.

7th-9th August 1937 - Prof. G. Dal Piaz confirms the chosen location for a 180 m high dam.

22th June 1940 - SADE designs the hydraulic Boite-Piave-Vajont system. A further geological report of Prof. G. Dal Piaz corroborates the choice already made and underlines once more the suitable conditions of the Vajont valley. The project is approved by the Public Works High Council on 15th October 1943

15th May1948 - SADE submits the detailed design of a 202 m high dam with a new geological report of Prof. G. Dal Piaz (25th March 1948) which repeats and confirms his previous favourable conclusions.

11th October 1948 - Eng. C. Semenza asks to Prof. G. Dal Piaz the possibility to increase the height of the dam to an elevation of about 730 m a.s.l.

21th December 1948 - In another geological report, further improved in 18th November 1953, Prof. G. Dal Piaz pays attention to the stability of the La Pineda landslide and, mainly, to the stability condition of the village of Erto on the right slope of the valley.

THE CONSTRUCTION OF THE DAM: JANUARY 1957 - SEPTEMBER 1959

January 1957 - Construction works begin.

31th January 1957 - SADE presents the "Great Vajont Project": impounded waters will derive from the torrents Vajont, Maè and Boite. SADE requests the maximum level of the reservoir to be raised to 722.5 m a.s.l., accompanying the demand with an integration of Prof. G. Da Piaz to his geological report dated 25th March 1948, that confirms his previous conclusions.

2nd April 1957 - SADE presents the detailed design for a 266 m high dam (150x10^6 m^3 capacity), later approved (15th June 1957) by the High Council of Public Works that, however, asks for further geological surveys.

1st April 1958 - The High Council of Public Works appoints the "Commissione di Collaudo", a board of experts with the aim to control works execution and procedures: first inspection on 19th July 1958: Prof. Penta and Prof. Mueller agree on the consolidation of the down-valley slopes with nails and rock anchors.

September 1959 - The construction of the dam is accomplished: 261.6 m high, 190.2 m long, 22.1 m thick at base and 3.4 m at crest, 725.5 m a.s.l. at crest.

22th October 1959 – Second field survey of the "Commissione di collaudo".

26th November 1960 - "Commissione di collaudo" field survey.

10th April 1961 - Fourth field survey of the members of the "Commissione di collaudo" Prof. Penta and Eng. Sensidoni.

17th October 1961 - Fifth field survey of the "Commisione di collaudo": the filling of the reservoir may continue, but further coincidental movements cannot be escluded.

16th November 1961 - The filling of the reservoir may continue up to 640 m a.s.l. elevation and later up to 655 m a.s.l. (December 1961) and to 675 m a.s.l. (6th February 1962).

GEOLOGICAL AND GEOMECHANICAL STUDIES

After the design phase, a great number of geological studies and reports accompanied the construction and the operation tests of the dam as a consequence of both the variations requested by SADE and the continuously raising problems related to the geological and stability problems of the area.

31st January 1957 - Prof. G. Dal Piaz report, integrating his 25th March 1948 report, is favorable to the increase of the dam height to 266 m, but with some precautions regarding the dam shoulders and the needed waterproofing works.

6th August 1957 - A report of dr. L. Mueller underlines the poor characteristics of the rock mass on the left slope of the valley.

September 1957 - Prof. G. Dal Piaz report (raft dates 9th June 1957), attached to the Eng. C. Semenza detailed design (2nd April 1957) confirms the validity of all the studies until then carried out.

29th October 1958 - The left Vajont slope is studied by

Prof. G. Dal Piaz for the construction of a road: only small rock falls are forecasted.

10th October 1959 - Doubts are expressed dr. L. Mueller on the stability of the left slope which requires new field surveys.

4th February 1960 - Prof. P. Caloi, resting on data obtained with a seismic station installed on December 1959 near the dam, states that the left slope is composed by sound rocks showing very high elastic moduli, with a shallow (10-12 m) detritic cover.

June 1960 - On the basis of field surveys carried out (1959-spring 1960) the presence of an old wide and deep landslide on the left slope is supposed by geologists dr. E. Semenza and dr. Giudici.

9th July 1960 - Prof. G. Dal Piaz confirms his previous conclusions and only small and slow phenomena might be possible. However, he doesn't consider the Semenza-Giudici hypothesis.

October 1960 - On M.t Toc slope a 2 km long M-shaped fissure opens up at 1200-1400 m a.s.l., defining an area about 1700 m long and 1000 m large.

15-16th November 1960 - A sketch in the report of Prof. Mueller shows that he had actually considered the instability of a huge rock mass on a deep slip surface.

26th November 1960 - Prof. Penta supposes that the M-shaped fissure, opened in October 1960, could be the proof either of a very deep landslide or of a more superficial and slow one. More accurate and deep geological surveys are suggested (memo 1st December 1960) and were accepted and prescribed by SADE.

3rd February 1961 - Resting on all surveys and studies carried out by Prof. P. Caloi, by the geologists E. Semenza, Giudici and Penta and by Dr. Broili, dr. Mueller concludes: i) the volume of the moving mass is about $2x10^8$ m^3; ii) the moving mass is split in different independent parts; iii) if so, the three parts of the landslide will occur in different times; iv) the landslide could be partially controlled by artificial landsliding.

10th February 1961 - Prof. Caloi, integrating his 23rd February 1961 report, concludes: i) seismic wave velocities are less than those previously measured (1959); ii) the velocity decrease might be attributed to both unavoidable differences in the execution of the seismic surveys and an intense degradation of the rock mass characteristics due to the deformation processes.

2nd March 1961: - Prof. Caloi, in a letter to the Eng. Tonini writes that the bedrock was sufficiently sound.

5th May 1961 - Dr. Pacher, assistant of dr. Mueller, analyses the results of a 100 m long exploratory tunnel dug on to the left of the Massalezza creek at an elevation of about 900 m a.s.l. (spring 1961), and concludes with the existence of a number of although limited slip surfaces, a fact that contrasts with the hypothesis of a unique deep shear surface.

31st October 1961. Prof. Penta, on the basis of 10th April and 17th October 1961 field surveys, confirms previous conclusions (15th April 1961 letter) on the existence of a shallow, possibly dormant landslide.

3rd May 1962 - No new landslides are observed by Eng. Beghelli (Belluno Public Works Bureau ("Genio Civile") during the field survey.

THE CHRONICLE OF A CATASTROPHE

A mess of almost impenetrable and contrasting events, technical aspects and human behavior imprinted the long inexorable approach to the 9th October disaster. The beginning might be set on 22th March 1959 when a $3x10^6$ m^3 landslide occurred in the near valley of the torrent Maè, falling into the reservoir of Pontisei and generating a water wave about 20 m high. The consulting geologist is Prof. Penta and a few days after Prof. P. Caloi write that the landslide had been exactly forecasted in one of his report. Considering only the lapse after the end of the dam construction (September 1959), a concise list of the main facts is the following.

19-21th July 1959 – First field survey of the "Commissione di collaudo", the board of experts charged to control works execution and procedures: no problems are reported.

2th February 1960 - The first filling of the reservoir (up to 595 m a.s.l. elevation) begins.

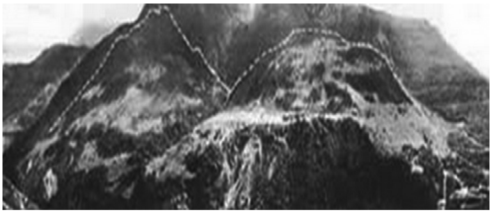


Fig. 3 - The M-shaped perimeter fissure (photo E. Semenza)

March 1960 - A landslide occurs on the left slope just upstream of the Massalezza creek confluence, at an elevation of about 850 m a.s.l., that is at the border of Pian della Pozza.

June 1960 - The geologists E. Semenza and Giudici expose the hypothesis of the existence of a huge old landslide on the left slope.

11th June 1960 - A reservoir water level to 660 m a.s.l. is allowed.

October 1960 - A long M-shaped fissure, 1800 m long and 1100 m wide as a mean, opens on the left slope, defining an area of about 2 km$^{2.}$

4th November 1960 - A landslide of 7-8x10^5 m^3 occurs on the left slope.

15th÷16th November 1960 - Following this event, the Eng. C. Semenza, the dr. L. Mueller, the geologist E. Semenza and alii decide the drawdown of the reservoir and the construction of a by-pass gallery with the aim to control the water level in the eastern part of the reservoir in case of the occurrence of the deep and huge landslide that dr. L. Muller hypothesizes.

November 1960÷January 1961 - A slow drawdown of the reservoir down to 600 m a.s.l. is carried out and the level maintained until October 1961. The lapse is necessary for the construction of the by-pass gallery, that begins on january 1961.

31st January 1961 - SADE charges the "Centro Modelli Idraulici di Nove di Fadalto", a SADE research centre entrusted to Prof. A. Ghetti (Institute of Hydraulics, University of Padova), to model the dam and the reservoir and to evaluate the effect of a landslide into the reservoir. The assumed model hypotheses are: two different and consecutive 20-40x10^6 m^3 landslides; reservoir water levels at 680 m and 720 m a.s.l.; the rock mass modelled by rounded gravels.

Fig. 4 - The 4th November 1960 landslide (Photo Semenza)

21st February 1961 - The risk of the failure of the Vajont left slope is reported in an article of the local daily.

3rd February 1961 - Dr. L. Muller supposes a 2x108 m3 landslide and such a landslide cannot be stabilized.

10th April 1961 - Prof. Penta and Eng. Sensidoni, members of the "Commissione di collaudo" state: i) surface displacements are no more present; ii) no indication about a deep landsliding phenomenon is evident; iii) no immediate danger is discernible.

15th April 1961 - Prof. Penta after a new field survey affirms that no hazard can be detected with the reservoir water level at 600 m a.s.l..

20th April 1961 - After the drawdown no more displacements are detected, but landslides phenomena are suspected (letter of Eng. C. Semenza), even if Prof. G. Dal Piaz and Prof. Penta are optimist.

10th May 1961 - The by-pass gallery is accomplished.

August-September 1961 - Four standpipe piezometers are installed on the left slope at depths between 167 m and 221 m. One of them is immediately out-of-order.

31st October 1961- the filling of the reservoir can be continued as the by-pass gallery is finished (Prof. Penta report on 10th April and 17th October 1961 field surveys).

10th April 1962 - On the basis of data obtained by the seismograph installed near the dam during 1959, Prof. P. Caloi concludes: i) the microseismic activity observed in 1960, during the first reservoir water level raise to 630 m a.s.l., has not been observed during the second raise to 650 m a.s.l. (November-December 1961 to January 1962); ii) corresponding displacements velocities are very low with respect to those monitored in the 1960 fall; iii) no other surface facts are observed.

15th June 1962 - A rather intense seismic activity is registered in the period 27th April-13th May 1962: it is attributed to natural phenomena and not dependent on the reservoir filling, as shakes are external to the landsliding area (Report of Prof. Caloi and his assistant dr. Spadea).

3rd July 1962 – The 700 m a.s.l. reservoir water level is considered precautionary: for that elevation, results of physical modelling at "Centro Modelli Idraulici di Nove di Fadalto" indicate that, in the worst case of possible landslides, the volume of the displaced water would be about 20.000 m^3 with an instant discharge of 2.000 m^3 for 20 seconds.

8th July 1962 - A displacements acceleration is observed during the reservoir filling from 660 to 685 m a.s.l. New fissures open parallel to the valley axis; displacements at monitored points show different settlement values; water levels in installed piezometers are as in the reservoir (field observations of the Government's person in charge). But, further landslidings is deemed to occur, in case, slowly and involving a mass limited uphill by the new fissures. A new geological survey is considered, however, necessary, and SADE requests the possibility of local inhabitants evacuation.

17th November 1962 - Water level in the reservoir reaches 700 m a.s.l.

2nd December 1962 - Drawdown up to 647.5 m a.s.l. achieved on 10th April 1963.

10th January 1963 - With respect to July 1962 an increase of the displacements velocities is observed: it begins with the December 1962 drawdown from 700 to 650 m a.s.l., but at a reservoir elevation of 650 m a.s.l. velocities are very slow. Piezometers show water levels always as in the reservoir.

20th March 1963 - SADE requests the filling of the reservoir up to 715 m a.s.l.

22nd July 1963 - The presence of "cloudy water of reservoir, continuous rumbles and tremors in the area" is exposed (The Major of Erto).

4th September 1963 - The water level in the reservoir reaches 710 m a.s.l.

2nd September 1963 - A new seismic shake. The displacements of the monitored points increase continuously.

15th September 1963 - A new fissure opens in the slope and the perimeter M-shaped fissure widens.

27th September 1963 - The drawdown of the reservoir begins.

Fig. 5 - The hollow of Pian della Pozza

2nd October 1963 - New fissures open and further displacements are observed.

5th October 1963 –A settlement area in Pian della Pozza is observed (Prof Caloi and dr. Spadea report).

7th October 1963 - New fissures about 10 m long open. In the night the evacuation of inhabitants of Mt. Toc area is ordered.

9th October 1963, morning - The discharge channel of the dam is clogged up and the displacement velocity further increase.

9th October 1963, 13:00 local time - A new fissure 5 m long and 0.5 m wide opens and develops.

9th October 1963, 20:00 local time - The road on the left side is no more passable.

9th October 1963, 22:39 local time: a single 2.7x10^8 m^3 landslide occurs. The resulting water wave flows in the Vajont razing a number of villages to the Est (Frasein, San Martino, Col di Spesse, Patata) and, after overtopping the dam, to the West (Longarone, Codissago, Castellavazzo, Villanova, Pirago, Faè, Rivalta). About 2.000 people dead, but the dam is intact!

11th October 1963 - The Public Works Minister appoint a bord of enwuiry on the disaster.

15th February 1997 - After about 34 years all the penal and civil suits are definitely concluded.

THE STUDIES BEFORE THE FAILURE

Before the catastrophe, many geological studies were carried on the Vajont valley. Initial geological studies interpreted the Vajont Valley as a typical example of a syncline (the Erto Syncline), located along the axis of the valley (Boyer, 1913). Specific geological studies, related to the dam construction project, date back to 1901 A.D., even if for a dam only 8 m high.

The first geological studies for an important dam date at 1925 A.D., when the Swiss geologist Prof. J. Hug recommends the neighbourhood of the Casso Bridge for the dam location, where he considered the

Fig. 6 - The dam reservoir after the landslide

outcropping rocks ("Fonzaso" and "Scaglia Rossa" Formations) more suitable in comparison with those outcropping near the Colomber Bridge, supposed to be too permeable.

Except these very preliminary studies, the geological and geomorphological setting of the valley for a significant high dam was studied by Prof. G. Dal Piaz, the head of the Geology Institute of the University of Padova, from 1928 A.D. until on 20th April 1962.

The Vajont valley, between M.t Toc to the South and M-t Salta to the North, is a very narrow gorge stretching from the confluence with the Piave river to the West up to the site of Casso village. Proceeding towards East the valley widens, remaining however very narrow in its lower part. The steep slopes are characterized by many wide morphological steps and one of these, 700-800 m long, is present on the left valley side at an elevation of about 850 m a.s.l.

According to his initial geological report (4th August 1928 and 7th-9th August 1937) the Vajont valley is eroded along the axis of an East-West trending asymmetrical syncline plunging upstream to the East (Erto syncline). It is set in dolomitic limestones, no tectonic accidents are evident and rock masses are uniform and sound. The rock masses at the Colomber Bridge section are uniform and compact and permeability problems would be easily passed considering the techniques available at that time. Instead, Giurassic and Cretaceous marly limestones outcropping at the valley bottom near the Casso Bridge area are characterized by many fractures both parallel and normal to the valley axis as a consequence of the overturning of the whole stratigraphic series.

Fig. 7 - *The village of Longarone before (left) and after (right) the catastrophe*

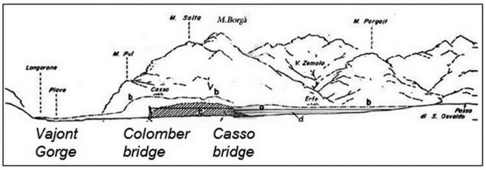


Fig. 8 - *Longitudinal sketch of the ajont valley with the two considered location of the dam. Approximate length scale 1:100.000*

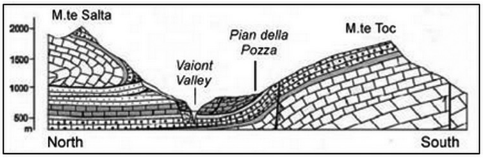


Fig. 9 - *The Erto syncline (left valley slope) and the overturned anticline (right valley slope) (from* Semenza *&* Ghirotti*, 1998)*

In the following Prof. G. Dal Piaz studies in more depth the geological features of the valley, but considering only the rock mass of the abutments and the right side of the valley (5th June 1940, 25th March 1948, 21st December 1948, integrated on 18th November 1953, 31stJanuary 1957 and 9th June 1957 geological reports). The Vajont valley has been cut in Jurassic to Eocenic rocks: in its narrower lower part, the strata (Dogger) dip to East and their thickness progressively decrease towards the valley bottom . The overturning of the stratigraphic series on the right side of Vajont valley is confirmed: a great overturned anticline (Dogger and Lias limestones) recumbent to South and with an axis inclined to East, lying unconformably on the Eocenic "Scaglia Rossa", is described. This geological structure is complicated by the presence of two synclines folds having the Eocenic "Scaglia Rossa" formation at the core one of which is found near the

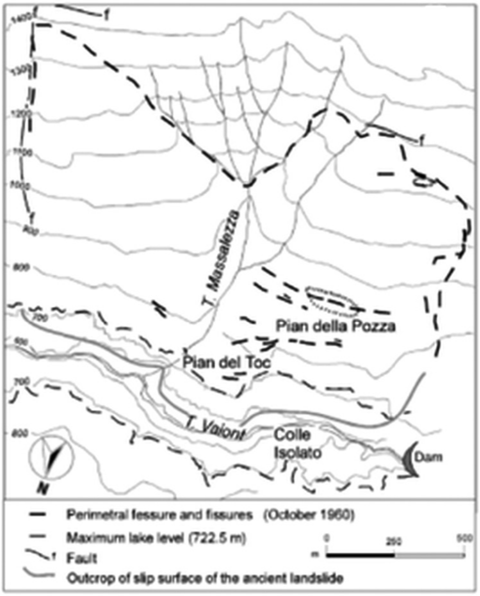


Fig. 10 - *Map of the pre-1963 Vajont landslide area (from* Genevois *&* Ghirotti*, 2005)*

village of Casso. The presence of Flysch (alternances of marls and sandstones) and some small shallow landslides are observed in the area of the village of Erto. Two joint systems, parallel and normal to the valley, are described on the right side and considered responsible for the development of existing rockfalls.

From a geomorphological point of view, the presence of morainic and landslide deposits is described on the uphill part of the Vajont right side. There, a huge rock mass is hypothesized to have slid in the past covering also great part of the left valley side where, new but not relevant landsliding phenomena could occur as a consequence of the filling-drawdown operations. The area of the village of Erto on the right valley side was investigated by a number of boreholes and small exploratory galleries dug at 730 m a.s.l. elevation. The bedrock turned out to be constituted by sound marls (“Scaglia Rossa” and “Scaglia Cinerea” formation) under a 20-40 m thick detrital cover made by calcareous and marly blocks and fragments in a sandy-clayey matrix (Technical report on boreholes carried out during 1954 in the Erto area by geologist E. Milli).

The good quality of the rock mass of the abutments is corroborated by the results of some boreholes, carried out for the preliminary project and by the new road gallery excavated on the right side at about the same elevation of the planned crest dam (725 m a.s.l.). Unconfined compression tests, carried out on Jurassic limestones, shown on the average a strength decrease from 209 MPa, at the bottom of the valley, to 119-134 MPa at 725 m a.s.l. elevation (crown of the dam). In conclusion, geological and morphological conditions at the Colomber Bridge area are deemed suitable as a location for the planned dam.

In order to complete the field surveys in the area of Erto, new boreholes were carried out in 1960 finding the bedrock (Flysch and “Scaglia Rossa”) at depths from a few meters to 18 m under a detrital cover considered stable.

Fig. 11 - The “Pian della Pozza” depression

The left side of the Vajont valley is studied and described by G. Dal Piaz only on 1960 A.D. (9th July 1960 report), also in the wake of the landslide occurred (4th November 1960) on the left slope just upstream of the Massalezza creek confluence (December 1960 annex). Some but shallow landslides, probably involving the morainic deposits, are described between the "Pineda" and "Pian della Pozza" areas. The "Pian della Pozza" is interpreted as a glacial morphological terrace characterized by a shallow elliptical doline where limestones, under the detrital cover, present very intense karst features (karren) and long and deep fractures parallel to the valley. Many other dolines are observed near the border of the cliff were occasional rock falls and shallow but substantially slow slides might occur.

Landslide deposits are described between "Pian della Pozza" and the dam site, but the rock mass is depicted as generally sound. In the "Pian della Pozza" and "Pian del Toc" areas long fractures parallel to the valley are reported and attributed to movements of the rocks underlying the morainic deposits. Vertical fractures normal to the valley are also indicated. As observed outcropping limestones are deeply fractured on the higher parts of both the left and right abutments but, downwards, the quality of the rock mass progressively improves. The concave feature of the left slope between "Pian della Pozza" and the Vajont river bed is attributed to a previous landslide.

At the beginning, the good quality of the rock mass is confirmed by the results of a seismic survey carried out on the left valley side (4th February 1960, Prof. P. Caloi report). The bedrock, with high elastic moduli, results covered by 10 m to 18-20 m thick landslide deposits. However, further seismic surveys (December 1960) showed the presence of 20-40 m thick loose materials over a rock mass deeply fractured with elas-

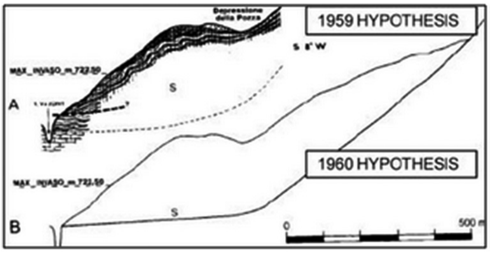


Fig. 12 - Semenza’s hypothesis on slip surfaces of the ancient landslide (from Semenza & Ghirotti, 2000)

tic moduli 10 times smaller than before, while more rigid material was individuated only at depths of about 100-150 m (10th and 23th February 1961, Prof. P. Caloi report). The strong drop observed in both longitudinal velocities (from 5-6 to 2.5-3.0 km/s) and frequencies (from 200 to 50 Hz) is attributed to the rocks crushing due to the failure of rock masses located at higher elevations consequent to the seismic shakes occurred all along the 1960.

On the same year, geologists E. Semenza and F. Giudici recognized the presence of an enormous and ancient landslide deposit on the left side of the Vajont valley, in the area of “Pian del Toc” and “Pian della Pozza”. The landslide deposit was deeply cut by the Vajont stream forming the present gorge and leaving a portion on the right side of the valley ("Colle Isolato). This hypothesis was confirmed later on during the excavation of the by-pass tunnel (1961) when at the base of the "Colle Isolato" alluvial gravels and a thin layer of cataclasites were found.

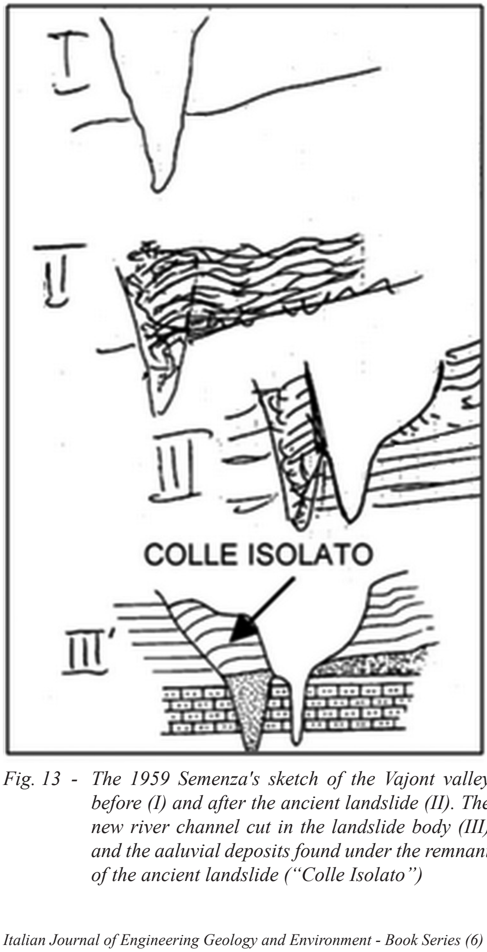


Fig. 13 - The 1959 Semenza's sketch of the Vajont valley before (I) and after the ancient landslide (II). The new river channel cut in the landslide body (III) and the aaluvial deposits found under the remnant of the ancient landslide (“Colle Isolato”)

The geological structure of this sector of the Vajont valley is reconstructed and its role in the landslide mobilization is stressed. The Vajont Valley coincides with the axis of an East-West trending, asymmetrical syncline eastward plunging. The northern slope of Monte Toc has a “chair-like” structure, clearly visible from the Piave Valley in front of Longarone. The landslide involved mainly limestones and marls of the Socchér Formation (Jurassic and Cretaceous), that is supposed to slid down over one or more thin clay layers contained in the Fonzaso Fm (Malm). The failure surface was supposed to be bounded to the North by the level of cataclasites outcropping at 600 m a.s.l., to the South by the elongated depression of "Pian della Pozza", and to the East by a vertical fault. In conclusions the landslide mass could be mobilized.

The possibility of a very deep and huge landslide was hypothesized also by Prof. Penta based on the 28th November 1960 field survey. He concluded, however, that the data so far collected were not sufficient to specify the nature and the characteristics of the observed phenomenon and recommended a very slow drawdown of the reservoir. After the opening of the long M-shaped fissure on October 1960, the geological studies of G. Dal Piaz and E.Semenza-F. Giudici were considered substantial by L.Mueller and his collaborators dr. Fally and dr. Broili. They integrated them with stratigraphic and displacement data collected at the time and evaluated the volume of the landslide in about $2x10^8$ m^3 with a shear surface located at a depth variable from 250 m, in the western part, to 200 m in the eastern one. Besides, they recognized two sectors in the landslide mass separated by the Massalezza creek and characterized by different sliding mechanisms. The western sector with displacement vectors dipping N20° as a mean with inclinations decreasing

Fig. 14 - Part of the perimetral M-shaped fissure opened on October 1960

from 27°-34° to almost zero proceeding downwards. In the flat part of the "chair" there are antithetic fractures attributed to rotational movements.

Muller hypothesized a pulsating glacier-like movement of the lower half of the landslide mass initiated since many centuries or more before and facilitated by the presence in the lower part of the landslide mass of a number of folds with axes almost horizontal. The seismic surveys of P. Caloi, indicating the absence of an effective slip surface, supported on one hand this hypothesis, but on the other hand were opposed, indicating the presence of sound rocks in the lower part of the landslide mass. The eastern sector was supposed to behave as the higher part of the western one, that is sliding on a more or less inclined and planar surface.

Many triggering factors were indicated (low values of the shear and tensile strength; strata, fractures and fold axes orientation; high and different permeability of rock masses; high water pressure and cyclic stresses due to earthquakes). The water level in the reservoir is indicated to influence directly the displacement rate, as can be inferred by the 4th November 1961 landslide, occurred with the reservoir level being increased to 646 m a.s.l.). Fast movements are forecasted to occur with the drawdown operations. In conclusions the landslide cannot be stopped, but only controlled. Besides, considering that the 4th November 1960 landslide caused in the reservoir a 2 m high wave, a greater landslide is supposed to determine a water wave 40 m high possibly causing the instability of the dam abutments that have to be, thus, consolidated (3rd February 1961 report). A small test gallery was excavated during 1961 in the Massalezza area with the aim to get the hypothesized failure surface: at 28th February 1961 it had a length of 37 m, but no data are available.

Fig. 15 The 4th November 1960 landslide on the left reservoir slope

In a following report (20th September 1962) the displacements, measured by the instruments installed on the dam abutments in the period 1959-1961, were considered by L. Mueller a consequence of the first filling and drawdown operations and confirmed the results of the tests carried out by ISMES on a physical model. However, up to this time no alarming deformation was observed on the abutments: small deformations were observed as a consequence of the reservoir level variations.

At the beginning of 1961 SADE proposes to the”Centro Modelli Idraulici” (Hydraulic Modeling Center) of the University of Padova to carry out a research on a hydraulic model to examine the effects of a landslide on the Vajont reservoir, as regards mainly the consequent flood on the reservoir slopes and over the dam.

The 1:200 scale model (29 m long, 12 m wide and 1.80 m high) was considered suitable to represent the wave motion. The natural landslide is reproduced with round gravels either placed on a metallic plane surface or placed on a curved surface representing the geologically forecasted failure surface. The mass is, then, artificially drag in such a way to obtain both independent movements of the two hypothesized sectors and different velocities, so that the landslide effects could be examined in different cases. Tests were carried out considering the water level at 722.5 m, 700.0 m and 670.0 m elevation. Considering the maximum elevation of the water in the reservoir, the effects of the landslide, occurring in 3 or 1.5 minutes, are most relevant for the downstream sector: discharges over the dam range from 12.000 m^3/s to 30.000 m^3/s and wave heights over the dam from 11.5 m to 22.0 m. Hypothesizing two different sectors, landslide time results between 1 and 3.5 minutes with a time interval of 2.5 and 10.5 minutes: discharge results of 20.000 m^3/s with a wave height over the dam of 16.0 m. Lower values of both discharge and wave height were obtained considering the occurrence of the only downstream sector of the landslide or a water level in the reservoir maintained below 700 m a.s.l. (Prof. A. Ghetti 3rd July 1962 report).

As it may be noted, until approximately the Spring 1959 the concern of people involved on the dam construction was mainly, if not only in the stability and characteristics of rocks of the dam abutments, while the stability of the whole reservoir slopes was not considered with exception of the Erto area. Studies on the whole reservoir area began when the construction of the dam body was already accomplished (1959), driven also by the 4th November 1960 landslide occurred with about 700.000 m^3 on the left side of the valley. The water level in the reservoir was at 650 m a.s.l. following the first filling operations initiated on February 1960.

Piezometers and topographic marks were planned and installed on the left side slope to monitor groundwater level and displacements. Besides, a seismometer was installed on the dam and operated from May 1960. The main purpose, behind the limited instrumentation at that time available, was to possibly relate the reservoir level with the vertical and horizontal displacements. In general, data on horizontal displacements seem to suggest that the slide was moving as a rigid body. It should be noted that piezometers didn't reach the sliding surface and they were perforated pipes providing, thus, only information on the average water pressures crossed by the tube.

Geological knowledge of all the people involved in the dam planning and construction from 1960 to the tragic 8th October 1963 should be checked considering also the diagram showing the trend of monitored data in conjunction with both the filling-drawdown operations and specific events.

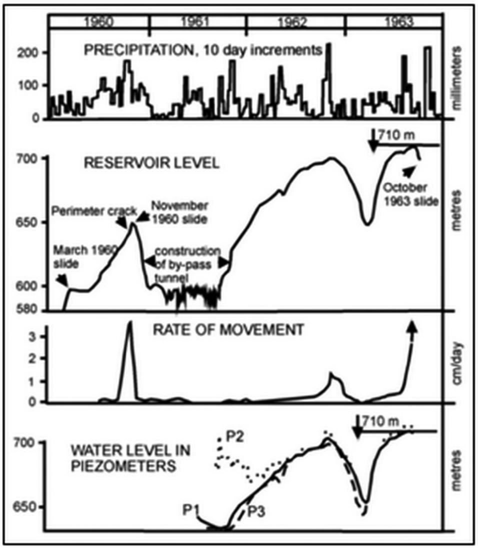


Fig. 16 - Relationships between precipitation, horizontal rate of movement and levels of piezometers and reservoir. (after Hendron & Patton, 1985)

FIRST FILLING AND DRAW-DOWN OF THE RESERVOIR

It initiates on February 1960. A small detachment occurred by March 1960 when the level of the reservoir reached about 610 m a.s.l. In October 1960, with the reservoir level at 650 m a.s.l., the displacements rate rapidly increases to about 3.5 cm/day and a long fissure opens up, suggesting that a quite large landslide could have been mobilized. On 4th November a 700,000 m^3 landslide occurred. The reservoir level is gently dropped back to 615 m a.s.l. and the displacements rate reduces drastically.

The designers were conscious that was not possible to arrest artificially the landsliding mass or to accelerate the sliding process and that the danger arising by an uncontrollable reservoir level would have been too great. They assumed that the huge landslide mass could have been controlled carefully varying the reservoir level. They, besides, calculated that, in case of the occurrence of a sudden failure, over-topping of the dam would be avoided, so long as the landslide would have not filled the reservoir in less ten minutes. The following draw-down to 615 m a.s.l. leads to a decrease of the movement rates to less than 1 mm/day. By this time the landslide mass had moved an average of about 1 m.

SECOND FILLING AND DRAW-DOWN OF THE RESERVOIR

It begins on October 1961 and through to early February 1962 the reservoir level is raised to 665 m a.s.l. In November 1962 the level reached 715 m a.s.l.. By the end of the filling (March 1963) velocities, substantially constant, increased to 1.2 cm/day. The draw-down to 665 m a.s.l. in four months leads the displacements rate to zero and the designers were convinced that the control of the landslide was effectively possible.

THIRD FILLING AND DRAW-DOWN OF THE RESERVOIR

The reservoir level was increased to 711 m a.s.l. in two months (April-May 1963), the velocities never exceeding 0.3 cm/day. and The displacements rate reached 0.4 cm/day for a reservoir level at 717 m a.s.l.

(June1963) and 0.5 cm/day when the level reached 720 m a.s.l. (mid-July 1963). During the following month the level was maintained (mid-August), but the velocities increased to 0.8 cm/day, further increasing in early September to as much as 3.5 cm/day, when water level reached 725 m a.s.l.. In order to control creep velocities, the reservoir level was slowly lowered reaching 715 m a.s.l. by 9th October 1963 , but the velocities continuously increase, and rates of up to 20 cm/day were registered.

In short, some general considerations might be drawn from the observation of data gathered by the installed instrumentation.

During the period 1960-1963, 43 extensional and compressional events were registered, ascribed to a regional stress field characterized by N–S compression (Caloi & Spadea, 1966) . The seismic activity registered on the Vajont valley on 23rd, 29th April, 2nd May 1962 and 2nd September 1963 is attributed to natural phenomena: seismic shakes have a too much deep hypocenter to be due to the presence of the reservoir (P. Caloi & Spadea, 15th June 1962).

In general, the water levels in the piezometers follow rather closely the levels of the reservoir with the only exception of Piezometer n. 2, during the initial part of the recording period when it showed water pressure corresponding to a water column of 90 m above the reservoir level. It is also possible to note how increasing the water level the sliding velocity increased, but this relationship is not linear tending towards an asymptotic limit, indicating the failure. The observation that the second reservoir filling leads to a different asymptotic value for the reservoir water level, may indicate that the movements along the shear surface are not governed by the effective normal stresses acting on it. This consideration, perhaps, induced to the third filling operation when rate of movements continuously increases and the lowering of the reservoir level in the attempt to reduce the velocity of the slide did not work.

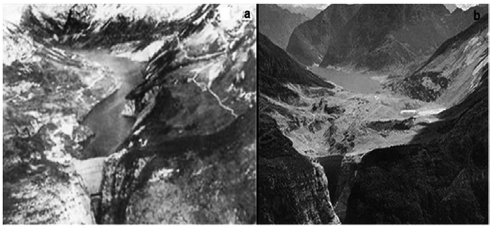


Fig. 17 - A panoramic view of the Vajont reservoir before (a) and immediately after (b) the landslide failure

From the above observations the Vajont event is to be considered a slide reactivation with the sliding surface located in discontinuous layer of plastic clays: thus, the effective friction angle should not be larger than 10-14º. Furthermore, no direct information of the position of the failure surface and on the characteristics of this material is available.

In order to estimate the evolution of the landslide a sort of conceptual method has been applied based on displacements rates and reservoir levels: a reduction of the reservoir level has to follow too much high displacements rates, accepting that a unique slide was possible but generating a water wave whose height was modeled by carried out experiments. However, reservoir levels do not necessarily provide true values of existing pore pressures on the failure surface and the conceptual model was not based on a mechanical analysis.

However, considering the difficulties that continue to be present still today to handle large landslides, we must reconsider what Carlo Semenza, the designer of the dam, wrote in a letter dated April 1961 : "... *things are probably bigger than us and there are no adequate practical measures ... I am facing something that, due to its dimensions, seems to escape from our hands* …" .

At 22:38 GMT on 9th October 1963 the catastrophic landslide occurred.

Albert Einstein
Learn from yesterday,
live for today, hope for tomorrow.
The important thing is not to stop questioning.

STUDIES AND RESEARCHES AFTER THE FAILURE

After the tragedy, many studies and researches were carried out on different aspects of the phenomenon, in order to explain both the kinematics and dynamics of the landslide and its effects. Information reported in related papers greatly increased the understanding of such phenomena, so strongly reducing the risk conditions for the populations in mountainous areas.

In order to re-evaluate the currently existing information on the slide, an electronic bibliographic database has been developed, giving to researchers the availability of a great part of the technical reports and scientific articles, published or not (Superchi *et alii*, 2010). For simplicity, only a part of these papers is considered here and main conclusions are shortly reported.

Papers, written just after the catastrophic landslide, are mainly represented by the technical reports written by experts charged by public organizations to investigate factors and causes of the landslide.

Immediately after the disaster, Prof. A. Moretti and Prof. A. Valdinucci, members of the Italian Geological Service, were charged by the government to investigate on: the possibility of future extension of the landslide; the risk conditions of the villages of Erto, Casso and Cimolais; the future behavior of the dam stressed by the landslide-induced water wave ("Relazione sulla frana del Vajont - Nota preliminare" - Preliminary report on the landslide of the Vajont basin, 27th November 196 -). After a summary of the geological and geomorphological setting of the area, the authors conclude on the unfavorable geological, tectonic, morphological and hydrogeological setting of the area, underlining the wrong interpretation and forecast of the landslide evolution. Considering the stresses acting on the dam by the landslide body, the hypothesis of the demolition of the higher part of the dam is also contemplated.

The stability of Casso and Erto villages is negatively considered and their transfer recommended: for Casso, in consequence of the possible re-activation of an ancient rock fall whose equilibrium was perturbed by the 1963 landslide, and for Erto, due to the possibility of a new huge landslide.

The geology of the Vajont valley is the object of the "Sutdio geologico della frana del Vajont" (Geological Study of the Vajont Vallet) by Prof. R. Selli and Prof. L. Trevisan for the Government Board of Inquiry (1964) . The description of the area and of the events is quite accurate. Oucropping formations, consisting of cherty limestones (Malm) and marly limestones with clay interbeds (Cretaceous), are folded and faulted by the tectonic sliding over the Dogger limestones of the bedrock. The landslide volume is estimated in 200 Mm3 and the total displacement in 450-500 m. Two different rock masses are individuated separated by the Massalezza creek, the western one being characterized by glaciers-like movements. The slip surface is set in the Malm strata, while in the eastern part it is set in the stratigraphical higher Cretaceous strata. The whole mass moved in two different steps: initially it slipped on a deep surface until it arrived on the opposite slope; afterwards, it slipped on surfaces progressively less deep, but always characterized by the presence of "plastic" terms in the stratigraphical series. The running time of the landslide is evaluated in about 100 s and the maximum velocity in about 16 m/s. The causes of the landslide are indicated in the stratigraphical (overlapping of deformable strata on more rigid ones and presence of clayey thin strata) and tectonic (strata dip and folding of deformable strata) setting, besides the morphology of the valley consequent to the glacial and fluvial erosion. Triggering causes are indicated mainly in the effects of groundwater level variations, due to rainfall and reservoir filling-drawdown cycles. However, the sudden change in the velocities of the landslide cannot be explained.

The dynamics of the water wave induced by the landslide has been firstly analyzed in the "Studio sull'onda di piena seguita alla frana del Vajont" (Study on the water wave induced by the Vajont landslide) by Prof. M. Viparelli and Prof. G. Merla, charged by the Government Board of Inquiry (1964). The water wave, with a maximum height of 200 m, is due to the 48 Mm^3 of rocks entered in the reservoir, while the volume of the water overtopping the dam is estimated in 25 Mm^3. The water wave, after the dam overtopping, took 4 minutes to reach the Piave river at a distance of 1.400 m and the discharge at the dam site is estimated in 50-100.000 m^3/s: lower mean values are obtained for the whole event (30.000 m^3/s) and much larger values for the instantaneous discharge (1 Mm^3/s). The water wave at the entrance in the Piave river valley is calculated 100 m high; this wave reaches at 8:00 o'clock of the day after a site 84 km distant, as high as 2.33 m.

The geological and mechanical factors and the hydraulic effects of the landslide have been investigated by a Commission composed by lawyer M. Frattini and Professors F. Arredi, A. Boni, C. Fassò and F. Scarsella, charged by the Board of Inquiry of the National Organization for the Electrical Energy (ENEL) on 1964.

Fundamentally, the members of this Commission conclude that the landslide, exceptional for volume and velocity, is the consequence of the nature of the involved rocks, their "chair" structure and previous erosional processes but, above all, of the effective stresses decrease due to the saturation caused by the reservoir infilling. The observed displacements are due to creep phenomena and a rather good correlation is found between horizontal displacements and reservoir levels while correlations with rainfall and seismic activity are questionable. Maximum displacements, North directed, are initially located between the dam and the

Massalezza creek but, after June1963, they are found just above the dam. The displacement could be interpreted also as simply preparatory to a series of small landslides and not to an instability involving the whole slope. The measured phreatic groundwater level varies with rainfall until the reservoir level reaches the groundwater level, from here on it strictly follows the reservoir level. The landslide, with an estimated volume of 250 Mm^3, developed contemporary in the eastern and western parts in a total time of 10’30”, running up on the opposite valley side up to 125 m with a rather small rotation. Triggering factors are indicated in: i) the low friction resistance due to the presence of clayey interbeds, to previous movements (presence of cataclasites and milonites) or to the effective stresses decrease; ii) the seismic activity in the neighborhood. The water wave induced by the landslide had a volume of 48 Mm^3 with a maximum elevation of 200 m on the previous reservoir level; 30 Mm^3 is the water volume that overpassed the dam. The results of the experiments carried out on the 1:200 scale model by the University of Padova are considered hydraulically reliable and the differences with what really happened is to be attributed to the great differences in involved volume and movement rate. Finally, the phenomenon, considered exceptional for volume and velocity, is the reactivation of the ancient landslide.

A first summary of both the characteristics of the area and the events associated with the landslide, together with some interpretations of the occurred landslide mainly derived from the technical reports of the different boards of inquiry, is edited by A. De Nardi on an Italian journal (1964). The first scientific paper published on an international journal, describing the 1963 Vajont landslide and related events, is that of Müller (1964). After a detailed and thorough description of the studies carried out and of the phenomena observed during the different phases of the Vajont reservoir history, he observes: “... *The peak velocities increased progressively during the early days of October. According to the report of the “Commissione di Inchiesta” the velocity had reached 20 cm per day by October 9. Compared with the final velocity of the sliding mass (about 25 m/sec), all movement, even the last phase, must be considered a creeping movement up to the very instant of the slide itself...*”. He concludes that the transition from the initial long creeping stage of the mass to a true rock slide was caused by, “the slight excess of driving forces, due to the joint water thrust or to the decrease in resisting forces, resulting from the buoyancy and softening of clayey substances during higher water level [...] with a progressive rupture mechanism at the base of the moved mass”. Besides, Müller attributes to the landslide a velocity of 25-30 m/s, consequence of a “spontaneous decrease in the interior resistance” and favored the hypothesis of a new first-time landslide contrasting his initially agreement with GIUDICI & SEMENZA (1960) on the existence of a prehistoric landslide. In conclusion, he strongly believes in the substantial unpredictability of many aspects of the landslide.

KIERSH’S (1964, 1965) considers the existence of a prehistoric landslide and the presence of a weak zone of highly fractured rocks due to the effects of the last glacial period. He concludes that the collapse was triggered by a rise of the groundwater level with increased hydrostatic uplift and swelling pressures. His hypothesis and sections were assumed valid in many subsequent studies on the Vajont landslide.

A comprehensive work on the geological characteristics and the hydraulic and seismic phenomena that accompanied the event is written by SELLI *et alii* (1964) on an Italian journal. The authors support the hypothesis that the mass moved with a generally pseudo-plastic behavior and that the main causes have to be ascribed to the particular geological structure, to the morphology of the slope and to the variations in the water level in the reservoir. The maximum velocity of the landslide is calculated in 17 m/sec.

After the first detailed study of local stratigraphy by GIUDICI & SEMENZA (1960), many other studies were carried out by different authors, but their basic lithostratigraphy is still considered valid and confirmed by other authors (e.g.: CARLONI & MAZZANTI, 1964; SELLI & TREVISAN, 1964; FRATTINI et al., 1964; ROSSI & SEMENZA (1965); NONVEILLER, 1967; ROSSI, 1968; MARTINIS, 1978; HENDRON & PATTON, 1985), except for some particular chronological considerations. In synthesis, the landslide involved a complex sequence of cherty and marly limestones dating from middle Jurassic to upper Cretaceous.

After the GIUDICI & SEMENZA work (1960) and the landslide event, the first detailed geological and geomorphological study on the Vajont area is carried out by CARLONI & MAZZANTI (1964). According to these authors the deep and narrow Vajont gorge was cut by the river through the deposits of a previous landslide and their stratigraphy may be summarized as follows: 1. Flysch (Eocene): alternances of arenites and mudstones. 2. Erto Marls (Paleocene): marls and marly limestones, representing the transition between the Scaglia Rossa and the Flysch. 3. Scaglia Rossa (Upper Cretaceous): a monotonous succession of marls and red marly limestones. 4. Soccher Limestones (Lower-Upper Cretaceous): alternances of of limestones, calcarenites and calcirudites with conglomerates and breccias characterised by a great lateral continuity and visible in the landslide. 5. Rosso Ammonitico (Kimmeridgian Titonian): reddish and grey massive micrites. 6. Fonzaso Fm. (Oxfordian): calcarenites and cherty brown limestones with claystone interbeds. 7. Vajont Limestone (Dogger): massive calcarenites intercalated with micrites and intraformational.

Two detailed geological maps of the Vajont landslide area, before and after the 9 October 1963 catastrophe, are published for the first time in 1981 (Rossi & Semenza). The main aspect of the geological interpretation is the presence of the rock mass located on right side of the river (Colle Isolato) representing the remnant of an ancient landslide already hypothesized by Giudici & Semenza (1959).

With the aim to perform the numerical modeling of the landslide, the available geological data have been completed with a geomechanical survey of the outcropping rock masses (Ghirotti, 1993, 1994).

A list of the main interpretative studies undertaken on the Vajont landslide is reported on the paper by Semenza & Ghirotti (2000), in which particular attention is paid to a landslides occurred in another nearby reservoir.

The last contribute of E. Semenza is represented by his palinspastic reconstruction of the Vajont slide, from the postglacial mass movement to the 1963 failure (Ghirotti, 2006), based on geological and geomorphological features that led him to define the shape and the boundary of the ancient landslide.

A new engineering-geological model for interpreting the catastrophic event is proposed by Paronuzzi (2009) on the basis of a detailed geomechanical field survey of the sliding surface. The model displays the presence at the landslide base of a 30-70 m shear zone constituted by coarse angular gravels with blocks and clay lenses that, in the opinion of the Author, can explain the fast groundwater level variations caused by filling and draw down of the reservoir.

In the following years, a great number of papers have been published on specific aspects of the catastrophic landslide differently interpreting and strongly debating particular aspects of the landslide event. They range from geotechnical properties to physical and rheological behavior and to stability analyses, in the attempt to understand the role of factors involved in the landslide triggering and development.

All these aspects are, however, strictly connected to a first primordial question: was the landslide a first-time one (e.g.: Selli *et alii*, 1964; Skempton, 1966; Broili, 1967; Mueller, 1968) or the re-activation of an

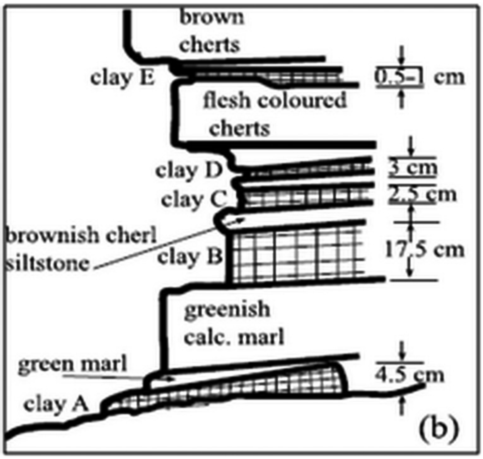


Fig. 18 - Stratigraphy at the Vajont gorge (from Hendron & Patton, 1985)

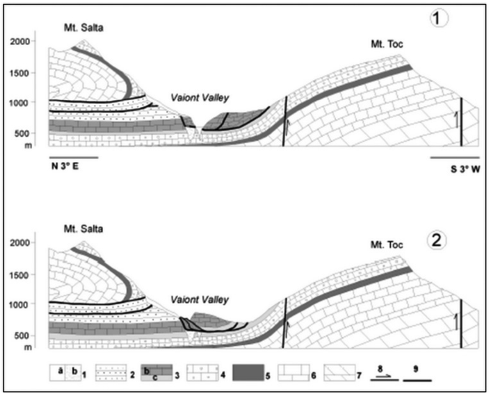
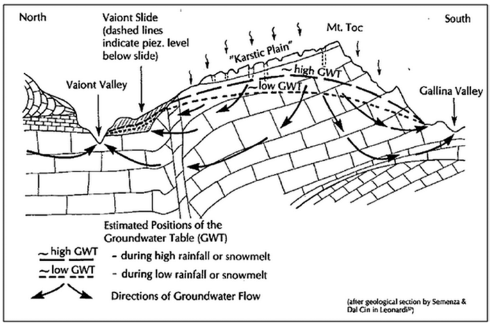


Fig. 19 - N-S geological sections before 10/9/1963 (1) and after 10/9/1963 (2). 1) Quaternary (a); stratified alluvial gravels (b); 2) Scaglia Rossa Fm.; 3) Socchér Fm. sensu lato: Socchér Fm. sensu stricto (b), Rosso Ammonitico and Fonzaso Fms. (c); 4) Calcare del Vajont Fm.; 5) Igne Fm.; 6) Soverzene Fm.; 7) Dolomia Principale; 8) Faults and overthrusts; 9) Failure surfaces of landslide (from Semenza & Ghirotti, 2000)



(after geological section by Semenza & Dal Cin in Leonardi[3])

Fig. 20 - A schematic section through the Vajont Slide showing the estimated regional groundwater flow system

old one (e.g., Hendron & Patton,1985; Pasuto & Soldati, 1991; Semenza & Ghirotti, 2000; Semenza, 2001; Vardoulakis, 2002)? This controversial aspect was initially faced up by Hendron and Patton in their technical reports (1983, 1985), but still now is the object of studies and discussions (Paronuzzi & Bolla, 2012).

It is generally thought that the landslide occurred at least in part, on the slip surface of an old landslide, but some different hypotheses exist. For instance, the reassessment of the morphological and structural evidence have suggested to some authors (Mantovani & Vita-Finzi, 2003) that slip surface coincides with a normal fault plane juxtaposing Cretaceous limestones and highly fractured rock mass, consistent in strike with the regional lineament pattern.

Hendron & Patton work (1985) may be considered as the first attempt to analyze the Vajont landslide from a more complete geological, geomorphological and geotechnical point of view. Based on the works of Rossi & Semenza (1965) and Semenza (1965), the landslide is considered a reactivation of a probably post-glacial one slid over one or more clay levels, acting both as a continuous impermeable layer and a very weak level with residual friction angle as low as 5°. In the northern slope of Mt.Toc, two aquifers have been detected: the upper one (highly fractured and permeable landslide mass) was influenced mainly by reservoir's level, while the lower one (Calcare del Vajont Fm.) was fed by both rainfall in the hydrogeological basin and reservoir's water. This hydrogeological scheme, supported by a new interpretation of the piezometric levels, may give rise to high water pressures in the hypothesis that clay strata separating the two aquifers were continuous.

One, and perhaps the greatest drawback of the data gathered during the years preceding the collapse is the lack of reliable water pressure data throughout the landslide mass and displacement records along the failure plane, both essential for correlating slide movements with reservoir levels. Moreover, a good estimate of the relationship between stress and permeability is necessary when analyzing landslides because the permeability of fractured rock masses is particularly sensitive to stress changes at shallow depth (Rutqvist & Stephansson, 2003).

Hendron & Patton (1986) re-construct the hydrogeological model of the Vajont slide area on the basis of water level data measured from the summer of 1961 until October 1963 inside pipes placed in three open drill-holes. As a result, the water levels could reflect some average value of the water pressures and hydraulic conductivities of the units encountered. They, however, commented: "*As a result, the water levels recorded inside the casing could reflect some average value of the different water pressures and hydraulic conductivities of the units encountered"* and conclude*: "The piezometric data of the Vajont slope is too little and questionable; it is not sufficient for drawing up a reliable hydrogeological model, which is necessary in these cases to make reasonable assumptions about the pore water pressures for slope stability analysis"*.

Probably, the first comprehensive hydrogeological study of the Mt. Toc area has been carried out by Besio (1986), that realizes a hydrogeological model of the area on the basis of the census and characterization of the existing springs. He recognizes the presence of four aquifers corresponding to: the quaternary deposits; the sequence Scaglia Rossa, Calcare di Soccher and Rosso Ammonitico, whose impervious bedrock is the Fonzaso Formation; the Calcari del Vajont, widely karst as shown by the existing sinkholes, whose impervious bedrock is represented by the marly limestones and marles of the Igne Formations; the Calcari di Soverzene and the Dolomia Principale, constituting the main aquifer. The springs are numerous, but only a few have significant discharges (1-10 l/s).

The problem of the existence and continuity of clay beds in the calcareous sequence, a fundamental feature for the location of the slip surface, is a rather discussed aspect. Examining the borehole logs carried out after the landslide, Broili (1967) concludes for the absence of clay beds, a conclusion already reached by Müller (1964), who asserted that no clay beds exist on the slip surface, if not some films of pelitic materials, a few mm thick, seldom observed in the limestone bedding planes; they, however, could not have played any significant role in the slope failure. Afterwards, the same Müller (1968), re-analyzing available data reaches different conclusions stressing, instead, the relevance of the "chair-like" shape of the slip surface. At present days, it is generally accepted that failure occurred along thin (5–15 cm thick) clayey (Ca-montmorillonite, smectite, illite, vermiculite) beds intercalated to the limestones strata and rather continuous over large areas that acted also as an impervious layer favoring the rising of the groundwater level and, then, the consequent decrease of shear strength values.

A significant loss of strength is required to explain the high velocity of the landslide, but many doubts remain as regards the mechanisms controlling the rate of movement and its sudden acceleration. Various interpretations have been given and they mainly differ in treating the event as a first-time landslide or as the reactivation of an old prehistoric one (Mencl,1966).

As classical analyses for Vajont slide fails to explain the sudden collapse and the final velocities achieved, several mechanisms responsible for the frictional evolution of the Vajont slide have been investigated using different models and formulating different assumptions in order to ascertain the evolution of the friction coefficient with both time and deformation (e.g., Vardoulakis, 2002; Kilburn & Petley, 2003; Helmstetter et al., 2004; Sornette *et alii*, 2004; Veveakis *et alii*, 2007; Pinyol & Alonso, 2010).

The reduction of frictional resistance is related by Müller (1968) to creep phenomena and progressive failure mechanism, noting that the friction angle value, required in conditions of limit equilibrium, was too small if compared to the strength properties attributable to the material directly involved in the movement.

Several authors tried to explain the relevant loss of strength in terms of pore water frictional heating and thermal pressurization. The thermoplastic softening behavior of clays has been studied since '70s (e.g., Hicher, 1974; Despax, 1976; Modaressi & Laloui, 1997) reaching the conclusion that the friction angle at critical state of some clays may be a decreasing function of the temperature, depending on clay mineralogy.

The pressurization mechanism, that could explain the total loss of strength of large slides, is based on the original "vaporization" concept of Habib (1967, 1975) and later discussed by, e.g.,: Voight & Faust, 1982; Vardoulakis, 2000 and 2002; Veveakis & Vardoulakis, 2007; Goren & Aharonov, 2007.

The grassroots idea is that frictional heat, due to the mechanical energy dissipation inside the slip zone, and the consequent vaporization of pore water may lead, if the surface of failure is deep enough, to a strong increase in pore water pressure that produce in turn a cushion of very reduced frictional resistance. A first approximation gives the possibility to calculate the critical displacement necessary to create vapor in the slide zone, while a second approximation gives the relation between the critical displacement and the rate of shear displacement (Habib, 1975).

First in a rather long succession, Ciabatti (1964) proposes a pore water pressure rise due to frictional heating and, considering a variable friction coefficient, estimates a maximum velocity of 17 m/s.

Voight & Faust (1982), starting analysis from the model of Ciabatti (1964), propose a thermal mechanism as a possible explanation for the low kinetic friction mobilized by the Vajont landslide. On this basis they calculate acceleration, velocity (maximum: 26 m/s) and elapsed time as functions of displacements. The same mechanism is proposed by Nonveiller (1978, 1987) who estimates, however, a maximum velocity of 15 m/s. Semenza & Melidoro (1992), considering the frictional heat developed in the final accelerated phase, try to explain both the high velocity and the run-out of the landslide, but they conclude that this mechanism, even if it can really induce very high velocities due to the shear strength decrease, could not be effective just from the triggering of the movement, but only after rather long times.

Recently Vardoulakis (2002), assuming that creep is localized in a clay-rich water-saturated layer, demonstrates that frictional heating can even trigger an explosive pressurization phase after the long-term phase of accelerating creep. The final total loss of strength is explained by the onset of thermal pressurization, on turn triggered by the temperature rise within the clay layers. The pore pressure increase, also enhanced by elevated friction coefficient, porosity and deformability, can convert the slow sliding into a catastrophic failure. With this approach, the author calculates a velocity of 20 m/s just 8 s after its activation, corresponding to a slide displacement of only 74 m.

Results of simulations obtained using a similar thermo-poro-elastic mechanism at the base of landslides (Goren & Aharonov, 2007), indicate the development of high pore water pressure and reduced friction resistance, causing large sliding velocities and run-out. Pore pressure diffusion rates from the shear zone is mainly controlled by the depth-dependent permeability, so that greater landslides are able to maintain high pore pressure for longer times, that results in lower values of the dynamic friction angle.

With the aim to determine appropriate values of the friction coefficient, Tika & Hutchinson (1999) carried out ring shear tests on two clay samples from the slip surface at slow and fast rates of shearing, observing a relevant loss of strength increasing the shear rate. While the obtained residual friction angle at slow rate (9.7°-10.6°) compares rather well with the previously reported values (8°-11°), at rates greater than 100 mm/min and after an initial increase above the slow residual value, the dynamic residual value falls to 4.4°. In the opinion of the Authors, these results may explain the high acquired velocity of the landslide without invoking other strength loss mechanisms.

Laboratory tests with higher shearing rates have been carried out by Ferri *et alii* (2010, 2011), obtaining even smaller values of the friction coefficient. At room humidity the friction coefficient initially increases from 0.45–0.48 (24.2°-25.6°) at low velocity to 0.68 (34.2°) at 0.04 m/s and, then, falls to 0.09 (5.1°) for slip rates up to about 1.3 m/s due to the shear heating causing a temperature increase to about 260°C.

The increase in water content drastically reduces the shear strength enhancing the velocity weakening mechanism as already observed by Tika & Hutchinson (1999) and in agreement with the model proposed by Helmstetter *et alii* (2004) and Sornette *et alii* (2004). In saturated conditions, presumably existing during the collapse, obtained results show that thermal and thermo-chemical pressurization are not required to explain the high slip rates achieved during the final collapse of the landslide, at least for shear rate lower than 1.31 m/s, that is the maximum velocity investigated.

In order to explain the accelerations preceeding catastrophic landslides, Sornette *et alii* (2003) propose a slider-block model, providing a physically based derivation of the phenomenological model suggested by Voight (1988). The model gives, for the Vajont landslide, good predictions of the critical time-to-failure up to 20 days before the collapse. Helmstetter *et alii* (2004) apply to the Vajont landslide the state and velocity-dependent friction law established and used to model earthquake friction. They show that observed displacements can be reproduced with the slider block friction model, suggesting that the Vajont landslide belongs to the velocity-weakening unstable regime. The Authors consider also that friction can be another possible process able to reproduce the same accelerating pattern as crack propagation on a basal shear plane (Petley *et alii,* 2002; Kilburn & Petley, 2003).

The high velocity of the landslide has been attributed also to other deformation mechanism such a slow rock cracking process. When clay layers are deformed, the stresses are concentrated at the tips of existing micro-cracks that, in the long run, make the cracks to grow at an accelerating rate and to coalesce in a unique shear plane or band (Kilburn & Voight, 1998). This process can be also enhanced by the chemical effects of water, if present (Atkinson, 1984). Laboratory studies (Burland, 1990; Petley, 1995) show that brittle behavior can occur also in undisturbed and water-saturated clays stressed to loads corresponding to depths more or less coinciding with the depths of the deforming clay layers in Mt Toc.

Slow cracking represents an interesting deformation mechanism as it can accelerate under constant applied stress and it is quickly enhanced by circulating water, chemically attacking molecular bonds at crack tips (Kilburn & Petley, 2003). The mechanism is initially dominated by the formation of new cracks that increase exponentially with time (Main and Meredith, 1991), and, later, by the exponential growth of cracks length (Main *et alii*, 1993) until a unique failure plane is formed (McGuire & Kilburn, 1997; Kilburn & Voight, 1998). On the basis of a technique proposed by Saito (1965, 1969), conceptualized by Voight (1988, 1989) and developed by Fukozono (1990), a new model for the development of progressive failure in brittle landslides is proposed by Kilburn & Petley (2003). The system is initially driven and controlled by stress but, once the failure surface reaches the unstable crack growth stage, it is stress driven while the failure is strain controlled. The linear inverse-rate velocity trend with time, obtained by equating the time of failure to the condition for which rates of deformation become infinitely large, is representative of the existence of movements dominated by crack growth, a process that indicates the approach to catastrophic collapse.

Some researches indicate that clays can behave as a brittle material under high loads such as those acting on deep-seated slope failures (e.g.: Burland, 1990; Petley, 1995). However, even if is still rather difficult to explain the reached velocity in quantitative terms, observations on slope movements (Voight, 1988) are consistent with the failure behavior of clays at high pressure: the basal failure mechanism evolves through time from an essentially ductile process, during the creeping phase, to a brittle process at collapse phase (Petley & Allison, 1997, and Petley, 1999).

In the attempt to explain the increasing velocities of the Vajont lanslide, the possibility of internal rock strength degradation has been invoked by Alonso & Pinyol (2010) who state that the Vajont landslide is a good example of the reduction to minimum values of strength available along “dormant” sliding surfaces in high plasticity clays. In their two-blocks model the cohesion on the separating plane is progressively degraded as a function of displacements but, even the full degradation of the cohesion cannot lead to velocities higher than 3 m/s, and the Authors conclude that this process must be accompanied by other mechanisms.

With the aim to predict the response of the Vajont landslide, a multi-block sliding model has been applied by Stamatopoulos & Aneroussis (2006): computed and observed duration of motion and peak slide velocity, as well as predicted deformation and back estimated soil strength, reasonably agree with the measured values.

A large number of stability analyses have been performed on the Vajont landslide, mainly concentrating on the evaluation of the friction angle necessary for stability using limit equilibrium methods and obtaining values in a wide range, but hardly larger than 12 degrees (Jäeger, 1965; Nonveiller, 1967; Mencl, 1966; Skempton, 1966; Kenney, 1967). In particular, Kenney (1967) results show that the filling of the reservoir reduces the stability by only 5-10%.

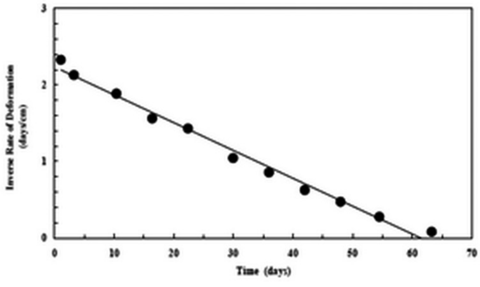


Fig. 21 - Acceleration in slope movement before the catastrophic collapse of Mt Toc on 09 October 1963 (from Kilburn & Petley, 2003)

Lo *et alii* (1971) uses Janbu’s method for noncircular surfaces, considering a sliding mass formed by two wedges separated by a vertical discontinuity. The back-calculated friction angle at limit equilibrium is 13° for a groundwater level corresponding to the water level in the reservoir.

Using two-dimensional limit equilibrium, the friction angle required for stability is back-calculated by Hendron & Patton (1985), who obtain values ranging from 17° to 28°, rather high if compared to values obtained by laboratory tests that range from 5° to 16° with an average value of about 12°. These values are less than those required for stability and, since the slope was at least marginally stable for a long period before the collapse, the Authors concluded that other factors were not considered. They perform, then, three-dimensional stability analyses considering all the available geometrical, geological, geotechnical and hydraulic data and conclude that the 1963 landslide occurred because of the water pressure distribution on the slip surface consequent to the combined effects of the reservoir level raise and the piezometric levels increase resulting from rainfalls; the necessary resisting force to ensure equilibrium is provided by the side friction on the Eastern edge of the slide.

Chowdhury (1978), considering the progressive failure concept, observes that in the landslide mass exists an upper portion, fundamentally unstable, that gradually creeps down and thrusts on a lower more stable portion: forces are progressively increased up to cause the sudden failure of the lower portion. This model is consistent with that proposed by Jäeger (1972), in which it is proposed the existence of a non-uniform weakening zone separating the upper from the lower sliding mass.

In order to really incorporate kinematics in the analyses Sitar & Maclaughlin (1997) introduced the DDA (Discontinuous Deformation Analysis) technique for which the actual mode of failure does not have to be assumed a priori, and displacements and velocities are computed as an integral part of the analysis. Using a simplified cross-section of Hedron & Patton (1985) and subdividing the landslide mass, by vertical lines, in a number of blocks from 1 to 105, they find that the friction angle required for stability increases from 7° to 16°, depending on the inter-block friction and the position of the vertical discontinuity. They obtain a trend rather similar to that shown by Chowdhury (1978) using a limit equilibrium method and modeling the progressive failure.

After that, the DDA method has been used by Sitar *et alii* (2005) to demonstrate that computed velocity are dependent on the number of used blocks, so indicating that disintegration of the landslide during failure results in acceleration of the slide mass. They find, moreover, that the pore pressure rises, consequent to the frictional heating, has an effect of the same order of magnitude as the process of landslide mass disintegration. Considering both of these processes, they obtain peak velocity values comparable to that estimated by Hendron & Patton (1985), that are 25–30 m/s, suggesting that both mechanisms might have had a fundamental role.

The problem of velocity determination, and connected energy-lines and Fahrböschung function, was already faced by Erismann & Abele (2001) who stated that considering the scientific knowledge at that time (e.g.: Heim, 1932) the Vajont catastrophe, especially as regards the transition from slow to fast motion, could have been foreseen.

In the attempt to address the evident inconsistency between friction angle values in the range of 18º-28º, as obtained by back-analyses (e.g.: Kenney, 1967; Hendron & Patton, 1985) and those reasonably attributable to the sheared clay beds of the sliding surface (not larger than about 10º-12º), Alonso & Pinyol (2010), analyzing the stability of a simple two-wedge models, find that the rock shear strength value being mobilized between the two wedges is practically in accordance with the expected strength of present Cretaceous marls and limestones.

Recently, a new model for the final collapse stage has been proposed by Cecinato *et alii* (2010) accounting for the pressurization phase due to frictional heating. Parametric analyses results show that the thermal friction softening mechanism may be considered secondary, if compared to mechanisms of static and dynamic friction softening that mostly affects the timescale of final collapse. Thermal pressurization will cause, besides, thicker slides to accelerate faster.

The landslide generated water waves, a particular type of tsunamis water waves, have been studied in the past using mathematical theories, physical model experiments and numerical simulations (e.g., Watts *et alii*, 2005). The study of these waves is quite complex as different base models have to be built in order to describe: (i) the triggering of the landslide, that relies on quantity and quality of available data and information; (ii) the propagation, that needs the knowledge of the material rheology; iii) the landslide-water interaction, strongly affected by the permeability of the collapsing material; and (iv) the propagation of waves along a reservoir, that is usually modeled using depth integrated models. The water wave generated by the landslide collapsing at high velocity into reservoir has been numerically modeled only in the recent years.

Panizzo *et alii* (2005) developed some empirical formulations to characterize the generated impulse waves and their application to three real cases (the Pontisei landslide and the 1960 and 1963 Vajont landslides) estimate quite well the values of both the maximum generated wave height and run-up.

Dealing with an application of the SPH (Smooth Particle Hydrodynamics), a three-dimensional simulation of the Vajont landslide induced water wave is presented by Roubtsova &Kahawita (2006) technique to treat free surface problems.

More recently, Ward & Day (2011) simulate the Vajont landslide and flood disaster applying the new developed «tsunami ball» method and considering the Vajont landslide as a semi-coherent slump. The full sequence of events is captured in three dimensions, finding that a landslide of that dimension and volume can effectively splash water up to about 200 m on the northern slope, push more than 30 million m^3 of water over the dam and flood the valley below. The authors stress the consideration that a compelling physical quantity, emerging from the analysis, is the astounding rate at which water run away from Vajont reservoir.

The technical literature on Vajont is quite copious, as a result of the inconsistencies noted in the interpretations of the event. However, a considerable part of major questions on the characteristics of the landslide, particularly on the failure mechanism, have not been adequately explained yet.

Too many contradictory statements and conclusions are present in the literature regarding especially the existence and the mechanical relevance of significant clays or clayey material along the failure surface. Besides, the not definitively resolved dispute if the 1963 slide was a new slide or the reactivation of a prehistoric slide has some obscure aspect yet, even if the deep trenches on the northern slope of M.t Toc seem to corroborate the Semenza' hypothesis (1965) of the presence on an ancient landslide.

The Vajont disaster demonstrated the critical relevance of geological features within and surrounding the reservoir sites, so that a growing interest in understanding and predicting such catastrophic phenomena after that widely developed. Moreover, the large scientific literature on this landslide and the obtained results, frequently contrasting, demonstrates that we are only at the very beginning in the development of concepts and tools in modeling and predicting these type of events. On the other hands, the issues emerging from the Vajont disaster have induced to a changing emphasis in researches on catastrophic rock slope failures that points to a more integration between geoscience and engineering so a better understanding of landslide events, triggers, and processes can be obtained.

> *I know one thing, that (I know nothing).*
> *ἓν οἶδα ὅτι οὐδὲν οἶδα*
> ***Socrates***

FURTHER RESEARCH AND DEVELOPMENT

The catastrophic Vajont landslide demonstrates the overwhelming need to integrate geology, geomorphology and geotechnical engineering analyses in the study of slope instability. The Vajont event promoted a large mass of studies and researches that greatly enhanced our capacity to understand such phenomena, especially as regard their precursory activity, causes of failure, dynamic behavior and triggering and deposition mechanisms. Failure mechanism of large landslides is rather complex and difficult to evaluate if all involved significant factors are not carefully identified, understood and considered. The Vajont rockslides has its own geology and characteristics, but similar large rock masses can be found characterized mainly by unfavorable structural configurations, rock weakening by mechanical processes, long creeping behavior and triggering mechanism. Results of past and current studies and researches on the Vajont event will improve our capacity to understand and at least partly forecast the behavior and development of large rockslides.

In the opinion of the authors, however, some areas still need to be developed.

1) Geological, hydrogeological and engineering geological investigations should be considered fundamental. The presence of unknown geological structures must be verified, continuously updating models with the acquisition of new data. 3-D modelling should be upgraded, allowing for a better representation of three-dimensional spatial and kinematic effects. In that way, the models will more accurately represent the real conditions, especially as regards the frequent complexity of sliding surfaces.
2) The assessment of shear strength of weak fissured clay rocks is a subject of paramount relevance in lito-stratigraphical complex sequences. New laboratory experiments and back-analyses of already occurred landslide should be carried out in order to assess more accurately change in rock properties that could be applied in a more continuous fashion in the predicted model. The brittle behavior of large landslides, including the relationship between displacement velocity, mechanics, and shear strength on the failure surface has to be investigated in detail, using also new techniques and apparatus.
3) The pre-failure deformation trend in large landslides must be more accurately observed and analyzed. In the case of Vajont landslide, in facts, the early knowledge of a complete set of experimental data (mainly, slip surface geometry, water pressure distribution on it and material type and characteristics) would have been essential to build a more reliable model of the slide. The only observation of the decrease of slide velocity with the reservoir level reduction resulted to be tragically misleading: it provided a reservoir filling criterion which however led, at the end, to the landslide collapse.
4) There is a need of a better understanding of the basic fatigue and progressive failure processes, to be properly modeled studying the development of deep-seated rockslide. Past sliding activity causes the reduction of the available strength down to the residual values or less, depending on the acquired velocity and associated thermal effects. The possibility that a landslide reaches high velocities depends on the amount and duration of the acceleration, in turn depending on the amount and duration of the disequilibrium between resistant and destabilizing forces and on the actions applied to the landslide body. In these conditions, the reduction of strength to residual conditions

may be particularly evident in fractured rocks, where stability is assured mainly by the presence of rock bridges within discontinuities. Crack propagation can lead to the rock bridge failure, resulting into catastrophic failures occurring, what's more, with very few warning signs. Both empirical and numerical methods, existing for the assessment of landslide velocity and propagation, and data gathered by monitoring systems should be improved. Monitoring data have been used to predict the time of failure and to assess the velocity trend. This approach implies that the mechanism of movement and the boundary conditions remain unchanged until the failure, a condition that has to be checked in the study of different cases. A further problem is represented by the fact that available monitoring data are related to specific conditions, that will not necessarily be the same for a future stability crisis, even of much larger magnitude. Improvements in this type of analysis will only derive from a deep understanding of the geological characteristics and the mechanical behavior of the rock masses.

The last unresolved question is: could the Vajont landslide have been really avoided? That is, a detailed geology and a more complete knowledge of the strength properties of the sliding surface would have given, at that time, the possibility for a better conceptual and mechanical model of the slide that, in turn, would have provided a reliable criterion to stop the motion? It should be stressed, however, that even today, to deal with very large landslide is a formidable task. We are able to obtain field data, such as water pressures, surface and deep displacement absolute values and trend, rocks and rock masses characteristics by laboratory experiments and "insitu" tests, but chiefly in the first more or less 200 of meters. Greater depths require not only sophisticated and not easily available instrumentation, but their interpretation is often difficult because the need of vast site investigation, not always feasible, time-consuming efforts for collecting them and frequent uncertainties related to the possible number of installed instruments.

The difficulties to handle large landslides continue to be still present and the words of Eng. Carlo Semenza, the dam designer (his April 1961 letter), must considered a vivid testimony of the formidable challenge he was at the time facing and we have to face nowadays:

"[…] *things are probably bigger than us and there are no adequate practical measures* […] I *am in front of a thing which due to its dimensions seems to escape from our hands* […]

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