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The 1963 Vaiont Landslide

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ABSTRACT. On the 9th October 1963 a catastrophic landslide suddenly occurred on the southern slope of the Vajont dam reservoir. A mass of approximately 270 million m^3 collapsed into the reservoir generating a wave which overtopped the dam and hit the town of Longarone and other villages: almost 2000 people lost their lives. Many studies and researches were carried out on the geological and geomechanical aspects and several attempts were made to explain the kinematics and dynamics of the landslide. This large mass of studies and researches has greatly increased the understanding of such phenomena, recognizing their precursory activity, predicting their dynamic behaviour and identifying likely areas of triggering and deposition. This paper reports briefly all the information reported in related papers, referring to the geological studies, to the chronology of events before 9th October 1963 and to the different interpretations of the landslide triggering and actual mechanics and dynamics.

Key terms: Landslide, Vaiont, Engineering Geology, Geology, Geomorphology

Introduction

The 9th of October 2003 was the 40th anniversary of the Vaiont landslide. Many questions, legal, economic, social and scientific have accompanied the history of the dam and the management of the emergency concerning the Vaiont reservoir slopes instability. The studies carried out on the landslide until today can be considered emblematic of the evolution of Engineering Geology during the last 40 years, both concerning field investigation techniques and slope stability methods.

The Vaiont dam, a double curvature thin arch dam 276 meters high, constructed between 1957 and 1960, is located in the narrow and with steep side slopes valley of the Vaiont River (northeastern Alps).

The Vaiont landslide has been the subject of numerous studies, not only because of its catastrophic consequences, but also because of its unexpected behavior.

Many researchers have studied the geology but, except for a few old generic geological surveys of the Vaiont Valley (BOYER, 1913; DAL PIAZ, 1928), the first detailed geological studies were carried out in 1959-60 by F. Giudici and E. Semenza, who were given the job by L. Müller, the first to formulate a technical study programme for the reservoir area. Their geological report (GIUDICI & SEMENZA, 1960) gave a clear detailed discussion of the geology and put forward the hypothesis of the existence of a very old landslide on the left bank of the Vaiont reservoir area. During their surveys they discovered, in fact, a very fractured zone (named “mylonite”) extending about 1.5 km along the left side of the valley corresponding to the sliding plane of the prehistoric landslide. Nevertheless, the designers of the dam concluded that a deep-seated landslide was very unlikely to occur, mainly because of both the asymmetric form of the syncline, that was expected to act as a natural break on possible slope movements, and the good quality of in situ rock masses, as derived from seismic surveys. But, after nearly 3 years of intermittent, slow slope movements, beginning with the first filling of the reservoir, on the 9th October 1963 at 22.39 local time and during the third reservoir emptying operation, a catastrophic landslide suddenly occurred on the southern slope of Mt. Toc and the whole mass collapsed into the reservoir in less than 45 s. The slide mass, of a volume of approximately 270 million m^3, generated a wave which crested 140 meters above the top of the dam and that still had a height of about 70 m downstream, at the confluence of the Vaiont with the Piave Valley. The wave hit the town of Longarone and other villages: almost 2000 people lost their lives.

After the tragedy, many studies and researches were carried out on the geological and geomechanical aspects and several attempts were made to explain the kinematics and dynamics of the landslide, also by using back analysis to study the many factors involved in the landslide development.

Numerous investigations into the conditions triggering slope collapse have been undertaken, including those of MÜLLER (1964; 1968; 1987a, 1987b); SELLI ET ALII (1964); HENDRON & PATTON (1985) and SEMENZA & MELIDORO (1992). It is now generally agreed that failure occurred along bands of clay within the limestone mass. Persistent rainfall shortly before the catastrophic failure may also have contributed significantly to the maintainement of elevated water pressures (HENDRON & PATTON, 1985). Collapse has been considered either as the reactivation of a relict landslide (Hendron & Patton, 1985; Semenza & Ghirotti, 2000; Semenza, 2000;) or as a first-time landslide (Skempton, 1966; Müller, 1968). Dynamic analysys attributes rapid collapse to unusual mechanisms, such as the vaporization of ground water during sliding (Voight & Faust, 1982; Anderson in Hendron & Patton, 1985; Nonveiller, 1992), the decrease in clay shear strength with increasing strain rate (Tika & Hutchinson, 1999), or else to self-accelerating rocks producing an abrupt drop in resisting stress. However, some doubts remain regarding the conditions of the failure plane before collapse, relative both to the mechanism that controlled the rates of movement during the three years preceding the failure and to the sudden acceleration of the mass, from a few centimeters per day up to about 30 m/s (Kilburn & Petley, 2003).

The thin arch dam resisted the forces imposed by the landslide failure and suffered only minor damages. Leonards (1987) stated that the Vaiont dam withstood a load eight times greater than it was designed to withstand.

The story of Vaiont is more than a chronology of technical operations and natural events: it appears to be a set of factors which can be considered in different ways.

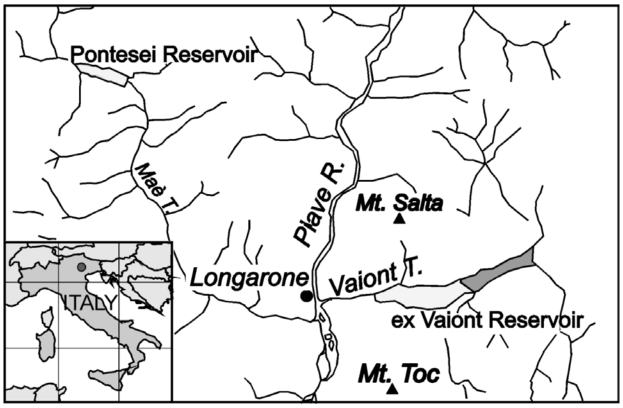

Figure 1. Location of the Vaiont and Pontesei reservoirs.

Those who built the Vaiont dam were working for a masterpiece in engineering history, and the Vaiont dam actually is a masterpiece. However, even if Mt. Toc gave important reasons to suspect the stability of its northern slope, technicians and experts of that time expected a very large and slow moving landslide but controlled by reservoir operations (Müller, 1961;1964).

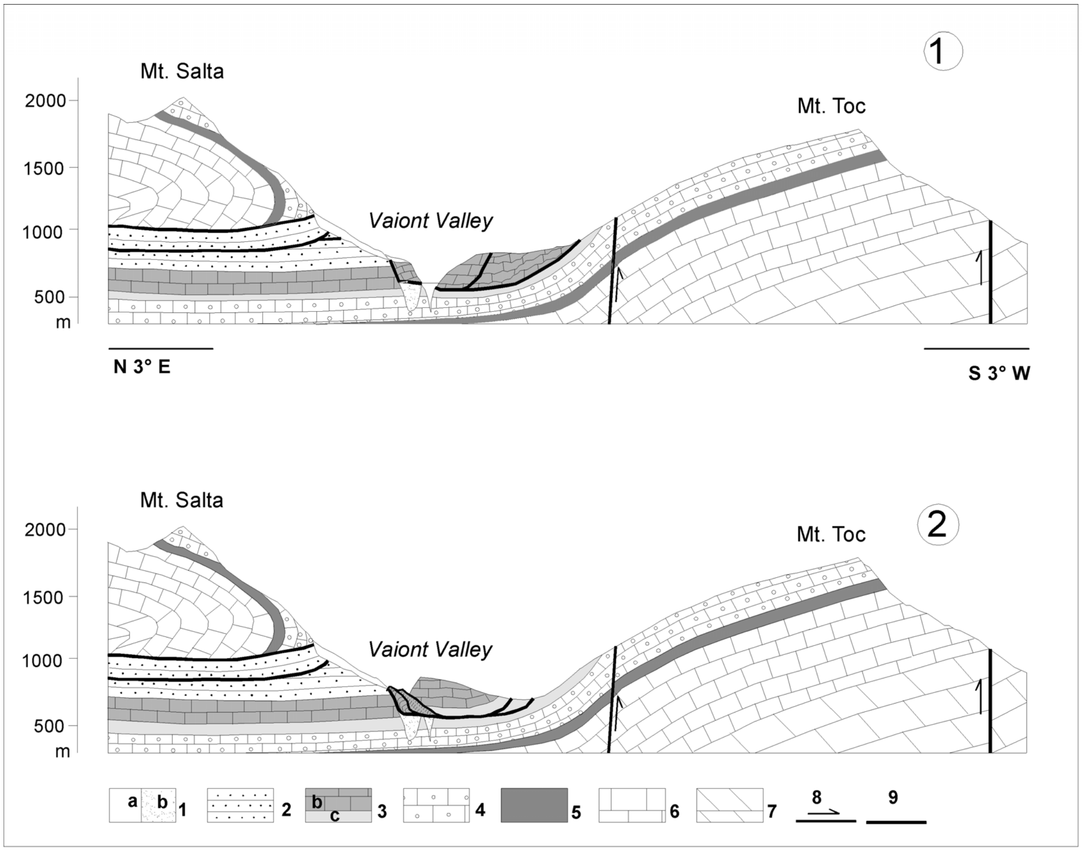

Figure 2. Two N-S geological sections from Monte Toc to Monte Salta. a) before 10/9/1963, b) after 10/9/1963. Legenda: 1) a Quaternary; b stratified alluvial gravels; 2) Scaglia Rossa Fm. (Upper Cretaceous - Lower Paleocene); 3) Cretaceous-Jurassic Fms. (Socchér Formation sensu lato and coeval): b) Socchér Fm. sensu stricto, c) Ammonitico Rosso and Fonzaso Fms.; 4) Calcare del Vaiont Fm. (Dogger); 5) Igne Fm. (Upper Liassic); 6) Soverzene Fm. (Lower and Middle Liassic); 7) Dolomia Principale (Upper Triassic); 8) Faults and overthrusts; 9) Failure surfaces of landslide (from Semenza & Ghirotti, 2000).

The catastrophic 1963 landslide failure has demonstrated to professionals and researchers in the fields of civil engineering and engineering geology, the importance of performing detailed geologic investigations of the rim of narrow steep-walled valleys, which are planned as the reservoir for large dams. The failure mechanism of a large landslide mass may be very complex and difficult to evaluate and even leading experts may fail to reach correct conclusions if they do not fully understand all factors affecting the mechanism and the evolution of the landslide. Nevertheless, in any subsequent consideration and judgment on the Vaiont history, the knowledge and the technologies available at that time for facing slope stability problems, that is the state of art of Engineering Geology, have to be taken into account.

This paper will consider the events that accompanied the construction of the dam and some of the relevant researches and suggested explanations for the landslide.

Geological studies on the Vaiont landslide

The history of the Vaiont landslide began on March 1959, during the first filling of the nearby reservoir of Pontesei (FIG. 1), when a landslide of approximately $6x10^6$ m^3 slid into the reservoir and the huge wave it generated overtopped the dam by a few meters. In that period, the Vaiont dam was already at an advanced stage of construction and, therefore, the need to verify whether there was any possibility of slope failures arose.

Geological setting of the Vaiont Valley

The Vaiont dam, a 276 meter high thin arch dam, was the highest double-arch dam in Europe. It was supported by the steep flanks of a deep canyon cut into dolomitic limestones of Malm and Dogger age. The full reservoir was to have a volume of 169 million m^3.

The Vaiont Valley was eroded along the axis of an east-west trending, asymmetrical syncline plunging upstream to the East (Erto syncline). An abrupt monoclinal flexure on the southern limb of the syncline formed a peculiar and important aspect of the geology of the slide. The southern slope of Mt. Toc evidenced a "chair-like" structure of the bedding planes with a steep back and a flat toe in correspondence with the failure surface (FIG. 2), which is clearly visible on the steep eastern slope of the Piave valley in front of Longarone.

The landslide involved Jurassic and Cretaceous rocks (limestones and marls mainly of the Socchér Formation), more or less fractured, that slid down along the "chair-like" bedding planes, in the Fonzaso Fm. New data on the chronostratigraphy of the Vaiont gorge section date the Fonzaso Formation as Callovian-Kimmeridgian (Dogger-Malm age) (COBIANCHI & PICOTTI, 2003). The 1963 slide mass moved mostly on one or more clay layers contained in the Fonzaso Fm., which are supposed to be continuous over large areas of the slip surface (FIG. 3).

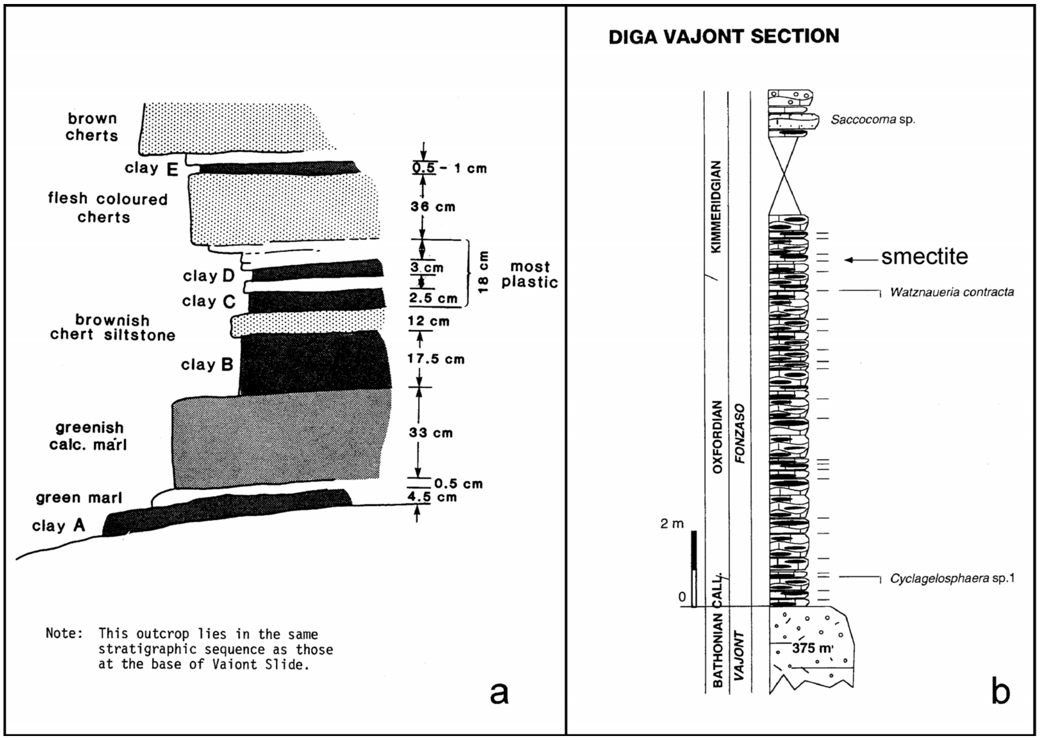

Figure 3. Stratigraphy at the Vaiont gorge. a) Schematic column of a series in the same position as the sliding surface. Many clay interbeds varying from 0.5 to 17.5 cm thick are present (from HENDRON & PATTON, 1985). b) a particular of the Vaiont dam section relative to the bottom of the Fonzaso Formation (from Cobianchi & Picotti, 2003).

Moreover, geological and tectonic evidence suggested that parts of the 1963 landslide perimeter and the prehistoric one closely correspond to one or more faults (ROSSI & SEMENZA, 1965; HENDRON & PATTON, 1985; MANTOVANI & VITA FINZI, 2003). The majority of the slide moved as a whole and reached the opposite side of the valley without any change in shape except a general rotation, as indicated by the surface morphology, by the geological structure and sequence that remained essentially unchanged after the movement. The thrust of the slide mass was so strong as to push uphill, for about 50 m on the right side of the valley, a large hill called *Colle Isolato* (about 2.5 millions of m^3), representing the vestiges of the prehistoric landslide.

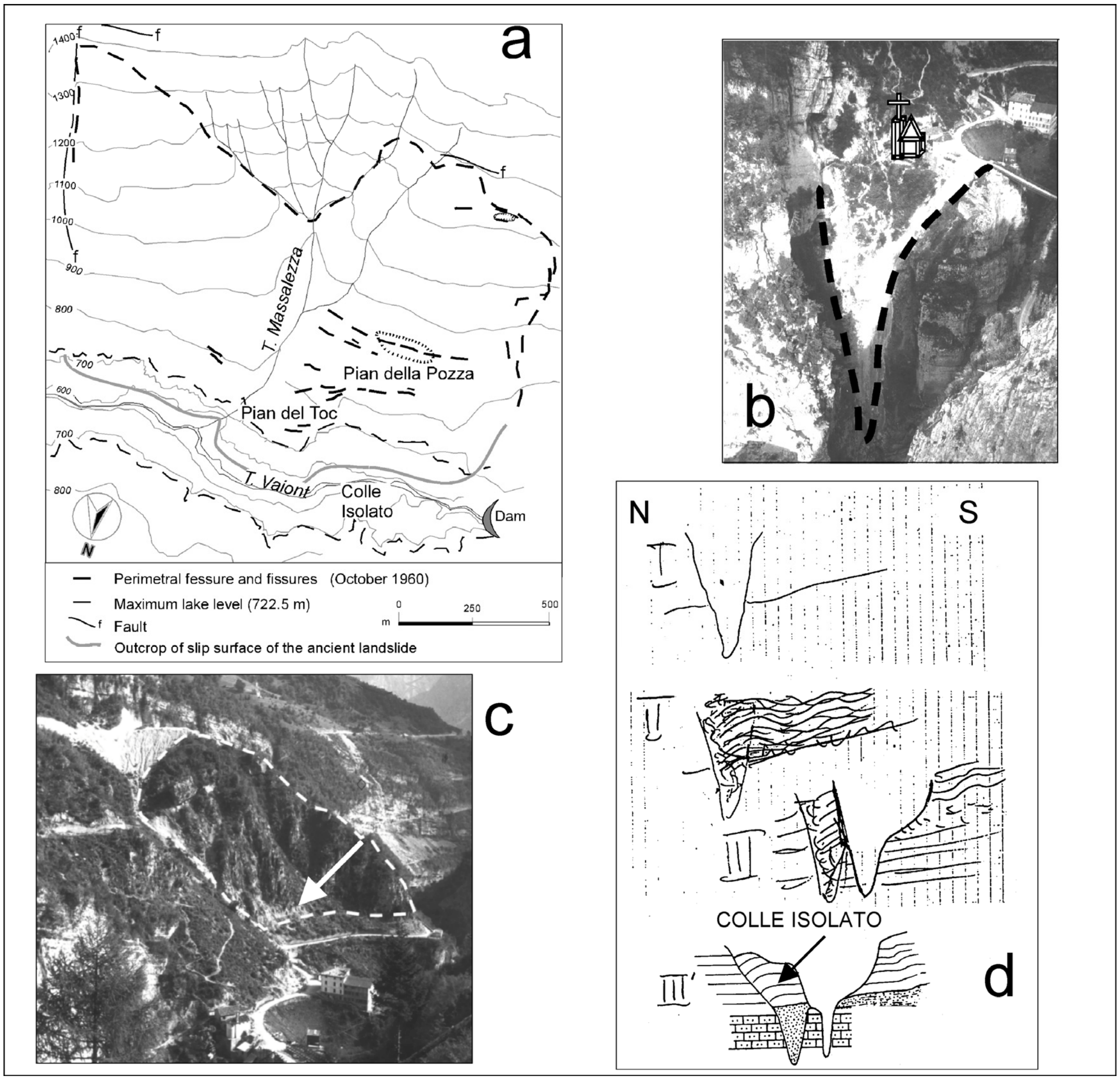

Figure 4. Main features of the Vaiont site and geomorphological evidences of the paleoslide: a) Map of the pre-1963 Vaiont landslide area. The name of the cited sites are also indicated; b) The Vaiont Valley seen from the left abutment of the dam: below the church is evident the very narrow epigenetic gorge of the Vaiont paleochannel (dashed line) (photo by Semenza, September 1959;modified); c) Dashed line delimits the "Colle Isolato" seen from the left slope of the Vaiont Valley. Above the road, a thin horizontal layer of white cataclasites (see arrow) separates the in-situ rock from the sub horizontal layers of the overlying old landslide (photo by Semenza, 10-9-1959;. d) Semenza's sketch of 1959: (I) the setting before the ancient landslide;(II) its movement down valley; and (III) the cutting of the new river channel further south. Despite its rough graphic scheme, the general scenario was confirmed (III') in 1961: at the bottom of "Colle Isolato" alluvial deposits of the old postglacial Vaiont River were found.

Chronology of events before 9th October 1963

At the time of the Vaiont dam construction, a reservoir slope stability evaluation was not usually included in the projects. Therefore, no specific studies on the Vaiont Valley had been carried out before except the general geological studies by BOYER (1913) and DAL PIAZ (1928) who did not indicate any ancient landslide on the southern slope of Mt. Toc.

After Pontesei, the emerging problem of a slope stability evaluation of the Vaiont reservoir was entrusted by the reservoir owner (the electric company S.A.D.E.) to Leopold Müller (MÜLLER 1961, 1964,1968,1987), who formulated a technical study programme for the basin area and entrusted Edoardo Semenza with the geological study.

The main result of Semenza's studies was the identification of an old enormous landslide, that had slid down the northern side of Mt. Toc into the Vaiont Valley, just upstream of the dam site. The main geological and geomorphologic evidence (FIG. 4) to support this hypothesis can be summarized as follows:

- A zone of uncemented cataclasites was present at the base of the Pian del Toc (FIG 4 a). This level, extending some 1.5 km along the left wall of the Vaiont Valley, corresponded in the stratigraphic sequence with the Fonzaso Fm.. Moreover, in correspondence with this cataclastic band many solution cavities, sinkholes and high discharge springs were observed.
- The landslide deposits filled the Vaiont River valley excavated after the retreat of the Würm glacier, as testified by the presence of a very narrow epigenetic gorge (FIG. 4 b). Subsequently, the "new" Vaiont stream incised the landslide deposit leaving the main part of the old landslide mass on the left side of the valley, while a portion remained on the right side. Only this landslide deposit was distinguishable from the in situ rock mass, and was consequently called "*Colle Isolato*" (i.e.: Isolated Hill) (FIG. 4c and FIG. 4d).
- The southern slope of Mt. Toc was characterized by a "chair-like" structure of the bedding planes, with the upper portion dipping rather steeply toward the valley and a seat portion flattening into a more horizontal configuration (FIG. 2).
- On the eastern part of Pian del Toc a fault separated the in-situ rock mass from the old landslide (SEMENZA, 1965; ROSSI & SEMENZA, 1965; HENDRON & PATTON, 1986; SEMENZA & GHIROTTI, 2000).

All together, these geological and geomorphological features led Semenza, during August 1960, to define both the shape and the perimeter of the failure surface, the geometry and the volume of the old landslide (FIG. 5). He was also convinced that the old mass could move again during the filling of the reservoir (GIUDICI & SEMENZA, 1960).

Actually, both consulting experts of those times and most of the scientific community in the following years did not accept the hypothesis of the existence of this old landslide, mainly because of the general appearance of its deposit: the landslide front mass really showed regular, apparently undisturbed strata. In fact, it was this feature, together with the relative inaccessibility of the slopes, that prevented accurate examinations and hindered recognition of the old landslide for some time.

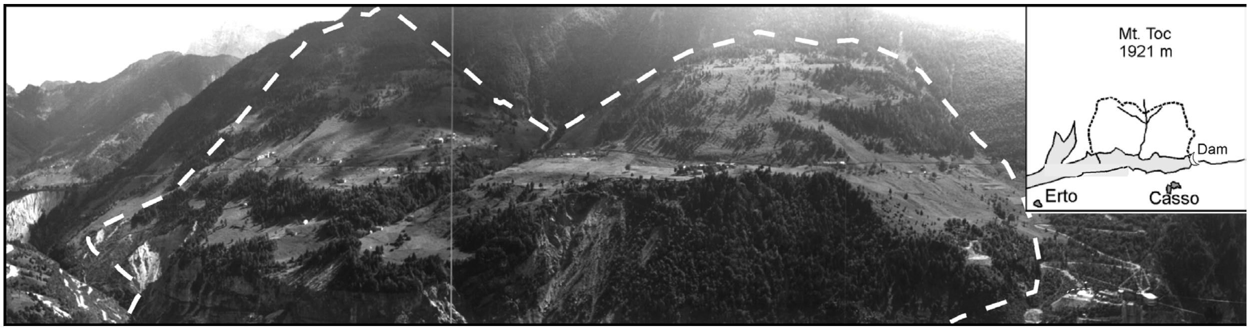

Figure 5. The northern slope of Monte Toc seen from the village of Casso. The dashed line delimits the ancient landslide mass. A large part of it would coincide with the boundary of 9 October 1963 landslide. (photo by Semenza, September 1959).

Chronology of events between 1960 and 9th October 1963

On the basis of Semenza's hypothesis, Müller in February 1961 suggested to S.A.D.E. the adoption of some precaution measures, which mainly consisted in daily topographical surveys of superficial movements and controlled changes of the reservoir level (MÜLLER, 1961) according to the observation of eventual movements (FIG. 6).

The first movements in the Vaiont slope started in March 1960 with the level of the reservoir at 590 m a.s.l., at the same elevation as the toe of the old failure surface. Afterwards, in June 1960, with the reservoir level more than 600 m a.s.l., small movements of the old landslide mass started in the part closest to the lake. In that period, three boreholes were drilled in order to verify the existence and to localize the failure surface, but it was not reached at the expected depth.

A second geological survey, carried out by Semenza during the summer of 1960, revealed, in an area at an elevation of about 920 m a.s.l., the transition from the sound bedrock to a very fractured rock mass, corresponding to the upper boundary of the old landslide. Just in correspondence with this limit, a continuous crack, about one meter wide and two and a half kilometers long, appeared at the end of October 1960 with a rate of movement that exceeded 3 cm/day.

On the 4th of November, at a reservoir level approximately at 650 m a.s.l., a landslide of 7×10^5 m^3 detached from the western part of the old deposit and slid into the reservoir, creating waves about 30 m high. The level was, then, slowly reduced to 600 m a.s.l. (reached at the beginning of January 1961), and a by-pass tunnel was realized on the right side of the valley. The lowering of the reservoir level afforded a clear observation of the bottom of the *Colle Isolato*, which was proved to rest on stratified alluvial gravels of the old Vaiont River (FIG. 4d).

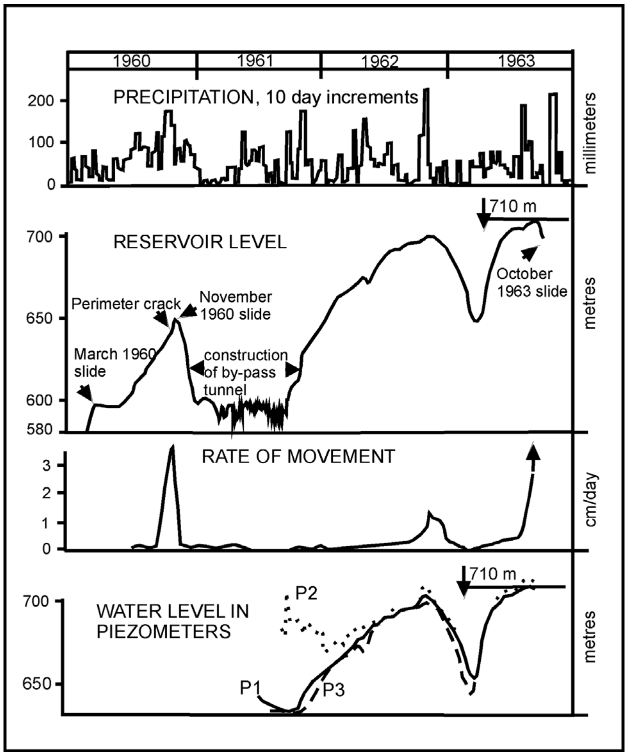

Figure 6. Comparative diagrams showing the lake levels, the piezometer levels, the rates of the landslide movement and the precipitation, from 1960 to 1963 (from HENDRON & PATTON, 1985, based on data from MÜLLER, 1964).

In the period between July and October 1961, four piezometers were installed in uncemented boreholes and three of them recorded the groundwater level until October 1963 (FIG. 6). In October 1961, when the construction of the by-pass tunnel was completed, the reservoir level was gradually raised again until, in December 1962, it reached 700 m a.s.l.. At that moment, since the displacement rates exceeded 1.5 cm per day (that is, much less than the velocity reached during the first filling), the level was lowered again to 650 m (reached in March 1963), and the movements on the slope stopped.

The behaviour of the slope with respect to filling and drawdown operations seemed to confirm Müller's hypothesis that movements were due to the first saturation of the rocks. The belief that this phenomenon was the main cause of the instability led the S.A.D.E. to raise the lake level once again, whilst maintaining the rule of the gradualness formerly followed.

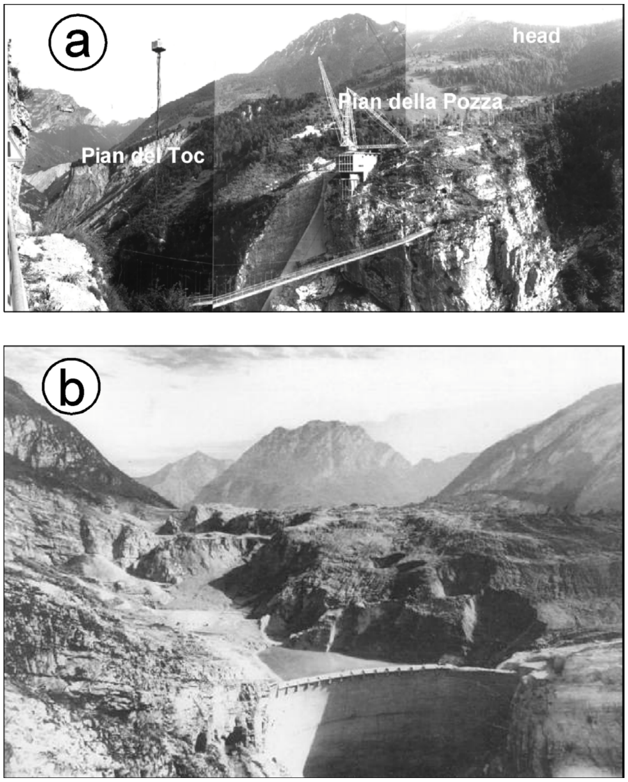

Figure 7. a) The northern slope of Monte Toc seen from the dam before (photo by Semenza, 8-25-1959) and b) on 10 October 1963 (photo by ZANFRON, 1998).

The lake level started to be raised again during April 1963. The movements started again only after the reservoir level reached 700 m: as the velocity was low, the reservoir level was raised once again. The velocity of the mass remained low until, in early September, at a level elevation of 710 m, an immediate increase in the rate of slope movement from 0.5 to 1.0 cm/day was observed and continued to increase throughout September, reaching 2 to 4 cm/day at the beginning of October. In the same days, the lowering of the reservoir began and the reservoir elevation dropped to about 700 m. The velocity of the slide by that day had increased up to 20 cm/day. At 22.39 h on 9 October 1963 the southern rock slope of M.Toc failed suddenly over a length of 2 km and a surface of 2 km^2. The slide moved a 250 m thick mass of rock some 300 to 400 m horizontally with an estimated velocity of 20 to 30 m/s, before running up and stopping against the opposite side of the Vaiont Valley. The mass drove the water of the reservoir forward, giving rise to a wave, which overtopped the dam more than 100 m above the crest and hurtled down the Vaiont Gorge to the bottom of the Piave River. The flood destroyed the villages of Pirago, Villanova, Rivalta and Faé and most of the town of Longarone, with a loss of almost 2000 lives (FIG. 7).

Interpretations of the landslide mechanism

Since the catastrophic failure, a huge range of work has been undertaken on the causes of the Vaiont landslide. However, this event still raises two main questions: how was the landslide initially activated and why did it move so fast? Several investigations and attempted interpretations of the slope collapse have been carried out during the last 40 years, but a comprehensive explanation of both the triggering and the dynamics of the phenomenon has not yet been provided. Papers on the Vaiont landslide, published in the international literature after 1963, can be schematically subdivided into the following groups:

1) papers based on geological and geomorphological data collected at the Vaiont site (CARLONI & MAZZANTI, 1964 a, b; SELLI & TREVISAN, 1964; ROSSI & SEMENZA, 1965; SEMENZA, 1965; BROILI, 1967; MARTINIS, 1979; RIVA ET ALII, 1990; SEMENZA & GHIROTTI, 2000; MANTOVANI & VITA-FINZI, 2003);
2) papers mainly dealing with some specific aspects ranging from geotechnical properties of the involved material, to physical and rheological behavior of the mass, up to different types of stability analysis as a means to understanding the role of the many factors differently involved in the landslide triggering and development (CIABATTI, 1964; CORBYN, 1982; VOIGHT & FAUST, 1982; BELLONI & STEFANI, 1987; KIERSCH, 1964; JÄEGER, 1965 A, 1965 B; MENCL, 1966; SKEMPTON, 1966; KENNEY, 1967; JÄEGER, 1972; HABIB, 1975; CHOWDHURY, 1978; TROLLOPE, 1980; HUTCHINSON, 1987; NONVEILLER, 1967; 1987; TIKA & HUTCHINSON, 1999; ERISMANN & ABELE, 2001; VARDOULAKIS, 2002; KILBURN & PETLEY, 2003);
3) papers dealing with the Vaiont landslide in a more comprehensive way (MÜLLER, 1964; 1968; 1987 a, 1987 b; SELLI ET AL., 1964; HENDRON & PATTON, 1985; BELLONI & STEFANI, 1987; NONVEILLER, 1987; SEMENZA & MELIDORO, 1992).

The first and undoubtedly one of the most important papers describing the 1963 Vaiont landslide 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 Vaiont reservoir history, he concluded that, "the interior kinematic nature of the mobile mass, after having reached a certain limit velocity at the start of the rock slide, must have been a kind of thixotropy". The transition from a 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 attributed the behaviour of the sliding mass, that moved all at once at an estimated velocity of 25-30 m/s, to a "spontaneous decrease in the interior resistance". In his work, Müller seemed initially to agree with GIUDICI & SEMENZA (1960) on the existence of a prehistoric landslide in the M. Toc area. However, after the results of both borings and geophysical surveys (CALOI, 1966), he favoured the hypothesis of a new first-time landslide. Finally, as regards to the shape of the sliding surface, *a posteriori* he stated that: "Many experts…are brought to assume a slide plane curved approximately like a circular cylinder or a spiral-cylinder plane (KIERSCH, 1964)". This assumption, subsequently adopted by many scientists, would provide a very simple and logical explanation of the behaviour of the sliding mass, but "exact kinematic observation and comparison of the slid mass before and after 1963, indicate that on the front of the mass a translation and shoving up have in fact taken place, and not simply a raising of the toe". In conclusion, if many important aspects of the landslide are explained, for some others the Author strongly believes in their substantial unpredictability.

The papers of KIERSCH (1964, 1965), cited by MÜLLER (1964), had a great diffusion especially in the Anglo-Saxon scientific community and Kiersch's hypotheses and sections were assumed valid in many subsequent studies on the Vaiont landslide. Essentially, he considered the existence of a prehistoric landslide and the presence of a weak zone of highly fractured rocks due to the de-stressing effects resulting from the last glacial period (18,000 years ago). On this basis, he concluded: "Actual collapse was triggered by a rise in subsurface water level from bank infiltration with increased hydrostatic uplift and swelling pressures throughout an additional part of the subsurface…".

Again during 1964, SELLI ET ALII (1964) published a comprehensive work on the Vaiont landslide giving full details of the geological characteristics, mainly used for the reconstruction of the sliding surface, and of the hydraulic and seismic phenomena that accompanied the event itself. They stated, besides, that the mass moved with a generally pseudo-plastic behaviour: the movement was actually possible because of the appearance of secondary shear surfaces at the base of the front of the landslide. The main causes of the landslide were ascribed to the particular geological structure and to the morphology of the slope, and also to the variations in the reservoir level. Finally, a dynamic approach to the movement allowed the Authors to establish a maximum velocity of 17 m/sec in about 45 seconds.

Several researchers besides Müller and Selli, and among these MENCL (1966), conjectured the need to assume a significant loss of strength to explain the high acquired velocity of the landslide. Many doubts remain, in fact, as to the mechanisms controlling the rate of movement before the catastrophic failure and the sudden acceleration up to 30 m/s. Various interpretations have been given and they mainly differ in treating the event as a first-time landslide (SKEMPTON, 1966; BROILI, 1967; SELLI ET ALII, 1964) or as the reactivation of an old prehistoric one (HENDRON & PATTON,1985; PASUTO & SOLDATI, 1991).

The detailed knowledge of the local stratigraphy has been considered fundamental for the location, the continuity and the existence itself of clay beds in the calcareous sequence (CARLONI & MAZZANTI, 1964; SELLI & TREVISAN, 1964; FRATTINI ET AL., 1964; NONVEILLER, 1967), a controversial aspect that was definitively clarified only after 1985. The first detailed study of local stratigraphy was that by GIUDICI & SEMENZA (1960), but several others followed (MARTINIS, 1964; CARLONI & MAZZANTI, 1964; SELLI & TREVISAN, 1964; BROILI, 1967). The extensive paper of BROILI (1967) carefully examined the logs of the borings made by ENEL (the national electricity board) after the landslide and finally concluded "..the succession does not include any clay beds or intercalations which some authors consider may have been responsible for some aspects of the phenomenon.".

Afterwards, Müller (MÜLLER, 1968), re-analysing all available data and presenting additional considerations on the rock slide, drew similar conclusions, stressing the importance of the "chair-like" shape of the slip surface. Contrary to his 1964 work, Müller stated that no clay beds existed on the slip surface; even if very thin films of pelitic materials (1-3 mm thick) had been seldom observed in the limestone bedding planes, they could not have played any significant role in the slope failure. Furthermore, he stated that the friction angle value required to maintain a condition of limit equilibrium, was ridiculously small if compared with the strength properties that could be attributed to the material involved in the movement. So, as static calculations methods should be considered inadequate to explain the different phenomena which occurred during the Vaiont reservoir history, he noted the influence of creep phenomena and related the reduction of frictional resistance to a progressive failure mechanism of the slope.

Nowadays, it is generally agreed that failure occurred along planes of weakness represented by clay beds (5–15 cm thick) within the limestone mass. The increase of the pore water pressure, due to the raising of the water level in the reservoir, besides causing a decrease in effective normal stress, might have favoured the mobilization on these clay layers.

Voight's observations (VOIGHT, 1988) on slope movement before the catastrophic failure have been shown to be consistent with the failure behaviour of clay at high pressure (PETLEY & ALLISON, 1997; PETLEY, 1999). This interpretation has been considered problematic as it implies a brittle failure of clays, but recent experiments (e.g.: BURLAND, 1990; PETLEY, 1995) indicated that clays really can behave as a brittle material under high loads such as those expected for deep-seated slope failures. However, even if after the verifying of clay levels along the slip surface, it is still very difficult to explain the velocity of the landslide in quantitative terms.

Recently, slow rock cracking has been considered another deformation mechanism controlling the acceleration to the giant and catastrophic slope failure. With the layer being deformed, stresses are concentrated at the tips of already existing small cracks and, if a critical value is exceeded, these concentrated stresses become large enough to break existing bonds and cracks grow at an accelerating rate until they coalesce into a general unique failure plane (e.g.: KILBURN & VOIGHT, 1998). Moreover, slow cracking is readily enhanced by circulating water, as a result of chemical attacks, especially at crack tips (ATKINSON, 1984). Thus, water presence could have had a double effect in triggering the Vaiont deep-seated failure, both reducing the shear resistance by raising pore pressures and, in some way, catalyzing the failure of the stressed layer.

The low kinetic friction value required for the limit equilibrium conditions of the Vaiont slope has been explained also in terms of frictional heat and the consequent increase in pore water pressure. Indeed, mechanical energy dissipated as heat inside the slip zone may lead to vaporization of pore water, creating a cushion, as in reality happened. VOIGHT & FAUST (1982) showed that heat generation may rise high pore-water pressures inside the shear band. More recently VARDOULAKIS (2002) re-formulated the set of equations governing the motion of a rapidly deforming shear-band, showing how they contain, as unknown functions, the pore water pressure, the temperature and the velocity field inside the shear-band. The increase in pore pressure, enhanced by elevated friction coefficient, porosity and deformability and maintained under conditions of fast slip, can induce rapid frictional strength loss, such to convert a moderate sliding into a catastrophic failure. VOIGHT & FAUST (1982) also tried to find an explanation for the dynamic problem of the Vaiont slide proposing a thermal mechanism. They started their analysys from the model of CIABATTI (1964) who estimated a maximum velocity of 17 m/s and a total duration of slide of 45 s, but considering both a variable friction coefficient and a pore water pressure rise due to frictional heating. Acceleration, velocity (maximum: 26 m/s) and elapsed time of the Vaiont mass are, then, calculated as functions of the displacements. NONVEILLER (1978; 1987) regarded the frictional heat development on the failure surface as a necessary mode to explain the high velocity and the long trajectory of the Vaiont slide. He estimated a maximum velocity of 15 m/s, obtained considering the whole reduction of the shearing resistance of the mass. More recently, also SEMENZA & MELIDORO (1992) considered the effects of the frictional heat developing during the final accelerated movement to explain the high velocity and the long trajectory of the Vaiont slide. They concluded, however, that this mechanism may really induce a decrease in the clay shear strength such that the whole mass could reach a very high velocity, but on the other hand it could be effective only after a certain time from the beginning of the movement.

HENDRON & PATTON (1985), starting from Semenza's results, made significant progress in resolving some of the problems previously mentioned. The main results of their study may be summarized as follows: 1) the 1963 Vaiont event was a reactivation of an old landslide, probably occurring in post-glacial times; 2) the mass slid over one or more clay levels, some of which, as much as 10 cm thick probably could have represented both a continuous impermeable layer and a weak level with a residual friction angle as low as 5°; 3) on the basis of the evidence of karstic and solution features in the crown area, the existence of two aquifers in the northern slope of Mt.Toc, separated by the above mentioned clay levels, could be conjectured. A re-examination of the measured piezometric levels (FIG. 6) supports this hydrogeological model, adopted for the stability analysys. The groundwater level of the highly fractured and permeable landslide mass was mainly influenced by the reservoir level, while the lower aquifer, represented by the Calcare del Vaiont Fm., was fed not only by the reservoir but by the precipitation that fell in the Mt. Toc hydrogeological basin. This hydrogeological scheme suggests, thus, the possibility of a development of high water pressure due to the rainfall or snowmelt infiltration on Mt. Toc.

A large number of two-dimensional limit equilibrium analysys were performed after the failure by various researchers. LO ET AL. (1971) performed limit equilibrium analysys of the Vaiont slide using Janbu's method for non-circular surfaces. They considered a sliding mass formed by two wedges separated by a vertical discontinuity located near the center of the slide mass. In the case of a groundwater corresponding to the water level in the reservoir, they obtained a friction angle at limit equilibrium as low as 13°.

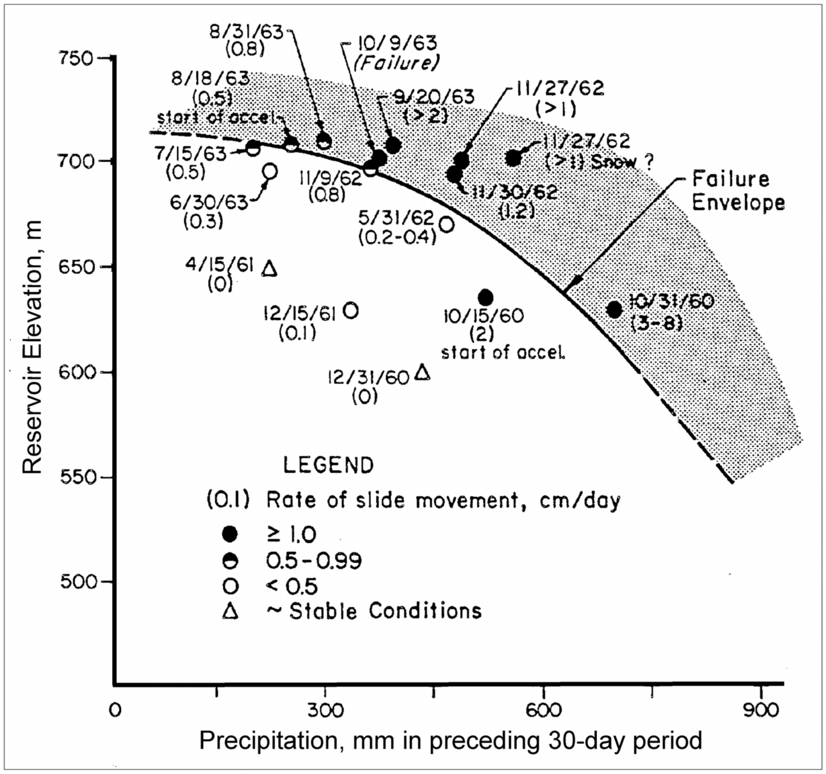

Figure 8. The stability of the Vaiont Slide for reservoir elevation vs. 30-day precipitation (from HENDRON & PATTON, 1985).

The friction angle required for stability, back-calculated by HENDRON & PATTON (1985), ranged from 17° to 28°, but strength test data on the clay material along the failure surface showed friction angles ranging from 5° to 16°, with an average value of about 12°. These values are definitely less than those required for stability and the slope would not have been stable even before the filling of the reservoir. Since the slope was at least marginally stable for some time prior to failure, the Authors concluded that some factors controlling the stability conditions of the slope were not accounted for in the two-dimensional limit equilibrium analysys. To resolve this discrepancy they carried out three-dimensional stability analysys accounting for the history of movements, the record of reservoir levels, the shape of the failure surface, the assumed distribution of water pressure and water levels and, finally, appropriate shear strength values; high velocity of the landslide was attributed to water pressures generated by vaporization along the failure surface. In conclusion, the 1963 landslide occurred because of the combined effects of raising the reservoir level and the increase in piezometric levels as a result of rainfalls. The relationship between cumulative rainfall and reservoir levels shows the conditions yielding a water pressure distribution that would cause an instability condition (Fig. 8).

For a realistic incorporation of kinematics in the analysys Sitar &MacLaughlin (1997) introduced the technique of Discontinuous Deformation Analysis whose main advantages are that: i) the actual mode of failure does not have to be assumed before; ii) the computation of displacements and velocities, not easily obtained with limit equilibrium methods, is really possible. For the analysis they used a simplified cross section of Hendron & Patton (1985) subdivided into a different number of blocks. The results indicated that, in dry conditions, a single block would require for stability a friction angle of only 8°. But, if the mass is divided only by a single vertical discontinuity into two blocks, the required friction angle along the sliding plane rises to values between 8° and 14°, depending on the position of the vertical discontinuity and the considered inter-block friction angle.

Chowdhury (1978) using the limit equilibrium method but modeling progressive failure, obtained similar results. The behaviour observed in this analysis is consistent with the model proposed by Jäeger (1972), who also noted the existence of a non-uniform zone of physical weakening separating the upper sliding mass from the lower one. This model may be considered an extension of the progressive failure concept: the unstable upper portion of the slide gradually creeps down slope and so, forces on the lower stable portion are progressively increased up to the point where they are high enough to cause a sudden failure within the lower stable zone.

Tika & Hutchinson (1999) recently proposed a new hypothesis for explaining the high velocity of the landslide based on the results of ring shear tests carried out on two samples, from the slip surface at slow and fast rates of shearing. Both samples showed a fairly relevant loss of strength increasing the shear rate: a minimum friction angle of 5°, that is up to 60% lower than the residual value, is obtained at rates greater than 100 mm/min. This mechanism of strength loss, alone or in combination with other mechanisms, might have taken place and would explain the fast movement and the catastrophic failure.

Another attempt to perform a dynamic analysis of the Vaiont slide is presented in the paper of Vardoulakis (2002) who accepted the rapid drop of the friction angle of the Vaiont's clayley material as determined by Tika & Hutchinson (1999), from its peak value (22.3°) to the dynamic residual one (≈ 4.4°), and calculated that the velocity of the slide reached 20 m/s 8 s after its activation, corresponding to a slide displacement of 74 m.

Erismann & Abele (2001) presented an interesting examination of selected "key events" of rock slope failure processes. In the critical discussion on the Vaiont landslide they were faced with the problem of velocity-determination, energy-lines and Fahrböschung function and stated that, with the basis of scientific knowledge at that time, the Vaiont catastrophe, especially as regards to the transition from slow to fast motion, could have been foreseen (Heim, 1932).

The growing interest in understanding and predicting catastrophic phenomena derives from their large-scale societal impacts, but the scientific community is only beginning to develop the concepts and tools to model and predict these types of events. Even if the prediction of catastrophes is considered to be almost impossible, some researchers have found evidence of a predictability degree, at least of certain catastrophes. Sornette et al. (2003) proposed a simple physical one, based on a slider-block model, to explain the accelerating displacements preceding some catastrophic landslides. The model, that predicts two different regimes of sliding (stable and unstable) leading to a critical finite-time singularity, is quantitatively calibrated to the displacement and velocity. The data preceding the Vaiont landslide provide good predictions of the time-to-failure up to 20 days before the collapse.

Lessons learned

Landslides occur in a wide variety of geomechanical contexts, geological and structural settings, and as a response to various loading and triggering processes; they are often associated with other major natural disasters such as earthquakes, floods and volcanic eruptions. The question of the predictability of landslides, which constitutes a major geological hazard of great concern, is still not solved. By its nature, any specific landslide is essentially unpredictable, and the focus is on the recognition of landslide prone areas. This "time-independent hazard" amounts to assuming that landslides are a random process in time, and it uses geomechanical modelling to constrain the future long-term landslide hazard. On the other hand, the approaches in terms of a safety factor do not address the preparatory stage leading to the catastrophic collapse.

Giant and catastrophic slope collapses, a natural result of accelerating deformation due to different and, up to now, only poorly explained phenomena, are still less understood. The catastrophic Vaiont landslide demonstrates the importance of performing detailed geological, geomorphological, hydrogeological and geotechnical investigations both of rock masses and slopes, especially if they are planned as the reservoir for large dams. Following the catastrophic failure, a huge range of work has been undertaken on the causes of the failure; the reason for this is that the failure mechanism of a large landslide mass is very complex and difficult to evaluate if all significant factors affecting the landslide are not carefully identified, well understood and considered in all decisions regarding stabilization, control and hazard evaluation. Some slopes may in fact react quite hazardously to triggers as a result of a crisis of the internal equilibrium that could be difficult to envisage and expensive to investigate. It is, then, advisable to define and validate reference models to plan prevention measures and to manage emergency conditions.

The catastrophic Vaiont landslide promoted a large mass of studies and researches and the information reported in the related papers has greatly increased our understanding of such phenomena, recognizing their precursory activity, predicting their dynamic behaviour and identifying likely areas of triggering and deposition, strongly reducing in this way the risk conditions for populations in mountainous areas.

Acknowledgements

The Authors dedicate this paper to the memory of Professor Edoardo Semenza (1927-2002), one of Italy's leading landslide researchers. Edoardo Semenza put his distinctive mark also on the understanding of Alpine chain structure, making original and important contributions to the geology, tectonics and geomorphology of the Dolomites. He was the geologist who discovered, some years before the beginning of the first movements, that an ancient landslide mass was present on the left side of the Vaiont Valley. Semenza stressed the need to collect field data in order to understand slope failure conditions for basing correct modeling. He strongly believed both in the role of geology and geomorphology as fundamental support to any engineering project and in the importance of a good communication between the various specialists working on large projects. He spent more than 40 years of his academic career at Ferrara University as full professor in Engineering Geology: his geological insight, humanity and culture (he also wrote many Latin and Italian poems) remain in the memory of colleagues, students and the Italian scientific community.

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