History of the 1963 Vaiont slide: the importance of geological factors

E. Semenza · M. Ghirotti

Abstract In view of the length of time that has elapsed since the 1963 Vaiont landslide and the recent renewed interest in this complex phenomenon, it was decided to look back over its history through unpublished documents and pictures of that period (1958–1963). Particular attention was paid to the geological and geomorphological features in order to explain how, since 1959, an ancient landslide has been identified on the left side of the Vaiont valley. The Vaiont landslide has been the subject of much research and discussion and as more than 30 years later many questions are still open, it is a source of stimulus for many researchers. The paper considers the main interpretative studies undertaken to date and proposes an hypothesis of what may really have happened.

Résumé À cause de la longue période écoulée depuis le glissement du Vaiont en 1963, et de l'intérít renouvelé autour de ce phénoméne complexe, on a décidé de réexaminer cette longue histoire en utilisant aussi des documents inédits (photos et ecrits) de la période 1958–1963. Ici on décrit, en particulier, les aspects géologiques et géomorphologiques de la zone en question, dans le but díexpliquer comment, depuis 1959 déjà on avait décelé sur le flanc gauche de la Vallée du Vaiont un ancien glissement. La connaissance de la complexité géologique locale et des risques potentiels qu'elle présentait, ont été dans cette periode étroitement liés aux choix décidés par la Société SADE et par la Société Nationale d'Élctricité (ENEL). On a formulé ici une hypothése pour expliquer comment ce désastre a pu réellement se produire. Sur l'interprétation de ce glissement, toujours objet de recherches et de discussions, on présente ici les principaux travaux, dont la plus grande partie est basée sur l'hypothése de E. Semenza. Toutefois, à distance de presque 30 ans, beaucoup de questions sont encore sans réponses complétes, et pour cela deviennent une source d'intérêt, ce qui stimule de nombreux chercheurs.

Key words Vaiont · Ancient landslide · Geology · Geomorphology

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Introduction

The Vaiont dam disaster has been well reported in the literature. The lessons learned from the failure have had a significance influence, particularly in the fields of civil engineering and engineering geology. In order to obtain a better understanding of this catastrophe, this paper considers the events that preceded and accompanied the construction of the dam and the functioning of the reservoir. Some of the relevant research is reviewed and some of the suggested explanations for the landslide considered.

Chronology of events

Before discussing the history of the 1963 Vaiont slide, it is important to appreciate that a previous project was undertaken in 1925. This earlier dam was located at the bridge at Casso, some 1500 m upstream of the site where the Vaiont dam was eventually built (Fig. 1). Had the reservoir been built at this original location, it is likely that there would have been no problems with landslides. However, the construction of the dam would have been difficult because

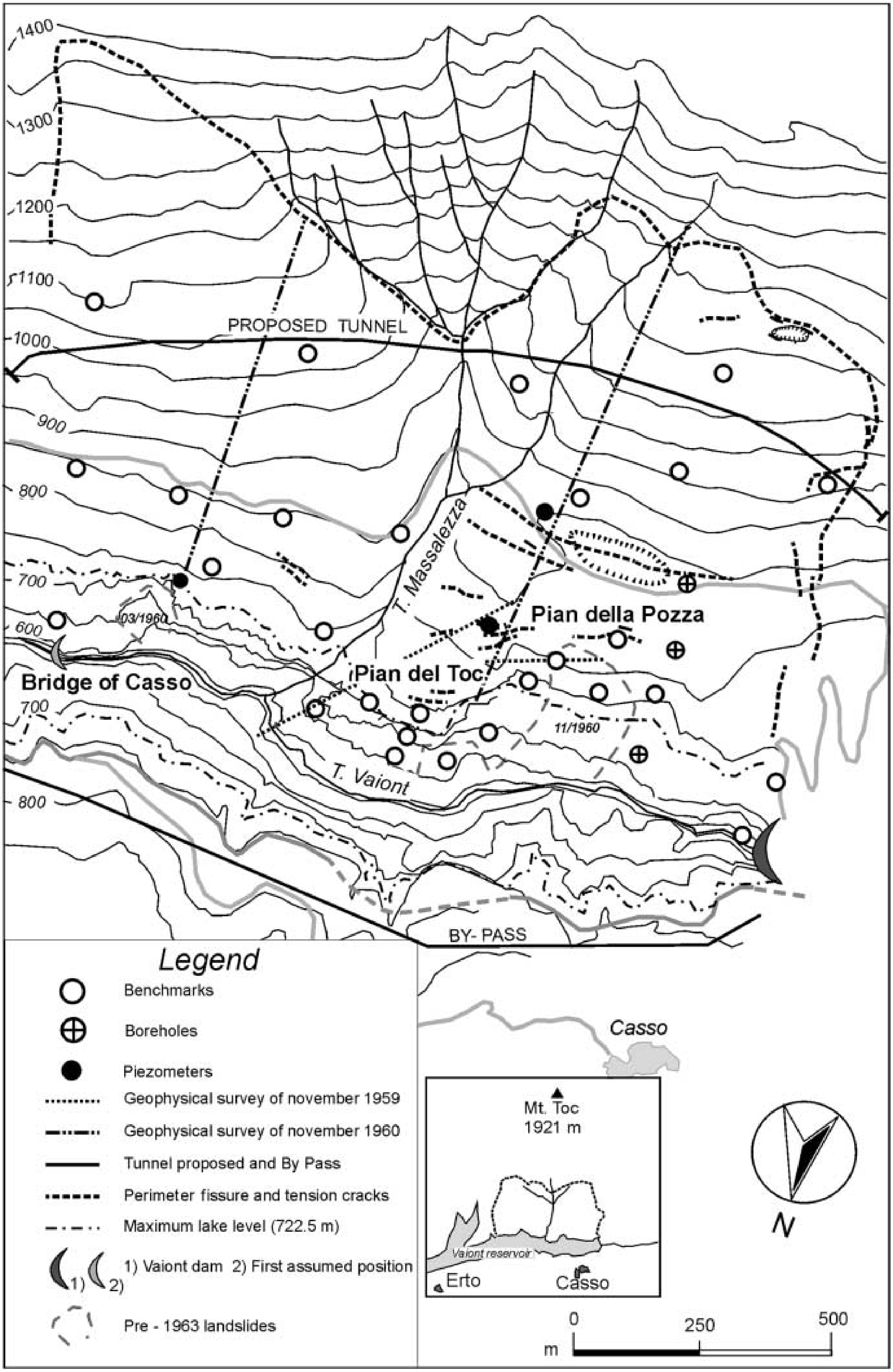

Fig. 1
Map of surveys and landslides before 9 October 1963

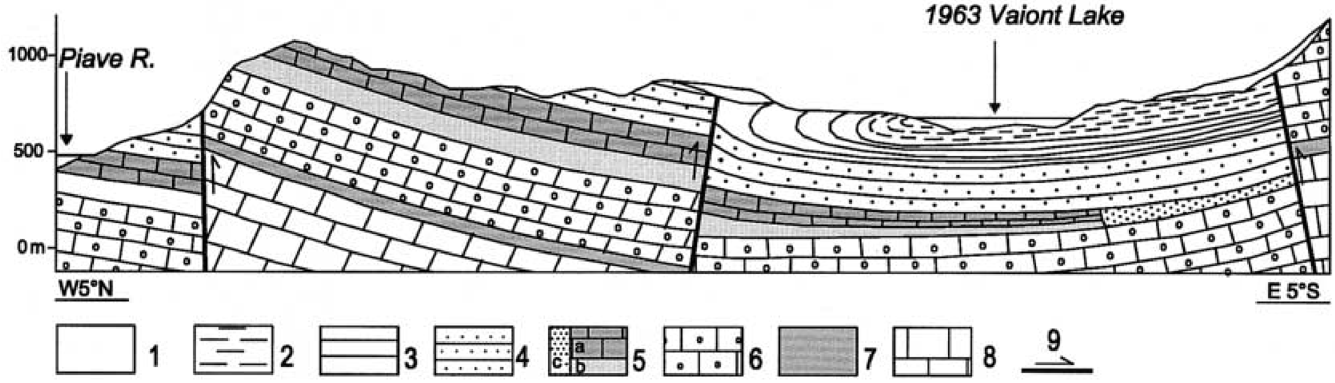

Fig. 2
W-E geological section from Piave River to Vaiont reservoir with Vaiont River to *right*. *1* Quaternary; *2* Flysch Formation (Eocene); *3* Marne di Erto (Paleocene); *4* Scaglia Rossa Formation (Upper Cretaceous–Lower Paleocene); *5* Cretaceous–Jurassic Formations (Socchér Formation *sensu lato* and coeval): *a* Socchér Formation sensu stricto; *b* Ammonitico Rosso and Fonzaso Formation; *c* condensed series; *6* Calcare del Vaiont (Dogger); *7* Igne Formation (Upper Liassic); *8* Soverzene Formation (Lower and Middle Liassic); *9* faults. (Modified from Riva et al. 1990)

here the Cretaceous limestones of the Socchér Formation are not as solid as those of the Dogger Formation. In addition, the capacity of the dam would have been much smaller and it is probably for this reason that the planners preferred the downstream location where the sound Jurassic limestones of the Calcare del Vaiont dip slightly eastwards (Figs. 1 and 2).

It is also relevant to consider the earlier problems at Pontesei, in the valley of the Maë River, a tributary of the Piave River north of Longarone (Fig. 3). On 22 March 1959, during the second filling of the artificial reservoir at Pontesei, a landslide began on the left side of the valley. Small movements had already been noted some days before, but it was believed that these related to only a slow shallow disturbance. Further, at this time the level of the reservoir had already been lowered by about 30 m as a 3-year-old landslide near the left abutment of the dam had begun to move again. The failure of 22 March 1959 was very rapid and resulted in the formation of a huge wave which knocked over a workman biking along the road on the right-hand side of the lake. It flowed over the top of the dam by a few metres but caused no serious damage in the valley below.

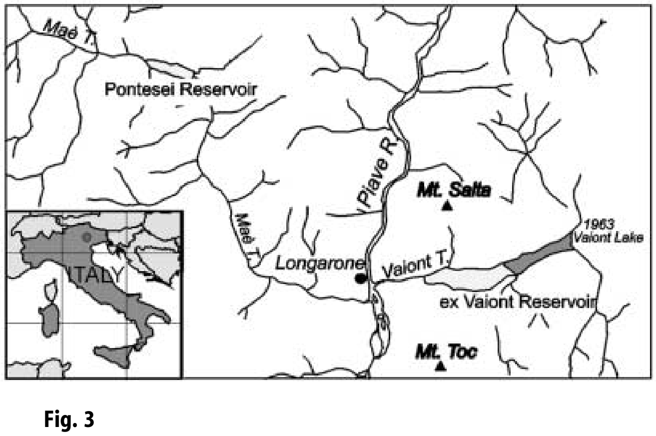

Fig. 3
Location of Vaiont and Pontesei reservoirs

At that time the Vaiont Dam was already at an advanced stage of construction and hence it was thought necessary to verify whether there was any possibility of landslides on the slopes above the Vaiont reservoir. It is important to remember that at that time research on the slope stability of reservoir valleys was often not included in the planning for dam construction projects and therefore insufficient detailed studies had been carried out at Vaiont.

Topography and geological survey of the Vaiont area between 1959 and 1960

The consideration of the stability of the Vaiont reservoir slopes was entrusted to Leopold Müller who proposed a technical study programme for the basin area, which commenced in July 1959. The general topography of the western part of the area at that time can be seen in Fig. 4. This photograph, taken by Semenza on 25 August 1959, shows the Calcare del Vaiont in the area of the crane and the excavation for the left abutment of the dam. The detailed geological survey led to the identification of various ancient landslides, only one of which was recognised as potentially dangerous – that on the left side, slightly upstream of the dam, which included the Pian del Toc and the Pian della Pozza areas. The different parts of the ancient landslide (a, b and c) are shown in Fig. 4. On the right side of the valley a small part of the ancient landslide was preserved, clearly distinguishable from the regular in-situ rock mass and referred to as “Colle Isolato” (Isolated Hill). Figure 5 shows the right-hand slope of the Vaiont valley. In the centre is the Colle Isolato, outlined by the white dashed line, where the dense vertical fracturing can be seen. To the left, the photograph indicates a strata dip of some 20° towards the north. The Colle Isolato is also seen in Fig. 6. Some 12 m above the roadway a lighter, almost horizontal band of mylonite has been highlighted with an arrow. This separates an ancient landslide from the in-situ bedrock. The deep gorge at Vaiont is seen in Fig. 7. To the right, beneath the church, is an earlier palaeochannel in which horizontal layers of gravel were observed during the excavation of the bypass tunnel in 1961. It is

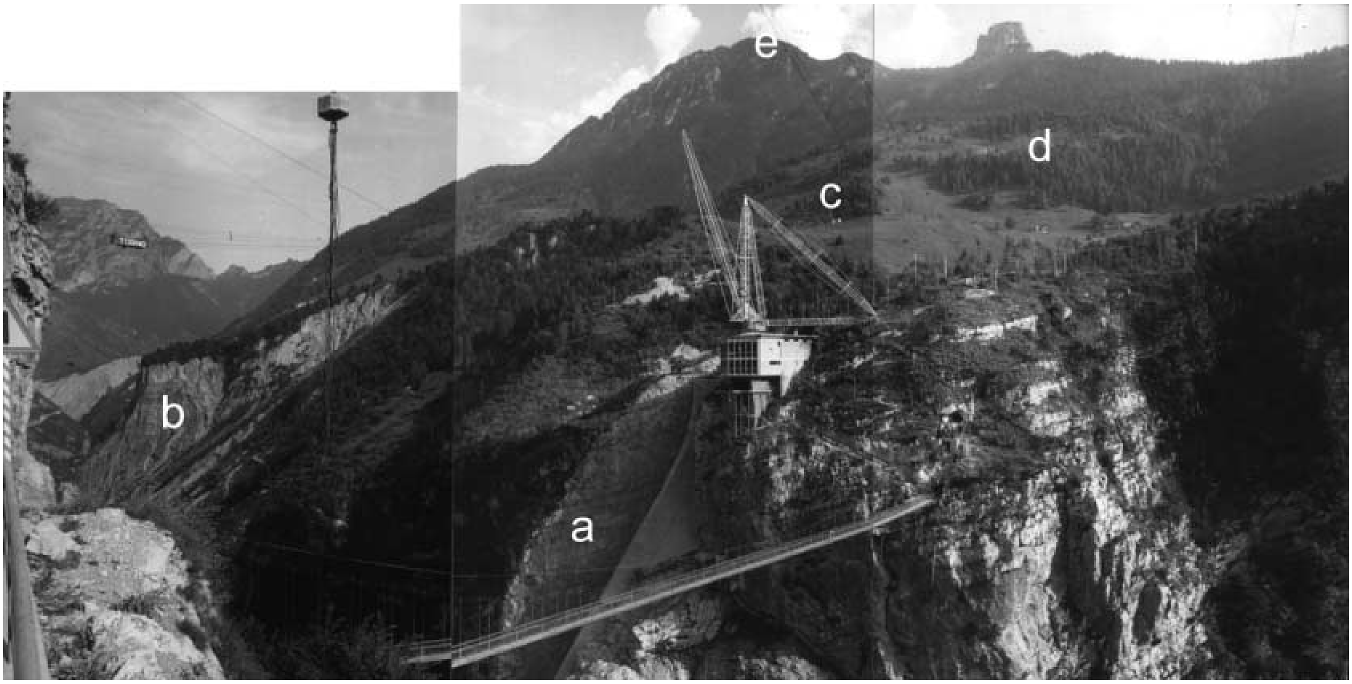

Fig. 4
Northern slope of Monte Toc, seen from new road downstream of dam (Semenza, 25 August 1959). *a* Calcare del Vaiont with excavation of left abutment of dam and pulvino; *b* north-western wall of ancient landslide; *c* Pian della Pozza; *d* highest part of western portion of ancient landslide; *e* north-eastern crest of Monte Toc

considered likely that the infill has a similar origin to the Colle Isolato. Semenza sketched these channels in August 1959 and postulated their evolution (Fig. 8). Although the original sketches contained some inaccuracies, the hypothesis was subsequently confirmed. Since that time, Semenza has updated the diagram, although the only major modification is to highlight the narrowness of the present gorge (Fig. 8). The eastern part of the old landslide can be seen in Fig. 9. Close to the gully is a slight fold which has been truncated by a movement zone where mylonites and tectonic breccias are now present.

A geological map was produced, based on the 1:5000 topographic map prepared for the reservoir scheme (Rossi and Semenza 1965). As noted above, this led to the identification of various ancient landslides, only one of which was recognised as potentially dangerous. The main findings of the study were as follows:

1. The Pian del Toc and the Pian della Pozza areas, together with an area east of the Massalezza River, were

Fig. 5
Right slope of the Vaiont valley, seen from left abutment of dam. *Right* Northern face of Punta del Toc; *left* regular face of Cretaceous limestones folding towards east; *centre* Colle Isolato (outlined with *dashed line*)

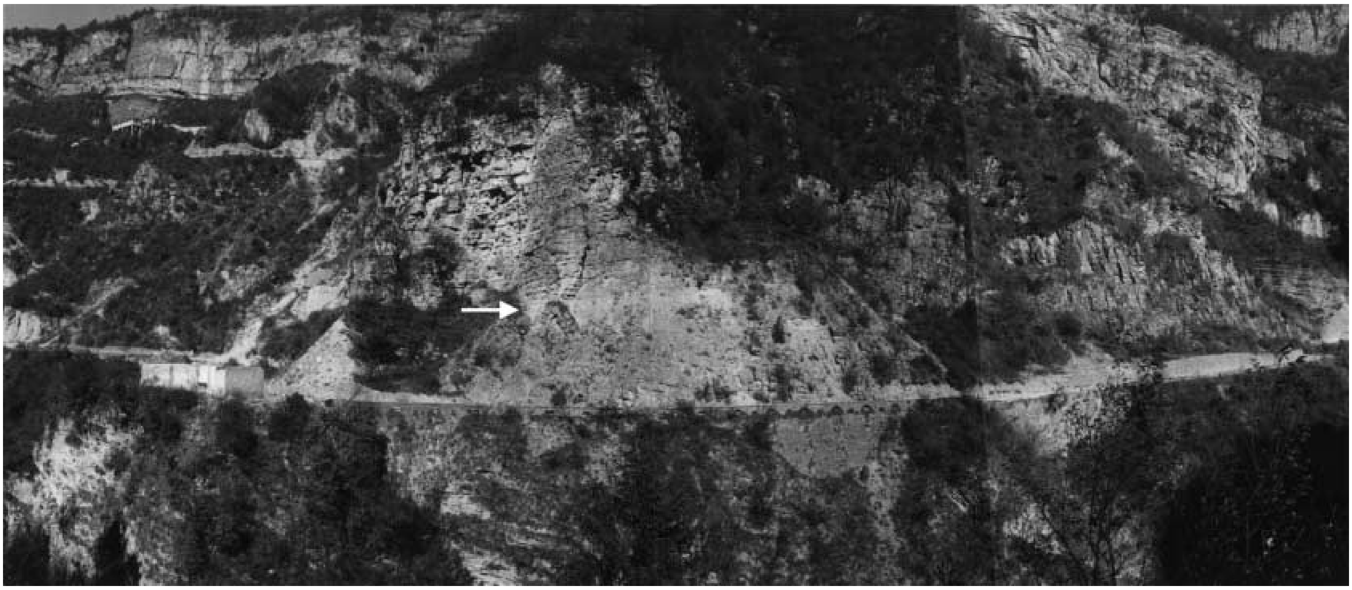

Fig. 6
Colle Isolato seen from left slope of the Vaiont valley. A thin horizontal band of white mylonite (*arrow*) separates in-situ rock from subhorizontal layers of overlying ancient landslide (Semenza, 9 October 1959)

part of an enormous ancient landslide which had moved down the north side of Monte Toc (Fig. 1). This entered the deep Vaiont valley, created at the end of the last glacial period (Würm), such that when the deposits settled, they covered the postglacial gravels and filled much of the valley.

2. The subsequent cutting of the Vaiont gorge had divided the large landslide mass into two unequal parts, the larger being on the left of the gorge. The landslide deposits, on the right of the gorge, were clearly distinguishable from the in-situ rock mass and have been named Colle Isolato by the authors (Figs. 5 and 6).
3. The left side of the valley had a "seat"-shaped structure, which is still clearly visible today on the steep eastern slope of the Piave Valley in front of Longarone (Fig. 10). This structure corresponds with the lower part of the southern side of the Erto syncline, which is well reported in the literature (Riva et al. 1990). It is a box fold and the flat part of its axial area is dipping slightly towards the east (Fig. 2).
4. At the time of the geological mapping it was thought that the ancient landslide had taken place on a more or less cylindrical failure surface, bounded by an outcrop of mylonites at some 600 m asl and an east-west elongated depression in the Pian della Pozza area at an altitude of approximately 850 m asl (Fig. 1).
5. The landslide mass was very fractured and folded in an east-west direction, as is clearly visible in the northwestern wall of Pian del Toc (Fig. 4) and at its eastern edge (Fig. 9).
6. The northern wall of the old landslide mass did not look disturbed; the unfolded strata were dipping slightly towards the east. This was thought to be due to a cementing of the rock, subsequent to the landslide. It is considered that this secondary cementation together with the relative inaccessibility of the rock wall was largely why the ancient landslide had not previously been recognised.

This geological and morphological evidence of the existence of a large ancient landslide raised concern that the mass could move again during the filling of the Vaiont reservoir. As a consequence, a field investigation was carried out including boreholes, seismic surveys and daily measurements of superficial movements (Müller 1964, 1968, 1987; see also Fig. 1).

First mass movements and an extension of the geological survey

In March 1960, when the level of the lake reached an elevation of approximately 590 m asl, the base of the old failure surface near the site of the previously proposed smaller dam (Fig. 1), part of the northern wall, became unstable and fell into the reservoir, probably by toppling and fall. Some 3 months later, when the lake level had reached more than 600 m asl, new small mass movements were observed close to the lake. Three boreholes (Fig. 1) were undertaken in an attempt to locate the failure surface of the old slide, but it was not found at the predicted depth. As a consequence it was suggested that as this surface must be at a greater depth here, it would have emerged upstream of the Pian della Pozza in an area that, in view of its altitude, had not been included in the previous mapping (Semenza 1965).

A new geological survey showed that in the two tributary streams that flowed into the Massalezza Stream from the east and the west at about 920 m asl, the transition from the bedrock (in the south; a in Fig. 11) to mylonites (b in Fig. 11) and a very fractured rock (in the north; c in Fig. 11) was clearly recognisable.

Corresponding with this transition, which continued beyond the two tributaries, a continuous crack about 1 m

Fig. 7
View from left abutment of dam (Semenza, September 1959). *Right* Very narrow epigenetic gorge of the Vaiont at Ponte del Colomber; *left* church, below which morphological indications exist of the Vaiont paleochannel. In 1961, during excavation at mouth of bypass tunnel, horizontal layers of gravel were observed here at the level of road, similar to those at Colle Isolato (cf. Fig. 12). It is likely that here, as at analogous points further upstream (Figs. 5 and 6), a frontal portion of ancient landslide remained which was subsequently demolished by erosion

wide and 2.5 km long appeared at the end of October 1960, accompanied by a short mass movement at a rate of more than 30 mm a day (Fig. 1). The development of the peripheral crack not only confirmed the hypothesis that the ancient landslide was likely to be reactivated as a result of the reservoir filling, but also delimited the area of the unstable zone which corresponded exactly with the old landslide.

November 1960–April 1963 (first large slide to commencement of the last reservoir filling)

On 4 November 1960, when the level of the lake was at about 650 m asl, some 700,000 m^3 of material detached itself from the western part of the mass and slid into the lake, creating waves about 2 m high and up to 20 m high against the dam. This event highlighted the possibility of more important movements and a new seismic survey was carried out (in 1960). The results were very different from those of only 1 year before; now the rock mass was found to be severely fractured. At this time, Müller was asked to study the problem and propose remedial measures. In February 1961 he considered it would not be possible to completely arrest the slide but described a series of measures for the mitigation of its velocity (Müller 1961). The first was the lowering of the reservoir level in a carefully controlled manner. The water level was to be reduced by 5 m and left at this level for a period of 10 days before a further 5 m reduction. This process began in November 1960 and continued until the water level had been reduced to 600 m asl in January 1961. As a consequence, the velocity of the movements suddenly diminished and then stopped.

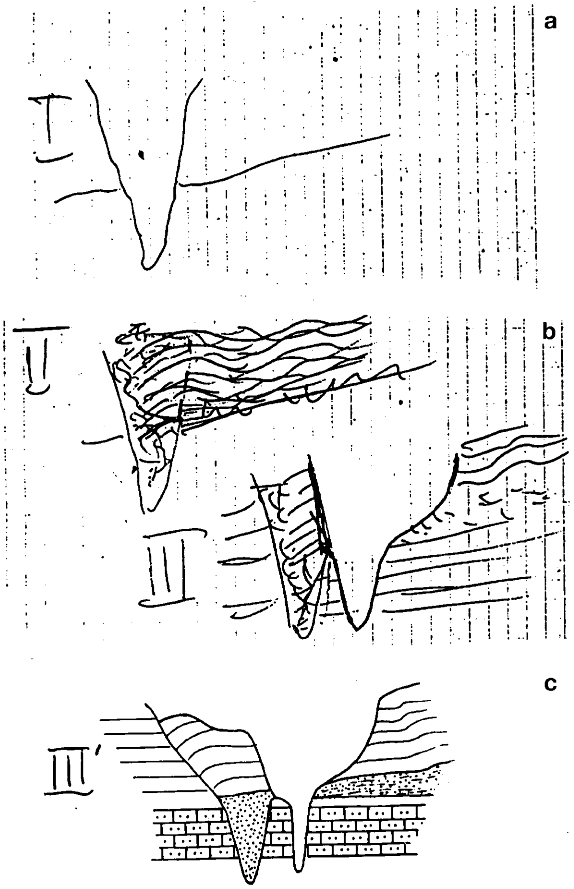

Fig. 8a–c
Sketch by E. Semenza (1959) postulating situation before the ancient landslide (**a**), its movement down valley (**b**) and cutting the new river channel further south (**c**). Despite its inaccuracies, the general scenario was subsequently confirmed

Other proposed measures included: (1) preventing or reducing the infiltration of water into the mass by drain-

Fig. 9
Easternmost part of northern wall of old landslide (cf. Fig. 4, point b) showing slight fold, truncated by a band of mylonites and tectonic breccia and in-situ layers of Cretaceous limestone. The anomalous contact plane corresponds with the eastern flank of the ancient landslide. This is the only area where slide failure surface was clearly seen in 1959

age; (2) removal of many millions of cubic metres of material from the mass; (3) cementing the sliding mass, especially along the failure surface; (4) building a buttress at the foot of the slide. All these measures were considered impractical to carry out. Similarly, the proposal to dig adits or tunnels in order to drain the mass and reduce the water pressure in the underlying Calcare del Vaiont would theoretically have been helpful but was found to be impossible following the trial excavation of two very short adits. In addition to the danger in undertaking the work, it was soon clear that both the excavation and the rock mass were

Fig. 10
Two N-S geological sections from Monte Toc to Monte Salta: ① before 9 October 1963; ② after 9 October 1963. *1a* Quaternary; *b* stratified alluvial gravels; *2* Scaglia Rossa (Upper Cretaceous–Lower Paleocene); *3* Cretaceous-Jurassic Formations (Socchér Formation sensu lato and coeval): *b* Socchér Formation sensu stricto; *c* Ammonitico Rosso and Fonzaso Formation; *4* Calcare del Vaiont (Dogger); *5* Igne Formation (Upper Liassic); *6* Soverzene Formation (Lower and Middle Liassic); *7* Dolomia Principale (Upper Triassic); *8* faults and overthrusts; *9* failure surfaces of landslides; *10* direction of water flow into aquifers. (Modified from Ghirotti 1993)

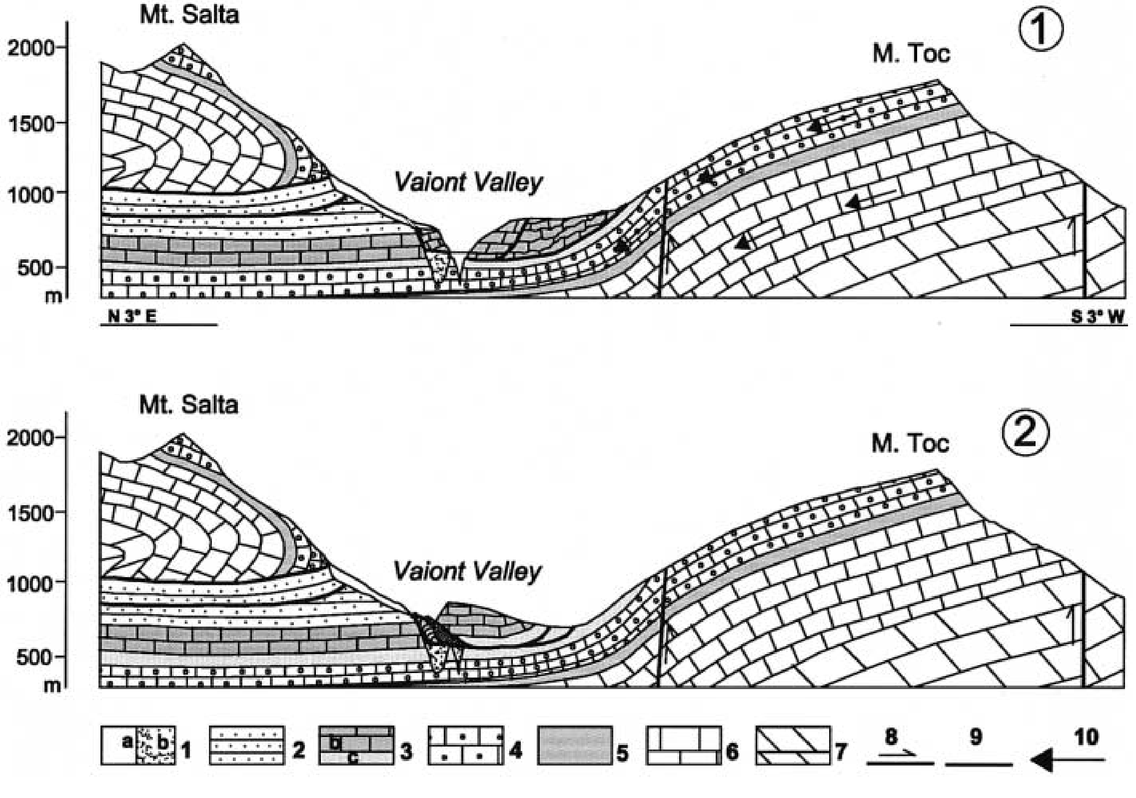

Fig. 11
Western branch of the Massalezza Stream at some 1000 m (1960). *a* Upper Jurassic layers dipping 40° to north; *b* mylonites and tectonic breccia; *c* very fractured Cretaceous limestones. This ancient failure surface was reactivated by the 1960 and 1963 movements

becoming unstable and hence the proposed long drainage tunnel (Fig. 1) was abandoned.

When the level in the lake had been progressively reduced to 600 m asl, a bypass tunnel was constructed on the right-hand side of the valley (Fig. 1) as a further safety precaution in case a future landslide divided the lake into two, such that all the water would not be able to reach the original diversion tunnel. Naturally, it was also useful to ensure that the water level was lower than the village of Erto.

The lowering of the lake level to 600 m asl also made it possible to clearly observe the bottom of the Colle Isolato. The water had removed the vegetation and hence this portion of the old landslide mass, composed of fractured rock resting on stratified alluvial gravels deposited by the old postglacial Vaiont River, could be clearly seen (Fig. 12).

Fig. 12
Base of western slope of Colle Isolato when lake water had dropped to below 600 m asl

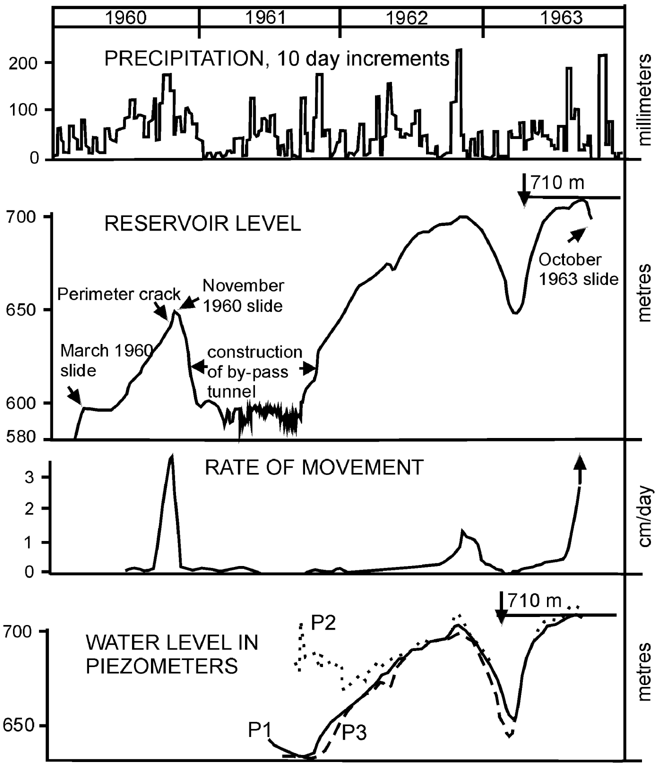

Fig. 13
Comparison of lake water levels, piezometer levels, rate of movement of landslide and precipitation, from 1960 to 1963. (Hendron and Patton 1985, based on Müller 1964)

In the same period, an hydraulic model was constructed. Despite the fact that the physical model differed greatly from actual conditions in both the type of movement and the type of material, the results obtained were considered to be useful for the prediction of possible movement of the whole landslide mass. In the period between July and October 1961, four standpipe piezometers were installed (Fig. 1); three of them were used to record the level of the groundwater table until October 1963.

In October 1961, when the construction of the bypass tunnel had been completed, the level of the lake was gradually raised again; this continued for more than a year until it reached a level of 700 m asl in December 1962. At this point, as the movements had exceeded a velocity of 15 mm/day – less than the velocity reached during the first filling – the lake level was gradually lowered again until it reached a level of 650 m asl in March 1963 and the surface movements stopped (Fig. 13). At this time it was noted that when the movement started during the second filling, the lake level was 100 m higher than when the previous movements had exceeded a velocity of 15 mm/day during the first filling. According to an hypothesis formulated by Müller, the movements were due to the effect of the saturation of the materials which, for the first time, were inundated by water. The belief that this phenomenon was the main cause of the observed instability led to the decision to gradually raise the lake level once again (Müller 1964, 1968).

The last mass movement

The raising of the lake water level began during April 1963 (Fig. 13) and the movements started again only after it reached 700 m asl, although at only a low velocity. This appeared to confirm Müller's hypothesis, hence it was decided to progressively raise the lake level once again. At the end of August, a level of 710 m asl had been reached and the rate of the movements increased. It is not clear why operations to lower the level of the lake were not started immediately but left until September when the velocity of the movements was some 20 mm/day. Despite the commencement of the lowering of the lake level, the velocity of the instability did not diminish but instead rapidly increased until the catastrophic movement on the 9 October 1963 (Fig. 13). Whilst the reason for the delay in lowering the lake level cannot be explained, it is possible that the transfer of the management of the plant from SADE to ENEL, which took place in the spring, resulted in making it slower and more difficult to decide on the necessary intervention measures for the control of the situation.

Possible cause of the 1963 landslide

After the disaster, which resonated around the world and had consequences in various fields, there was an immediate and exceptional interest in the scientific and technical fraternity and numerous researchers formulated hypotheses as to the causes of the landslide and in particular the reasons for the high velocity of the movement. It was the velocity that was the main cause of the height of the wave produced in the lake (Fig. 14) and therefore of the destruction that ensued.

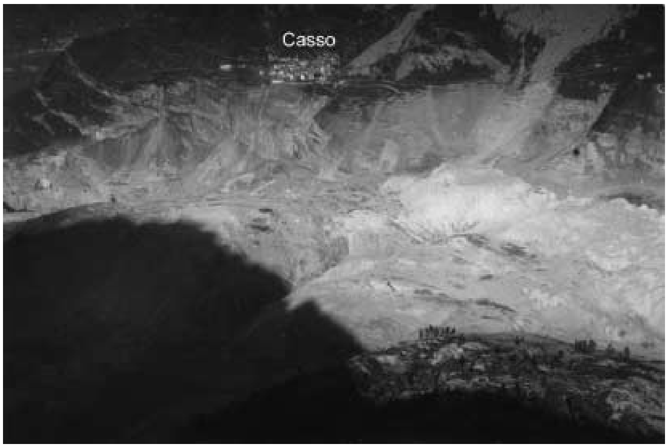

Fig. 14
From the helicopter (Semenza, 28 October 1963). *Above* is right slope of the Vaiont valley with the effect of the wave which reached 930 m asl at Casso and 950 m asl some 100 m to the west

In hindsight it appears that the main cause of the movements suggested by Müller was unfounded, i.e. it was not true that significant movements would only take place when the material at the bottom of the mass was inundated for the first time. Following the slide, experts immediately recognised the fact that an extremely complex set of phenomena were involved.

According to the existing literature the main factor was the geological structure of the northern slope of Monte Toc and in particular the existence of an ancient slide mass (Semenza and Ghirotti 1998). In partial justification of the lack of recognition of the ancient landslide, it should be noted that the folding of the strata was not observable before the final movement of the ancient landslide. Furthermore, on the western wall of Pian del Toc, the rock mass became more fractured from north to south. All these features can be now explained with a mechanism of progressive detachment of the mass from its bedrock, which began from the south and extended, over time, towards the north. It is for this reason that both prior to the 1963 event – and to this day – the northern part of the slope appears unfolded and scarcely disturbed. It is believed that only immediately before the last movement of the ancient landslide was this portion detached from the bedrock. During that final, fast movement, the formation of folds was not possible although some major vertical fractures were created.

The northern portion of the ancient landslide mass, the Colle Isolato, was also undisturbed, apart from several vertical joints. The northern wall itself corresponds to one of these major fractures. The aspect of this wall unfortunately deceived many geologists: only a careful observation and detailed geological survey of the other walls in the area could have allowed observers to make a more correct interpretation.

The existence of an ancient slide mass also implies that the pre-existing failure surface must have been characterised by a very low friction angle to trigger the 1963 slide and to explain the high velocity reached by the mass. Nevertheless, the Vaiont landslide still poses two main questions: how was the slide initially activated and why did it move so fast?

The triggering mechanism of the slide has been the subject of numerous hypotheses depending on which of the main causes is considered to be dominant:

1. The creation of the lake basin and the variations in its level.
2. The presence of clays along the failure surface.
3. The existence of the ancient landslide.
4. The geological structure.
5. The seismicity of the area.
6. The presence of a confined aquifer below the failure surface.

The majority of researchers tried unsuccessfully to establish a reliable correlation between the rainfall and piezometric levels and the level of the reservoir. Hendron and Patton (1985), starting from Semenza's results, made significant progress in resolving some of the problems previously mentioned. The main results of their study were:

1. Confirmation of the existence of the old landslide.
2. Recognition of levels of montmorillonitic clay along the failure surface and also outside of the slide zone; some of these were as much as 100 mm thick (with a residual friction angle ϕ'_r between 8 and 10°) and could constitute a continuous impermeable layer.
3. The probable existence of two aquifers (Fig. 10) in the slope, separated by the above-mentioned clay level; this is supported by the measurements recorded in the three functioning piezometers.

This latter result was particularly important and encouraged Hendron and Patton to re-examine the hydrogeology of the whole area. It is of note that the standpipe piezometers allowed the mixing of water from different strata. Two gave readings that corresponded with the variation of the lake level, while the third, P2, recorded much higher values until the middle of 1962 (Fig. 13). This anomaly was interpreted as the result of the influence of the pressure of the confined aquifer below. Its influence probably ceased after the movement during 1962, which cut the tube and interrupted the connection between the two aquifers such that subsequently the piezometer recorded only the upper water level.

The lower aquifer is contained in the only slightly fractured Calcare del Vaiont where some karstic phenomena were developed in the upper part of Monte Toc, especially along bedding planes. Some of these karstic features are also now visible in both walls of the Vaiont gorge, downstream of the dam. This confined aquifer was fed mainly by the precipitation that fell in the hydrogeological basin of Monte Toc. Consequently, the level of this groundwater table would have been related to the rainfall regime and to the quite lengthy periods involved in refilling the aquifer.

The permeability values and the shape of the two aquifers, as well as their recharge régime and refill times, were very different and consequently their piezometric levels were also different. In particular, following a spring thaw or prolonged rainfall, the water level in the lower aquifer could have gradually reached much higher values than in the upper aquifer and thus caused neutral pressures which would have diminished the shear resistance along the failure surface, leading to instability of the mass.

It is very difficult to explain the velocity of the slide in quantitative terms even knowing the existence of clay levels along the slip surface. Some authors (in Semenza and Melidoro 1992) analysing the high velocity and long trajectory of the Vaiont slide postulated the effects of frictional heat developed in the slip zone during the final accelerated movement. The frictional heat would have resulted in a pronounced decrease in the shear strength of the clay, such that the whole mass could move with a high velocity (estimated to be 20 to 30 m/s). However, this mechanism could only have come into play after a certain time had elapsed since the beginning of the movement.

More recently, Tika and Hutchinson (1999) have proposed a new hypothesis for explaining the high velocity of the landslide related to the speed of failure. These authors analysed two samples from the Vaiont slip surface and studied them in the ring shear at both fast and slow rates of shearing. Both samples showed a loss of strength, the ϕ'_r at the fast stage being up to 60% below residual value during the slow test, i.e. providing a minimum friction angle of only 5° at rates greater than 100 mm/min. In the opinion of these authors, this mechanism of strength loss, alone or in combination with other mechanisms, would explain the fast movement.

Summary

This paper has drawn attention to a series of events prior to the Vaiont disaster. Reference has been made to slips that occurred in another nearby valley and the appreciation that old landslips were present, although their full significance was not understood at the time. Only a careful observation and a detailed geological survey both of the northern slope of Monte Toc (which before 1963 and to this day remains unfolded and scarcely disturbed) and of the Colle Isolato area could have given geologists the possibility of making a more correct interpretation of the complex phenomena. Furthermore, insufficient investigation and field work was carried out prior to the commencement of the dam/reservoir project.

Müller, charged with the responsibility of examining the valley sides, clearly identified many of the problems but did not have the benefit of the detailed investigations that would be undertaken today, including field mapping, aerial photography and site investigation boreholes. With the exception of the proposed drainage tunnel in the southern slope of Monte Toc, the full implications of the confined aquifer were not properly appreciated at that time and the speed of the slide was clearly a totally unexpected phenomenon which has still not been conclusively explained. Various theories have been put forward, including the effect of heat created by frictional resistance in lowering the shear strength of the mylonitic materials. The recent suggestion by Tika and Hutchinson (1999) that the shear strength drops dramatically when a material is sheared at a high rate is an interesting explanation of the high velocity reached in the final stage of the catastrophic movement which took place at Vaiont in October 1963.

The paper provides an illustration of how engineering geology has evolved over the last 50 years and highlights the importance of good communication between the various specialists working on large projects.

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