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Lessons from the Vaiont landslide

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Abstract

The landslide of the northern flank of Monte Toc that slid into the newly-constructed Vaiont reservoir in northern Italy in 1963 continues to attract considerable attention from earth scientists and geotechnical engineers trying to explain its occurrence and behaviour, not least because of the speed of the landslide displacement and its tragic consequences. There are two major areas of difficulty in understanding the landslide mechanics: 1. A scientific consensus that assumes the 1963 failure was a reactivation of an ancient landslide with a 'chair'-shaped failure surface; and 2. The very limited site and movement data that were obtained during the three years leading up to the failure. These broad issues make it very difficult to identify other possible causal factors such as the degree of influence of the newly impounded reservoir on the stability of the mountain slope. The landslide can now be explained, and causal factors assessed, because it is now known that the 'chair' shape does not exist.

This paper identifies and briefly examines the separate elements that constitute the two areas of difficulty in order to assess other possible causal factors in the occurrence of the landslide, given what is now known about the landslide and its geomorphological, geological and geotechnical characteristics. New information regarding the potential role of rainfall and the influence of the failure surface shape on stability analysis results are presented to underpin some of these assessments.

The evidence seems to suggest that the landslide was probably inevitable, though not necessarily in 1963 immediately following the construction of the Vaiont dam and partial filling of the reservoir. Quantitative Risk Analysis at the time, had the techniques been available, would most probably have failed to predict the magnitude of the wave, especially in the light of the physical modelling that predicted a much lesser problem. Without that wave height, the full extent of the danger zone from a landslide into the reservoir would also have been under-predicted. The lessons for engineering are mostly well-known, including the need to investigate subsurface conditions to verify hypotheses based on surface observations alone and to thoroughly explore any questions or issues of concern raised at the design or indeed (early) construction stages of a project. A key lesson of science is also reinforced, i.e. to critically challenge prior 'knowledge' rather than to assume that what is generally regarded as being correct really is correct.

1 INTRODUCTION

On 9 October 1963, the northern slope of Mt. Toc, in the Dolomites of northern Italy, failed. The mass displaced water from the newly filled Vaiont reservoir, killing ~2000 people. This constitutes one of Europe's worst recorded natural disasters. However, many questions remain. The landslide will be forever associated with the Vaiont dam, a 264 m high concrete arch dam built across the Vaiont gorge opposite Longarone (Fig. 1). Many accounts attribute the development of the landslide to the influence of the reservoir on groundwater levels in the slope. If the occurrence of the landslide could be directly attributed to the creation of the reservoir, can it be described as a 'natural' disaster? Furthermore, setting aside the political context and considering only the scientific and technical aspects of the event, could the landslide have been avoided? Was it, in fact, inevitable?

The Vaiont landslide is probably the most analysed landslide ever (though rarely subjected to field studies) and continues to attract the attention of researchers worldwide because it had proved almost impossible to explain. The scientific community had reached a consensus, evident at the 50th Anniversary Conference on Vaiont held in Padua in October 2013, that the 1963 event was a reactivation of an ancient landslide with a 'chair'-shaped failure surface formed in clay layers at residual strength. The near-horizontal 'seat' of the chair provided a large area over which reservoir-induced raised pore water pressures could influence the stability condition. Unusually, there are some pre-failure data from the mountain slope including seismic records, piezometric levels and movement rates, but these data are extremely limited and have, we suggest, previously been largely misinterpreted.

Recently, we published a detailed explanation for the entire history and development of the Vaiont landslide (Dykes & Bromhead, 2018a). This is the first explanation that can account for the development and occurrence of the failure *and* the acceleration and post-failure retrogression of the landslide. This explanation arose from our willingness to challenge long-held assumptions, starting with the 'chair'-shaped failure surface. Indeed, a new 3D geological analysis of the Vaiont landslide (Bistacchi et al., 2013) validated our approach by demonstrating a failure surface geometry that was not 'chair'-shaped but was in fact more like a 'bowl' shape, the lower part of which was significantly inclined towards the reservoir throughout the landslide. A detailed review of all previous evidence, in the light of this critical finding, allowed a re-interpretation (Dykes & Bromhead 2018b), leading to the new analyses and explanations.

What went wrong at Vaiont? Many lessons have already been learnt from this event, but we are now able to offer some further thoughts on how the catastrophe arose and why it has proved so difficult to properly understand. We will first present our explanation of the event before identifying and assessing some of the elements of the story that led to the problems. Lessons will be re-emphasised and any new ones identified.

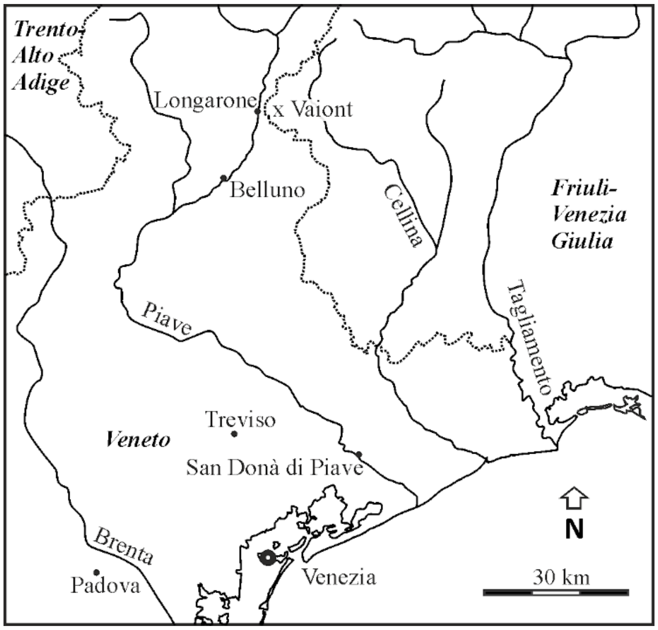

Figure 1. Location of Vaiont in northern Italy, showing major rivers, selected towns/cities and administrative divisions.

2 THE VAIONT LANDSLIDE EXPLAINED

This explanation for the landslide is summarised from Dykes & Bromhead (2018a). The Vaiont gorge was probably cut by glacial meltwater during the late Pleistocene–early Holocene, creating a new natural drainage route from the Erto Basin. The gorge was cut through tectonically deformed and fractured rocks, its depth and steep sides being susceptible to large rock mass failures including at least one that had blocked the lower part of the gorge (Wolter et al., 2016). Tectonic deformations created an eastward-dipping shallow 'bowl' shape for the interbedded clay layers and limestones.

Progressive failure was probably initiated by transient perched groundwater above the eventual failure surface resulting from unusually high rainfall that coincided with the first phase of reservoir filling from February to early November 1960 (but see Section 3.4 of this paper). Transient raised pore water pressures caused brittle cracking and micro-shearing to begin (Kilburn & Petley 2003; Havaej et al. 2015). This led to locally reduced shear strengths and the mobilisation of additional shear strength in adjacent areas, i.e. the ‘progressive failure’ of Bishop (1967).

A large surface crack that defined the eventual outline of the 1963 landslide was discovered in October 1960, and filling of the reservoir was stopped on 4 November 1960 when a 700,000 m^3 landslide occurred from the lower mountain slope. However, no part of this slide was ever influenced by the reservoir (Semenza, 2001, 2010) and the change in the overall stability of Mt. Toc was equivalent to no more than 0.1° of friction angle (dry conditions) (Dykes & Bromhead, 2018a). From October 1960, measurements of the crack and of reference positions throughout the slope were recorded. Velocities were initially highest in the lower west side of the slope nearest the dam, where the future failure surface cropped out and was unsupported at the gorge. These initial velocities reduced anticlockwise round the slope to the lower east side (Müller, 1964), where the eastward dip caused the clay layers that formed most of the failure surface to be deeply buried below the overlying limestone beds.

The reservoir level was lowered for several months to allow a bypass tunnel to be built (a precaution in case a landslide blocked the catchment drainage outflow), then filling of the reservoir resumed. Rainfall was normal but ground movements of 1-2 mm d^{-1} continued, suggesting ongoing propagation of micro-cracks independent of any water. No acceleration was recorded until November 1962, coinciding with further unusually heavy rainfall that is though to have again formed a perched water table on top of the weakening clay layers. As the available shear strength of the clay layers reduced, more of the shear stress was transferred to the stratigraphically higher limestone beds particularly near the eastern margin, probably by means of rock-bridges (Sturzenegger & Stead 2012). Seismicity was observed to migrate eastwards during 1960-63 (Delle Rose 2012).

The final acceleration during the ’third filling’ started during high though not unusual rainfall in August 1963. By 9 October, enough of the clay layers had formed shear surfaces at residual strength that there was insufficient strength in the remaining unfractured rock-bridges to resist further movement of the mass. At 22.39 h, brittle failure of limestone beds, particularly at the eastern margin, occurred. The maximum available (and mobilised) shear strength suddenly fell from peak (limestone) to residual (montmorillonite-rich clay), allowing the observed rapid acceleration and around 400 m of displacement to occur. No other mechanisms (e.g. see Section 3.2) are required to explain the movement. A large retrogressive expansion of the eastern side occurred following subsidence of the flood wave, and a smaller retrogression of the west side head followed later the next day.

3 WHAT WENT WRONG AT VAIONT

The apparently very high scientific and technical complexity of the Vaiont landslide problem make it very difficult define a logical structure for any overarching study such as this. Therefore we use a historical timeline as a framework for reviewing and assessing some of the critical elements. This has the advantage of maintaining context for some of the elements and their consequences. These elements are presented and discussed as causal factors for the initial misunderstanding of the landslide and subsequent difficulties of explaining the event, not as causal factors for the occurrence of the landslide (although these may overlap).

3.1 The geologist

The project engineer for the Vaiont dam was Carlo Semenza. In 1959, a landslide into the recently completed reservoir at Pontesei, 11 km NW from Vaiont, raised his concerns about the possibility of such an event at Vaiont. He brought in several highly experienced geotechnical and geological experts as consultants to assess the site and advise accordingly. Edoardo Semenza, Carlo’s son, had recently graduated as a geologist and was tasked with undertaking a programme of studies devised by Leopold Müller, one of the expert consultants.

The fundamentally different findings of the two sources of advice were (Hendron & Patton, 2010): (i) the experts were confident that there was no landslide (although later in 1960 Müller, at least, accepted that there was) and that any movements of the slope – although not preventable by drainage – would not critically affect the project; whereas (ii) Semenza E had identified a large ancient landslide, seated on weak clay layers, that could be reactivated by rising reservoir levels and potentially fill the gorge.

Having identified the landslide, Semenza E set out to find evidence that could indicate the nature and scale of any such reactivation. His ideas were largely rejected by the experts, leaving his father very uncertain and probably ‘distressed’ (Semenza, 2010, p.89). Hendron & Patton (2010) concluded that: ‘As we now know, Edoardo was correct.’ In fact, our investigations strongly suggest that Semenza E was probably *not* correct in his key interpretations of the evidence (likewise many others: see Section 3.2), although he cannot be faulted for his motives and efforts – and his predictions 'accidentally' turned out to be the most accurate overall. We suggest that Semenza E's persistence in trying to convince people of the risk of a major landslide prior to and indeed following his father's death in 1961, followed by such a landslide in 1963 (though more devastating than ever imagined), led to his work forming the basis of the scientific consensus that still seems to persist (Genevois & Prestininzi, 2013 and papers therein; Dykes & Bromhead, 2018b).

3.2 The geological structure

Broili (1967) identified a likely 'bowl'-shaped failure surface for the landslide. However, 2D slope profiles based on this model corresponded with Semenza E's early cross-sections, i.e. displaying the 'chair' shape, clearly visible in the cliffs above Longarone, that was the defining characteristic of the landslide for 50 years. A critical early assumption was that this visible structure persisted eastwards along the Vaiont gorge, underlying the whole extent of the landslide. In the context of the well-established Erto syncline, this assumption appears reasonable for the time. However, it underpinned some flawed attempts to understand the ground movements and possible consequences prior to 1963 – again, not unreasonable but perhaps a factor that contributed to the scale of the disaster.

Almost all attempts to understand the landslide afterwards were hampered by unquestioning acceptance of the 'chair' shape, which we are now confident does not exist (Dykes & Bromhead, 2018b, after Bistacchi et al., 2013). A 'chair'-shaped ancient landslide cannot have moved as far and as fast as it did without some unusual and complex mechanism(s) having occurred. However, pore water heating (e.g. Romero & Molina, 1974; Nonveiller, 1992; Pinyol & Alonso, 2010) cannot occur in the initial, slow phase of acceleration, and neither can residual strength rate effects (Tika & Hutchinson, 1999). Formation of internal shears (Alonso & Pinyol, 2010) must have already happened if it really was a pre-existing landslide – and would need continual development as the slide moved, against a declining nett thrust.

3.3 Geological evidence

Semenza E undertook a comprehensive and wide-ranging field mapping campaign to find and interpret all possible geological exposures and features within the Vaiont valley up to 850 m elevation initially, then later higher up the northern slope of Mt. Toc. These observations and interpretations are presented and explained in his book (Semenza, 2001, 2010). He identified what he thought was evidence of an ancient landslide on the northern slope of Mt. Toc, i.e. south of the gorge. Ultimately, he interpreted the geological evidence as being consistent with this 'ancient landslide' hypothesis. Furthermore, his early formulation of the hypothesis included a failure surface with a near-horizontal lower part, as seen in the cliffs above Longarone (see Section 3.2).

We reviewed all of Semenza E's evidence and explanations, including the entire photographic record (Masè, 2004), and found that all of the key geological features can be interpreted differently (Dykes & Bromhead, 2018b). Indeed, some of our alternative interpretations are testable (in principle). For example, the northern slope of Mt. Toc looked like a landslide in pre-1963 air photographs but the basin-shaped upper-midslopes reflect the underlying geological structure. Furthermore, the bench-like feature known as the Pian della Pozza is likely to have been sculpted by ice from the Piave Valley glacier overflowing the low ridge that previously separated the Piave Valley from the Erto Basin and being pushed against the upper part of Mt. Toc. Evidence for this overflow has recently been reported (Pasuto, 2017). We consider Semenza E's interpretations to be reasonable for the time though perhaps influenced by his desire to prove the existence of, and risk from, the ancient landslide.

3.4 Ground movement data

Measurements of ground movements were made at up to 24 positions across the northern slope of Mt. Toc from May 1960 (Müller, 1964). Broadly, as at Pontesei previously, it was observed that when movements accelerated and the reservoir level was lowered in response, the movements largely ceased. This happened twice, but at a higher water level the second time. This led to the mistaken belief that the landslide could be controlled by changing the reservoir level (Müller, 1964, p.166).

Careful examination of the data show that the accelerations and decelerations were in fact largely independent of reservoir levels but were strongly correlated with periods of very high rainfall (Hendron & Patton, 1985; Dykes & Bromhead, 2018b). This leads to the conclusion that rainfall-induced pore water pressures on and within the clay layers, associated with transient perched ground-water but acting in combination with raised reservoir levels, must have played a significant role in the development of the failure.

If the rainfall effect had been fully recognized at the time, it would probably not have changed events. Even if a reliable understanding of the shear surface had been gained, Müller's (1964, p.166) assessment – which did consider the possible influence of rainfall with a high reservoir level – would still be valid: 'It appeared hopeless to arrest the slide artificially, because all means that would have had to be applied were beyond human bounds. It was also impossible either to seal the surface of the area, to shift the weight, or to cement the fractured rock by means of injections.'

The construction team on site had clearly shown that they were able to excavate tunnels and so, had the problem been understood, drainage tunnels or adits into the Mt. Toc slope (with or without bored drain arrays) would have been a realistic option – but for one important problem. The amount of water needed to be removed and the consequent head drop would have been rather small. Rather than resolving the failure issue for all time, it would probably only have postponed the eventual failure to some time in the future when there was more extreme precipitation. Had this occurred when the reservoir was full, the magnitude of the wave and its impacts would have been even more catastrophic.

The rainfall recorded during 1960-63 has been described as 'exceptional' in many papers (e.g. Müller, 1964), but inspection of the available data suggests that it was not so unusual (Fig. 2). In particular, 1926 had a 3-month period with 28.5% more rainfall than the wettest 3-month period in 1960 and 1928 had a similar 3-month total to 1960 but this included one substantially wetter month (571 mm, part of 933 mm in two months).

Clearly, the progressive failure could have begun in the late 1920s – or possibly even earlier when higher rainfall was undoubtedly experienced – and failure-triggering rainfall after 1963 must be considered probable (Hendron & Patton, 1985).

3.5 Site investigations

With a crack in the ground surface defining a (plan) area of 2.25 km^2 of mountain slope known to be moving, three boreholes were drilled and, at separate locations, four piezometers were installed during 1961. The three boreholes were all located within about 400 m of the dam in the NW corner of the unstable area, which reflects the focus on the area nearest the dam where the largest movements were being recorded. Their purpose 'was to verify the existence of the palaeoslide and establish its thickness' (Semenza, 2010, p.93).

The piezometers were sited as two pairs in the lower east side (approximately 200 and 400 m from the edge of the gorge) and at the upslope and downslope edges of the Pian della Pozza (middle west side, 300 m apart). In addition to these installations, two short adits (horizontal access shafts) were driven into the mountain close to where the Massalezza Ditch crossed the edge of the landslide area to enable the subsurface structure and stratigraphy to be inspected in-situ, a shallow trench was dug in a depression south of the Pian della Pozza, and seismic surveys intended to establish the condition of the rocks within the slope were conducted in 1959, 1960 and 1961.

Irrespective of the information obtained from the boreholes and the piezometers, the adequacy of the site investigation must be questioned. In part, the limited scope of these investigations probably resulted from Semenza C's experience of the Pontesei landslide that led to the interpretation that only a moderate impact (displacement wave) would arise from slow movement of the failed mass. In turn, the results obtained from the investigations were so limited, unexpected and difficult to interpret that it seems inconceivable now that further drilling (at least) was not undertaken to clarify the subsurface conditions. However, we are not convinced that to do so would have changed the eventual outcome. Core recovery from the boreholes was so poor (Hendron & Patton, 1985) that it seems highly unlikely that a significantly different failure surface would have been interpreted.

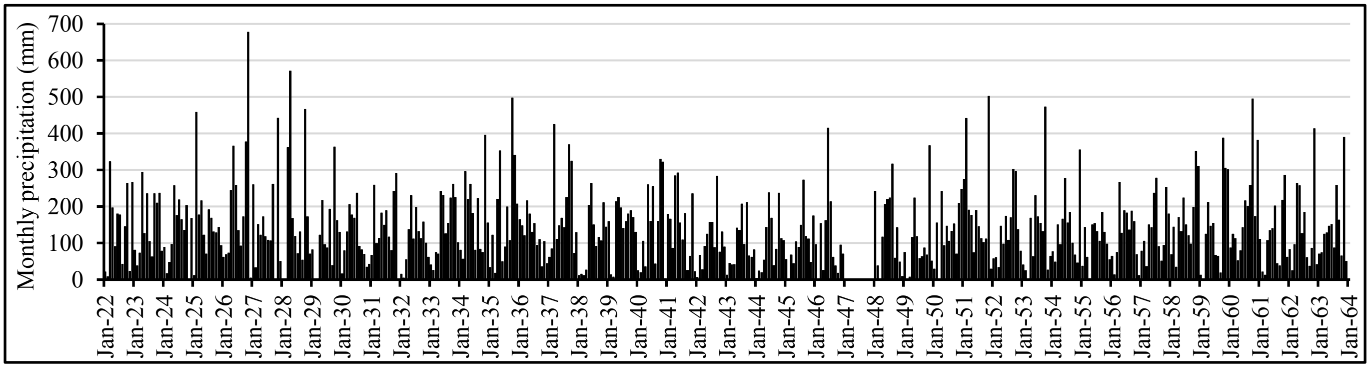

Figure 2. Monthly rainfall at Erto, 1922-63 inclusive (1947 missing).

3.6 Site investigation results

The first seismic study, in 1959, indicated essentially strong, intact rock within the moving mass – significantly at variance with field observations and the results from the subsequent seismic surveys (Caloi, 1966; Belloni & Stefani, 1992). The boreholes did not encounter strong, largely intact rock that was thought to underlie the failure surface of the palaeoslide. Semenza E interpreted this as demonstrating that the failure surface must extend much further back into the slope nearly horizontally, thereby creating the 'chair' shape that underpinned all other interpretations and analyses (see Section 3.2). In fact, we are confident that there was no existing failure surface to be found at that time – but that the boreholes did indeed pass through the layers that would later fail (Dykes & Bromhead, 2018b).

The piezometer data were also misinterpreted, because their depths and the water levels they recorded were compared with the estimated elevation of the sub-horizontal basal part of a 'chair'-shaped failure surface. Water levels in three of the piezometers were higher than this assumed failure surface, implying artesian water pressures acting on the unstable mass. In fact, reference to the new failure surface of Bistacchi et al. (2013) shows that the recorded water levels were below the failure surface prior to filling of the reservoir, indicating underdrainage of the landslide. Piezometer P4 'failed very early' (Müller, 1964), but we think that it was seated in the unsaturated zone between the water table and the failure surface (Dykes and Bromhead, 2018b). Unfortunately the investigations that were based on an incorrect understanding of the landslide also mean that there is no information about the perched groundwater conditions within the landslide mass.

3.7 Unchallenged assumptions

The shape of the failure surface is possibly the most critical element of any understanding of this landslide. The 2D 'chair'-shape in cross-section arose from Semenza E's misinterpretation of poor quality borehole cores (Section 3.6) and became accepted as the true shape of the landslide because his predictions of a very large landslide blocking the gorge were realised (Section 3.1). Bistacchi et al.'s (2013) new 3D model of the failure surface shows it to have a gentle 'bowl'-shape, similar to but less angular than Broili's (1967) geometry, and in cross-section the western part shows the lower west side surface significantly inclined (around 10°) towards the gorge, as suggested by Kiersch (1964).

For 50 years after the event, no-one questioned the validity of the 'chair' shape (at least, not in any formal publication!). Furthermore, as far as we have been able to establish, no-one even considered the effect of the 'seat' of the chair not being horizontal, which would have been easy to do as part of any stability analyses and should therefore have been done as part of the pre-failure studies.

3.8 Stability analyses

Stability analyses and indeed physical experiments such as the concrete 1:200 scale model constructed at Nove in 1961 (Semenza 2001, 2010), underestimated the risk from a posible landslide because they all used the incorrect geological structure. This is not unreasonable for the time, but it seems that no form of sensitivity analysis was ever undertaken to examine the relative influences of key assumptions such as the shape of the failure surface.

We have examined the effects of (a) increasing the gradient of the lower part of the failure surface from the toe, i.e. with reduction of total landslide mass and therefore stresses (Fig. 3a) using Broili's (1967) cross-section, and (b) increasing the gradient with as little change in the total landslide mass as possible (Fig. 3b), based on Rossi & Semenza's (1980) 'Profile 2'. We used increments of 2.5° and a dry unit weight of 23 kN m^{-3}, and following Dykes & Bromhead (2018a) we analysed the landslide dry and then with a horizontal water table at 600 m, 650 m, 700 m and 722.5 m corresponding with external reservoir water levels. Results are presented in Table 1 (some combinations omitted for reasons of space) in terms of the minimum mean angle of internal friction required for stability.

The actual failure surface, according to Bistacchi et al. (2013), has a mean gradient of around 10° but slightly steeper from around 1100 to 1300 m (Fig. 3). Tables 1 and 2 shows that even this modest gradient needs at least 15-20% more shear strength to remain in-situ than for the assumed horizontal lower part – pushing the values higher than residual strengths for clays. It is plausible that similar analyses were done but never considered because they negated the 'ancient slide' hypothesis.

4 OLD AND NEW LESSONS

The site looked like a landslide mass to Semenza E and in many cases – although not always – something that looks like a landslide, and displays movement consistent with landslide behaviour, usually *is* a landslide. The northern slope of Mt. Toc actually *was* a landslide, but one in the course of initial development and with a morphology that was a result of the glacial history of the site. One

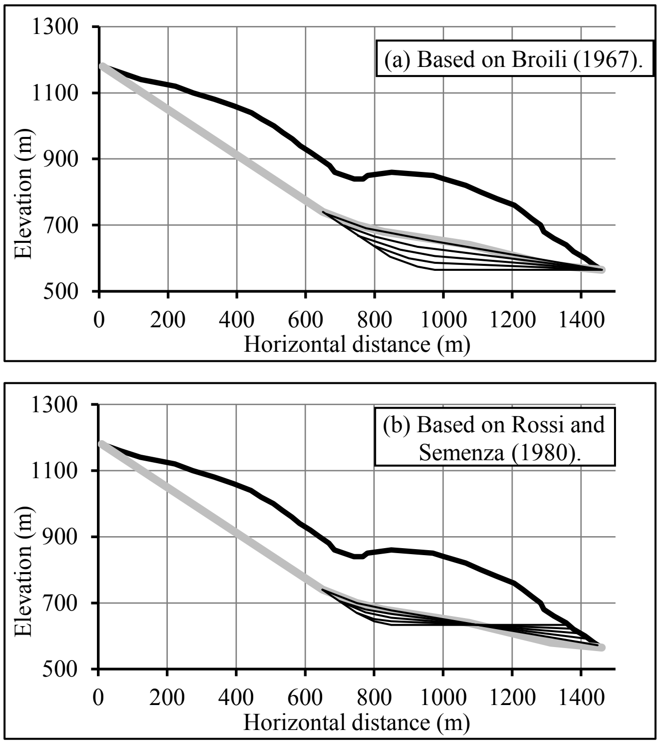

Figure 3. Sensitivity analyses of the stability of the slope in terms of the gradient of the lower part of the failure surface, showing the analysed forms (thin black lines) and Bistacchi et al.'s (2013) 'W' profile failure surface (thick grey line).

Table 1. Minimum friction angles required for stability of failure surfaces based on Broili (1967) shown in Fig. 4(a), with percentage differences from the horizontal case.

Water level (m)	0.0°	5.0°		10.0°	
None	17.2°	18.4°	(+7%)	19.8°	(+15%)
600	17.8°	18.5°	(+4%)	19.8°	(+11%)
650	18.6°	19.2°	(+4%)	20.1°	(+8%)
722.5	19.4°	20.2°	(+4%)	21.0°	(+8%)

Table 2. Minimum friction angles required for stability of failure surfaces based on Rossi and Semenza (1980) (Fig. 4(b)), with percentage differences from the horizontal case.

Water level (m)	0.0°	5.0°		10.0°	
None	16.3°	18.0°	(+11%)	19.7°	(+21%)
600	16.3°	18.0°	(+11%)	19.7°	(+21%)
650	16.6°	18.3°	(+10%)	20.0°	(+21%)
722.5	17.9°	19.4°	(+9%)	20.9°	(+17%)

should therefore be cautious in interpreting geomorphological and geological field mapping, treating it not as definitive but as indicative, until any hypothesis based on appearance has been tested by subsurface exploration.

Nowadays, many reservoir engineers would look on the Vaiont investigations as rudimentary, but of course today's actions are a response to what had happened in the past, including Vaiont. In 1963, methods of analysing slopes even with limit equilibrium were primitive, especially for 'non-circular' slip surfaces; computers were not widely deployed; geotechnical instrumentation was also primitive; the theory of residual strength and progressive failure was poorly articulated (if at all); and one should not forget the familial connection between the two Semenzas, father and son.

Another lesson one should learn is that if, as a design engineer, a serious technical question is raised about a design, then that question needs to be thoroughly explored and not rejected out of hand. Recent examples from various fields of engineering include the failure of Carsington Dam (e.g. Kennard & Bromhead, 2000), the collapse of the Genoa Morandi bridge (Wikipedia, 2019 and references therein), and the ongoing (summer 2019) problems with Boeing's new B737-MAX aircraft. We gain no comfort from the fact that doomsayers are as likely to be wrong as right.

Risk analysis (e.g. Lee & Jones, 2013) would have pointed out the extreme vulnerability of Longarone to any failure at Vaiont. However, the dam did not fail. Moreover, the predicted wave height from a landslide was to be accommodated by the lowered water level and the team making that prediction lost their lives in the wave. One imagines that no amount of predictive risk analysis would have seen a wave cause the 27 fatalities in Casso, over 200 m higher than the reservoir.

5 CONCLUSIONS

The catastrophe at Vaiont was caused by an enormous landslide displacing a large volume of water from the nearly full reservoir. If there had been little or no water in the gorge, the socio-economic impacts would have been minor (apart from to the dam project). Initiation of instability may have pre-dated the dam project, and it is possible – though still uncertain – that the reservoir promoted an earlier occurrence of the final landslide than was otherwise likely. If the reservoir was a causal factor then the reasons for this arise from inadequate site investigations that were based on initial incorrect understanding of the landslide.

The half-century of post-failure investigations also serve to reinforce the lesson for science that one must never assume 'accepted knowledge' (in this case, an ancient landslide with a 'chair'-shaped failure surface) to be correct without critical objective and impartial evaluation. The lessons of Vaiont for engineering practice have largely been learnt, the ultimate lesson being that one should proceed cautiously with any engineering works for which failure is likely to be disastrous.

6 ACKNOWLEDGEMENTS

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