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Review Article

The Vajont Landslide: an overview of 60 years of research

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Abstract: The Vajont Landslide, one of the most catastrophic events in history, has been extensively studied for over 60 years. Navigating the extensive Vajont literature presents challenges due to the volume of information, persistent questions, ongoing controversies, and even unreliable information. This review offers a novel synthesis by identifying the most influential hypotheses through the lens of updated geomorphological reconstructions, evolving interpretations of the sliding surface, and conflicting assumptions. It highlights how certain long-held assumptions may have led to biased conclusions, presents a concise dataset of key geotechnical parameters, and stresses the need for future analyses that integrate rainfall and reservoir effects over time, account for possible progressive strength degradation, and revisit slope stability under more realistic boundary conditions. By clarifying closed questions and spotlighting persistent uncertainties, this paper aims to guide future research and reframe understanding of the Vajont landslide.

Keywords: Vajont Landslide; Slope Stability; Reservoir-Induced Landslides; Rock Slides

1. Introduction

The Vajont Landslide is one of history's most catastrophic and extensively studied landslides. It occurred in Italy on October 9th, 1963, when an enormous mass of about 270-300 million m³ of rock and debris slid into the Vajont Dam's reservoir, generating a wave that overtopped the dam and destroyed the village of Longarone (Figure 1), killing more than 2000 people. Over the last six decades, this disaster has been the subject of hundreds of scientific papers and reports, reflecting not only its significant importance but also its complexity.

Despite the evident scientific effort to thoroughly understand the causes and the mechanisms of this event, several aspects of its kinematics and dynamics are still not completely understood, and many controversial interpretations of the event are still reported in the literature [1–3]. The occurrence of so many controversies and open questions about the landslide is, as previously mentioned, partly due to its complexity. However, it is worth noting that other factors contributed to that, such as the lack of data from before the catastrophe, the limited understanding of engineering geology before the slide, and the limited technology available at that time.

These factors significantly influenced research on the Vajont Landslide, as researchers often had to rely on hypothetical scenarios rather than empirical data. This phenomenon created a cascade effect in the literature in which interpretations of the predisposing aspects and triggering mechanisms of the slide derive from the hypothetical assumptions made at the outset of analyses. Therefore, conclusions regarding the slide's triggering mechanisms, kinematics, and dynamics vary significantly depending on which hypothesis researchers adopted.

Over the years, advancements in rock mechanics and engineering geology, coupled with technological progress, have led to a deeper comprehension of the Vajont Landslide. The continuous evolution of research can exemplify this progression through time: initial research on the geology of the Vajont Valley, for example, is dated from 1928-1937 [4], but the understanding of the geological setting of the area has been constantly expanded with numerous studies [5–10,1,11,12].

After six decades of ongoing research, publication on the slide spans a spectrum, from focused studies on specific aspects of the slide to comprehensive reports that address a wide range of factors related to the event. Table 1 presents a compilation of pertinent studies categorized into different subject areas.

Examining the extensive Vajont literature involves navigating a large volume of information, compounded by the complex nature of the phenomena, persistent questions, and ongoing controversies. This process can be time-consuming and pose challenges in identifying crucial findings related to various aspects of the disaster and in discerning evidence-based conclusions from those rooted in unverified assumptions. This paper aims to facilitate this process by reviewing the literature on the Vajont Landslide. It describes the geological setting of the Vajont Valley by summarizing the main findings of the last 60 years of research. It also presents the different hypotheses on the mechanisms that influenced the instability of the Monte Toc slope, how they have evolved in the last six decades, what questions were closed, and what remains unsolved.

Figure 1. (a) Satellite image showing the Vajont valley with Longarone, Vajont Dam, and Mount Toc. (b) Location of the Vajont Dam in north-eastern Italy. (c) Perspective view of Mount Toc and Vajont Dam (Images obtained from Google Earth).

2. Chronology Of the Events

The history of the Vajont Dam dates back to 1925, when the first geological investigations were carried out at the Vajont Valley. The subsequent years were marked with a sequence of studies conducted to base the dam design that started to be constructed in 1957 by the electricity supply and distribution company of North-Eastern Italy at that time, SADE - *Società Adriatica di Elettricità.* A detailed description of the events that unfolded throughout these years before the slide is provided by Genovois and Tecca [4]. The construction of the dam was completed in September 1959. At that time, the Vajont Dam was the tallest concrete double-arched dam in the world, with its crest at 725.5 m above sea level. In contrast with the magnitude of the project, no specific slope stability analysis was carried out on the Vajont Valley, and the design of the dam was developed based on general geological studies by Boyer [74] and Dal Piaz [74] (cited in [21]).

Due to the occurrence of the Pontesei landslide in the vicinity of the Vajont Valley in March 1959 [53], concerns about the stability of the Vajont slopes were raised, and the geologist Leopold Müller was entrusted with developing a technical program for the basin area. Müller expressed concerns about the stability of the slope located on the left side of the valley and assigned Edoardo Semenza and Franco Giudici to carry out a new and more detailed geological evaluation of the area [21].

In these first detailed studies, the existence of an old failed rock mass on the left side of the Vajont Valley was hypothesized (see section 4.1) [4]**.** It was pointed out that the reservoir filling could cause a large rock slide that was not considered by any geologist or engineer involved in the dam construction. They believed that no significant slides could happen, only superficial ones [17]. Nevertheless, the concerns motivated a very controlled process of changing the water level in the reservoir. The impounding was done in steps and carefully monitored by several measuring devices to identify any potential instability [16].

From 1960 to 1963, three different cycles of filling and drawdown of the reservoir took place. During the first filling of the reservoir in October of 1960, major displacements were recorded, and a series of cracks were formed on the slope. On November 4 of the same year, a significant slide occurred along the toe of the Monte Toc, with approximately 700,000 m³ sliding into the reservoir. The level of the reservoir was lowered immediately, and the displacements were controlled [9].

In the two successive cycles of filling and drawdown of the reservoir, intermittent slow movements continued to be observed in the Monte Toc, mainly in relation to the different levels of the reservoir: increased water levels were essentially associated with higher rates of movements, while low levels of water in the reservoir slowed down or even ceased the displacements [9].

This behavior convinced the dam designers and engineers that it would be possible to control the movements of the slope effectively [21]. On 9 October 1963, during the third reservoir drawdown, the catastrophic Vajont Landslide happened on the southern slope of Monte Toc, drastically changing its form (Figure 2). Figure 3 shows a timeline of the key events leading up to the 1963 Vajont Landslide.

The dam itself resisted the landslide. However, the wave destroyed the town of Longarone and parts of other villages in the valley. Among the more than 2000 lives lost, 45 were engineers, technicians, and other laborers who were part of the workforce of the Vajont Dam project [9]. The collapse of the Vajont landslide occurred in a remarkably short duration of less than 45 seconds, resulting in the formation of a wave that exceeded 100 meters in height above the crest of the dam. The failed rock mass, with a thickness of approximately 250 meters, traveled horizontally for about 300 meters, mainly maintaining its shape except for overall rotation. The extremely high velocity and the en masse movement of the Vajont landslide were not only surprising but remain incompletely understood to this day.

Figure 2. Monte Toc a) before the 1963 failure (photo by Edoardo Semenza, available at http://www.k-flash.it/mostra_vajont/2.html) and b) after the failure, showing the detachment surface (Image obtained from Google Earth)

3. Geological Setting

3.1. Stratigraphy

The Vajont Dam is located in the southeastern part of the Italian Alps, approximately 100km from Venice. A complex fluvial network and a very narrow and deep gorge between Monte Toc to the South and Mont Salta to the North characterize the Vajont Valley. It is well established that the geological formations in the region are composed of very steep cliffs formed by the Jurassic Dogger formation along with underlying Triassic formations. In the slide area, the bedrock consists of a sequence of limestone and marly limestone beds of the Upper Jurassic and Lower and Upper Cretaceous ages [9].

The stratigraphy of Monte Toc has been the subject of several detailed studies [5–7,18,8]. Through the decades, different terminologies have been used to identify the main units involved in the slide: in the past, they were mainly named “Calcare di Soccher” and “Calcare del Vajont” [8]; more recently, the “Calcare di Soccher” formation has been presented as three different formations: Biancone, Rosso Ammonitico, and Fonzaso formations [1,75,3].

Table 1. Different categories of studies on the Vajont Landslide

Subject areas	References
Comprehensive documents, including papers, maps, books, and reports at the Vajont Valley, serve as a basis for understanding the slide.	Carlini and Mazzanti [6]; Kiersch [13]; Müller [14–17]; Selli and Trevisan [7]; Rossi and Semenza [18]; Martins [8]; Hendron and Patton [9]; Riva et al. [19]; Semenza [20]; Genevois and Ghirotti [21]; Genevois and Tecca [4].
Structural Geology	Mantovani and Vita-Finzi [22]; Paronuzzi and Bolla [1,23]; Bistacchi [24]; Massironi [25]; Francese et al. [26]; Bistacchi et al. [27]; Petronio et al. [28]; Pasuto [12]; Dykes and Bromhead [3].
Hydrogeology	Besio [29]; Fabbri et al. [30]; Margiotta [31].
Clay Properties	Hendron and Patton [9]; Tika and Hutchinson [32]; Ferri et al. [33]; Paronuzzi and Bolla [23]; Bolla et al. [34]; Paronuzzi et al. [35].
Slide velocity	Habib [36]; Trollope [37]; Corbyn [38]; Voight and Faust [39]; Nonveiller [40]; Vardoulakis [41]; Kilburn and Petley [42]; Alevizos et al. [43]; Alonso and Pinyol [44]; Pinyol and Alonso [45]; Del Ventisette et al. [46]; Ibañez and Hatzor [47]; Zhang et al [48].
Generated Wave	Bosa and Petti [49]; Crosta et al. [50]; Franci et al. [51,52]; Panizzo et al. [53]; Vacondio et al. [54]; Ward and Day [55]; Xu et al. [56,57]; Xia et al. [58]; Manenti et al. [59].
Stability and Back Analysis	Mencl [60]; Chowdhury [61]; Ghirotti [10]; Alonso and Pinyol [44]; Paronuzzi et al. [62–65]; Hungr and Aaron [66]; Wolter et al. [67]; Boon et al. [68]; Havaej et al. [69]; Zaniboni et al. [70]; Zaniboni and Tinti [71,72]; Dykes and Bromhead [2].

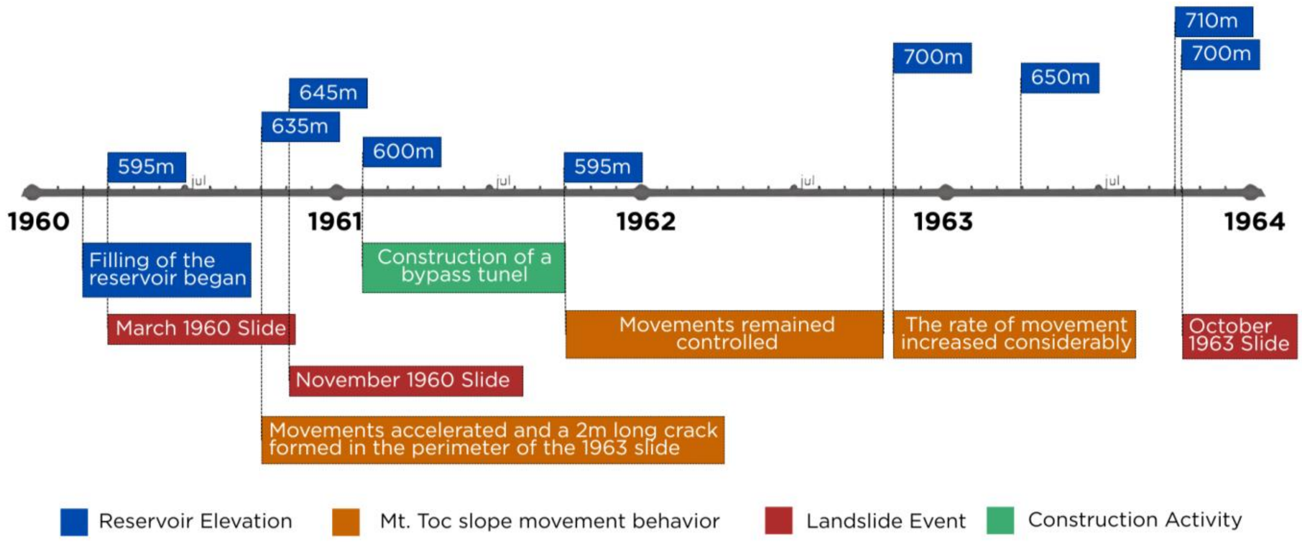

Figure 3. Timeline of key events leading up to the 1963 Vajont Landslide, including reservoir level fluctuations, observed slope movements, and precursor slides.

Similarly, these units have been subdivided in different ways. Currently, both the stratigraphic columns by Carloni and Mazzanti [6] (Figure 4a) and Rossi and Semenza [18] (Figure 4b) continue to hold validity and serve as a reference for geotechnical analyses of the landslide. Table 2 shows the correspondence between the symbols used in these two main interpretations and briefly describes the stratigraphic units.

Records from numerous boreholes conducted after the 1963 slide provided information on the failure surface: the Calcare del Vajont was not involved in the basal failure [8]. Instead, the slide's base predominantly resides within the Fonzaso Formation, particularly within the cherty limestone layers intercalated with clay lenses [9].

One of the most significant aspects of the stratigraphic data on the Vajont Landslide was the observation of the clayey material in the limestone sequence. The Fonzaso Formation, which encompasses the cherty limestone and marly limestone involved in the basal rupture, is characterized by the presence of clay interbeds, which likely played a significant role in the instability of Mont Toc. Hendron and Patton [9] identified, within a distance of 20 to 30 meters of the slide, a succession of five continuous clay interbeds, ranging from 0.5cm to 17.5cm in thickness. The schematic drawing of this outcrop is shown in Figure 5.

3.2. *Material Parameters*

After the identification of the clay interbeds, Hendron and Patton [9] provided a complete report on the results of a five-year investigation on the properties of the clays encountered along the failure surface. These tests include grain-size analyses, Atterberg limits, direct shear strength tests, and clay mineral analyses. The authors concluded that the clay functioned as an essentially continuous impermeable layer with low frictional resistance.

Building upon these conclusions, several subsequent studies have assumed the clay interbeds to be almost continuous [9,76,21] and, therefore, representative of the slip surface. This assumption has led to a significant focus on the shear strength parameters of the clay beds, with particular attention to the friction angle. Over the years, these properties have been measured in laboratories [9,32–35], obtained from back analyses [60,60,38,40,44,68] and also estimated based on the literature. Table 3 provides a summary of friction angle values obtained experimentally for the failure surface clayey material.

Friction angles and cohesion of the failure surface that were either back-calculated or adopted for calculations are shown in Table 4, while Table 5 presents the material parameters in regards to the rock mass, also even back-calculated or estimated for further analysis.

The clay beds show highly variable friction properties, that was recently explained by Bolla et al. [34], who have shown the relationship between the mineralogical composition of the clays and their shear strength characteristics: low values of friction angles are related to samples with a more considerable prevalence of clay minerals, while greater values of friction angles were related to samples with a higher content of granular minerals such as calcite and quartz.

In contrast to the significant focus given to the properties of the slip surface and the clayey material, only a few studies have addressed the mechanical properties of the limestone sequence that are essential for reliable stability calculations. Of particular note are three Ph.D. theses (Superchi [85]; Nigro [86]; Rigo [87]) that provide information on the mechanical parameters of the different stratigraphical units, such as uniaxial compressive strength, Young's modulus, and Poisson's ratio. Additionally, these studies evaluated the rock mass based on classification systems such as the Geological Strength Index (GSI), Rock Quality Designation (RQD), and Rock Mass Rating (RMR). Table 6 presents a summary of the critical parameters reported in these theses.

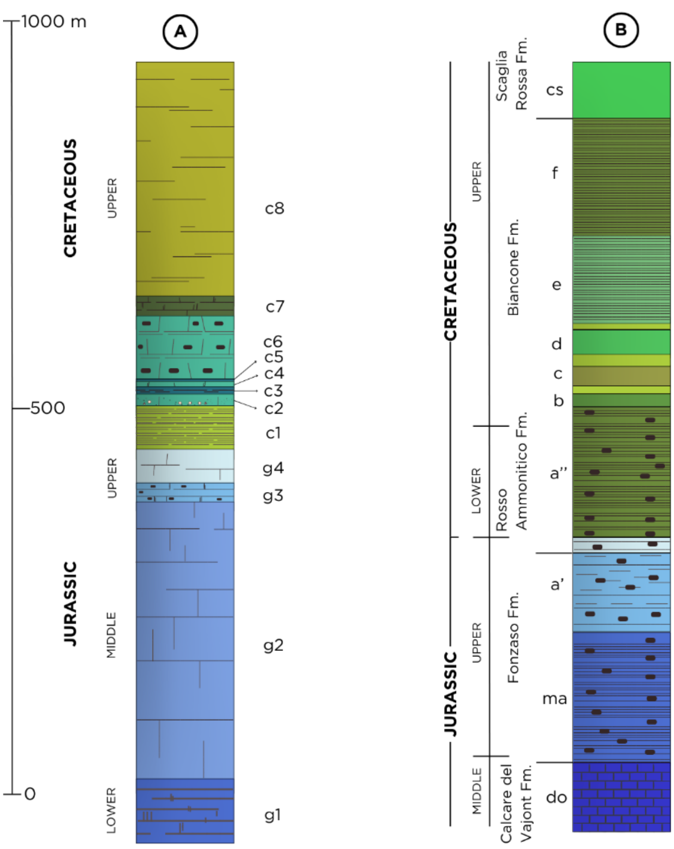

Figure 4. Stratigraphic column according to a) Carloni and Mazzanti [6] (modified from [6]) and b) Rossi and Semenza [18] (modified from [1]).

Table 2. Geological description [1] of the stratigraphic columns by Carloni and Mazzanti [6] and Rossi and Semenza [18].

[6]	[18]		Stratigraphic unit [1]	Geological description [1]
c8	cs		Scaglia Rossa[1]	Layered red-colored marly limestone and marls.
c7	f		Biancone Formation	Marly limestone layers with alternating thin strata of green and red marl.
c6	e		Biancone Formation	Intercalated layers of limestone strata and cherty limestone. It contains nodules of white or light grey chert.
c5, c4 and c3	d		Biancone Formation	Marly limestone with nodules of red chert. A layer of calcareous conglomerate is present.
c2	c		Biancone Formation	A thin and stratified sequence of grey-colored limestone intercalated with marly limestone. It contains nodules of black chert.
c2	b		Biancone Formation	A very compact and thick layer of calcareous conglomerate.
c1	a	a”	Biancone and Rosso Ammonitico	Micritic limestone, marly limestone, and marl.
		a'	Fonzaso Formation	Layered thicker limestone sequences formed by light red or grey nodular limestone. The layers are separated by thin beds of marl.
g4 and g3	ma		Fonzaso Formation	Limestone sequence with abundant nodules of dark brown or black chert. This layer is characterized by thin intercalations of cay material (yellowish-brown or green clays).
g2	do		Calcare del Vajont	Massive oolitic limestone

[1]Only present on the right side of the Vajont Valley, not in the Monte Toc.

Table 3. Experimental Values of Friction Angle of the Clayey Failure Surface of Vajont

Reference	Sample Location	Sample Specification	Friction Angle (°)
Hendron and Patton [9]	Samples were taken from the sliding surface	Remolded clayey soil after removing all rock and coarse sand retained	7.44-9.1 (residual)
		Remolded clayey soil after adding back the coarse sand retained	9.6-16.4 (residual)
		Not specified	5.9-9.6 (residual)
Nonveiller [40]	Samples taken from bedding planes in the Lower Cretaceous Limestone beds and from the upper part of the sliding plane from the Upper Jurassic	Clayey silty sand with angular limestone fragments	26.5 (residual)
		Sandy and clayey gravel, well graded, with silty clay of low plasticity and angular limestone fragments	22.4 (peak)
		Clayey gauge from limestone fissures	15.0 (peak)
		Clay of high plasticity with minute quartz fragments from fissures in Malm	6.8 (residual)
		Sandy clay of high plasticity with angular limestone fragments from Malm	5.6 (residual)
Tika and Hutichinson [32]	Samples were taken from the western lower part of the exposed failure surface	The samples were taken so as to be as nearly representative as possible of the clay, followed by the slip surface	9.7-10.6 (residual)
Ferri et al. [33]	The samples were collected from a 5–15 cm thick clay-rich gouge layer at the hanging wall of the sliding surface.		25.6 (peak) 6.8 (peak) 9.46 (peak)
Bolla et al. [34]	Samples were taken from the failure surface in both eastern and western limestone slabs, as well as from the opposite side of the valley, near Casso	Failure scar, West	8.9-26.7 (residual)
		Failure scar, East	6.8-9.1 (residual)
		Casso	6.7-9.7 (residual)

Table 4. Friction Angle and Cohesion of the Clayey Failure Surface of Vajont either obtained by back analysis or estimated based on the literature.

Reference	Method of choice	Friction angle (°)	Cohesion (MPa)
Mencl [60]	Back calculated	17.5	
Nonvieller [77]	Back calculated	17.6, 20.6	
Chowdhury [61]	Adopted based on literature parameters of limestones around the world	28 (residual)	0
Corbyn [38]	Back calculated	18.43	
Voight and Faust [39]	Adopted based on Ciabatti [78]	13.17	
Hendron and Patton [9]	Adopted based on average values of experimental results	8.0-12.0	0
Nonveiller [40]	Adopted	22.5 (residual)	
Vardoulakis [41]	Back calculated	22.3	
Sitar et al. [79]	Adopted based on Hendron and Patton [9]	12 (residual)	
Veveakis and Vardoulakis [80]	Adopted based on Vardoulakis [41]	22.3	
Alvezios et al. [43]	Adopted based on [41]	22.3 (peak)	
Alonso and Pinyol [44]	Adopted based on Hendron and Patton [9]	12 (residual)	0
Paronuzzi and Bolla [1]	Back calculated	21.7	
Hungr and Aaro [66]	Adopted based on the exposed southern parts of the surface	12	0
Paronuzzi et al. [63]	Back calculated	17.5-27	
Boon et al. [68]	Back calculated	18-26	
Zaniboni and Tinti [71]	Back calculated	9-12, 17.7-18.8	
Havaej et al. [69]	Adopted based on Ghirotti [10,81]	12.0-18.0	
Llano-Serna et al. [82]	Back calculated	6.0-10	
Pronuzzi et al. [65]	Back calculated	21.7	
Crosta et al. [50]	Adopted based on Skempton [83], Hendron and Patton [9] and Tika and Hutchinson [32].	7.5 6	10
Pinyol et al. [84]	Adopted based on Tika and Hutchinson [32] and Ferri et al. [33]	11 (residual)	
Dykes and Bromhead [2]	Adopted (2D), Adopted (3D)	30 (peak), 25	0
Ibañez and Hatzor [47]	Adopted based on Hendron and Patton [9]	12	
Franci et al. [51]	Adopted based on Pinyol et al. [84]	11 (residual)	

Table 5. Rock Mass parameters, either obtained by back-calculations or estimated based on the literature.

Reference	Method of choice	Unit Weight (kN/m³)	Friction angle (°)	Cohesion (MPa)	*UCS* (MPa)	E_{rm} (GPa)	*v*
Voight and Faust [39]	Adopted based on Ciabatti [78]	23.5					
Alevizos et al. [43]	Adopted based on Vardoulakis [41]	24					
Alonso and Pinyol [44]	Back calculated		38	0.768			
			40	0.561			
	Adopted based on Hendron and Patton [9]	23.5	38.5	0.787	50		
Hungr and Aaron [66]	Adopted based on the observation of the exposed southern parts of the surface		34	1.500	50		
Boon et al. [68]	Adopted based on Alonso and Pinyol [44]	23.5	40	0.787	50	7.68	0.25
Havaej et al. [69]	Adopted based on Ghirotti [10,81]		45 (intact rock)	6.0		20	0.25
Paronuzzi et al. [65]	Adopted	24	41	0.4	35		
		25	48	3.5	100		
Crosta et al. [50]	Adopted based on Skempton [83], Hendron and Patton [9] and Tika and Hutchinson [32].	24	17	0.300			0.23
		24	23	0.100		100	0.23
Pinyol et al. [84]	Adopted based on Tika and Hutchinson [32] and Ferri et al. [33]		43(peak) 34(residual)	2.800		5.0	0.33
Ibañez and Hatzor [47]	Adopted based on Hendron and Patton [9]		40				
Franci et al. [51]	Adopted based on Pinyol et al. [84]		34	0.100			
Xu et al. [56]	Adopted based on Nigro [85]		30			30	0.5

Table 6. Parameters of the different units of the Monte Toc [85–87]

Limestone unit	Nigro [86]	Rigo [87]	Superchi [85]			
	[MPa]	GSI	UCS [MPa]	E_{sec50} [GPa]	v	Density [kg/m³]
f	119,5	30-45	164	63,96	0,31	2700
e	96,0	30-45	155	62,09	0,31	2680
d	107,5	30-55	135	55,06	0,34	2670
c	96,0	30-50	136	63,25	0,27	2700
b	112,8	45-55	-	-	-	-
a	108,0	30-45	149	56,27	0,31	2690
ma	156,0	30-40	166	62,71	0,35	2660
do	148,8	55-75	207	69,20	0,35	2640

3.3. Structural Geology

The structural features of the Vajont Valley seem to have had an important influence on the behavior of the landslide, with fold systems defining the shape of the failure surface and faults delimitating its release. The first geological maps to represent part of these features, before and after the landslide of 1963, were developed by Rossi and Semenza [18], and they are available in the report of Hendron and Patton [9]. In addition to representing the important tectonic lines that delimitated the slide mass, these maps show 15 lines representing proposed geological sections.

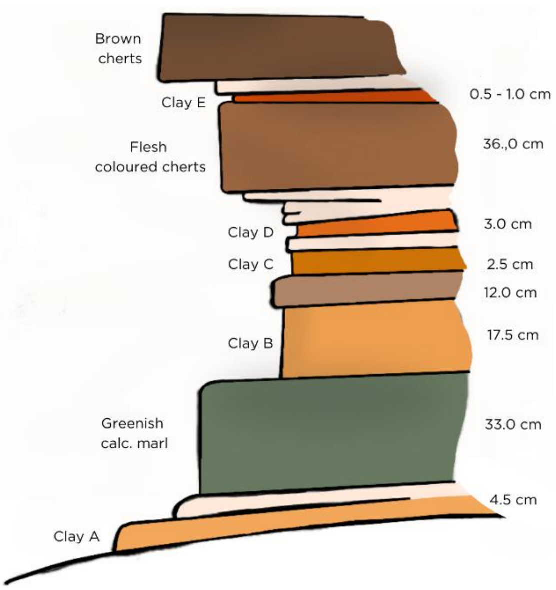

Figure 5. Schematic column of a succession of five continuous clay interbeds located 20 to 30m of the slide area. (modified from [9])

One of these sections became particularly popular due to its orientation closely aligned with the slide direction. This geological section is commonly known as "Geological Section 2 of Rossi and Semenza" and has been widely used as a representative cross-section in numerous analyses of the landslide [10,44,46,50,47]. Figure 6 shows Section 2 before the 1963 landslide, presenting a fault at the top of the slide and dashed lines representing previous slides, including the one of November 1960.

In addition to the cross sections, another significant contribution of the geological maps was the documentation of an outcrop, the "Colle Isolato", first reported by Giudici and Semenza [5]. A mass of rock characterized this outcrop on the right side of the gorge, which was structurally discordant with the in-situ rock on the right side but showed consistency with the left side, reinforcing the well-known hypothesis that the Vajont Landslide was a reactivation of a pre-historic landslide (discussed in section 4.2) [9,3]. Geological Section 2 also shows Colle Isolato and identifies it as an "old slide mass" (Figure 6).

A more detailed representation of the tectonic features of the slide area was later provided by Riva et al. [19], with the characterization of the faults that intersect the Monte Toc: the failure was delimited by a system of sub-vertical faults: the "Croda Bianca-Col Tramontin" system and "Col delle Erghene." These faults, shown in Figure 7, played a crucial role in facilitating the release of the unstable rock mass, determining the boundaries on the sides (east and west releases) and the upper boundary (southern limit) [1].

The slide has occurred in the southern limb of a well-documented E-W trending asymmetrical syncline known as the Erto Syncline, in which the Vajont Valley has been eroded [9,19,40,76]**.** This fold, which dips 30° to 50° towards the north-northeast and north, interferes with another fold system, only identified later by Massironi et al. [25], the Massalezza Syncline, that might have controlled the sliding direction of the two different lobes of the failed rock mass. This fold is delineated by the strata along the sliding surface, which have an average dip of 45° and dip direction N 340° in the eastern side, 35°/N 360° in the central part, and 35°/N 020° in the western side [25].

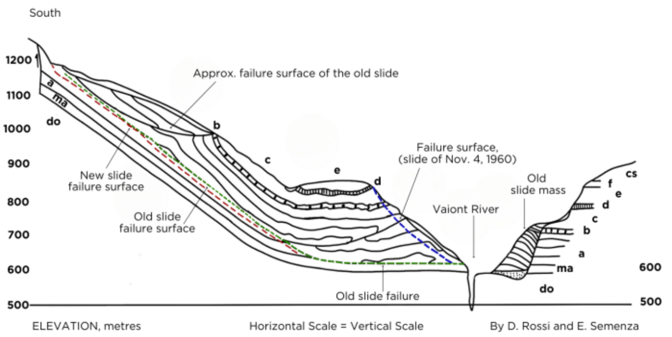

Figure 6. Geological Section 2 of Rossi and Semenza (modified [9]).

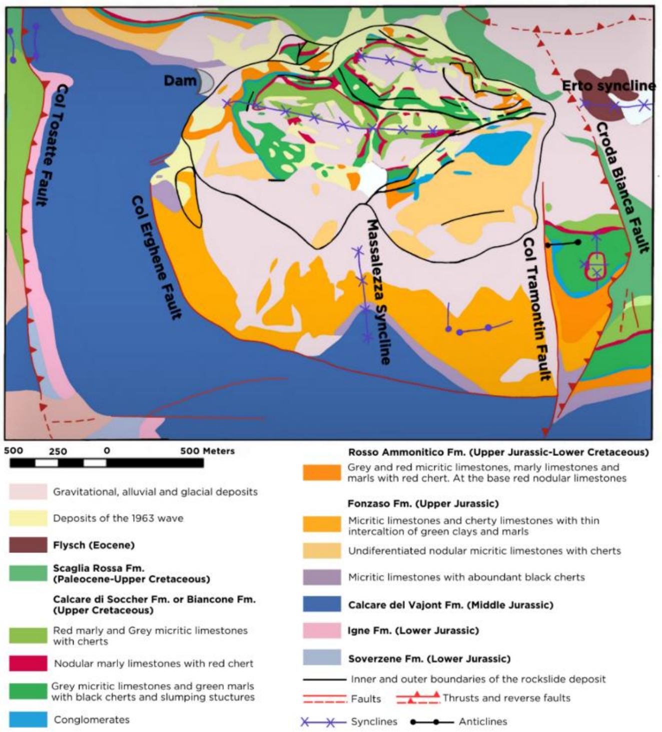

Figure 7. Geological map showing the Synclines and Faults that characterize the sliding area (modified from [25]).

In the last two decades, with remote sensing analysis, the structural setting of the area has been updated, allowing for a more detailed description of joints, fractures, and minor localized structures that might be less significant to the understanding of the slide but that provide essential information regarding the geomorphology of the Vajont Valley. A comprehensive description of these structures is provided by Massironi [25], who also developed an updated geological map of the Vajont area (Figure 7) and Wolter et al. [88]. The continuous mapping of the geological structures of Monte Toc also allowed for the development of the first 3D geological models of the slide area before and after the failure [24,27].

4. Controversial Features and Open Questions on the Landslide

The preceding section on the geological setting has predominantly presented well-documented and generally accepted formulations of the geological setting of the Vajont Valley, providing a foundation for understanding the Vajont Landslide. However, it is important to acknowledge that different interpretations of this setting, and conflicting hypotheses on how it predisposed and triggered the slide, have emerged. In this section, the ongoing questions and the controversial interpretations of the Vajont Landslide features and mechanisms are presented.

4.1. Hydrogeology of the Vajont Valley

In contrast to the numerous publications on the Vajont Landslide, only a few studies have specifically addressed the hydrogeological setting of the Vajont Valley. That might be explained by the lack of availability and reliability of groundwater data from the slide area. Even now, most data comes from groundwater information obtained from piezometers used from 1961 to October 1963 and rainfall records from 1960 to 1964, available in the report by Hendron and Patton [9]. The effects of both rainfall and reservoir water level on the instability of Monte Toc are discussed in section 4.4.

Four piezometers (P1, P2, P3, and P4) were installed on the slope between April and November 1961, but piezometer P4 malfunctioned shortly after its installation, limiting the recording of the measurements to the remaining piezometers (P1, P2, and P3).

Based on the piezometers data, rainfall records, and the identification of karstic features and solution cavities on the slide area, Hendron and Patton [9] present one of the first hydrogeological models of Vajont. They suggested that two aquifers might have been present on the northern slope of Monte Toc. The groundwater level in the upper aquifer was predominantly influenced by the fluctuating water level in the reservoir. In contrast, the lower aquifer, comprised of the "Calcare del Vajont Formation", received water from both the reservoir and precipitation in the Mt. Toc hydrogeological basin. This hydrogeological arrangement indicates the possibility of significant water pressure build-up due to the rainfall infiltration on Mt. Toc.

Later, Besio [29] (as cited in [4]) conducted a comprehensive hydrogeological investigation in Monte Toc, identifying four aquifers and several springs, with only a few showing significant discharge. Fabbri et al. [30] reaffirmed the limited number of springs with significant discharge in Monte Toc and attributed it to karstic groundwater circulation.

Paronuzzi and Bolla [1] proposed a reevaluation of these features on the Vajont rockslide. According to their detailed field investigation, the "Calcare del Vajont" Formation consists predominantly of compact oolitic limestone, exhibiting minimal evidence of karstic processes and landforms. Surface karstic features are scarce and poorly developed, and underground karstic features such as caves and springs are virtually absent in the region.

The existence of the aquifers proposed by Hendron and Patton [9] is also a debated question. Based on a different interpretation of the failure shape surface (discussed in section 4.4), Dykes and Bromhead [3] suggest that there is no evidence of artesian groundwater in the underlying bedrock. The same conclusion was made by Paronuzzi et al. [35] after they analyzed a sequence of borings performed after the 1963 failure and current surface water flow evidence.

4.2. The prehistoric landslide and the shear zone

Most of the contradictory interpretations of the predisposing aspects and triggering mechanisms of the slide derive from the assumptions made at the outset of subsequent analyses, in particular, in considering the slide as either a first-time failure or a reactivation of an old, prehistoric landslide. The choice between these hypotheses has a decisive influence on any other conclusion, as the latter implies the presence of a preexisting failure surface at residual strength.

The existence of a prehistoric landslide was first hypothesized by Edoardo Semenza, in 1959, after he identified the "Colle Isolato" outcrop on the right side of the Vajont gorge. As this outcrop did not match the expected stratigraphy of that side but instead corresponded to the left part of the valley, Semenza assumed that this block of rock was the result of an ancient landslide. Later, during the excavation of a bypass tunnel in 1961, alluvial gravel and a thin layer of cataclasites was discovered at the base of "Colle Isolato", reinforcing Semenza's hypothesis [4,21]**.** According to Paronuzzi and Bolla [1], scientists and engineers responsible for the stability analysis during the dam construction refuted this hypothesis, followed by Leopold Müller, who, after the slide, believed that the existence of a prehistoric slide was not compatible with the proposed progressive rupture mechanism. It was after Kiersch, 1964, as cited in Genovois and Tecca [4] and Hendron and Patton [9] conclusion that the slide was indeed a reactivation of a previous post-glacial slide, that the prehistoric landslide seemed to be mostly accepted as valid [39,9,40,32,55, 62,63,89,50].

To date, the most comprehensive work on the prehistoric landslide, despite those presented by Semenza, comprises an updated geological model proposed by Paronuzzi and Bolla [1]. Based on a detailed reexamination of the literature and an extensive geological and geotechnical survey, the study presents an elaborated reconstruction of the entire structure of the prehistoric failure characterized by an "en masse" downslope movement. They concluded that the ancient slide was a very rapid multistage failure that settled in the Vajont Valley, resulting in the part of Monte Toc's northern slope that later failed in the 1963 rockslide. The reconstruction of the prehistoric landslide led to the identification of a thick shear zone (40-50m) formed by a chaotic assemblage of blocks, limestone angular gravel, and montmorillonitic clays. Figure 8 shows the updated stratigraphic column of the Monte Toc based on the identification of the shear zone.

The presence of the shear zone would account for the effects of the reservoir water level changes on the instability of the slope and for the en-masse motion of the failed rock mass. The angular gravels with abundant voids would have caused a high permeable area at the toe of the slope, facilitating its inundation. As for the en-masse motion, the thick shear zone would have formed a surface where the rigid rock masses slid, preserving their primary structures [1]. While this model presents a detailed reconstruction of the hypothesized ancient slide, it relies heavily on the assumption that the shear zone is a direct consequence of such failure. However, the origin of the shear zone may not be exclusively linked to an earlier landslide event; it is also plausible that it developed through other geological processes, such as tectonic deformation [11].

In addition, if the slope had already been resting on a surface at residual strength, questions arise on how such a large, steep mass remained stable for decades, or even centuries, under these low-strength conditions without signs of progressive movement or collapse earlier. This raises the possibility that the shear zone may not have been entirely at residual conditions prior to failure or that additional mechanisms, such as progressive failure, played a more significant role than previously assumed.

The emergence of the first pre and post-failure geomorphological maps of the Vajont Valley [11] has added a new dimension to the hypothesis of a prehistoric landslide, revealing the possibility of an alternative scenario that, in our view, offers a more plausible explanation of the observed geomorphological and geological evidence. Wolter et al. [11] suggest that the ancient slide was actually a deep-seated, slow, gravitational slope deformation that was initiated during deglaciation and continued to move up to 1963 rather than a catastrophic failure. Figure 9 illustrates the hypothesized sequence of events that would have led to the formation of the Vajont Valley and the 1963 landslide.

Building upon this, Dykes and Bromhead [3] reexamined the published evidence on the prehistoric landslide, and based on new geological investigations, they concluded that the Vajont landslide was a first-time failure. According to their new hypothesis, a smaller slide from the face of the other side of the gorge could have formed "Colle Isolato," and the shape of the pre-failed morphology of the slide could have been formed by glacial processes. In addition, in accordance with [25], Dykes and Brom head [3] suggest that tectonic movements and deformations formed the structural irregularity of the failure surface, explaining the characteristics of the so-called "shear zone."

4.3. The clay layers

The presence of clay in the landslide area was once a debatable question: Müller [15] believed that clay material could not be present within a limestone rock mass. This question was later closed by Hendron and Patton [9], as they collected several clay samples on site. At present, the prevailing consensus among studies is that the failure took place within thin clayey beds present in limestone strata [76]; what remains in question is how these layers could have triggered the slide. It is worth noting that conclusions on the influence of the clays on the failure of Monte Toc are strongly related to the assumption of a first-time failure or a reactivation of a previous slide, as the latter suggests that the clays could have been at, or near, residual strength.

Hendron and Patton [9], assuming the slide to be a second-time failure, argued that the clay beds, at residual strength, were continuous over large areas of the slide surface, and they acted as a weaker, impermeable layer that favored the rise of the groundwater level due to the reservoir infilling. After these conclusions, it was generally accepted that the increased pore pressure caused a decrease in effective stress and facilitated the mobilization of the clay layer, triggering the slide. However, Paronuzzi et al. [35], based on field evidence, point out that the clay layers are somewhat discontinuous, with maximum continuities ranging from 10 m to 15 m in very specific locations. They state that the influence of the clay layers in the failure is only related to a decrease in the average shear strength due to previous displacements on the basal shear zone of the slide. The limited spatial continuity of the clay layers, as reported by Paronuzzi et al. [35], opens important questions about the validity of earlier models that relied on extensive, continuous clay beds to explain pore pressures across the failure surface. If the clay layers are, in fact, discontinuous and confined to relatively small, localized zones, as field evidence suggests, then their role as an impermeable barrier becomes less significant.

Paronuzzi et al. [36] also highlight that the shear strength of the basal rupture surface cannot be related to the clays' low residual strength values in an isolated manner. Instead, the shear strength of other materials involved in the basal rupture has to be accounted for. This consideration is related to the proposed shear zone comprised of clays, among other materials, such as limestone angular gravels and cherty limestones.

Wolter et al. [11], assuming a first-time failure, suggest that the decreased effective stress is related to the softening of the clays already affected by stress-induced damage, weathering, erosion, and the slow downslope movements hypothesized by the authors. In accordance with this hypothesis, Dykes and Bromhead [2] suggest that the clay was initially at peak strength, arguing that residual values would have been insufficient to provide stability until 1963. Following Kilburn and Petley [42], they hypothesize that localized 'brittle' crack initiation and propagation happened within the clay layers, decreasing the available shear strength locally and mobilizing additional shear strength in adjacent parts of the rock mass. This process would have occurred progressively until enough layers of residual strength clays were formed.

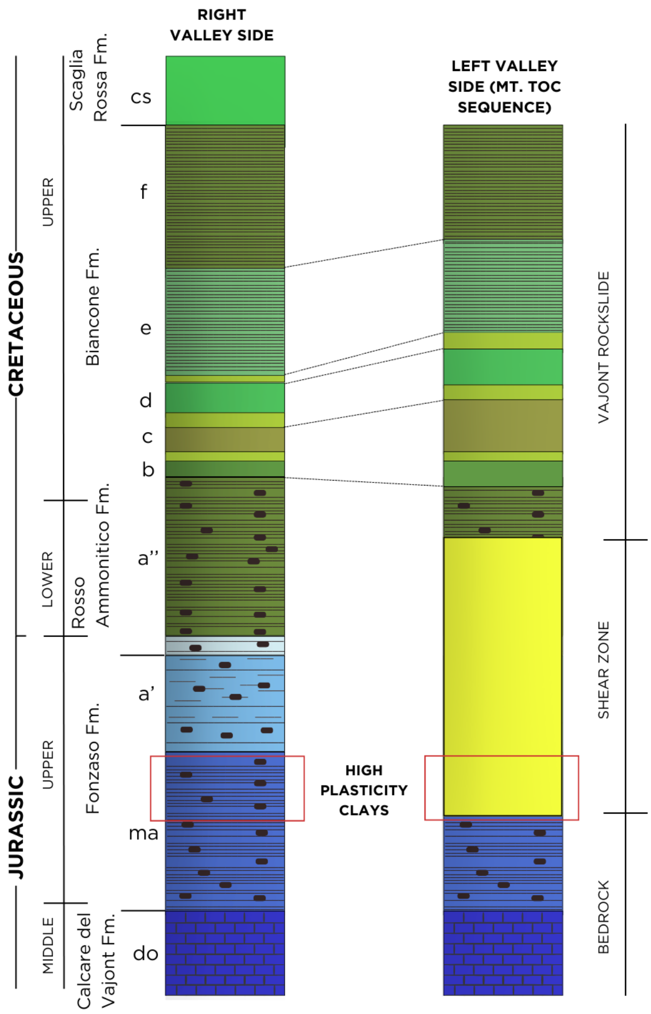

Figure 8. Updated stratigraphic sequence of Monte Toc based on the shear zone hypothesis (modified from Paronuzzi and Bolla [1]).

Kilburn and Petley [42] propose that under high stress conditions, even materials like clays, which typically exhibit ductile behavior, can undergo brittle failure through progressive microcracking. This process involves the initiation and propagation of cracks, leading to a sudden drop in shear resistance and potentially triggering rapid slope collapse. Applying this model to the Vajont clays requires careful consideration. Clays are generally known for their ductile deformation, especially when saturated. The specific conditions of the Vajont clay layers must be thoroughly evaluated to determine if brittle failure mechanisms are indeed applicable.

4.4. The sliding surface shape

As previously discussed, it has been continuously reported that the Vajont Valley has been eroded along the Erto Syncline [9,19,40,76], and it seemed to be a consensus that the southern folded limp of the Erto Syncline comprised an almost horizontal lower part and a highly steeply inclined upper part that gave the sliding surface a "chair-like" shape [5,60,9,90,16,32,42,68,89,50].

Lately, with the identification of the Massalezza Syncline by Massironi [25] and the development of 3D geological models that reconstructed the geometry of the Vajont Valley before the 1963 failure [24], the "chair-like" shape has been questioned, and the failure surface has been represented as having a concave "bowl" shape [24,25,68,28,3,2]. The most recent hypothesis is that compressional movements that formed the Massalezza Syncline deformed the "chair," creating a "bowl" that only happens to look like a chair when observed through the left wall of the Piave Valley above Longarone [3].

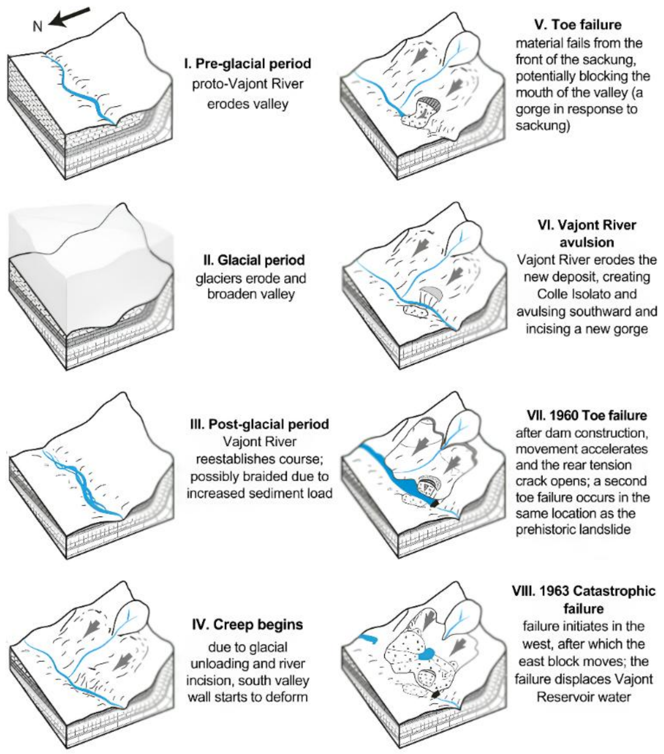

Figure 9. Hypothesized sequence of events that would have led to the formation of the Vajont Valley and the 1963 landslide [11].

Based on the new representation of the slide shape, Dykes and Bromhead [2] opened a new debate on the landslide interpretation. The authors carried out limit equilibrium stability analysis and showed that, when considering the failure surface as having a "chair" shape, back-analysis results will necessarily provide an effective angle of internal friction and cohesion values that can only correspond to the residual strength of clays. Therefore, the assumption of the "chair-like" failure surface seems to have significantly influenced the widespread acceptance of the prehistoric landslide hypothesis, as it leads to stability analyses that support a reactivation scenario under residual strength conditions. With the new "bowl-like" geometry now proposed, further analyses are needed to reassess the slope's stability under this configuration and to evaluate the viability of a first-time failure scenario.

4.5. The reservoir water level and the precipitation

It is broadly accepted that the different cycles of filling and drawdown of the Vajont Dam's reservoir and the heavy rain periods are closely related to the trigger of the 1963 failure. This association is mainly based on the interpretation of 3 years of recordings provided by Hendron and Patton [9], which shows the relationship among the different cycles of reservoir filling and drawdown, the rate of precipitation, and the movements on the northern slope of Monte Toc, together with the readings of the piezometers that were installed in 1961 (Figure 10).

The first cycle of filling and drawdown of the reservoir started in February 1960. By March, when the water reached an elevation about 600 m above sea level, a small detachment happened at the toe of the east end of the 1963 slide. As the filling proceeded, significant movement rates were observed in the slope, causing the formation of multiple cracks in the rock mass. On November 4, a large slide happened when the reservoir level was at about 650 m. Figure 10 shows that the period of accelerated movements was not only marked by the increased water level but also by the maximum 10-day precipitation of the year. In an attempt to control the movements, the reservoir level was lowered to 600m. Coincidently, during the drawdown period, precipitation also decreased considerably, and the movements on the slope ceased [9].

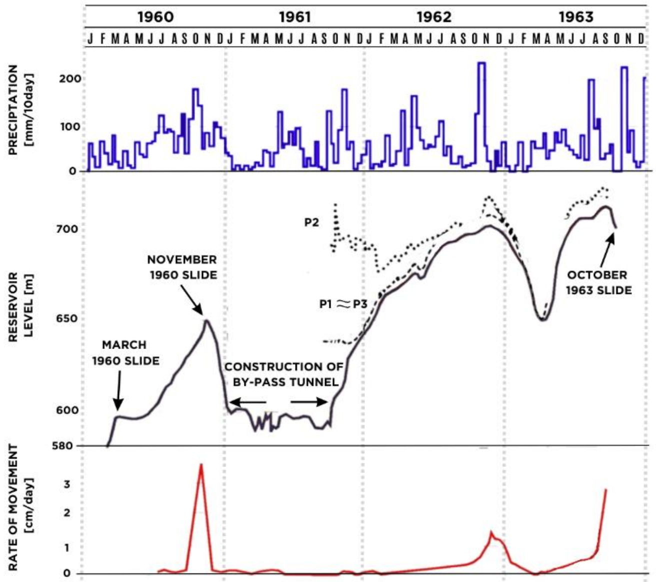

Figure 10. Recordings of precipitation, reservoir level, and slope rate movements from 1960 to 9 October 1963. Piezometer recordings started in 1961 – P1, P2, and P3 (modified from [9]).

From January to October 1961, during the construction of a bypass tunnel, the reservoir was held between 580 and 600 m. In this period, rainfall was moderate, and the slope movements were negligible. The second cycle started in October 1961; by January 1962, the reservoir was at 650m again. The movements seemed to be controlled and remained at low velocities of less than 0.1 cm/day. It was only at the end of November 1962, when the reservoir was about 700 m, that the movements started to increase considerably, reaching about 1.2 cm/day. This period coincided with the maximum precipitation for the four-year period. Again, as the water level was lowered to 650 m, the precipitation also decreased, and the movements stopped [9].

The third filling started in April of 1963. During this cycle, as the reservoir level was increased from 650 m to 710 m, the rate of the movements increased, reaching 4.0 cm/day in September. In the first days of October, the reservoir level started to lower, reaching about 700 m when, on October 9th, the Vajont Landslide happened. The complete description of the events that occurred during the cycles of filling and drawdown of the reservoir is described Hendron and Patton [9].

Although there is a clear link between rising reservoir water levels and displacement rates, a definitive understanding of how the impounded reservoir and rainfall patterns triggered the slide remains elusive. Different interpretations of how these factors contribute to the slide persist, frequently influenced by the preliminary assumptions made in the analysis of the data presented in Figure 10. Three main interpretations stand out in the literature:

1) By plotting the water level in the reservoir versus the recorded precipitation data, Hendron and Patton [9] drew a boundary between the stable and unstable combinations of the slope, creating a "failure envelope," which suggests that the slide was caused by the combination of the effects of both rainfall and the impounded reservoir (Figure. 11). However, the final movements would also have occurred due to raised pore water pressure regardless of their primary origin. The water level in the reservoir could have caused enough uplift pressure to trigger the slide if it had reached its full supply level of 722.5m, even without any rain or snowmelt; at the same time, very high levels of precipitation, in the magnitude range of 130 to 200 percent of the 7 to 45-day precipitation recorded for 1960 to 1964, would have been enough to cause the failure even without the presence of any reservoir.

2) After the identification of a thick shear zone (40-50m) formed by a chaotic assemblage of blocks, limestone angular gravel, and montmorillonitic clays, the first coupled-seepage analysis of the Vajont Landslide was carried on in order to assess the effects of the reservoir operations on the stability of Monte Toc [63,64]. The results suggest that precipitation would only have been a significant factor influencing the

instability if the slope had already been very close to failure. The high permeability of the shear zone favored a rapid seepage inflow in the slope, leading to the formation of a reservoir-induced water table that was the triggering factor of the slide.

3) Considering that the slide was a first-time failure and had a "concave" slide surface, stability analysis shows that the reservoir water levels had little direct influence on the stability of Mt. Toc. The main cause of raised pore water pressure within the slope would have been the exceptionally high rainfall that induced local "brittle" cracks in the clays, progressively forming shear surfaces with friction angles reduced to their residual values [2,3].

4.6. The Slide velocity

Among the unresolved questions surrounding the Vajont Landslide, there persists a need for an explanation regarding the unexpected final velocities of the failed rock. As classical analysis failed to explain what factors led the rock block to travel horizontally, reaching velocities as high as 20 to 30 m/s, a variety of mechanisms have been investigated over the last six decades [37,39,40,42–44,47,84].

Of note, the "vaporization" concept of Habib [36] has been largely discussed in an attempt to explain the unexpected high velocities of the Vajont Landslide. The core idea is that frictional heat on the slip surface can transform pore water into vapor, creating a zero-friction zone of gas that sustains the rock mass and lubricates the motion. Later, Voight and Faust [39] proposed that even without vaporization, frictional heat can cause high pore-water pressures in the shear band, changing the fluid pressure ratio by the liberation of water from hydrous minerals such as clay and by the pressure dependence of water on enthalpy and its thermodynamic properties. Based on the frictional heat-induced pore water pressure, they calculated a maximum velocity of 26 m/s for a planar geometry of the Vajont Slide.

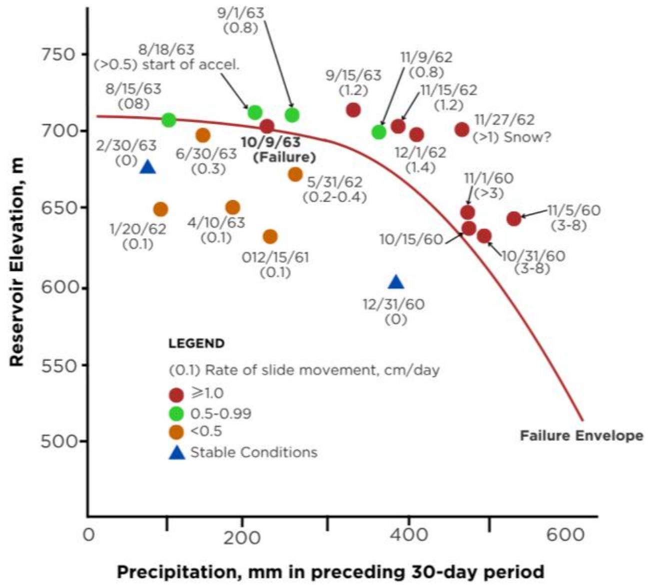

Figure 11. Reservoir water level versus precipitation (averaged over the preceding 30-day period) (modified from [9]).

Vardoulakis [41] summarized the equations that govern the heat-generated pore pressure phenomenon and demonstrated that heat trapped inside the shear band could have led to a pore-pressure explosion due to thermostatic collapse of the clay gouge, causing a total loss of strength and a rapid sliding motion on a frictionless base. Veveakis et al. [91] propose that this mechanism was preceded by a 2-3-year phase of accelerating creep localized in a clay-rich water-saturated layer. Modeling a rigid block moving over a zone of high shear strain rates, they reformulated the governing equations of a water-saturated porous material and estimated that the slide became critical 21 days prior to the final collapse, with shear heating being localized in the clay layer.

Temperature rise within the clay material triggered the onset of thermal pressurization that caused the total loss of strength in the slip zone during the last minutes prior to the final slide, but the process became unstable when the heat diffusion inside the basal shear zone changed from normal diffusion to the unstable uphill diffusion [91]. This transition point, referred to as the "Progressive Localization Threshold," not only marks when stable diffusion becomes unstable but also serves as a stability threshold for thermally driven slides [43].

Thermally-induced excess pore pressure was also included in a two-wedge evolutive model of the Vajont Landslide by Pinyol and Alonso [45]; sensitivity analysis indicates that the thickness of the sliding band, its confined stiffness, and its permeability are important parameters in explaining the slide motion. Permeability was shown to be the main one, with a threshold permeability in the range of 10^{-8} to 10^{-10} m/s that separates fast motions from slow motions.

Apart from the focus given to the explanations related to thermal pressurization, other possible mechanisms have been investigated as the cause of the extremely high velocity of the slide. Kilburn and Petley [42] investigated the processes of self-accelerating rock fracture. Using a "slow-cracking model," they suggested that in high rock slopes, rates of cracking control the slope movements, in which newly-created cracks may interlink, forming a major failure plane of residual shear strength, leading to a rapid failure. This mechanism would have happened due to a possible brittle behavior of the clay layer [92,93], highly influenced by the raised reservoir water level [69].

5. Conclusions

A detailed examination of the literature and a comprehensive review of the topic have highlighted certain aspects of the progressive understanding of the Vajont Landslide. Following the catastrophe and continuing until around 1970, there was a rise in research activity on the topic, resulting in the most comprehensive geological investigations conducted in the area. Subsequently, from 1970 to around 2010, studies predominantly relied on these pioneering geological investigations, leading to a set of contradictory conclusions. After 2010, due to advancements in technology and motivated by the 50th anniversary of the Vajont disaster in 2013, new studies came out. The use of remote sensing analyses allowed for the reconstruction of the geological setting of the Vajont region with greater precision, especially in regard to the identification of geological structures.

It now seems that some of the long-lasting debates about the Vajont slide have been closed: field evidence suggests that clay layers were somewhat discontinuous [35]; the high variability of the clay beds' friction properties is explained by their different mineralogical composition [34]; and the failure surface has a concave "bowl-like shape" instead of a "chair-like" one [24,25,2,3].

To date, debates persist regarding whether the landslide was a result of a first-time failure or a reactivation of an ancient slide. Consequently, if clay layers at the slip surface were at residual or peak shear strength. After an in-depth examination of the pertinent data on this subject, it appears that the use of more recent technologies shed light on these questions, pointing to the hypothesis that the ancient slide was actually a deep-seated, slow, gravitational slope deformation that has evolved throughout years, rather than a catastrophic slide, as suggested by Wolter et al. [11]. The clay beds could possibly have already been affected by stress-induced damage, weathering, erosion, and the slow downslope movements hypothesized by the authors.

Furthermore, the extent to which reservoir water operations and rainfall influenced the movements of Mont Toc continues to be analyzed. It is the authors' understanding that, as suggested early on by Hendron and Patton [9], the slide was triggered by the combination of the effects of both rainfall and the impounded reservoir.

6. Future work

Despite decades of research, the review revealed that key aspects of the Vajont Landslide remain insufficiently explored, especially regarding the mechanical behavior of the rock mass and the hydrogeological conditions of the slope. Much of the quantitative analysis in the literature is rooted in early geological models developed shortly after the disaster, which were based on limited data and field access. As a result, many back-analyses adopted simplified stratigraphic profiles, predefined slip surfaces, and did not account for the heterogeneous rock units or evolving pore pressure conditions. With more recent geological reconstructions identifying previously unmapped structures and refining the understanding of stratigraphy, there is a strong need for updated modeling that integrates these advancements.

It is important to emphasize that although the debate is often focused on whether rainfall or reservoir operations played the dominant role in triggering the Vajont Landslide, this binary perspective may overlook the complexity of the slope's progressive failure. Processes such as seepage, pore pressure changes, and saturation evolve over time, and their interaction can lead to progressive strength degradation of the slope materials. Therefore, focusing exclusively on the final reservoir operations in the days or weeks before the failure may not be sufficient. For a comprehensive understanding of the failure mechanism, stability analyses that account for the combined and time-dependent effects of both rainfall and reservoir level fluctuations should be carried out.

Furthermore, while considerable attention has been paid to the triggering mechanisms, the reasons behind the extremely high velocity of the slide remain elusive. This question is often addressed in isolation from the slope's long-term hydromechanical evolution, and it requires a more integrated analysis that considers progressive failure processes. Addressing these gaps is crucial not only for resolving the remaining uncertainties about Vajont but also for improving predictive models for similar large-scale, reservoir-related landslides.

The Vajont case underscores how critical it is to evaluate slope stability through a multidisciplinary lens, incorporating geological complexity, hydrological processes, and evolving stress conditions. As such, the insights drawn from this case continue to inform best practices in engineering geology and geotechnical analysis. Future research that builds on this foundation, while remaining critical of long-standing assumptions and sensitive to the limitations of historical data, has the potential to improve risk assessments and mitigation strategies for similar high-stakes settings around the world.

Author contributions

Conceptualization, writing — original draft preparation, writing — review and editing, Rafaela Oliveira Lapa and Gyula Bögöly. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All relevant data related to this manuscript are available and can be provided upon reasonable request.

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