A Geotechnical Analysis of the Behavior of the Vaiont Slide

In determining the safety of proposed reservoir slopes, engineers and geologists must have a thorough understanding of the causes of the Vaiont Slide.

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ON OCTOBER 9, 1963, in the Italian Alps near Longarone, more than 270 million m³ of rock slid from the side of Mt. Toc at speeds estimated at 20 to 30 m/sec into the newly completed Vaiont Reservoir. Some 2,043 persons died directly as a result of the wave of water that was displaced from the reservoir. The large volume and high velocity of the Vaiont Slide, combined with the great destruction and loss of life that occurred, make it a precedent landslide, particularly for slides caused by reservoir filling. The Vaiont Slide is frequently cited as illustrating one of the hazards that can be caused by dam construction even when the dam is shown to be safe. In fact, the 1963 Vaiont Slide marked a turning point in the amount of emphasis given in hydro projects to the reservoir slopes as compared to the damsite. Major dam projects were delayed or significantly altered in Mexico, Taiwan and Canada, apparently as a direct result of the Vaiont Slide. Modifications were made in many other projects around the world. In the post-Vaiont period, from 1964 to 1967, new regulations concerning reservoirs were introduced in France, Germany, Italy, Japan and the United States, and new recommendations were published by UNESCO.[1]

Engineers and geologists are now generally obliged to examine the slopes of proposed reservoirs. Where unstable slopes are identified, their impact on the project must be described. When the identified slides are large and the effects on the project could be significant, there is an obligation to explain why such slopes are different from and safer than the Vaiont slopes. Such technical evaluations and comparisons require detailed knowledge of the Vaiont Slide, its geology and the geotechnical evaluations made prior to and following the slide. If the engineers cannot give a reasonably complete and consistent explanation of the Vaiont Slide, in terms of currently available methods of stability analyses, then it is difficult to see how they can feel confident about their evaluation of other reservoir slopes. The disturbing aspect of previous reviews of the Vaiont Slide is that there are gross inconsistencies when the field data, slide behavior and the results of analyses are compared.

The technical literature on Vaiont is abundant, perhaps as a result of the inconsistencies noted. It is likely that more information has been published, and more analyses have been made of the Vaiont data, than for any other slide in the world. However, in spite of this attention, most fundamental questions regarding the failure mechanism and characteristics of the slide have not been satisfactorily explained. For example, an analysis has not been presented that takes into account:

- the obvious three-dimensional shape of the slide surface,
- the actual laboratory shear strengths from representative samples of the material on the slide surface, and
- reasonable piezometric levels related to both rainfall records and reservoir levels.

It is important that a satisfactory set of analyses should take into account these factors and permit the calculation of credible safety factors at various key moments in the history of slide movements in the Vaiont Valley.

In addition, there are many contradictory statements and conclusions in the literature concerning the Vaiont Slide. For example, many authors have claimed, or accepted the claims of others, that there were no significant clays or clayey units present along the failure surface.[2,3,4,5,6] Müller made a point of dismissing the influence of clay interbeds, stating, "Clay and loam, however, were not present in the stratification joints of the Mount Toc, contrary to some publications."[3] Yet, others have tested or described clay beds in the stratigraphic section or attributed them to the failure surface.[7,8,9,10,11,12,13,14,15,16,17]

Another essential factor in an evaluation of the Vaiont Slide is the determination of whether the 1963 slide was a new slide or whether it resulted from the reactivation of a prehistoric slide. Giudici and Semenza mapped and projected the outcrop of a failure surface along the left (south) side of the Vaiont Gorge before the slide occurred.[7] At the same time, they also mapped a unit of an old slide mass on the right (north) side of the gorge near the dam. The existence or absence of an old slide was discussed by Müller and dismissed.[4] He wrote that if one were present, it would not be large enough to be coincident with the actual slide's slip surface.

Objectives of This Study

Finding answers to these questions concerning the clays and the possible existence of an old slide were included as major objectives of this study. These and other questions could be answered by:

- first-hand field observations of the geology,
- an examination of pre-slide and post-slide airphotos,
- laboratory testing of samples of failure plane materials, and
- an examination and translation of geologic and other documents related to pre-slide and post-slide conditions.

Another objective of this study was to perform stability analyses of the Vaiont Slide that were relatively consistent with all the observed facts. Many back-calculations of shear strength parameters for the conditions at failure have been conducted by various investigators on the basis of two-dimensional cross sections. Most of the back-calculated angles of shearing resistance in terms of "effective" stresses (assuming zero cohesion) ranged between 17° and 22°, and several were higher. Even the highest values have been considered by some to be too low.[6]

In those instances where direct shear tests were made on clay materials found in the slide debris, the residual shear strength values of the clays were between 5° and 22°.[15,17] If the clays are moderately continuous, such low values for shear strength as measured in the tests could not readily be reconciled with the results obtained from the analysis of two-dimensional cross sections used by all previous investigators. Calculations would then show that the slide would be unstable, even without a reservoir, if a shear strength much less than 17° were used. For example, Kenney and Nonveiller back-calculated angles of shearing resistance of 19° to 22° and 17° to 39°, respectively, which were considerable higher than the angles of shearing resistance they had measured on samples from Vaiont.[14,16]

The problem was compounded when the water pressures used in many of the analyses appeared to be too low. This underestimation of water pressures meant that even higher strengths were required if the analyses were to achieve the calculated factors of safety. The enigma was confirmed when the authors, prior to this study, briefly visited Vaiont on two occasions (Patton in 1975 and both authors in 1976). On both occasions, extensive exposures of clay were found along the failure surface. Not only was clay present, but it was a clay with a low angle of shearing resistance.

Additional investigations appeared to be required before analyses could be made that were consistent with all known observations and laboratory data. Such investigations required:

- Direct examination of many locations on the sliding surface to confirm the actual presence or absence of clay
- Obtaining clay samples for shear strength tests, Atterberg limits and clay mineral analyses
- Obtaining a more complete history of the chronology of slide-related events
- Making geological field observations that would determine whether the 1963 event was a first-time slide or the reactivation of an old slide
- Making field observations that would help confirm the actual directions of slide movements
- Defining by field observation any geometrical aspects of the structural geology that would necessitate changes in, or invalidate, the two-dimensional analyses
- Collecting data and making field observations to improve the assessment of water-pressure conditions within the slide

Activities Undertaken

In order to investigate the items listed above, the authors made a one-month field visit to Vaiont during the summer of 1979. During this visit, the slide surface was traversed at numerous locations and extensive samples and measurements were taken. Dr. Edoardo Semenza provided assistance to the authors on pre-slide and post-slide geology. In addition, detailed information on rainfall records, survey displacements, post-slide boring logs and various technical reports were provided by ENEL (Ente Nazionale per l'Energía Elettrica, Compartimento di Venezia).

After the field visit, laboratory tests were conducted on clay samples recovered from the failure plane. Stability analyses were made that utilized detailed knowledge of the three-dimensional structural control of the slide movements and the shear strength data obtained from the clay samples. An analysis of the kinematics of the slide was also conducted and possible mechanisms were investigated that would have resulted in the loss of strength necessary for the slide to have moved to the position observed on the opposite valley wall. These kinematic studies are presented in a previous paper by the authors prepared with the assistance of Anderson.[18,50]

Description of the Slide

The Vaiont Slide is located east of Longarone, which is on the Piave River some 100 km north of Venice (see Figure 1). The slide developed along the north slopes of Mt. Toc where the Vaiont River had cut a canyon more than 300 m deep just above its junction with the Piave River.

The slide moved a 250 m-thick mass of rock (approximately 270 million m^3) some 300 to 400 m horizontally with an estimated velocity of 20 to 30 m/sec before running up and stopping against the opposite side of the Vaiont Valley wall. The new slide displaced an old slide mass that had been isolated on the north side of the valley. The old slide materials moved some 100 to 150 m above their original position before slumping backwards 30 to 40 m to the south.[12] The uppermost por-

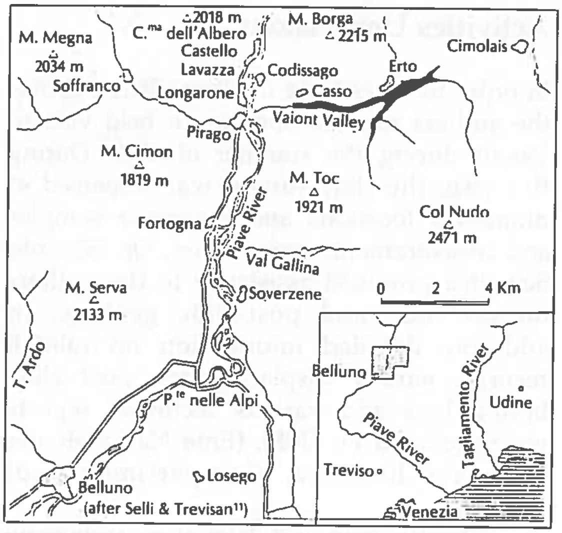


FIGURE 1. Location of the Vaiont Valley, Italy, approximately 100 km north of Venice, and northwest of Udine.

tion of the eastern half of the slide apparently moved over the main slide mass in a separate and slightly later movement. In a matter of a few tens of seconds, the slide filled the lower half of the Vaiont Reservoir (which had been drawn down to elevation 700 m from a level of 710 m just prior to the slide).

The wave resulting from the displaced water propagated both upstream and downstream. The wave eroded trees and soil on the north side of the Vaiont Valley up to a maximum elevation of 935 m (235 m above the reservoir level). The wave swept across the dam, reaching over 100 m above its crest (435 m above the downstream base of the dam), and moved down the Vaiont Gorge. The wave had a height of some 70 m at the confluence with the Piave River and it destroyed most of the town of Longarone and parts of other towns in the Piave Valley (see Figure 2). Some 2,043 persons died and many others were injured, almost all from the effects of the wave. Most of the loss of life occurred in Longarone, but the loss was also severe in nearby villages, especially Pirago. Forty-five men, who were part of a work force of engineers, technicians and laborers living in barracks on the dam crest, were killed. Over $16 million was reported paid for civil suits for personal injury and loss of life. Tens of millions of dollars of property damage resulted. The $100 million dam and reservoir were abandoned. The destruction associated with the Vaiont Slide and wave have been described by many authors.[10,19,20,21,22,23,24] The Vaiont Slide was a major tragedy of the 1960s.

If both volume and velocity of slide movement are considered, the Vaiont Slide has been exceeded in historic times in only a few cases, such as the 1974 Mantaro Slide in Peru and the 1911 Pamir Slide in the USSR. However, other slides of greater volume than the Vaiont Slide have been recognized, and

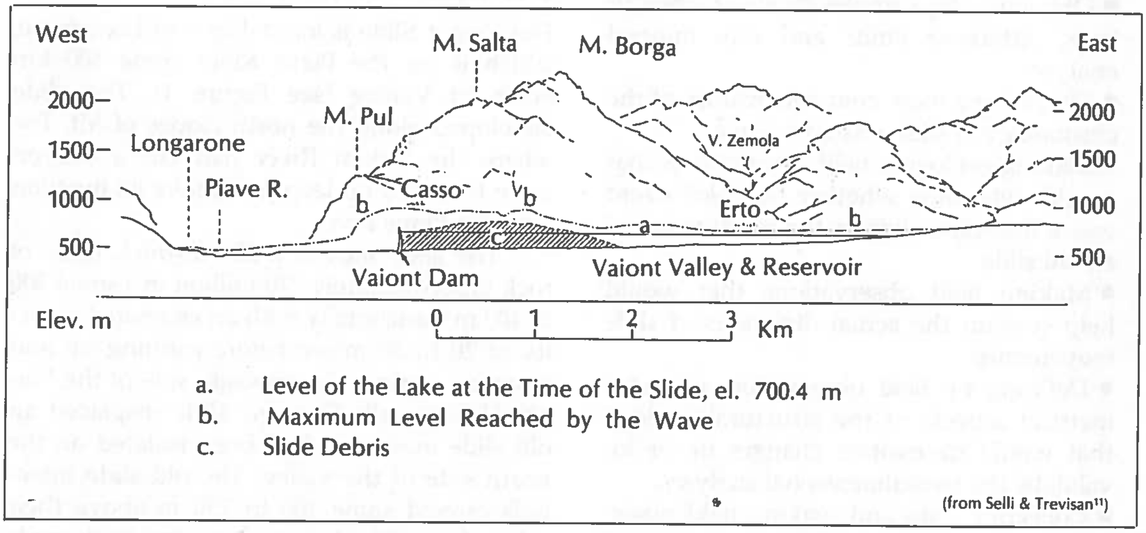


FIGURE 2. Longitudinal profile along the Vaiont Valley, looking north.

FIGURE 3. Photograph of the Vaiont Slide area, July 1979.

many higher-velocity slides of smaller volume are known.

A photograph of the Vaiont Slide as it appeared in July 1979 is given in Figure 3. This photograph shows the M-shaped outline of the slide as seen when facing Mt. Toc from Casso, north of the slide. A plan view of the immediate area of the slide prior to October 9, 1963, is given in Figure 4. The plan view shows the slide in relation to the Vaiont Dam and the maximum proposed reservoir level (el. 722.5 m). Prior to the slide, the principal feature in this area was the central north-south trending dry valley of the Massalezza, a tributary to the Vaiont River. This valley has been referred to as the Massalezza Ditch. On the left side of the Vaiont River, and just downstream from the junction with the Massalezza Ditch, was a prominent bluff at el. 777 m called the Punta del Toc. A prominent bench at about el. 840 to 850 m was present part-way up the western side of the slide. This plain was called the Pian della Pozza, or Pozza, and contained several enclosed depressions similar to those found in karstic or glaciated regions, or in areas with old landslide debris. Along the toe of the slide, the Vaiont River varied in elevation from 500 m near the dam to 560 m at the upstream side of the slide.

A few people lived on what became the slide area, but the closest town was Casso, perched above a cliff opposite the slide at about el. 940 to 980 m (see Figures 2 and 4). The lowest two buildings in Casso were damaged by water or by the air blast generated by the wave. The remainder of Casso escaped damage. The larger town of Erto, located on the north side of the Vaiont Valley some 3.5 km upstream from the dam and 1.5 km from the slide mass, escaped heavy damage from the wave since the town is over 760 m elevation. The wave at Erto reached about 740 m in elevation (40 m above the reservoir).

Previous Geologic Studies

The starting point for detailed geologic studies of the Vaiont Slide is the 1960 report, prepared in 1959-1960, by Giudici and Semenza.[7] Following the 1963 slide, many other geologic studies were made for one or the other of the investigative commissions and for the ENEL, the hydroelectric authority that had taken over control of the project prior to the slide. Of these post-slide studies, Semenza's is particularly helpful since it provides a history of the geological and geophysical studies from 1959 to 1964.[12]

Following the slide, other important geological studies were published.[2,4,9,11,20,25,26,27,28] Of these studies, only Broili's and Müller's reports are in English.[2,4,20] Kiersch wrote a brief summary in English providing an early account of the slide, its causes and associated flooding as well as the general geologic features noted following the slide.[10] Because of the timely nature of Kiersch's article, it received widespread attention in North America. The collected works of Selli and Trevisan, Carloni and Mazzanti, and Ciabatti constitute essential documents on the geology, slide observations, seismic data and dynamic eva-

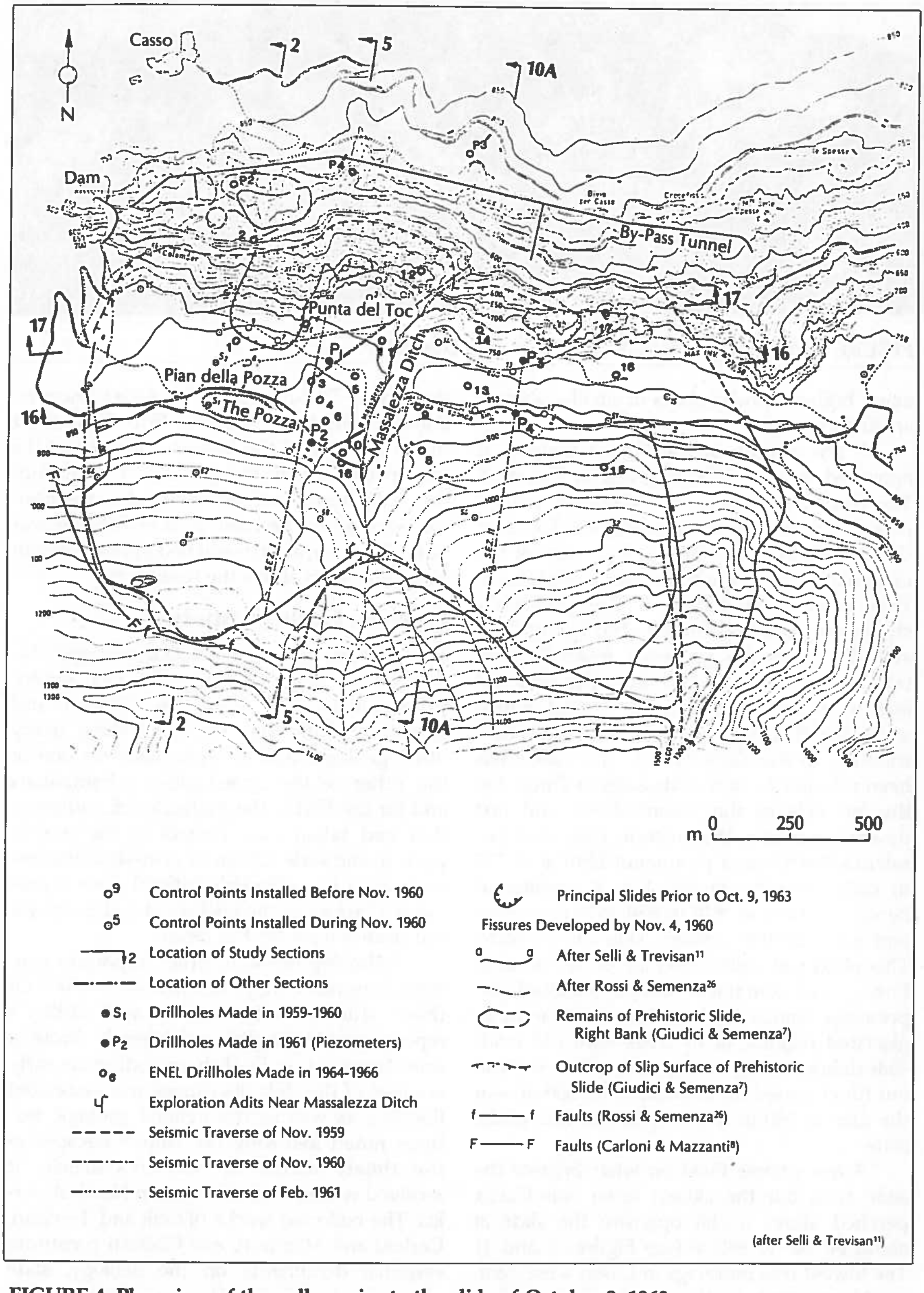


FIGURE 4. Plan view of the valley prior to the slide of October 9, 1963.

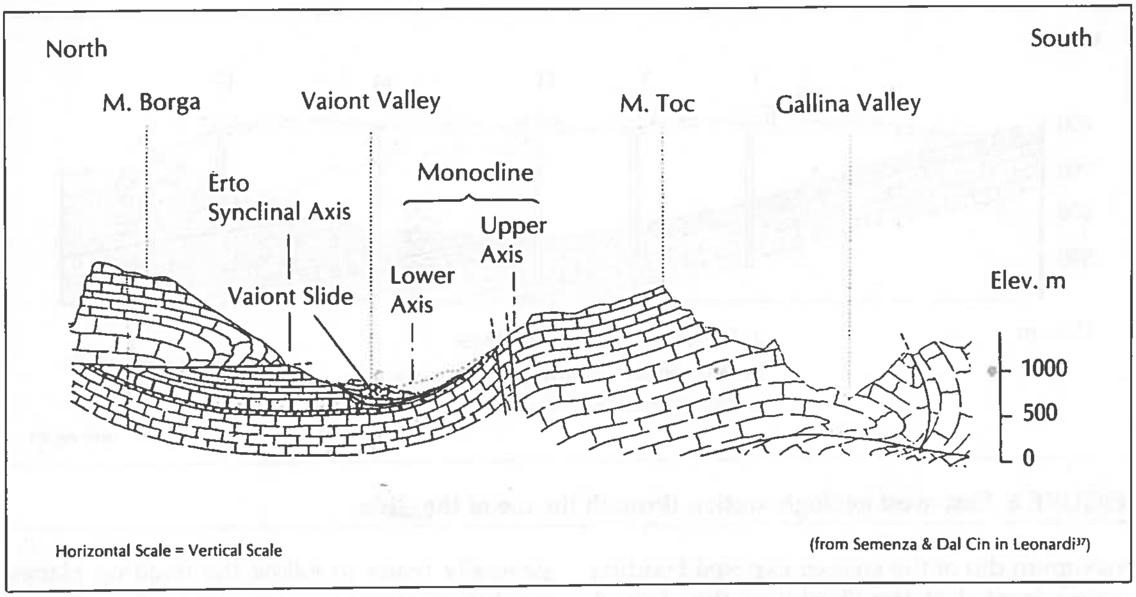


FIGURE 5. Regional north-south geologic section through the Vaiont Slide.

luation of the slide.[9,11,29]

The original geologic mapping of the Vaiont Valley was undertaken by Boyer.[30] Boyer prepared a cross section from Mt. Toc to Mt. Borga across the Vaiont Valley in the vicinity of the Vaiont Slide. However, his section does not indicate an ancestral slide. Müller reports that a geologic study of the reservoir sides conducted by Dal Piaz did not indicate any wall movements.[20,31] The regional geology of the Vaiont area has been studied in more recent times by Rossi and Semenza, Semenza, Leonardi and Semenza, and others.[26,32,33,34,35,36] Many of these studies are contained within the beautifully illustrated two-volume compendium on the geology of the Dolomites, *Le Dolomiti*, edited by Leonardi.[37]

General Geologic Setting

The Vaiont Slide is located in the southeastern part of the Dolomite Region of the Italian Alps. The mountains in this area are characterized by massive near-vertical cliffs formed by the Jurassic Dogger formation and underlying Triassic formations. The local valleys tend to be associated with outcrops of the weaker formations, particularly the Upper Jurassic, Cretaceous and Tertiary units that contain more clays and are more thinly bedded.

The Vaiont Valley has been eroded along the axis of an east-west trending, asymmetrical syncline plunging upstream to the east. This feature has been called the *Erto syncline*. The syncline is shown extending under Mt. Borga north of the slide on Figure 5. The upstream plunge is shown in Figure 6 on a section made by Broili through the toe of the slide.[2]

An abrupt monoclinal flexure on the south limb of the Erto syncline forms a distinctive and important aspect of the geology of the slide. The axis of the lower fold of the monocline is aligned subparallel to the Vaiont River, some 400 to 800 m to the north (see Figure 5). Between this axis, which forms the rear of the "seat of the chair," and the river there is a 9° to 20° eastward dip of the beds down the plunge of the syncline. South of this axis, the beds dip to the north towards the Vaiont River at 25° to 45°. These beds form the "back" of the slide. The axis of the upper fold of the monocline corresponds to the top of the head scarp of the western portion of the slide. This upper axis is shown in Figure 5 but does not show up on the sections shown in Figure 7 on page 74, since the sections do not extend far enough south.

Most sections of the slide presented in the literature have been drawn down the

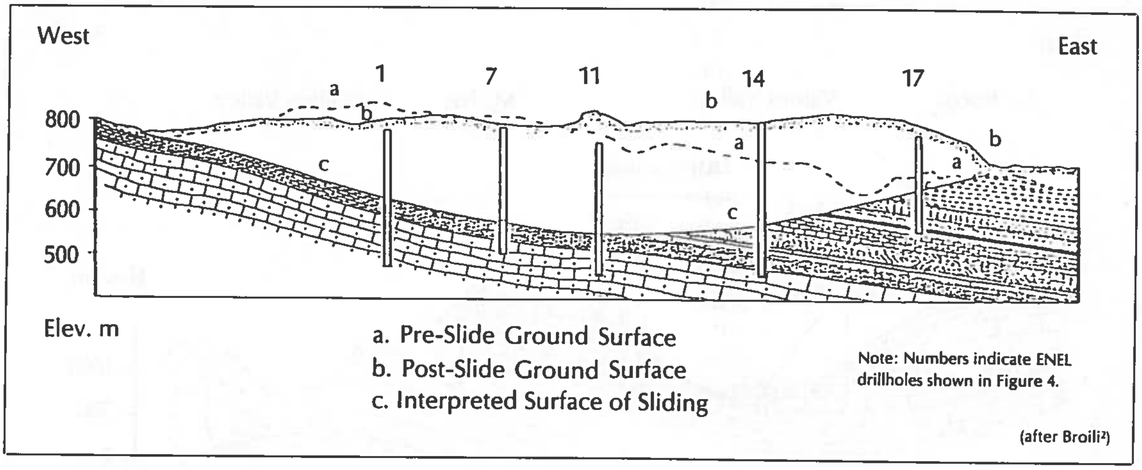


FIGURE 6. East-west geologic section through the toe of the slide.

maximum dip of the steeper exposed bedding planes located at the "back" of the slide. A number of these sections are depicted in Figure 7. Several of these sections show the flat apparent dip of the "seat" of the slide that, although it is reasonable for these sections, is misleading because the true dip of the beds along the seat is 9° to 22° to the east as noted above. The easterly plunge of the beds forming the Erto syncline had a significant effect on the behavior of the slide.

Evidence was found suggesting that the 1963 surface of sliding had a complex origin and corresponded with more than one previous period of rupture. These periods include both a prehistoric landslide, or landslides, and possibly a much older period of tectonic faulting. The seat of these different periods of shearing displacements were the weak clay interbeds in the Malm and Lower Cretaceous units. Evidence of the tectonic faulting observed in this study includes widely scattered outcrops of a cemented breccia and one occurrence of fault-like grooves. The outcrop of these previous rupture surfaces prior to 1963 corresponds with the one shown on Figure 4 as mapped by Giudici and Semenza along the left side of the Vaiont River gorge and described by Semenza.[7,12] The elevation of this plane varies from 700 m near the dam to 540 m about 1 km east of the dam. From there, the plain rises slowly to el. 650 to 660 m in the next 700 m upstream to join the east side of the slide. This rupture surface generally tends to follow the bedding planes on the downstream (western) side of the slide, but appears to cut across or step up to successively higher clay interbeds on the upstream (eastern) side of the slide. It seems unlikely that the surface of sliding would cut smoothly across the bedding as shown by Broili on Figure 6. The eastern side of the slide appears to follow, in part, a fault that was oriented roughly perpendicular to the river (see Figure 4). Faults have also been mapped along the headscarp of the slide, and some have been mapped along the western side of the slide.

The Vaiont Valley has an extremely deep and narrow inner gorge some 300 m deep that was eroded within a broader glaciated valley.[9] Following deglaciation, a predecessor to the present Vaiont Canyon was eroded into the syncline, thereby releasing one or more prehistoric rock slides. Part of one of these slides buried alluvium that was infilling a deep bedrock channel, possibly a pre-glacial valley. This channel and the overlying slide mass were first mapped by Giudici and Semenza (see Figure 7a).[7] After these early events, the present canyon was eroded at the site of the Vaiont Reservoir. The present canyon appears to have resulted from downcutting and erosion of the river through an old slide mass that had originated from the south side of the valley. This process set the stage for a repeat performance of the prehistoric slide. There is evidence that movements of the old slide on the south side of the Vaiont River occurred as the canyon was being eroded to its 1963 pre-slide configuration.

General Stratigraphy

The succession of stratigraphic units in the Vaiont Valley has been the subject of many reports and published papers. The first study containing details of the stratigraphy relevant to the slide included a brief stratigraphic sequence based on a review of literature and field work in the summer of 1959 and spring of 1960, describing the Jurassic-Cretaceous-Eocene sequence of rocks present.[7] The principal units were described in greater detail by Semenza and his stratigraphic description is presented on pages 86 - 87.

The bedrock in the slide area consists of a thick succession of limestone and marly limestone beds of Upper Jurassic and Lower and Upper Cretaceous ages. Brecciated limestones are present, frequently with chert nodules, in addition to lesser amounts of dolomites. Some of the local limestone and dolomite beds have a high porosity due to solution features. Clay interbeds are reported to be particularly common in the Upper Jurassic rocks. A simplified and independent description of the local stratigraphic units of the rocks exposed in the slide area is presented in Figure 8a.[9] The base of the Vaiont Slide lies within the Lower Cretaceous (the c_1 unit of Carloni and Mazzanti and the *a* unit of Semenza[9,12]) and within the Upper Jurassic Malm (unit g_3 of Carloni, unit *ma* of Semenza) that overlies the oolitic beds of the Dogger formation. The thickness of the beds at the base of the slide averages about 5 to 10 cm, but varies from 1 to 20 cm. However, the Dogger limestone (see Figure 8b), which lies a short distance below the failure plane, is "massive," with the thickness of the beds generally exceeding 0.5 to 1.0 m.

Clay Interbeds & Layers

The most significant aspects of the stratigraphy are the location, continuity and physical properties of the clay interbeds in the rock column. This topic has been a controversial one and was the subject of an extensive report and technical paper by Broili on work undertaken at the direction of L. Müller at the Institute for Soil Mechanics and Rock Mechanics, Karlsruhe.[2] Broili's work was based on a review of the core logs obtained from drillholes that were made for a study conducted by ENEL after the slide. The micro-paleontological and petrographic studies of these cores were undertaken by G.A. Venzo and A. Fuganti of the Geology Institute of Trieste University. Further studies of geologic sections in the slide area were also made by these geologists. Broili concluded that "the succession does not include any clay beds or intercalations which some authors consider may have been responsible for some aspects of the phenomenon" (p. 80).[2] Broili's work was cited by Müller to support his contention that "contrary to several publications, no clay existed on the slip surface."[4]

Consequently, the authors were surprised, during preliminary examinations of the failure surface in 1975 and 1976, to note extensive clay interbeds and layers of clay intimately associated with the surface of the 1963 slide. In July 1979 the authors, accompanied by H.R. Smith and G. Fernandez, had further opportunity to examine and sample the exposed portions of the failure surfaces during a three-week period. The locations of these observations and clay samples are shown in Figure 9 and are described in detail in Hendron and Patton.[18] A summary of the field observations of the clay layers is presented in Table 1 on pages 80 - 81.

Not all of the failure surfaces examined had resulted from the October 9, 1963, slide. Many of the visible rock faces were formed by later slides involving slabs of rock that "broke down" to one of the many adjacent underlying clay interbeds.

Where the surface of sliding is overlain by slide debris, the clays were generally found preserved (for example, see Figures 10, 11 and 12). However, where the failure plane has been exposed, the clays are rapidly eroded by rainfall and by debris flows from the large catchment surfaces (see Figures 13 and 14). Small folds and faulted monoclinal (cascade) structures, which are present in many areas of the slide but are not visible at a

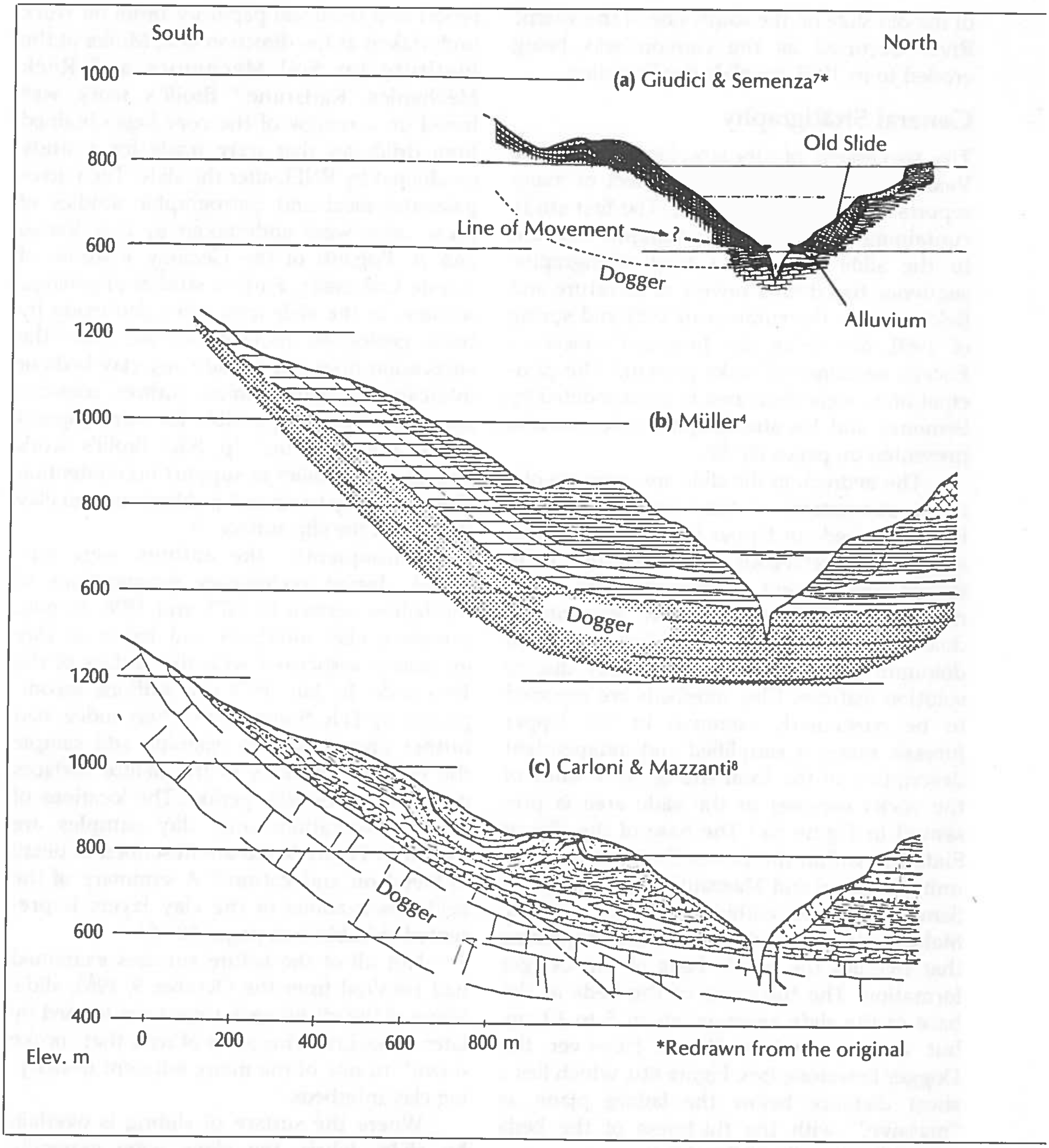
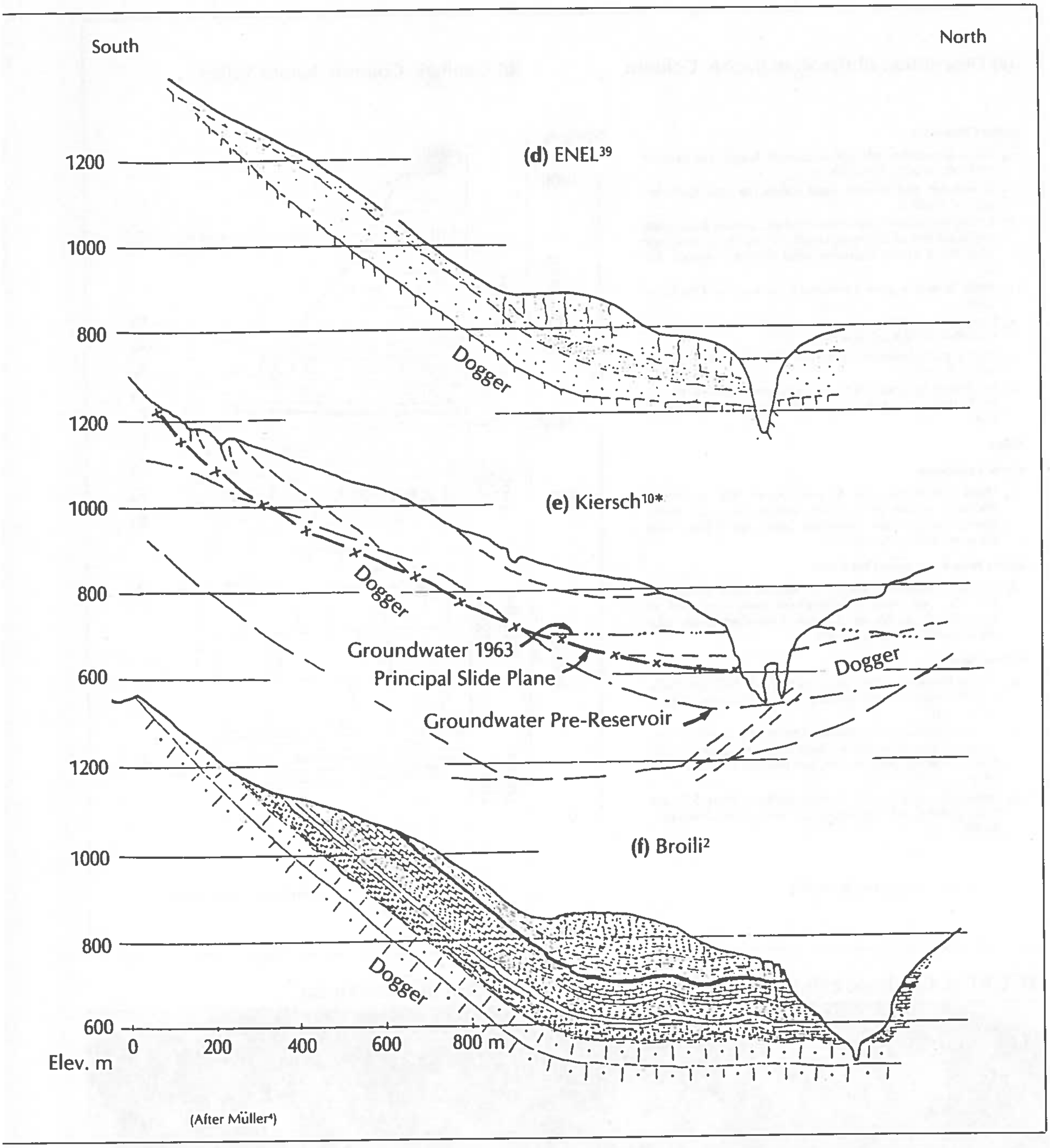


FIGURE 7. Geologic sections of six other investigators.

distance (Figure 15), have served to protect and preserve small portions of the clay interbeds that are strategically continuous with large adjacent areas of the 1963 sliding surface (for example, see Figure 16).

The lower 10 to 30 m portion of slide debris exposed along the base of the rock outcrops on the west side of the slide consists of an uncemented angular gravel and sand-sized breccia with frequent layers of clay and breccia with a clay matrix (for example, see Figure 17). The clay layers in this breccia fre-



quently exhibit structures that suggest shearing of the upper layers over the lower layers. Although the clays are often mixed with angular breccia, layers and interbeds of clay without noticeable sand-sized particles were observed with thicknesses of 10 to 15 cm, with occasional greater thicknesses. The clay layers in the breccia are commonly 1 to 4 cm thick. Lumps of clay were reported on the surface of the slide by Nonveiller, who tested the strength of one of these lumps.[16] Similar lumps were found by the authors at numerous locations on the slide debris surface. Clay layers along the surface of sliding of the 1963 slide are commonly 1 or 2 cm thick, but vary from 0.5 to 10 cm or more.

(a) Description of the Stratigraphic Column

Upper Cretaceous

c_8 Marly limestones, silty, pink-colored. *Scaglia Fm* beds 50 cm thick, total thickness 300 m.

c_7 Limestones, red-colored, *basal Scaglia Fm*, total thickness approx. 15-20 m.

c_6 Cherty limestones, grayish to reddish, nodular beds 5-200 cm, interbeds of gray-green marly limestone to marls, age *Turonian & Lower Senonian*, total thickness approx. 100 m.

c_5 Marly limestone, pink & red, age *Cenoman*, total thickness 1.5 m.

c_4 Limestone with some green clayey interbeds, age *Cenoman*, total thickness 3-4 m.

c_3 Marl & marly limestone, pink, age *Cenoman*, thickness 3-4 m (weak unit).

c_2 Brecciated limestone & marly limestones, beds 10-100 cm thick, slump structures, age *Albian*, total thickness 10-20 cm.

Hiatus

Lower Cretaceous

c_1 Marly limestone, pink & green color 5-30 cm thick, nodulars of dark chert, clastic limestones at top. Some green clay or marly limestone beds, age *Albian*, total thickness 45-60 m (weak unit).

Upper Jurassic to Lower Cretaceous

g_4 Compact limestone, grayish to reddish color sometimes with chert nodules, beds 30-40 cm thick (1 m thick in lower 20 m), age *Upper Malm to Lower Cretaceous*, total thickness 40-45 m (weak unit?).

Middle Jurassic

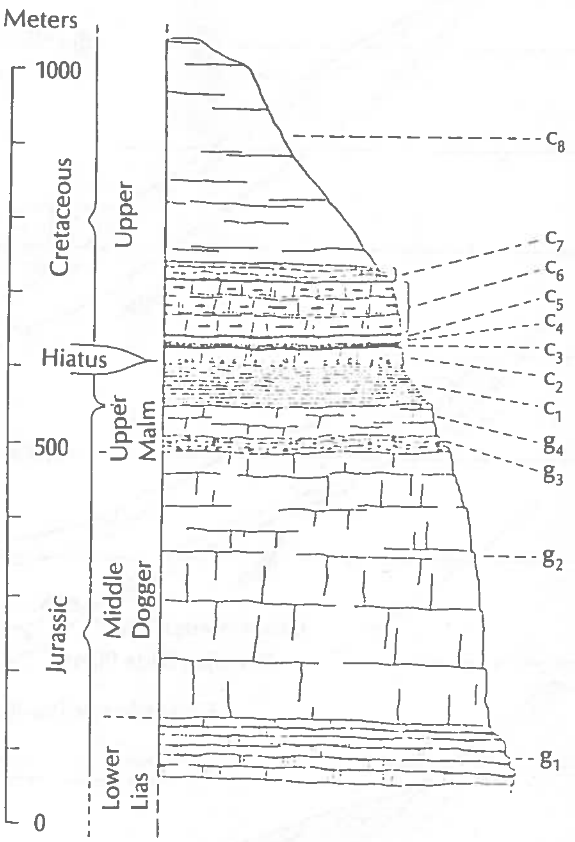
g_3 Cherty limestone, dark gray color, beds 5-20 cm thick, nodular reddish chert, age *Malm*, total thickness 25-35 m (weak unit?).

g_2 Oolitic limestones to dolomitic limestones, locally porous dolomite due to solution, beds in upper part 0.5-1 m thick, otherwise approx. 1 m, age *Dogger*, total thickness 350 m.

g_1 Limestone, gray to bluish well-stratified, beds 5-15 cm thick, partings of bituminous marl, age *Lias*, total thickness 80-100 m.

(after Carloni & Mazzanti, & Broili[8,2])

(b) Geologic Column, Vaiont Valley



(after Carloni & Mazzanti[8])

FIGURE 8. Geologic column of the valley, with a description of the column.

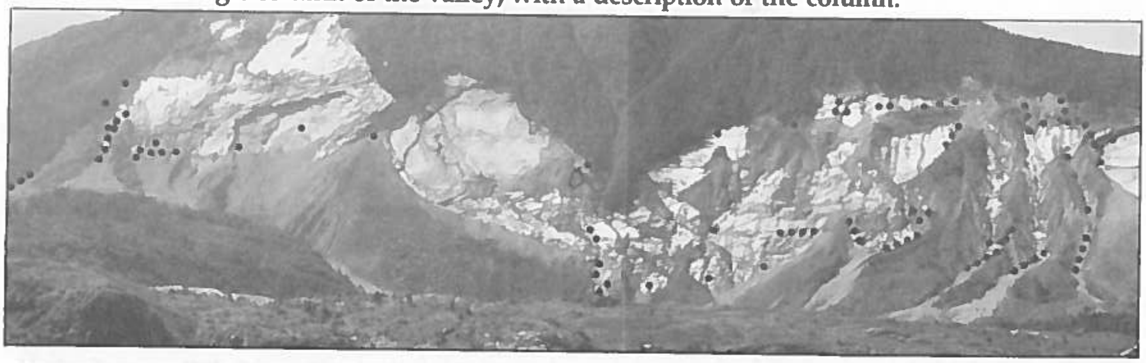


FIGURE 9. Photograph of the Vaiont Slide showing locations of field observations. Clay layers were observed at most locations. An arrow and open circle indicate the location of one of the exploratory adits.

FIGURE 10. A clay layer 5 to 20 cm thick along the failure surface at location 12-3, near the east side of the slide.

FIGURE 12. Clay interbed 5 cm thick along the failure surface at location 18-9. Other thin clay interbeds up to 0.5 cm thick lie in the rock mass.

When exposed in the field in a destressed condition, the clay is generally very soft and sticky and has a slight "popcorn" or cracked and fluffy surface because it has been subjected to frequent wetting and drying cycles. Such characteristics are typical of montmorillonitic clays. The presence of the clay layers in the field can often be inferred from the presence of small slumps whose failure surface corresponds to one of the clay layers. When these slumps are trenched and examined, the soft, sticky clays can be readily identified. The dry clay fragments slake rapidly in fresh water. When the clay interbeds remain in their original stratigraphic position within the undeformed bedrock, the material is much firmer. The thickness and frequency of clay interbeds seemed to diminish with increasing distance below the bedrock-slide debris contact. Thick layers of clay were found in the slide mass and at the contact with the underlying bedrock surface. In isolated areas of partly displaced slide debris at the top of the slide, clays were found indicating that at least one layer of clay occurred several meters above the surface of sliding of the 1963 slide that was thicker than any found at the base of the 1963 slide.

Evidence of the stratigraphic continuity of the clay interbeds found in the slide was sought away from the slide, particularly in the

FIGURE 11. A view of the failure surface below the headscarp at location 18-9, about at the western third point of the slide.

FIGURE 13. Slide debris overlies the failure surface where a clay layer 4 to 6 cm thick has been eroded from beneath the debris at location 11-7, the lower portion of the fourth gully from the west side of the slide.

FIGURE 14. A view of a clay interbed 7 to 10 cm thick protected by a small fold and associated with adjacent failure surfaces at location 22-8, the fifth gully from the west side of the slide, one-third the way up the rock face.

valley of the Mesazzo Torrent just east of the slide on the slopes above the dam on the north side of the Vaiont Valley south and west of Casso. At this location, a series of five continuous clay interbeds varying from 0.5 to 17.5 cm thick was located within 20 to 30 m of the same stratigraphic position as the surface of sliding of the Vaiont Slide. Outcrop 8-1 is near Casso and is shown in Figure 18. This outcrop lies just above the main path leading to Casso from the west at about el. 940 m. Samples taken from these clay interbeds have similar Atterberg limits (presented in Table 2

FIGURE 15. A monocline located in the middle of the western rock face. The surface, exposed after the October 1963 slide, is associated with a clay interbed 0.2 to 1 cm thick.

FIGURE 16. A clay layer, at location 11-7B, 10 cm thick lying between bedrock to the right and slide debris to the left. The clay is protected by a cascade structure, but is associated with the nearby failure surface.

on pages 82-83) to those taken from the failure surface of the slide. A sketch of this outcrop is shown in Figure 19.

The evidence from outcrop 8-1 indicates that clay interbeds are characteristic of the rock units that correspond to those forming the base of the slide. Such stratigraphic clay units would be expected to be continuous over substantial areas and would not have "originated during the sliding movement of the rock masses along the slip surface" as was concluded by Broili (p.80).[2]

Some of the confusion concerning the

FIGURE 17. Five clay layers 1 to 2 cm thick within the lower 1.5 m of slide debris at location 11-10, the fourth gully from the west side of the slide. The failure surface appears in the lower left corner.

FIGURE 18. Location 8-1 where in-situ clay layers outcrop southwest of Casso in the same stratigraphic horizon as the failure surface. The top of the Vaiont Dam is in the lower right.

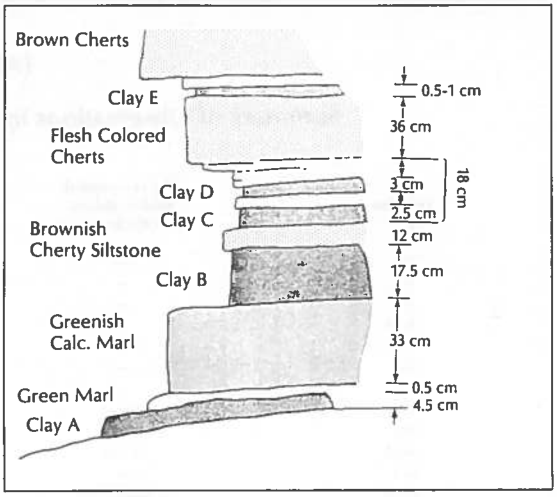


FIGURE 19. A sketch of the outcrop of Malm rocks southwest of Casso. This outcrop lies in the same stratigraphic sequence as those at the base of the Vaiont Slide.

clay layers seems to result from differences in terminology. Broili summarized some of the different descriptions and terminology.[2] Giudici and Semenza wrote, in reference to the Lower Cretaceous rocks, that "numerous intercalations of greenish clay, with thicknesses of a few centimeters, are present."[7] Kiersch mentions clay seams, claystone interbeds, marl and clay partings in the Malm and Lower Cretaceous beds.[10] Other descriptions of the clays mention "mylonitic" and "ultramylonitic facies."[12] Martinis described "reddish or greenish calcareous marls in the form of streaks or extremely thin layers" and "limestone interbedded with greenish foliated marls."[25] Others have described the clayey materials as "thin films of pelitic material."

Any clay bed in a folded stratigraphic sequence of alternating hard and softer units will be subjected to differential shearing displacements along bedding planes due to the flexural-slips as described by Skempton, and Patton and Deere.[13,38] Therefore, a sheared and slickensided structure would be expected in portions of all such clay beds. It seems to be of little consequence with respect to the slide to argue whether the layers are clay, pelite, argillite, foliated marl, clayey marl, marly clay, soft calcareous marl, biomictite or largely argillaceous. All such materials, when sheared, are likely to result in an uncemented clay-rich slickensided material.

Numerous stratigraphically continuous layers of uncemented clay-rich materials are present. The clay content varies from: 16 percent,[4] to 35 to 38 percent montmorillonite,[2] to 50 to 80 percent.[15,18] Because the predominant clay mineral is a calcium montmorillonite, all of the preceding percentages are sufficient to produce soil mixtures that have very low values of the residual angle of shearing resistance.

Broili, after his study of the core from post-slide drillholes, seemed to dismiss the influence of clay along the surface of sliding.[2] However, the core recovery was very poor (0 to 20 percent) in the lower Cretaceous materials, and often remained poor (20 to 30 percent) in the Malm and Dogger units below the failure surface. Under these circumstances of low core recovery, little clay was recovered from the drill core. Furthermore, for the first few years after the slide, many of the excellent outcrops now present were covered by the slide material. Thus, the number and thickness of the clay layers and interbeds may have been difficult to ascertain immediately after the slide.

During this study the geologic logs of the ENEL holes drilled after the slide were examined. The ENEL boring P′-2 (not piezometer P2), located on the north side of the valley

TABLE 1

Summary of Observations in Clay Layers & Related Features

Location No.	Clay layer noted in slide debris no. & thickness, cm	Clay layer on 1963 failure surface no. & thickness, cm	Other clay layers, + = above 1963 surface - = below 1963 surface no. & thickness, cm
9-1	1,—	—	—
9-2	—	—	-1, 0.2-1
9-3	—	—	(no thickness noted)
9-3A	—	possibly	—, 0.2-0.5
9-3B	—	—	—
9-4	—	1, 1-2	—
9-5	—	1, —	—
10-1	1, —	—	—
10-2	—	1, 2	—
10-2A	1, 1-2	1, 0.5-2	—
10-3	—	1, —	—
10-3A	6 layers, 1-10	1, 1-10	—
10-4	Several	1, 2-4+	-2 cm, 1-2
10-4A	Several	1, 1-2	—
10-4B	Several	1, 1-2	—
10-5	1, —	1, 4-6	—
10-6	—	1, 1-3	±5 layers, 0.4-1.5
10-6A	—	1, 1-3	+5 layers
11-1	> 5 layers in 1.5 m debris 12 m clay rich debris	— —	— —
11-2	—	—	-6 to 10 layers
11-2B	—	1, 0.5-1.0	—
11-3	Debris has clay matrix 1, -1 cm w/slick	— 1,1-2 w/slick	— —
11-4	—	1, 1-6	—
11-4A	—	1, 0.1-5	—
11-5	1 - 1 m	—	—
11-6	1, —	—	—
11-7	—	1, 2-6	-2, 4-6
11-7A	1, 0.3-0.5 (just above f.p.)	—	—
11-7B	—	1, 10	-1, 0.2
11-8A	—	1, 0.5-2	—
11-9	1, —	1, 2-10	—
11-10	4 layers (very clay-rich)	1, 1-2	—
11-10A	2, 1 & 15	failure plane at base of thickest layer	—
12-1	—	—	-1, 0.1-0.5
12-1A	—	—	—
12-1B	—	—	—
12-2	2, 20 cm breccia with clay matrix	1, 2	—
12-2A	—	—	—
12-3	1, 50 cm clay rich matrix	1, 5-20	—
12-3A	2, —	—	—
12-4	—	1, 0.1-1.5	—
12-4A	—	1, 0.2-0.5	-3, 0.2-0.5
12-5	—	1, 2-3	many, 0.2-0.4
12-6	1, 15	1, 1-2	—
12-7	1, 15	—	—
18-2	1, —	1, 2-4	—
18-3	—	contact not visible	—
18-4	—	contact not visible	—
18-5		contact not visible	—
18-6	—	no clays left on failure surface (rock-debris-rock contact)	

Location No.	Clay layer noted in slide debris no. & thickness, cm	Clay layer on 1963 failure surface no. & thickness, cm	Other clay layers, + = above 1963 surface - = below 1963 surface no. & thickness, cm
18-6A	—	—	—
18-7	—	—	—
18-8	—	1, 5-10	-1, 3
18-9	—	1, 5	+2, trace-0.5
18-10	—	1, 2	—
18-11	—	1, 2	—
18-14	1, 5	1, 2-10	—
22-1	—	no clay visible (cascade structure)	—
22-1A	1, several cm discontinuous	1, trace discon-tinuous	—
22-2	—	1, 1-4	-1 to 6 layers
22-3	1, —	1, 4-10	-2, trace
22-3A	1, —	1, 2-5 x 8 m +length	many, 0.5-8
22-4	—	1, 0-5	—
22-5	—	no clays visible (removed by erosion)	—
22-6	—	1, 1-3	—
22-6A	—	1, 1-4	—
22-7	—	1, 7-10	—
22-7A	—	1, 1-2	—
22-7B	—	1, 2-6	—
22-8	—	1, 2-10	+1, 1-3
23-1	—	no clays visible some buckling of rock slabs	—
23-2	—	—	-3 layers, 2-1
23-3	—	1, 8	—
23-4	—	1, 8-10	—
23-10	—	1, 2-3	-2 layers, 1-3 & 10-15
23-11	—	1, 2-3	—
23-12	—	1, 1-5	—
23-13	—	portal of old adit	—
23-14	—	top of Dogger (no clays visible)	—
23-15	—	no clays visible in Dogger Form (fault in Dogger)	—
23-16	—	no clay readily visible (access difficult)	—
23-17	—	old failure plane (no excavation for clays made) no clay visible 1-2 m cover	—
24-1	several, 1	1, 0.5-1	—
24-2	—	1, 0-6	—
24-3	—	1, 2-4	several, 1
24-3A	—	1, 2-3	—
24-4	—	1, 2-4	—
24-6	(on failure plane of post 10/9/63 slide)	—	-3 layers, 0.5
24-7	—	2, 0.5-1.5	—
24-8	—	—	-1, 1
69-1	—	1, 2-3	—
69-3	—	1, 2-5	—
69-4	—	1, 5	—
67-1	1, —	—	—
67-2	1, —	—	—
522-2	1, —	—	—
522-3	1, —	—	—
522-4	—	1, —	—
522-5	—	1, 1-6 x 80 m long	—
522-5A	—	2 layers	2-10
522-6	—	1, 0.2-1	—
522-7	—	—	1, 1-3

TABLE 2

Atterberg Limits on Clay Samples

Sample No.	Liquid Limit	Plastic Limit	Plasticity Index	Descriptive Notes
8-1	67	28	39	In-situ clay, same unit as base of slide
8-1A	80	35	45	In-situ clay, same unit as base of slide
8-1B	68	36	31	In-situ clay, same unit as base of slide
8-1C	50	30	20	In-situ clay, same unit as base of slide
8-1D	72	29	43	In-situ clay, same unit as base of slide
9-1	76	32	44	Clay in slide debris
9-3A	33	20	13	In-situ clay sample on failure plane
9-5	58	21	37	Clay on failure plane
10-2	52	30	22	Clay at rock-debris contact
10-2A	53	32	21	Same as 10-2 (4 m away)
10-3A	68	35	33	Lower 1 m of debris above failure plane
10-4	39	24	15	Clay at rock-debris contact
10-4A	40	24	16	Clay at rock-debris contact (8 m from 10-4)
10-6	38	26	12	Clay at rock-debris contact in-situ
11-1	70	21	49	Clay in debris 50 m from rock contact
11-2A	66	33	33	Clay at rock-debris contact
11-3	56	32	24	Clay layer 1-2 cm above failure plane
11-4	50	27	23	Clay layer at rock-debris contact (10 m from 11-3)
11-5A	92	36	56	Clay layer just above debris (8 m from 11-4)
11-6	55	31	24	Large clay block, float in slide debris
11-7B	61	26	36	Clay layer just (1-2 cm) above failure plane
11-8	48	27	21	Clay at rock-debris contact
11-9	76	26	50	Clay at failure plane (2-10 cm thick)
11-9	67	30	37	Direct shear tests by WES
11-10	76	36	40	Clay at failure plane, 4 layers (1-10 cm thick) in debris above sample
12-1	26	16	10	Clay silt layer, east scarp
12-2	72	22	50	Clay at slide debris-tectonic breccia contact
12-3	76	22	54	Clay layer at debris-tectonic breccia contact
12-4	73	29	44	Clay in-situ in failure plane
12-5	56	29	27	Clay in-situ on main failure surface over east side of slide

some 450 m upstream from the right abutment of the dam, encountered a series of layers of brecciated debris. In some of these layers, clay was noted. These clayey layers varied from 1 to 3 m in thickness. These layers are in the stratigraphic position of the extension of the basal rupture plane of Giudici and Semenza;[7] the area was mapped as old slide material by Rossi and Semenza as shown in Figures 4 and 7a.[26]

Although the core recovery was extremely poor in most other post-slide drillholes made in the slide debris, the following observations are noted in the ENEL logs drilled after the slide:

- Drillhole 7 encountered 5 m of reddish clayey rock fragments just above the in-situ rock
- Drillhole 8 encountered detritus with

Sample No.	Liquid Limit	Plastic Limit	Plasticity Index	Descriptive Notes
12-6	72	23	49	Clay in debris about 4 m above failure plane
12-6A	35	19	16	Clay on failure plane (10 m from 12-6)
18-6	49	27	22	Clay on failure plain at scarp
18-6A	39	20	19	Clayey debris on rock surface near scarp
18-8	45	32	13	Clay in-situ forms failure plane above
18-9	37	25	12	Clay in-situ forms adjacent failure plane
18-9A	48	33	15	Clay in-situ on failure plane
18-11	38	25	13	Clay in-situ forms failure plane below
18-14	43	30	13	Clay layer in debris above failure plane
22-1A	57	20	37	Clay layer on failure plane
22-3	42	14	28	Clay layer between slide debris & tectonic breccia
22-3A	50	25	25	Clay in base of debris just above tectonic breccia
22-4	54	32	22	Clay below cemented breccia on bedrock contact
22-6A	44	25	19	Clay layer, in-situ, forms failure plane above
22-7	48	26	22	Clay at rock-debris contact
22-7B	37	28	9	Clay layer, in-situ below failure plane
22-8	37	25	12	Clay layer, in-situ
23-3	46	32	14	Clay layer, in-situ, forms failure plane above
23-4	60	33	27	Clay layer between debris & rock
23-10	57	30	27	Clay layer, in-situ
23-11	57	35	22	Clay layer, in-situ forms adjacent failure plane
23-12	46	28	18	Clay layer, in-situ forms adjacent failure plane
23-17B	39	21	18	Clay layer, in-situ in fold
24-1	68	31	37	Clay layer with cemented breccia
24-2	82	22	60	Upper clay layer in cemented breccia
24-2A	64	32	32	Lower clay layer in cemented breccia
24-3	45	23	22	Clay layer along failure plane
24-7	39	22	17	Clay layer, in-situ, in fold
25-3	55	30	25	Clay layer, in-situ in Malm
522-5A	66	23	43	Clay layer on failure plane
522-5A	81	24	57	Clay layer on failure plane

clay in the lower 7 m of the slide mass

- Drillhole 9 encountered 31.5 m of clayey debris
- Drillhole 11 encountered two zones of "argilla" (clay) with detritus, at depths of 48 to 71 m and 91 to 107 m
- Drillhole 13 encountered 4 m of clay with rock fragments 0.7 m above the base of the slide mass
- Drillhole 18 encountered clayey debris near the base of the slide, and further encountered 3.5 m of calcareous chert intercalated with clay just above the in-situ rock

Therefore, it would appear that there is considerable evidence of clay and clayey debris at the base of the slide mass, in spite of the fact that soft clay with rock fragments can be very difficult to recover from drillholes.

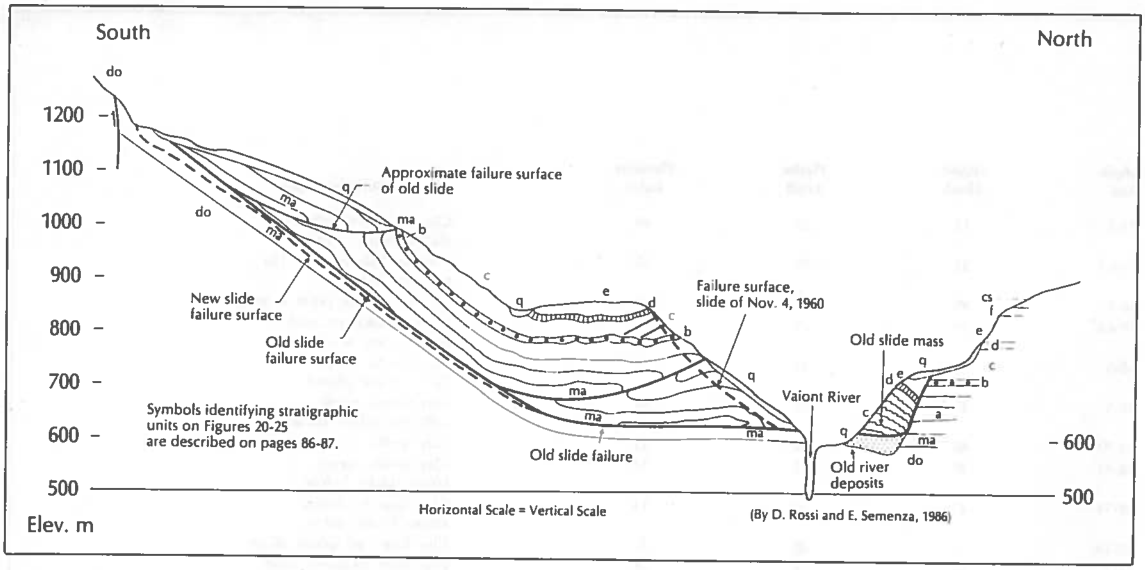


FIGURE 20. Geologic Section 2 before October 9, 1963.

Multiple layers of weak clays were present along much of the surface of sliding. These clays are largely stratigraphic in origin, although undoubtedly some shearing and development of slickensides had occurred prior to the sliding activity. This conclusion is not in agreement with the conclusions given in the principal technical papers on the slide in English.[2,4,20] However, this is in agreement with a conclusion of the Frattini Commission that noted:[39]

> "Yet, in the material accumulated by the slide we can see clay beds, a few centimeters thick, separated by small or less flinty, nodular calcareous strata.
>
> In our opinion, these strata, of a really clayey nature, cannot be considered the product of sliding; they may rather be of sedimentary origin... The Malm and the base of the Lower Cretaceous, which are calcareous-nodular, with flint nodules or beds and clay interstrata, forms a mass that can easily be deformed, minutely cracked and subject to cataclasis."

Structural Geology

The basic structures affecting the slide are:

- The steep back of the slide that provided the driving forces,
- The pronounced eastward dip of the seat of the slide,
- The continuous layers of very weak clays within the bedded rocks, and
- The faults along the eastern boundary of the slide.

Giudici and Semenza mapped the outcrop of a prehistoric failure surface along the Vaiont Canyon walls (see Figure 4), showed its limits at both ends and indicated that the entire area was a zone of possible sliding.[7] On their section (shown in Figure 7), they showed no uphill limit to the base of this zone that ended in question marks. However, a simple extension of their projected "line of movement," indicating the base of the slide, would extend to or beyond the depression of the Pozza. The steep back and flat toe (on a north-south section) of the slide was established by their mapping and interpretation of the Dogger-Malm contact. From their geologic map, the upstream dip of the failure surface along the walls of the canyon could be determined. They had also established the existence of a block of old slide material on the right abutment and stated that it had come from the south side of the valley in a previous slide. The outcrop of the failure surface mapped by Giudici and Semenza is essentially coincident with the 1963 surface of

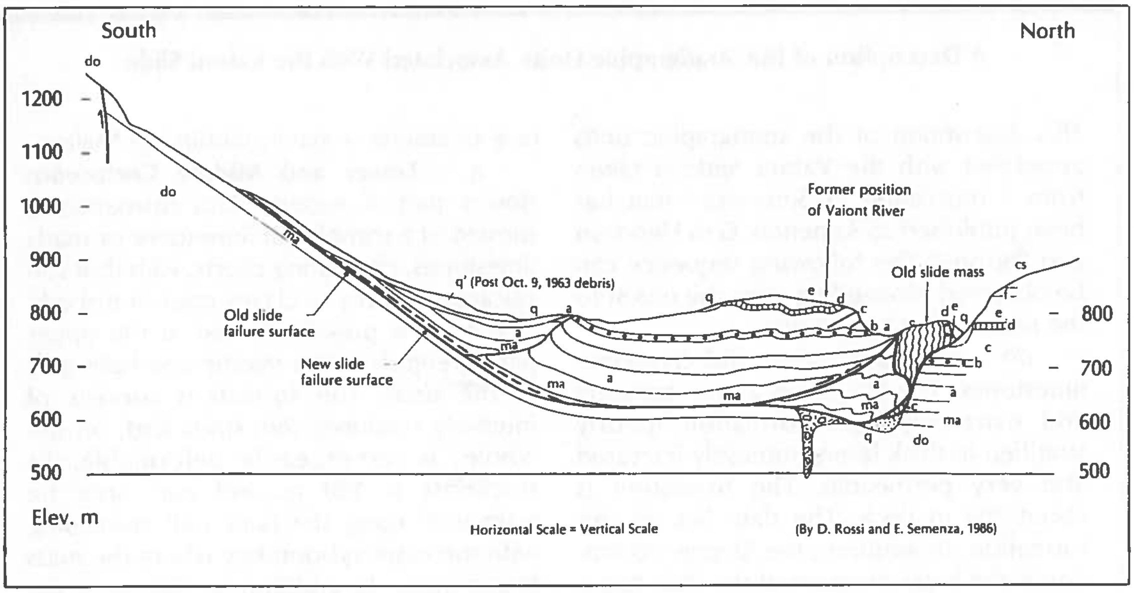


FIGURE 21. Geologic Section 2 after October 9, 1963.

sliding.

Two geologic maps prepared by Rossi and Semenza provide an accurate and detailed picture of the geologic structures present before and after the slide.[26] (These maps were reproduced as Figures 11 and 12 in Hendron and Patton.[18])

In the course of this study, particular interest was paid to Sections 2, 5 and 10A in Figure 4. These sections were selected as representative sections for use in stability analyses. They were also chosen because they appeared to be oriented relatively close to the direction of the original movement of the slide. At the request of the authors, Rossi and Semenza undertook to interpret the geology along these sections both before and after the 1963 slide. Their interpretations of Sections 2, 5 and 10A are presented as Figures 20 to 25. The symbols used for the units in these sections are given on pages 86-87.

Figure 20 depicts Section 2 before the October 9, 1963, slide. Two different minor variations in the interpreted surface of sliding are shown along the steeply inclined portion of the slide. Figure 20 also indicates a fault at the top of the slide area and some previous sliding within the future slide mass. A portion of the old remnant block of slide material on the right-hand side of the Vaiont Valley is also shown. The ground surface after the slide of November 4, 1960, is depicted by the dashed surface above the canyon wall. This surface approximates the surface of sliding of this precursor slide.

Figure 21 portrays Section 2 after October 9, 1963. It indicates a moderately simple downhill translation of the slide. The figure also depicts a remarkable upward displacement of the old slide material on the right-hand valley wall and some of the post October 9, 1963, debris and alluvial fans covering portions of the surface of the main mass. Figure 21 shows that the failure plane is parallel to the bedding in the upper part of the slide, but cuts across the bedding in the lower part of the back of the slide. The authors agree with the general position and orientation of the slide surface shown for the exposed portions of the failure surface. Whether the surface of sliding cuts across beds at depth or not is a matter of interpretation. Appreciably more drillholes would be required to better define the degree of conformity of the failure surface to the bedding.

Figure 22 presents Section 5 before October 9, 1963. It illustrates a section with a large stabilizing toe relative to the small volume that acts as a driving force.

Figure 23 shows Section 5 after October

A Description of the Stratigraphic Units Associated With the Vaiont Slide

This description of the stratigraphic units associated with the Vaiont Slide is taken from a translation of Semenza[12] that has been published as Appendix G in Hendron and Patton.[18] The following sequence can be observed proceeding from the oldest to the most recent formations.

do **Dogger:** oolitic and crystalline limestones. The Dogger is a very compact and extremely rigid formation, poorly stratified in thick layers, intensely fractured and very permeable. The formation is about 300 m thick. The dam lies on this formation. In addition, the Dogger formation is the basal structure of the slide zone. The Dogger outcrops on the Mt. Toc slopes above the area from which the landslide moved as well as to the west of that area and in the Vaiont gorge, below the dam. This formation was not involved in the movement.

ma **Malm:** gray cherty limestones with black cherts, which can be nodular. The Malm formation is composed of very thin strata (not more than 15 cm) with abundant interlacing of cherty material or scattered cherty nodules. The Malm has some interbedding of thin calcareous sheets or soft marly-calcareous materials. It is easily fractured or folded, but the Malm is much more compact than the formation just above it. The overall thickness of the Malm cannot be precisely evaluated, but ranges from 30 to 50 m. The Malm formation outcrops at the top of the Costa delle Ortiche and at other points along the slope of Mt. Toc beyond the surfaces where the landslide broke away. It can also be observed at the right side of the Vaiont Valley above the dam. (Note: Recent work by Semenza and Rossi to be presented this year has led them to conclude that the surface of sliding is mainly within the Malm.)

a **Lower and Middle Cretaceous** (lower part ≃ Aptian). This formation is formed of a complex of limestones or marly limestones, containing cherts, with thin soft calcareous, marly or clayey-marly interbeds. The color is prevalently red in the upper part, greenish in the middle and light gray at the base. The formation consists of intensely fractured thin strata and, on the whole, is rather easily deformable. Its thickness is 120 m and can only be estimated along the fault wall coinciding with the eastern boundary where the mass broke away. In addition to this area, the formation appears on slabs remaining along the rupture surface. In fact, the surface of sliding corresponds to many wide tracts of different strata of the lower part of complex a, which are joined by almost vertical cuts perpendicular to the strata. Complex *a* may be found in various places in the slide mass, usually at the peripheral zones, but also, in particular, in the zone of the craters near the dam, and in the eastern lobe.

b **Middle Cretaceous:** (middle-upper part) conglomerate with pinkish or gray cement. This unit forms a bed about 10 m thick, which is topped by a calcareous layer about 1 m thick. It can be distinguished from the conglomerate of level *d* because the cement uniting the fragments is pinkish or gray rather than white. This extremely compact conglomerate stands out from other formations, frequently forming a step. It is visible in numerous points; in particular along the western flank of the Colle Isolato, at the base of the Pinnacolo and on the southwestern side of the Conca delle Pozza.

c **Middle-upper Cretaceous** (Albian ≃Cenomanian). This complex was originally

9, 1963. This figure depicts almost complete removal of the activating forces after the slide. Just after the slide, Semenza discovered evidence of a 30 to 40 m southern movement of the mass after it had reached its maximum northern limit.[12] This backward movement is formed of rather compact beds of gray limestones that alternated with sequences of less resistant thin layers of greenish limestones and calcareous marls. On the whole, the original permeability probably was quite low; today the permeability is high due to intensive fracturing. This sequence may be easily observed on the Pinnacolo and at the southwest edge of the northwest wall of Punta del Toc.

d **Upper Cretaceous** (≃Turonian). This complex consists of red marly, silty limestones interbedded with conglomerates and limestones. Three distinct and characteristic units appear in this complex: the upper and lower units are red, and the intermediate unit is often conglomeritic, sometimes revealing syngenetic folds. All three units together are about 14 m thick. On the whole, they have low strength characteristics. This complex is found in many parts of the slide mass, in particular along the northwest and north walls of the Punta del Toc, and along both sides of the Massalezza Valley.

e **Upper Cretaceous** (≃Coniacian). This complex consists of fine-grained limestones with various colored cherts. It is about 27 m thick, formed of limestones of various types, rich in cherts and showing a prevalently nodular structure at the base. Originally, this complex must have been extremely strong and compact, even now its strength is greater than other horizons, as may be seen on the north wall of Punta del Toc and on the plateaus of the Pozza and east of the Massalezza where this cherty limestone outcrops extensively.

f **Upper Cretaceous** (≃Santonian). This is a complex of light red and green limestones and marls with red cherts. The general pinkish coloration of this complex is lighter than that of the levels described above. It is, however, more compact. This complex outcrops primarily in the northeastern zone of the slide mass.

cs **Scaglia rossa** of the Upper Cretaceous. The scaglia rossa consists of marly-limestones at its base and of marls in the remainder. These marls are generally red except for a gray intercalation. This formation was not involved in the movement.

q **Quaternary.** This unit consists of deposits older than the landslide — specifically, morainic, detrital and alluvial. For the main part, they consist of coarse detrital material containing somewhat rounded elements. This material is abundant in the northeastern zone. A limited area of lacustrine clays is visible on the Pozza plateau. The presence of morainic deposits remains problematic.

q o **Detritus:** deposited by the wave produced by the landslide. This unit consists of detritus of various origins stripped away from detrital or alluvial slopes or torn from outcrops of intensely fractured rock by the force of the wave. These materials are easily recognized because they show no cementation, compaction or settlement. The form assumed by these deposits permits a reconstruction of the movement of the wave. They are widely distributed over the area, especially in the lowest zones.

q d **Detrital masses and alluvial fans:** formed after the landslide. This material consists of detritus of rock slides that slid from the slabs exposed along the slide surface and of alluvial cones that formed primarily during the rains of November 1963. In various places, these materials have considerably modified the topography to the point that it no longer corresponds to the topographical conditions noted immediately after the slide. This applies, in particular, to the internal lake that was almost half-filled by such detrital materials.

portrayed by the two directions of movement noted on the planes of sliding at the toe. A comparison of Figures 22 and 23 reveals only modest changes in the structure of the majority of the displaced rock mass other than translational and rotational movements.

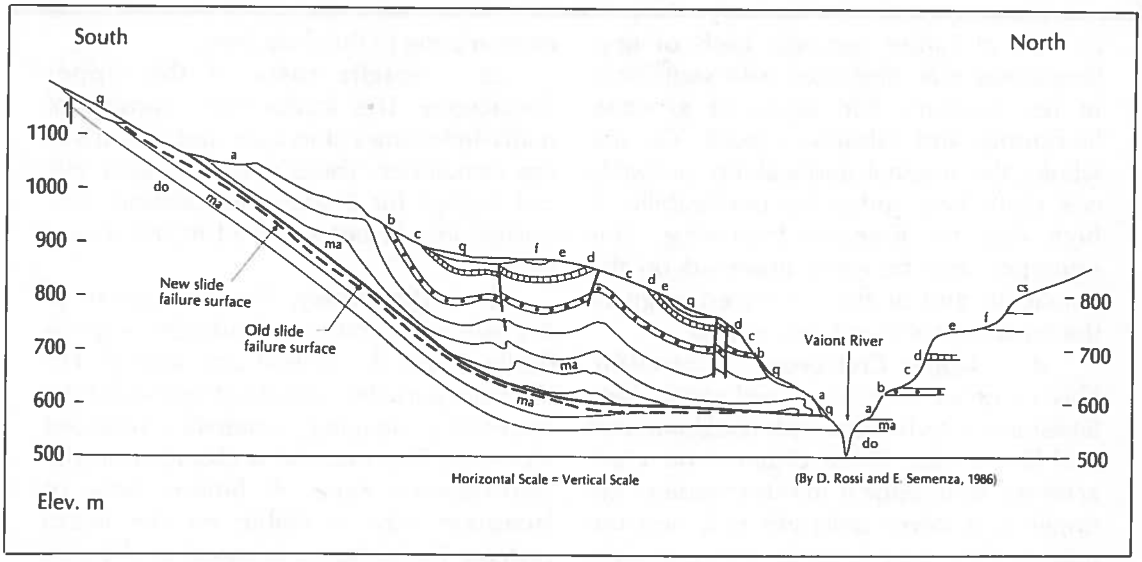


FIGURE 22. Geologic Section 5 before October 9, 1963.

Geologic Section 10A presented in Figure 24 shows the geologic structure of a representative section of the eastern side of the slide taken in the approximate direction of initial movement of the main slide mass. Most sections of this part of the slide presented in previous investigations have been oriented some 10° to 20° counterclockwise in plan view to give more emphasis to the direction of movement of the top of the eastern portion of the slide. Rossi and Semenza called this upper part of the slide the Eastern Lobe in Figures 24 and 25, and show it in the area A-B before the slide. Post-slide surface depositional features suggest that the Eastern Lobe did not start its movement until after the main slide mass had completed most of its movement. The two slide movements appear to be essentially independent and the Eastern Lobe appears to have followed the movement of the main slide and formed the slide material shown in the area A-B on Figure 25. Rossi and

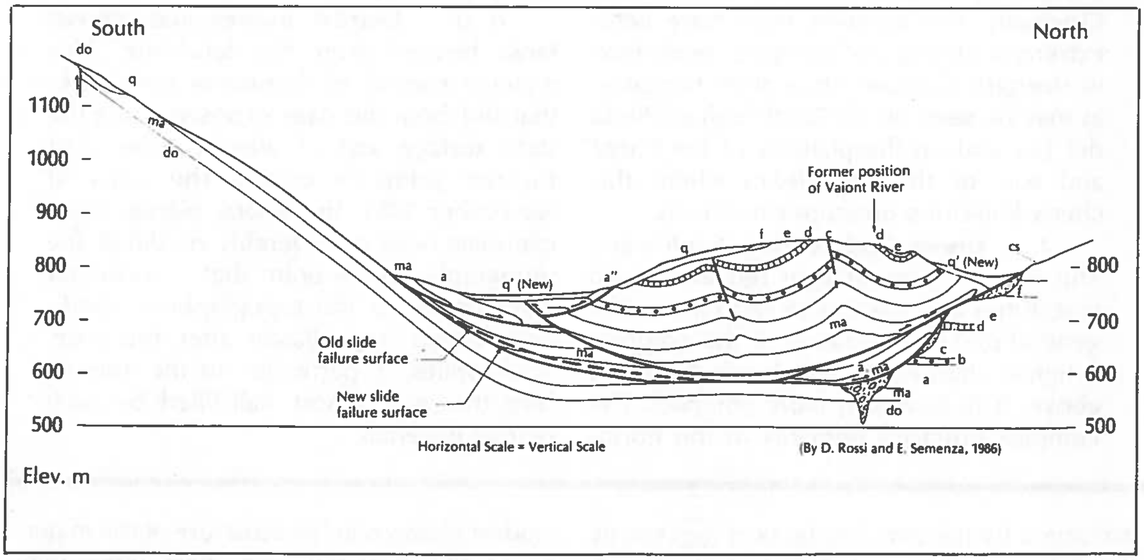


FIGURE 23. Geologic Section 5 after October 9, 1963.

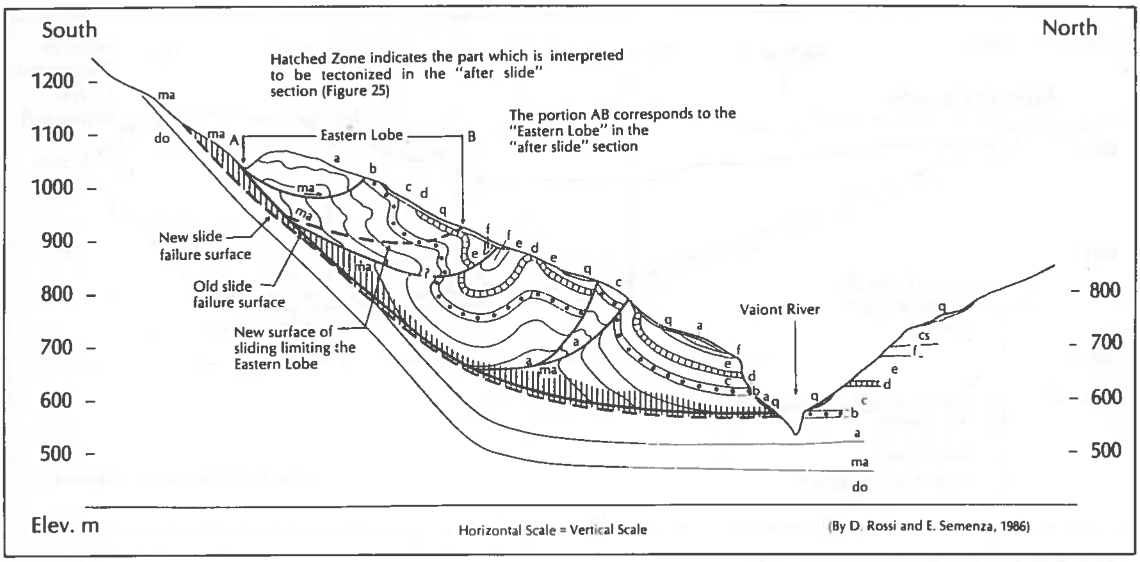


FIGURE 24. Geologic Section 10A before October 9, 1963.

Semenza have also speculated on the existence of a "tectonized" zone highlighted by the hatching along the failure surface in Figures 24 and 25. By comparing Figure 24 to Figure 25, it can be seen that there is relatively little surface deformation of the majority of the sliding mass that is not accounted for by a translational and rotational displacement, except for the deposit of the Eastern Lobe. Figure 25 also shows the near-horizontal surface of the slide mass following the 1963 slide, reflecting the very low shear strength along the base of the slide. In Figure 25, Rossi and Semenza note that a portion of the front of the pre-1963 canyon wall is missing. They have suggested that this portion fell into the gorge and was covered and spread by the slide movement. Presumably, part of this missing volume may have been removed by wave action.

An appreciation of the upstream dip of the seat of the slide cannot be obtained

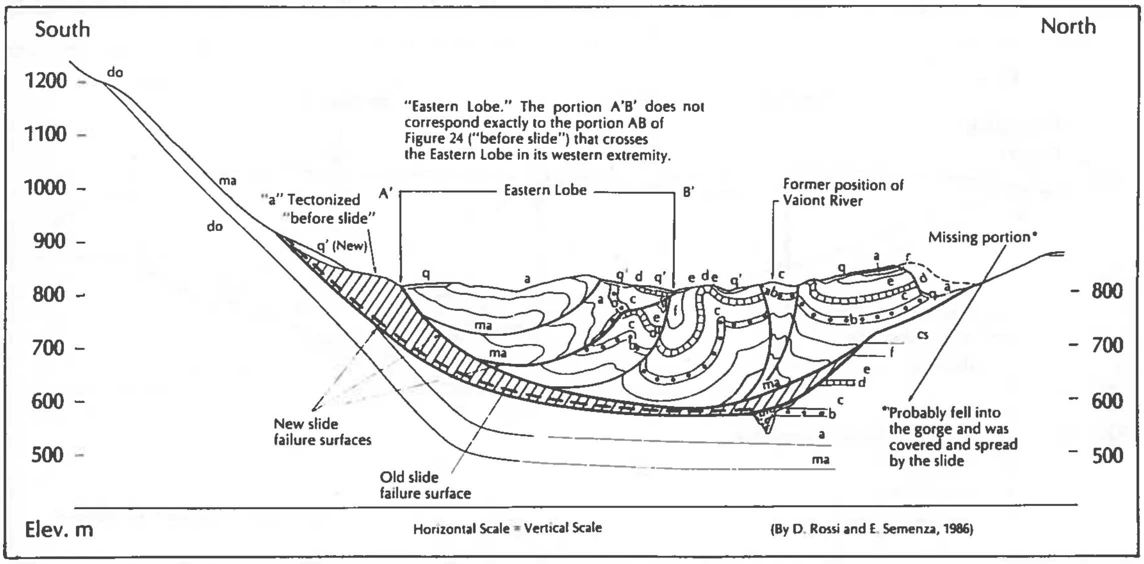


FIGURE 25. Geologic Section 10A after October 9, 1963.

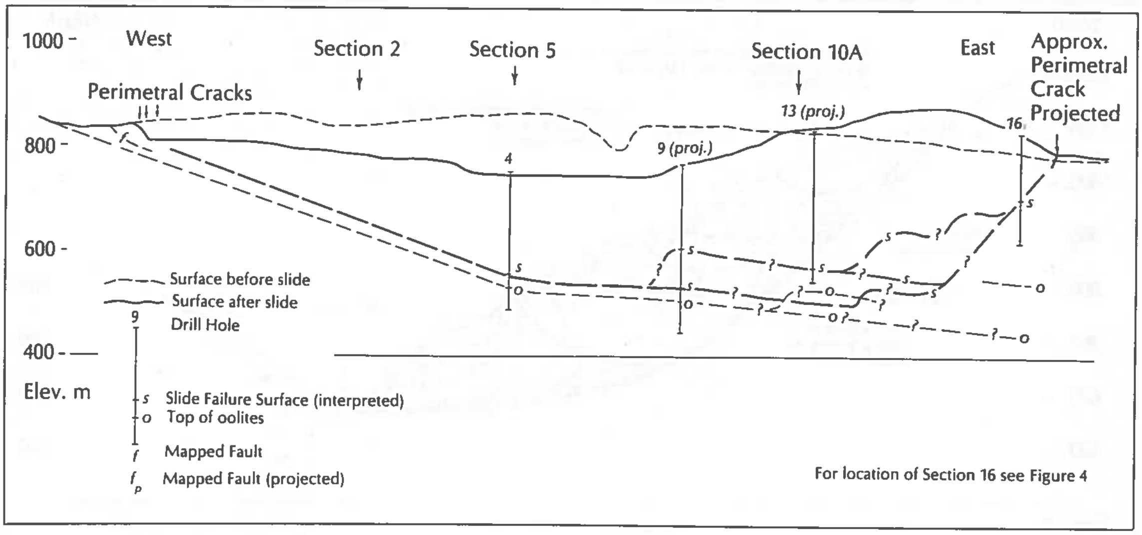


FIGURE 26. Geologic Section 16.

without an examination of an east-west section. Sections 16 and 17, shown in Figures 26 and 27, are east-west sections based on information obtained from drill-holes made after the slide. The dip of the beds along the seat of the slide is steeper (17° and 22°) on the west end near the dam and flatter (9° to 11°) in the central portion of the slide. The bedding steepens again to 30° to 40° just east of the slide (not shown in these sections). An interpretation of the stair-stepped seat of the slide on its eastern side is shown in Figures 26 and 27. The shapes of these steps are not known in detail. However, several drillholes provided local control points. A portion of one step was observed in the field. The treads of these steps will form in the weakest clay units, while the risers will form pre-existing faults and major joints.

Minor Structures

A number of folded structures were observed. One of these structures consisted of small, accordion-like, alternating synclines and anticlines with amplitudes of 2 to 15 m and wave lengths of 5 to 25 m. The axis of these folds

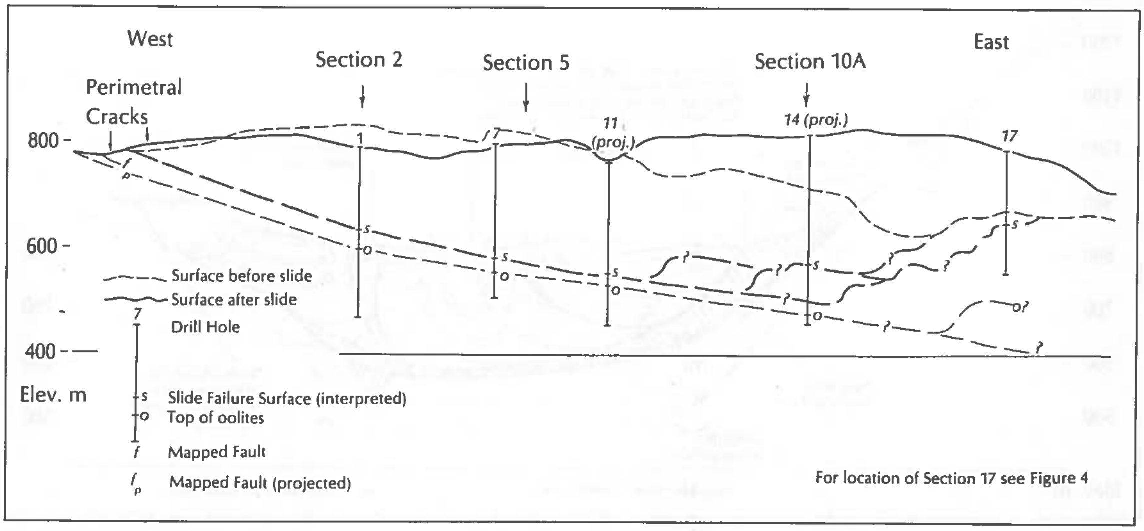


FIGURE 27. Geologic Section 17.

tends to be aligned at about 40° Az, which is within about 15° of the initial direction of movement of the slide mass. Therefore, these folds have a minimal effect on the shearing resistance of the base of the slide. However, they have had a significant effect on the distribution of the slide debris left on the in-situ bedrock surfaces. These folds underlie several of the ribs of debris that remain on the rock surfaces, especially in the western part of the slide scarp (see Figure 3). Where the folds were not aligned exactly in the direction of movement, they may have added a small geometrical component to the frictional resistance, thereby slightly increasing shearing resistance.

Perhaps the most frequently encountered structures on the exposed bedrock surfaces are the small folds and structures described as *a cascata* by Giudici and Semenza, here called cascade structures.[7] The small monoclines and cascade structures bear a dragfold relationship to the larger monocline forming the "back" of the slide. Figure 15 shows a small monocline running parallel to the strike of the beds half-way up the most westerly rock face. As the monoclinal structures develop and are subjected to continual shearing displacements, they turn into folds faulted on their bases. The stratigraphic unit forming the top of the folds continues below the cascade on the surface, but at a lower position. The deformation within the cascade structure can be complex in detail.

Small monoclines and cascade structures may serve to slightly increase the shearing resistance along the failure plane by introducing localized points of higher normal stresses that would result in some rock-to-rock contact. However, in general, the small monoclines are aligned in a stair-step fashion so that interruptions in the continuity of the clay layers are minimized with respect to slide movements to the north. The overall shear strength along a clay layer with a small monocline or cascade structure may be somewhat higher than for a smooth, continuous and uniformly dipping clay layer.

Another aspect of these folds is that they have served to preserve fragments of the clay layers that otherwise would have been eroded off of exposed bedding plane surfaces. Figure 16 is an example of a clay layer preserved in such a structure. Because of local increases in shearing resistance, the monoclinal and cascade structures also tend to collect the slide debris overlying them.

FIGURE 28. The western portion of the headscarp above location 18-6. The old headscarp is visible in the vegetated area above with a steep monoclinal fold changing to a fault at the scarp. Fragments of partly cemented breccia containing solution features remain attached to the cliff above.

The fault and associated dragfold found at the headscarp at the top of the western half of the slide are shown in Figure 28. The beds steepen appreciably close to the headscarp where they turn vertical or are faulted. Figure 28 shows that the recent headscarp is the lower portion of an older scarp whose shape is evident on the vegetated cliffs above. The fault mapped by Rossi and Semenza (shown in Figure 4) formed the eastern boundary of the slide.[26]

Fragments of partly cemented talus breccia are found along the new headscarp indicating that a peripheral crack had been opened prior to the 1960-1963 slide movements. Figure 29 shows the new scarp and the old scarp and a thick uncemented to poorly-cemented talus deposit that has filled a portion of the old peripheral crack. This crack opened up in 1960 and 1963. These old talus deposits are considered the best diagnostic evidence encountered for previous periods of movement of the Vaiont Slide in prehistoric, and perhaps during or since

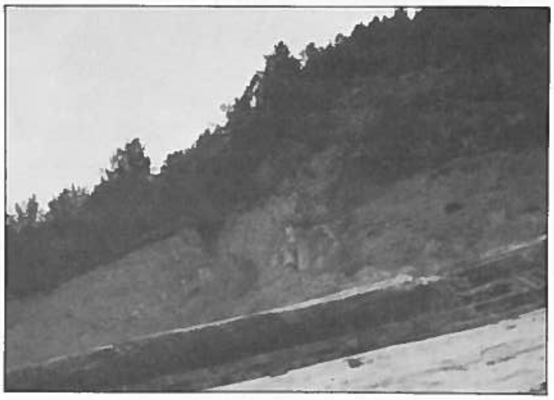


FIGURE 29. A view of the western portion of the headscarp. The old vegetated headscarp is continuous with the new 1963 headscarp. Two or more types of cemented breccia have infilled old "bergschrund." Solution cavities in better cemented, probably older, breccia are visible on the right.

FIGURE 30. A float boulder of partly cemented breccia in alluvium below rock slopes whose source is believed to be breccia at the headscarp similar to that shown in Figure 24.

Roman times. A close-up view of the partly cemented talus material from the old bergschrund-like crevasse at the scarp of the slide is shown in Figure 30.

Geomorphology

Perhaps the most significant question to be addressed by geomorphic studies is whether or not there is evidence of pre-1960 slope movement. A related and very practical question is: Could the Vaiont Slide been recognized as an old slide area prior to 1961 by using conventional airphoto interpretation techniques? The latter question is particularly important to the study of other reservoir slopes, for such reviews are done principally by airphoto studies followed by field geologic mapping.[40]

In order to answer these questions, airphotos taken in 1960 and another set taken a few days after the slide of October 9, 1963, were examined. One of the 1960 airphotos is presented as Figure 31. Figure 32 shows the geomorphic features delineated from the airphoto in Figure 31. Some of the major topographical features related to the slide have been depicted in Figure 32, including depressions and scarps, streams, gullies and sinkholes. Also outlined are the dam, reservoir, roads and visible traces of trails.

Two geomorphological factors delineated in the figure are of particular interest. The first factor is a series of depressions within the slide. These depressions occur in three areas:

- the Pozza plain
- the area between the Altopiano, or high plateau above the Pozza, and the cliff that traces the location of the dragfold, monocline or fault at what will develop into the headscarp of the western side of the 1963 slide
- the area of large scarps, one below the other, and small depressions on the eastern half of the slide

The eastern and western limits of the 1963 slide are defined in the 1960 airphotos by an abrupt change in morphology or by airphoto lineaments. The depressions in these three areas appear to be primarily the result of previous slide movements that occurred several thousand years ago. However, the depressions were no doubt enlarged by solution of the carbonate rocks present. Kiersch mapped a number of these depressions within the slide boundary and described them as sinkholes.[10] The time between the occurrence of the original landslide and the 1960 airphotos was sufficient for erosion to subdue the original landslide topography so that the evidence is not particularly obvious. However, it seems likely that, after detailed study, an experienced airphoto interpreter would recognize the area as a possible or probable landslide. Certainly, on-the-ground field investigations would be required to confirm such an interpretation. The appearance of the slopes above the slide, and west and northwest of the slide, suggest that they have been denuded by previous slides.

The second geomorphical feature of particular interest, and one of the most surprising aspects of the airphoto study, was the substantial area of pronounced karstic topography in a basin above the slide and to the west of the peak of Mt. Toc. Other small incipient sinkholes are present in the surface of the Dogger beyond the western and southern limits of the slide. These apparent kettles or sinkholes, which sometimes form small elongated doline-like depressions, are mapped in Figure 32.

Hydrogeology

The principal reason for studying the groundwater conditions within a slide is to determine the distribution of the water pressures acting along the sliding surfaces. When the average rainfall of an area is in the range of 1,200 to 2,300 mm/year and the terrain is mountainous, there is the potential for significant fluctuations in groundwater pressures and levels to occur. Detailed precipitation records for the village of Erto from 1960 to 1964 were supplied by ENEL.

The groundwater data available for the Vaiont Slide area are sparse and, unfortunately, questionable. The data consist of water levels measured in three drillholes (P1, P2 and P3) from the summer of 1961 until October 1963. The locations of these drillholes are shown in Figure 4. Water level measurements were made inside pipes placed in open drillholes. The annulus between the pipe and the rock was not sealed so that water pressures at different elevations in the rock would be expected to be connected (see Figure 33b). As a result, the water levels recorded inside the casing could reflect some average value of the different water pressures and hydraulic conductivities of the units encountered. However, if a natural seal developed on the outside of the pipe (for example, by a soft clayey layer squeezing around the pipe), then the water level inside the pipe would reflect average hydraulic pressure conditions in the formations below the seal as shown in Figure 33c. Such a seal could conceivably provide water pressure readings in the vicinity of the base of the slide as precise as if a fully-sealed standpipe piezometer, such as that shown in Figure 33a, had been installed. With continued but small displacements of the slide, the seal around the pipe could be eroded or the pipe could bend or be pulled apart and start to leak as shown in Figures 33e and 33f.

From early November 1961 (when P2 was first read) until late January 1962, the water level in P2 was 25 to 90 m above the reservoir levels. During this period the slide moved 5 to 10 cm. From February to July 1962, piezometer P2 showed levels lower than previously indicated, but still 2 to 10 m higher than piezometers P1 and P3. During this interval the slide had moved from 20 to 25 cm (since P2 was installed). After July 1962, the water levels recorded in P2 were generally within 1 to 2 m of those recorded in P1 and P3. Thus, the total displacement of the slide since P2 was installed was about 30 cm by July 1962. This much displacement was probably sufficient to pull out, rupture or pinch the end of the pipe in the manner suggested in Figures 33e and 33f.

One piezometer (P2) out of the three was apparently partially sealed and, for a period of about two months, gave more representative water pressures of conditions near the surface of sliding than the others. The other piezometers, P1 and P3, probably gave measurements that were representative of the groundwater table in the highly fractured rock mass above the basal clay-rich zone. The groundwater pressures in the bulk of the rock debris appear to have varied directly with reservoir levels, maintaining a slight (3 to 10 m) increase above reservoir levels. No groundwater data appears to have been obtained, or recorded, from the holes drilled after the 1963 slide.

The scarcity of groundwater data makes it important to develop a reliable concept of the basic hydrogeological conditions at the slide in order to make reasonable assump-

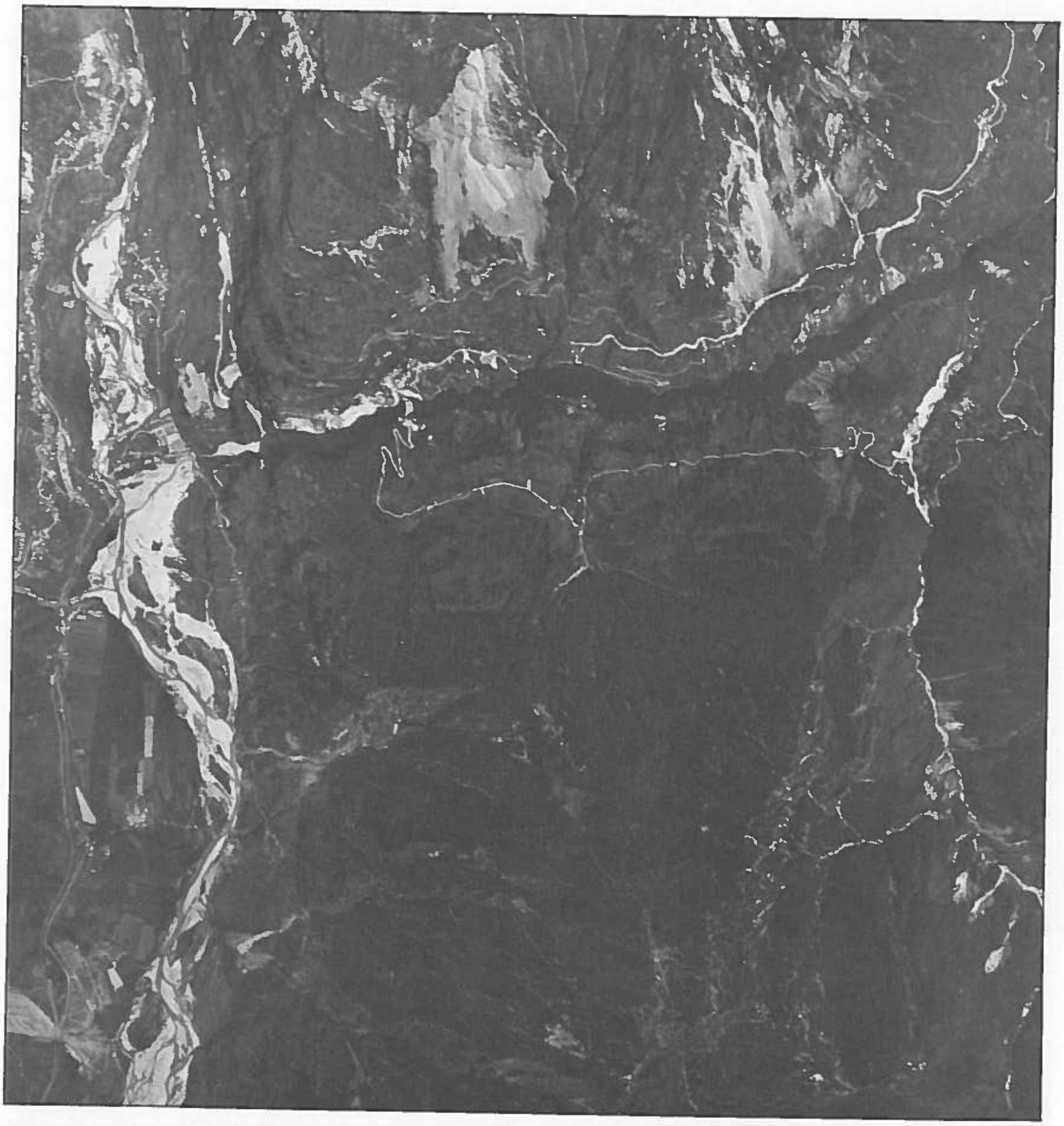


FIGURE 31. Airphoto of the Vaiont Dam and Reservoir area taken in 1960.

tions of water pressures for stability analyses. A knowledge of groundwater flow systems can be used to predict the typical pressure distributions to be expected.

Figure 34 on page 97 shows the general groundwater flow system that might be expected on a section through Mt. Toc, assuming a relatively homogeneous and isotropic distribution of hydraulic conductivities within the mountain. If on the northern slopes of Mt. Toc there was a tendency for higher conductivities along the bedding than across the bedding, there would be a corresponding tendency for the higher fluid potentials originating from infiltration in the area of the karstic topography on the upper slopes of the mountain to be transmitted to the Vaiont Slide region with minimal head losses. At the base of the Vaiont Slide mass, high fluid potentials would be held beneath the clay layers, whereas in the highly fractured rock above the more continuous clay

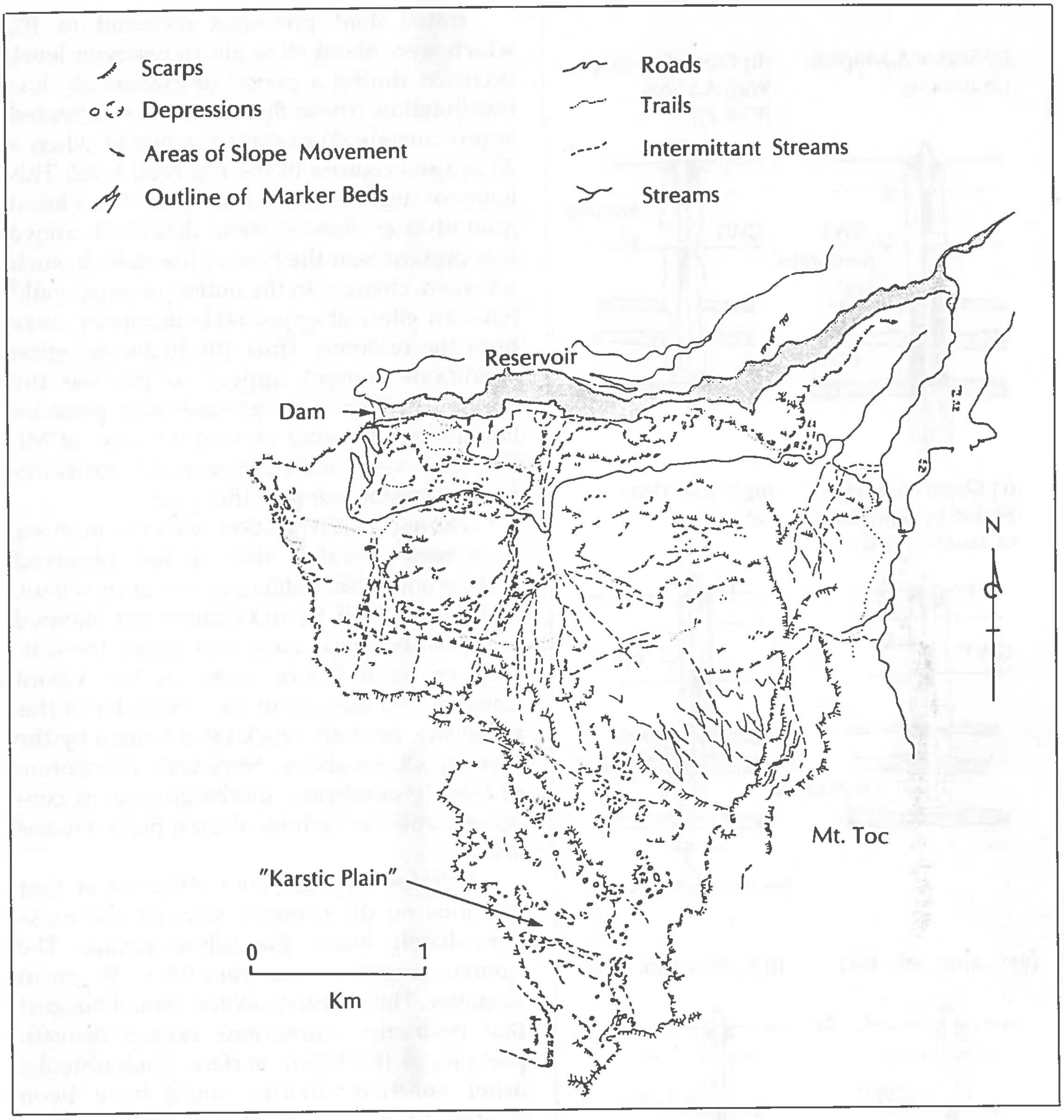


FIGURE 32. Geomorphic features of the Vaiont Slide area delineated from the 1960 airphoto (same scale as Figure 31).

layers, the fluid potential would be much lower, reflecting the fluid potential base level in the valley. The base level for the local groundwater pressures in the portion of the slide above a clay interbed is likely to be either the elevation of the intersection of the top of the clay with the valley wall or the reservoir level, whichever is highest. Beneath and within the zone of clay interbeds, the water pressures should vary with changes in the groundwater conditions (or levels) at the top of the mountain and with changes in the outlet pressure conditions in the valley at the base of the mountain. Therefore, the water pressures below the clay layers should directly reflect changes in infiltration rates because of rainfall or snowmelt above the slide and changes in reservoir levels. Kiersch was the first to comment on the importance of infiltration on slide mass stability.[10]

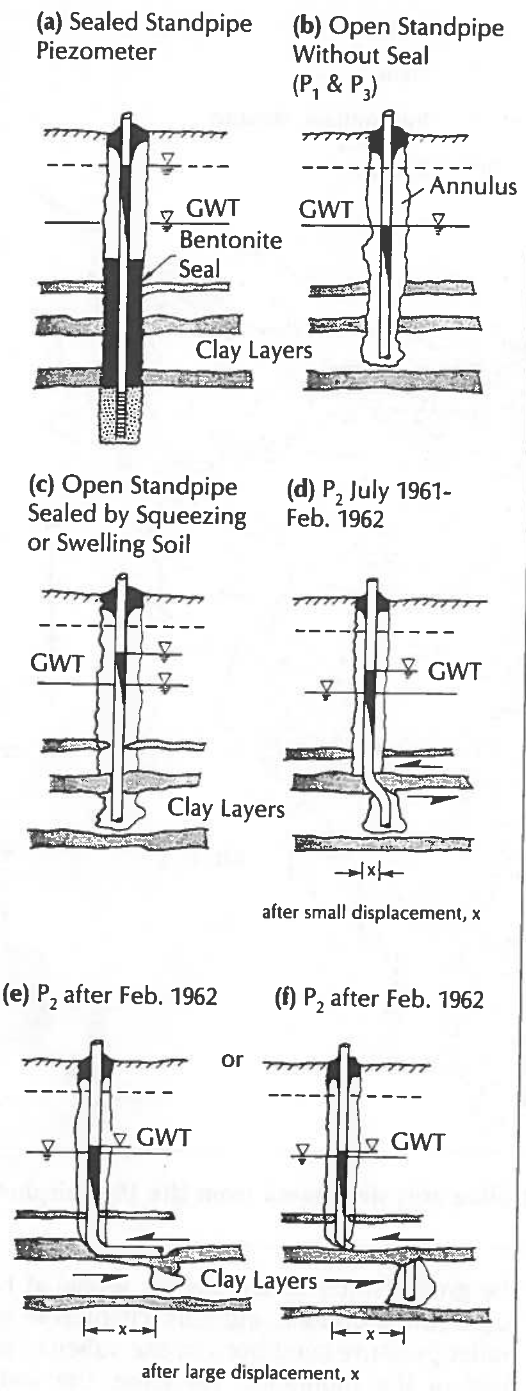


FIGURE 33. Sketches showing a possible explanation for the water levels recorded in P2.

Initial fluid pressures recorded in P2, which were about 90 m above reservoir level, occurred during a period of moderately low precipitation. These fluid pressures increased approximately 20 m during a period when a 20 m rise occurred in the reservoir level. This increase implies that the relatively closed groundwater flow system described above was present near the base of the slide. In such a system, changes in the outlet pressure could have an effect at appreciable distances away from the reservoir. Thus, the hydrogeological conditions present appear to provide the opportunity for large groundwater pressure fluctuations to occur around the base of Mt. Toc. The very limited piezometer measurements available support this view.

During a conversation with the authors, E. Semenza recalled that he had observed springs and moist patches in two areas where, in 1959 and 1960, he and Giudici had mapped the exposed shear zone that forms the outcrop of basal failure plane in the Vaiont Canyon. The outcrop of the remainder of this plane was beneath a rock talus formed by the raveling slopes above. Semenza's description of these groundwater discharge areas is consistent with the hydrogeological picture noted above.

Solution cavities were observed at four locations on the exposed scarp in the rocks immediately below the failure surface. The cavities ranged in size from 0.5 to 50 cm in diameter. The solution cavities would suggest that hydraulic connections existed beneath portions of the failure surface. Undoubtedly, other solution cavities could have been located if time was spent investigating these features. Solution cavities are most likely to be associated with small faults and folds in the bedding, and with beds that are more susceptible to solution than others.

During field visits to the Vaiont Slide, the authors observed that during moderate to heavy rainfalls no water flowed from the Massalezza Ditch onto the slide scarp, although many of the drainage paths down the scarp become torrents. This lack of flow in the Massalezza is believed to be indicative of the very high infiltration of precipitation into the karstic bedrock on the slopes above the slide

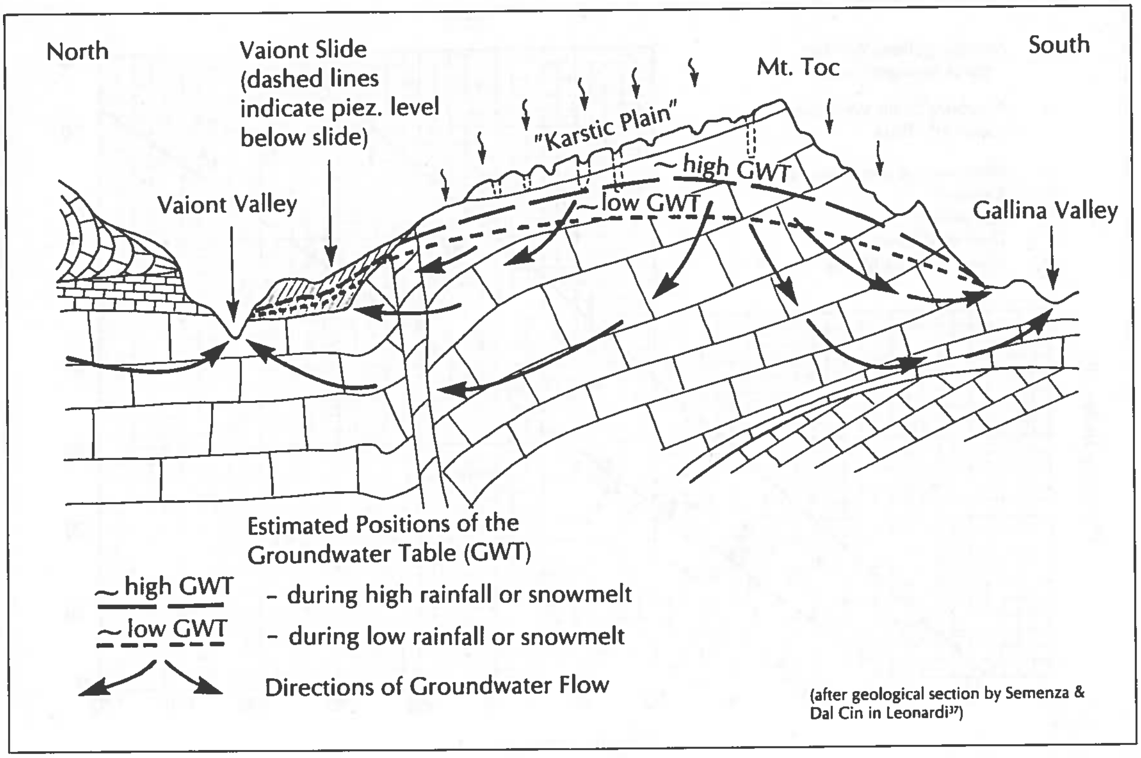


FIGURE 34. A schematic section through the Vaiont Slide showing the estimated regional groundwater flow system.

scarp. Presumably, water would flow in the upper Massalezza Ditch after heavy and prolonged rainfalls or snowmelts. But when this happens, the groundwater pressures in the underlying rocks would have to be much higher than when the Massalezza runs dry.

One of the main purposes of the adits placed in 1960-61 on either side of the Massalezza Ditch (see Figure 4) was to investigate the possibility of draining the slide.[20] One of these adits was encountered by the authors on the east side of the Massalezza. The top of the portal of this adit had approximately 1 m of cover below the exposed failure surface. Since these adits were so close to the Massalezza, which generally was dry, it is not surprising that very little water was encountered in them. The adits were located too high in the slide and too close to the ground surface to encounter the high water pressures that were undoubtedly present at greater depths and in more representative portions of the slide. This placement was unfortunate, since conclusions drawn from the lack of water encountered in adits were reportedly responsible for the 1961 decision that it was not practical to stabilize the slide by drainage.[41]

In 1979, E. Semenza described for the authors the sheared clay-rich zones (ultramylonites) that were exposed in the adits of the western side of the Massalezza and along the adjacent stream bed and noted earlier by Semenza.[12] Little attention has been given to these clay-rich zones in the literature. They, no doubt, were outcrops and subsurface exposures of previous or potential slide planes.

Lo *et al.*, and others, speculated on the probable existence along the base of the slide of artesian pressures.[42] Generally, these writers assumed that the pressure distribution along the failure surface followed a straight line from the reservoir to the top of the slide. Such an assumption for the distribution of fluid pressures results in piezometric levels that are much higher than the initial readings of piezometer P2 indicated. The water pres-

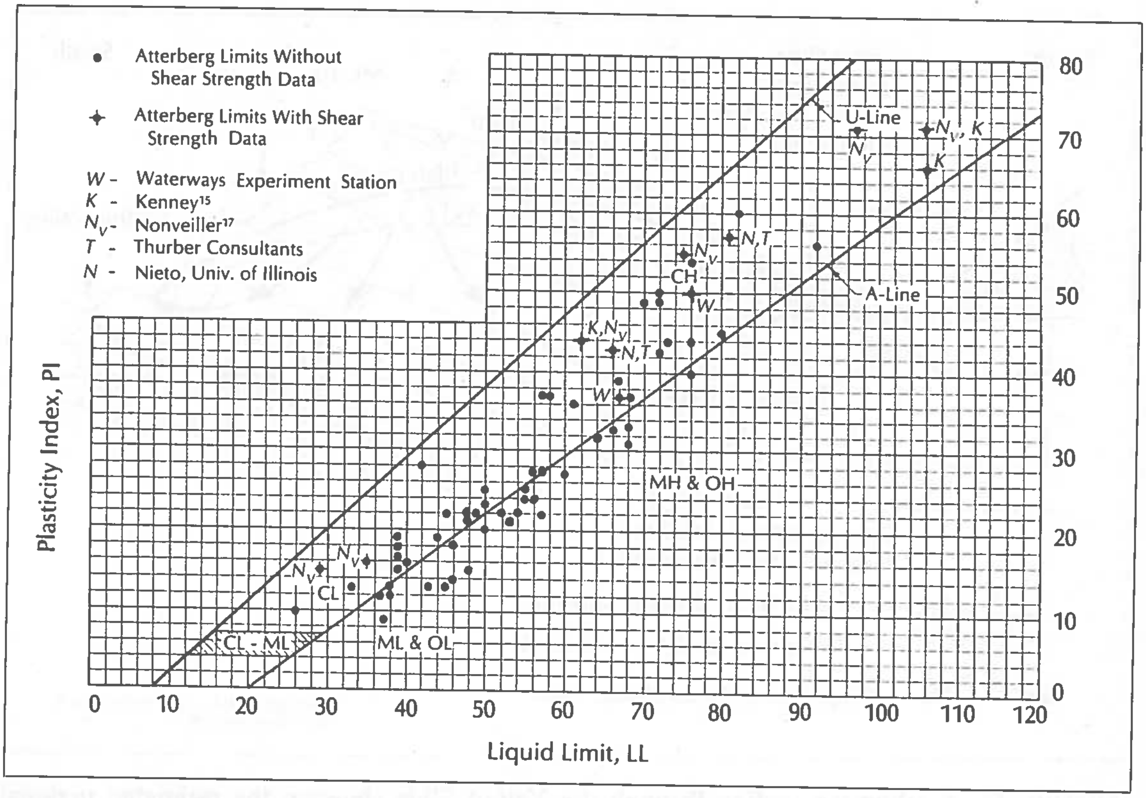


FIGURE 35. Plasticity chart for the clay samples from the slide site.

sure distributions used in the analyses in this study were made to agree with the initial P2 record for low rainfall conditions and were increased for high rainfall conditions.

Physical Properties of the Clays

The properties of the clayey materials found along the failure surface of the Vaiont Slide were tested by soil laboratories in several different countries during the course of this study.[43] The tests were conducted over a five-year period from 1976 to 1981. The initial tests in 1976 and 1977 were made for work on the Downie Slide undertaken by the authors for the British Columbia Hydro and Power Authority. The results of all these tests are presented in this section together with the results of tests on the Vaiont clay layers published by others. The tests performed include grain-size analyses, Atterberg limits, direct shear strength tests and clay mineral analyses.

A grain-size analysis completed on one of the clay samples indicated 51 percent clay, 36 percent silt, 7 percent sand and 6 percent gravel. Samples of the Vaiont clays were also examined by Kenney.[15] He reported similar results, with 52 to 70 percent of his samples less than 2 microns in size.

Atterberg limits are more directly related to the strength properties of the soil than are the grain-size analyses. Therefore, most samples were tested for their liquid and plastic limits. These results are presented in Table 2. Figure 35 is a plasticity chart that shows the Atterberg limits of the clay samples obtained.

The results are well distributed over a large range of liquid and plastic limits. However, there appears to be a tendency for the samples to fall within two general groups. One group plots nearly on the A-line, and the soils are classified as CL, ML and MH. Thus, these soils are inorganic clay of low plasticity and inorganic clayey silts of low to high plasticity. The liquid limits of this group vary from 33 to 60 and the plasticity indices vary from 9 to 27. The other group falls within the area of the plasticity chart distinctly above the A-line. These soils are classified as clays of high plasticity (CH soils). In this second group, the soils had liquid limits that varied from 57 to 91 and plasticity indices that varied from 30 to 61.

Results of tests by Kenney and Nonveiller for clay samples from the Vaiont Slide are also shown on Figure 35.[15,17] The liquid limits (29 to 116) and plasticity indices (15 to 71) of some of these samples exceed those measured in this study, but are consistent with the character of the clays noted in the field observations.

Shear strength test results are summarized on Tables 3, 4 and 5. Test results given in Tables 3 and 5 were conducted by reversing the direction of movement in a direct shear box, whereas the tests in Table 4 were made with a direct shear box that permitted approximately 5 cm of travel in one direction. All shear strength tests were made on samples of the remolded clayey soils.

Two series of tests were performed on one sample in Table 3. These tests were made at stress levels of 103 to 6,200 kPa (15 to 900 psi) and the surfaces of sliding were pre-cut. The first series of tests were conducted on that portion of the sample (83 to 87 percent by weight) passing the No. 10 sieve size. The second series of tests were conducted on the material that passed the No. 4 sieve. The thickness of the samples was 7 to 11 mm, and the rate of shearing varied from 1 to 0.003 mm per minute. The area of samples was 25.8 cm^2.

The results indicate a range of values from 5.9° to 16.4° for the drained residual angle of friction, with higher values generally being obtained from tests run at lower stress levels. If results from tests made at stress levels under 350 kPa (50 psi) are ignored, the results for samples 522-5 and 522-5A range from ϕ_r = 9.6° to 11.4° for "whole" samples and 7.4° to 8.5° for the fine-grained portion of the samples. The results for sample 11-9 for stress levels of 350 to 1,030 kPa (50 to 150 psi) range from ϕ_r = 5.9° to 9.6°.

The results of the clay mineral analyses are presented in Table 6 on page 102 together with the results of Kenney.[15] The clay mineral analyses indicate that some 50 to 80 percent of the whole samples are clay minerals predominantly of the type generally known in soil mechanics as calcium montmorillonites. However, in detail, the clays are composed of 25 to 75 percent of a mixed layer vermiculite/smectite composition with the remainder of hydrous mica illite to smectite composition containing something on the order of 60 percent smectite. An illite/corrensite composition is reported in one set of analyses. Such clay materials have an expanding lattice, are associated with low shear strengths and exhibit swelling properties when stresses are reduced and water is present. The residual angles of shearing resistance obtained from these samples compare favorably with the 8° to 10° reported by Olson for calcium montmorillonite.[44] Olson's tests were run with stress levels of 350 to 500 kPa (50 to 75 psi).

Correlations Between Reservoir Level, Precipitation & Rate of Movement

A chronological list of the events leading up to and following the Vaiont Slide is given on pages 106 - 111. Natural events, construction activities and the activities of engineers and geologists investigating the slide area have been included as an aid in understanding many of the technical aspects of the slide.

Comparisons between precipitation in 10-day intervals with reservoir level, rate of slide movement and water level in the piezometers from 1960 through 1963 are presented in Figure 36 on page 104. There was a small slide in March 1960 at the toe of the east end of the overall slide (shown in Figure 4). The time of this slide, which occurred before displacement measurements were made, is shown in Figure 36. The March 1960 slide occurred without a noticeably high 10-day incremental rainfall, although there were substantial 3-day rainfalls. This early slide also could have been associated with a period of snowmelt and probably was strongly influenced by the rising reservoir.

The first major slope movement that was monitored occurred in October 1960 during the first filling when the reservoir level had reached an elevation of about 650 m. By late October 1960, the displacements were sufficient to result in a series of cracks that

TABLE 3

Summary of Direct Shear Test Results on Remolded Vaiont Clays — Group 1

Sample No.	Water Content of the "as received" Soil (%)	Atterberg Limits LL (%)	Atterberg Limits PL (%)	Atterberg Limits PI (%)	Shear Test & Specimen Details: Test Conducted on	Shear Test & Specimen Details: Type of Test
Vaiont Sample 522-5A	26.2	66.2	22.5	43.7	Soil after removing all rock & coarse sand retained above sieve No. 10. About 13-17% by weight of total sample was removed which constituted the rock fragments & coarse sand.	Multistage direct shear test along a precut plane.
Reconstituted Vaiont Sample 522-5A	26.2	81.0	23.8	57.2	*Reconstituted* sample after adding back the coarse sand fraction between sieve Nos. 4 & 10 to the above sample. However, rock fragments were not added.	Multistage direct shear test along a precut plane.

Note: Results shown in this table were from tests performed by Thurber Consultants Ltd., Edmonton, Canada. Grain size distribution for the original sample was: Gravel 6%; Sand 7%; Silt 36%; and Clay 51%.

TABLE 4

Summary of Direct Shear Test Results on Remolded Vaiont Clay — Group 2

Sample 522-5

Vaiont Test No.	Test Type*	Deform. Rate (mm/min)	Initial Normal Stress (kPa)	Peak Shear Resist.** (kPa)	Displ. at Minimum Resistance (cm)	Normal Stress at Min. Resist. (kPa)
1W	1	0.0635	576	161	2.89	712
2W	1	0.0635	576	143	2.34	681
		0.00635			3.48	747
3W	1	0.0635	421	93.8	1.55	467
4W	1	0.0635	576	147	1.98	665
					2.41	685
5W	1	0.0635	576	154	2.34	678
6W	1	0.0635	576	150	2.97	713
7W	1	0.0635	288	89.6	2.54	346
					5.41	246
8W	1	0.0635	288	93.1	5.21	438
9W	1	0.0635	157	53	5.33	242
1F	2	0.0635	576	131	2.95	713
2F	2	0.0635	288	71	5.21	350
3F	2	0.0635	576	152	3.18	730
					3.68	381
					4.42	221
					5.51	572

Note: Results shown in this table were from tests performed by the Engineering Geology Lab, Dept. of Geology, Univ. of Illinois-Urbana. *Test Types: 1 = Whole Sample; 2 = Fraction passing #140 mesh; 0.15 cm sample between two 5 x 15 cm slabs of Berea sandstone unless otherwise indicated. **Displacement at peak resistance assumed to be zero.

Remolded Water Content (%)	Normal Stress σ_n (kPa)	Post-Shear Water Contents: Shear Plane	Post-Shear Water Contents: Away From Shear Plane	Residual Shear Strength τ_{res} (kPa)	Effectual Residual Strength Parameters: tan ϕ_r τ_{res}/σ_n	Effectual Residual Strength Parameters: ϕ_r
27.0	6205	25.9	25.3	810	0.131	7.44°
	1724			252	0.146	8.3°
	345			55	0.16	9.1°
30.0	6205			1047	0.169	9.6°
	103			30.3	0.293	16.4°

Minimum Shear Resistance (kPa)	Tan ϕ	ϕ deg.	Remarks
144	0.203	11.4	Added only enough water to work sample into a 0.15 cm layer.
126	0.185	10.5	Added additional water; allowed sample to soak for two days.
134	0.181	10.2	Ran sample for about 0.25 cm to test effect of deform. rate of ϕ_M. Ten-fold decrease in deform. rate resulted in 2% drop in ϕ.
70.3	0.150	8.5?	
114	0.172	9.8	Resistance increased slightly after passing through min. value (see next line)
121	0.177	10.0	
114	0.167	9.5	
122	0.171	9.7	
68	0.195	11.0	Sample was unloaded after reaching residual. Thin sample. Normal load = 1223 N.
47	0.193	10.9	
83	0.189	10.7	
54	0.223	12.5	
99	0.139	7.8	
48	0.135	7.7	
109	0.150	8.5	Sample was unloaded after reaching residual.
56	0.146	8.3	Normal load = 2237 N.
33	0.149	8.5	Normal load = 1214 N.
84	0.147	8.4	Normal load = 2842 N.

TABLE 5

Summary of Direct Shear Test Results on Remolded Vaiont Clays — Group 3

Sample 11-9

Specimen No.	Atterberg Limits LL	Atterberg Limits PL	Atterberg Limits PI	Initial Water Content %	Dry Density N/m³	Initial Void Ratio	Saturation %	Final Water Content %
1	76	26	50	35.4	13480	0.998	97.5	30.2
2	67	30	37	30.3	13866	0.944	88.3	27.7

Note: Results shown in this table were from tests performed by the Waterways Experiment Station, Vicksburg, MS. Shear plane precut & sample description: plastic clay (CH), gray.

TABLE 6

Summary of Clay Mineral Analyses on Vaiont Samples

Laboratory	Sample No.	Results
WES (A.D. Buck) (See Table 5)	1. Clay, 11-9	smectite-major component (50%) calcite-minor component quartz-minor component kaolinite-minor component
	2. Limestone (fine-grained greenish-gray)	calcite-major component quartz-minor clay & mica-minor "randomly mixed-layer"-smectite & vermiculite-minor
Dept. of Geology Univ. of Illinois (Dr. Eberl) (See Table 4)	1. Whole rock (*i.e.*, clay sample) 522-5	calcite-major component corrensite illite/smectite quartz (↓ decreasing order of abundance)
	2. Less than 2-micron fraction 522-5	corrensite* (vermiculite/smectite type) illite/smectite* (-60% smectite layers) calcite quartz-small amount (* = present in approx. equal proportions)
Alberta Research Council (Thurber) (See Table 3)	5A. 522-5A	illite hydrous mica mixed layer clay minerals containing montmorillonite
Kenney[15]		Massive Minerals (% Dry Weight)

Massive Minerals (% Dry Weight)

	Qtz	Feldsp	Calcite	Others	Total	ϕ_r
Vaiont I	5	5	30	10	50	10.25°
Vaiont II	10	—	7	5	22	9.0°
Vaiont III	5	—	40	—	45	15.75°

Clay Minerals (% Dry Weight)

	Kaolin	Chlorite		Mica (Hydrous mica Illite)	Mixed Layers with Montmorillonite		Montmorillonite
Vaiont I	—	—			—	50	—
Vaiont II	—	—	5	—	—	75	—
Vaiont III	—	—	30	—	—	25	—

Estimated Specific Gravity	Type of Test	Normal Stress kPa	Residual Shear Stress kPa	Deform. Rate mm/min	Displ. at Estimated Shear cm	tan ϕ	ϕ_r
2.75	Shear	171	23.0	0.0089	9.52	0.134	7.6°
	test	345	37.9		19.1	0.110	6.27°
	along a	689	86.8		24.1	0.126	7.18°
	precut						
2.75	surface	517	53.8	0.0089	4.6	0.104	5.9°
		1033	175		16.3	0.169	9.6°

essentially outlined the perimeter of the entire slide as it subsequently developed in 1963. This perimeter crack is shown in Figure 4 together with the outline of the October 9, 1963, slide. Figure 36 demonstrates that the development of the perimeter crack coincided with the maximum 10-day precipitation for the year. Also, the onset of significant movement coincided with the start of a period of unusually heavy and prolonged precipitation that followed an exceptionally wet July and August. The slide continued to move after the perimeter crack opened, reaching a maximum rate of 3 -4 cm/day at the end of October 1960.

On November 4, 1960, a major slide occurred along the toe of the future Vaiont Slide and some 700,000 m^3 of material slid into the reservoir. The outline of this slide is shown in Figures 4 and 20. The reservoir level was lowered immediately after the November 4 slide from a maximum level of 650 m and reached el. 600 m by early January 1961. Thereafter, slide movements decreased rapidly to less than 0.1 cm/day. The slide essentially stopped moving when the reservoir level was below el. 600 m and when the precipitation was low.

At the end of the first drawdown, the average total displacement on the western half of the slide area was 100 cm, and the total movement east of the Massalezza Ditch was less than 20 cm. Figure 36 shows that the decline in the rate of movement of the slide from November 1 to 4, 1960, corresponded to the end of an abnormally high rainfall. At this point the reservoir level was still rising.

The reservoir was held between el. 585 and 600 m from early January 1961 until early October 1961. During this period, a bypass tunnel was driven into the right bank of the valley opposite the 1963 slide area. This period was one of moderately low precipitation except for one wet 10-day stretch in May 1961. The rate of movement of the slide during this period was negligible. Piezometers P1, P2 and P3 were installed during this period and water level readings commenced as shown on Figure 36.

The second filling of the reservoir began in October 1961, and near the end of January 1962 the reservoir elevation was again at 650 m. As Figure 36 indicates, the rate of movement corresponding to the second filling to el. 650 m was negligible and the velocity was less than 0.1 cm/day. This behavior was in sharp contrast to the 3.5 cm/day velocity observed when the reservoir was just below el. 650 m during the first filling. Even as the reservoir approached el. 700 m at the beginning of November 1962, the velocity was only about 0.2 to 0.3 cm/day. The rate of movement increased abruptly to about 1.2 cm/day at the end of November 1962, although the reservoir remained nearly constant at the 700 m elevation. This increased movement followed a period of record precipitation for the four-year period shown on Figure 36. The reservoir was lowered to 650 m by the end of March

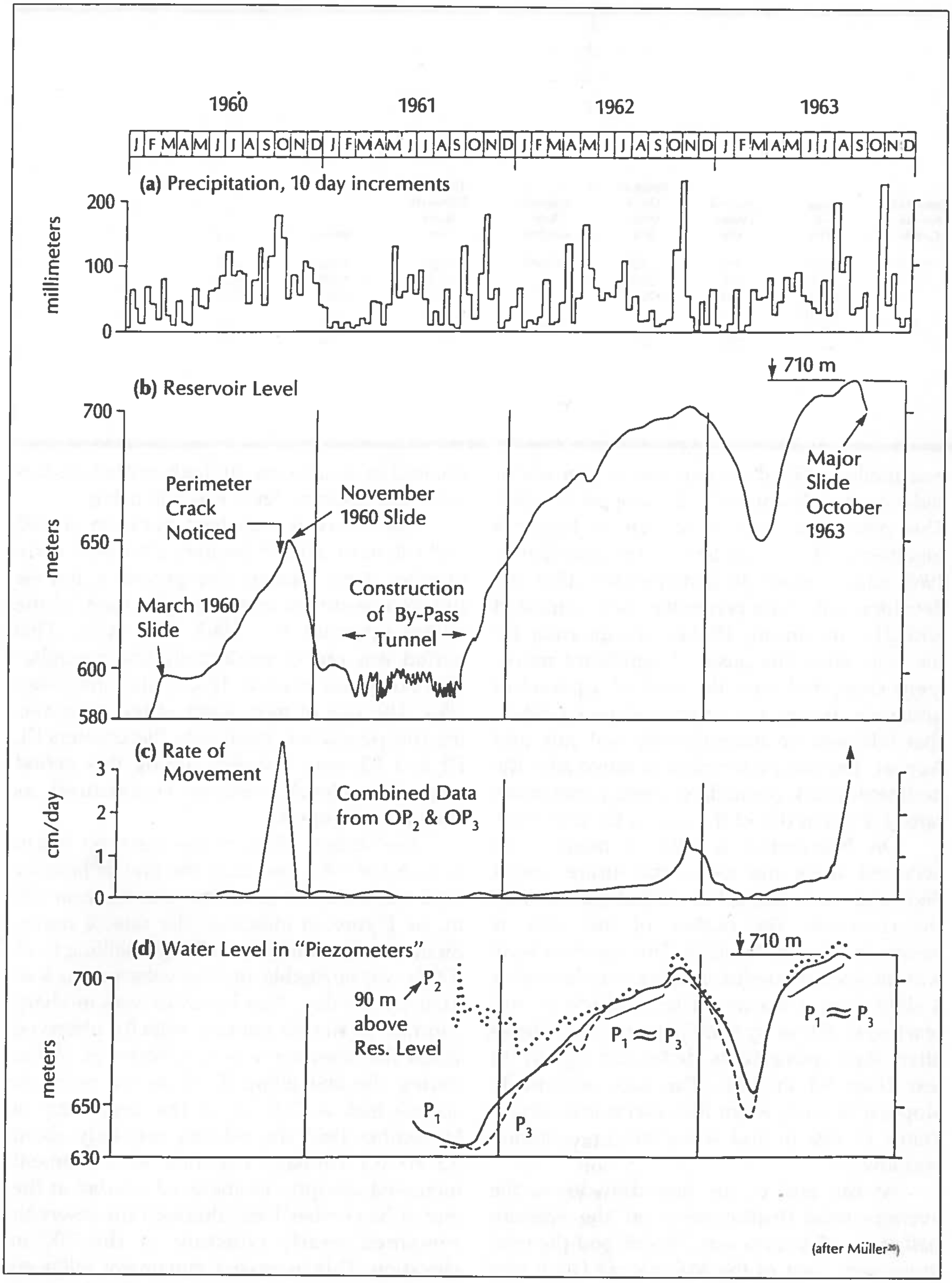


FIGURE 36. A comparison of the water levels, slide movements and precipitation from 1960 to 1963.

1963 and the movement stopped. But the movements that occurred during the second filling and drawdown to el. 650 m amounted to 130 cm. These movements were in addition to the 100 cm of movement that occurred due to the first filling.

The third filling of the reservoir began in April 1963, and the reservoir reached approximately el. 695 m by early June 1963. At this time the slide velocity was about 0.3 cm/day (see Figure 36). The reservoir reached 705 m in the middle of July 1963, and the rate of movement increased to about 0.4 to 0.5 cm/day.

In mid-August, the reservoir started to rise from el. 705 m and reached 710 m in early September. There was an immediate increase in the rate of slope of movement from 0.5 to 1.0 cm/day. This rate continued to increase throughout September, reaching 2 to 4 cm/day in the first days of October. In early October, lowering of the reservoir began. The elevation of the reservoir had dropped to about 700 m by October 9, 1963, when the major slide occurred. According to the report of the Bozzi Commission, the velocity of the slide by that day was about 20 cm/day.[45] Figure 36 shows that the final acceleration of movement began in late August 1963 and coincided with a period of near-record precipitation for the four-year period.

If other factors governing stability remain constant, then it is reasonable to assume that similar rates of movement should be observed for similar reservoir levels. The empirical observations at Vaiont, which showed that the movement of the slide in October 1960 was 3.5 cm/day when the elevation of the reservoir was at 650 m, seemed at variance with the observation of a negligible slide velocity in January 1962 when the reservoir was also raised to el. 650 m. Moreover, the rate of movement of 1.2 cm/day, which accompanied the reservoir elevation of 702 m in November 1962, was below the rate of 3.5 cm/day observed for the 650 m reservoir elevation in October 1960. Having such data available, Müller stated:[20]

> "The experiences gathered during the second period of storage seemed also to confirm the assumption, developed in the meantime, according to which it was considered possible to control the velocity of the slide by the effect of the water on the sliding mass itself. The observation that the movements generally had a higher velocity only if a new portion was wetted for the first time, whereas they remained always smaller than the previous one if a layer once wetted was flooded the second time, led authorities and technicians to the conviction that a gradual stabilization of the moving mass would be brought about by raising the water level in individual steps. It was assumed that the mass would eventually reach a certain equilibrium, or, at least would keep moving so slowly that no serious problems would occur" (p. 178).

The erroneous assumption that led to the conclusions quoted above was that all other factors were remaining constant and the reservoir level was the main variable controlling the stability of the slide. In fact, rainfall was significant and was not remaining constant. Figure 36 reveals that there were periods of high precipitation preceding all the major slide movements in October 1960, November 1962 and October 1963. In addition, when there are different movement rates for similar reservoir levels, the higher movement rate correlates with a higher precipitation rate. For example, the second time the reservoir reached el. 650 m in January 1962, there was negligible movement because of the low precipitation at that time and in the preceding months. Another example can be seen by comparing the rates of movement for June 1963 when the reservoir was at el. 700 m with those for November 1962 at the same reservoir level. The rate of movement was accelerating in November 1962 following a period of record precipitation, whereas in June 1963, with near normal precipitation, the rate of movement was nearly constant and at half the rate observed in November of 1962. Thus, from an evaluation of the records shown in Figure 36, rainfall appears as important as the reservoir level in determining the rate of movement of the slide.

The history of the three slide movements

Chronology of Significant Events

1928 Prof. Giorgio Dal Piaz examined the stability of the future banks of the reservoir. At that time no question was raised about the area of the 1963 slide.[20] The Bozzi Commission indicated that while Dal Piaz described a general phenomena of deep fissures near the Casso bridge, nevertheless the reservoir conditions were no worse than those met on the great majority of the mountain basins throughout the Venetian area.[45]

1956-57 Excavation at the dam.

July 1957 Construction of the dam began.

1957 Müller was consulted on problems of the stability of the rock abutments of the dam and on how the stability of the future reservoir banks should be determined. On the basis of a short inspection of the rock fabrics, Müller thought it possible that the reservoir "would cause slides, some of which might be perhaps as much as 1 million m³ in some parts of the future banks" (p. 156).[20]

1958 Dal Piaz reexamined the stability of the left valley slopes between the Pineda and the dam in connection with the construction of the new road along this bank. He concluded that the rock was fractured, but it was in place and showed no signs of an earlier movement with the exception of a small strip 500 m east of the Pozza where the rock was covered with moraine-like materials. Dal Piaz concluded that only local detachments of such materials could be expected; however, these would not be of a serious magnitude (p. 157).[20] The Bozzi Commission noted that Dal Piaz included a discussion of fissures in the area of the Pozza in his report.[45]

Spring 1959 Carlo Semenza, designer of the dam, invited Müller and E. Semenza, geologist, to inspect the banks of the future storage reservoir.[12] Semenza noted that following this visit, Müller, in his report No. 6 of 1959, outlined a general investigation program to assess the stability of the Vaiont banks.

Summer 1959 F. Giudici and E. Semenza conducted a geological survey of the banks of this proposed reservoir.[7] Field observations made during this survey led to the first doubts regarding the stability of the left bank.[12] (Much of the earlier concern had been for the Erto area). An uncemented mylonitic zone, extending some 1.5 km along the left wall of the Vaiont Canyon, was identified during this survey. Question marks on the geologic sections (see Figure 7a) indicated the authors' uncertainty about the upslope extent of a possible slide mass associated with this fault.

Rock masses with disturbed bedding were found lying on gravel and sand deposits on the righthand side of the Vaiont Valley. On the basis of these facts, it was then hypothesized that the area from the Pozza down to the Vaiont River represented the mass of an old prehistoric slide that moved down Mt. Toc in a northeast direction.

Oct. - Nov. 1959 Caloi started a

can be explained by considering the combined effects of precipitation and reservoir elevation. It is not necessary to consider another mechanism, such as "creep" or "thixotrophy," because the behavior only appears to be anomalous when the movements are correlated with reservoir levels without considering precipitation.[3,4]

As heavy rainfall or snowmelt penetrated into the slopes of Mt. Toc, uplift pressures could be generated on the failure surface corresponding to piezometric levels much higher than the reservoir level. At low reservoir levels, very heavy rainfalls would be required to develop uplift pressures large enough to cause slide mass instability. As the reservoir seismic survey of the Massalezza area along a profile that lay roughly parallel to the Massalezza Ditch and extended from the Vaiont Gorge to el. 850 m. The total length of the two traverses completed came to about 1 km. Caloi interpreted the results to be proof that the left valley wall consisted of "extraordinarily firm in-situ rock — covered with only 10 to 20 m of a loose slide material. Thus the hypothesis of an ancient very deep slide of the in-situ rock became improbable" (p. 159).[20]

In a letter to his father, Carlo, in April 1960, E. Semenza differed with Caloi's conclusions.[12] Semenza indicated that, in his opinion, the left side of the valley was a large rock mass that had slid in the past in a northeast direction. This opinion was discussed by Giudici and Semenza in their report submitted in June 1960 and was also noted by Müller.[20]

Feb. 1960 Filling of the reservoir began.

Spring 1960 Borings S-1, S-2 and S-3 (see Figure 4) were drilled to depths of 172, 71 and 105 m, respectively, in the toe of the western side of the slide under the supervision of F. Giudici and E. Semenza.

Trenches were excavated in the depression south of the Pozza. Heavily fractured and highly permeable (water circulation was frequently lost) green and pink marly-calcareous materials were found towards the bottom of the borings. No traces of the Dogger and Malm formations and of the old sliding plane were found in these borings. The borings could not be drilled any deeper because of the continuous collapse of the borehole walls.[12] In the trenches, well-stratified cherty limestones with open cracks were found.

March 1960 The reservoir was filled to el 595 m. Small rockfalls took place just east and west of the Massalezza Ditch.

May 1960 The first survey reference points were installed on the left slopes of the Vaiont Valley.

June 1960 Giudici and Semenza submitted their formal report that established the presence of "numerous intercalations of greenish clay, with thickness of a few centimeters" in the Lower and Upper Cretaceous material of the site.[7] The presence of the various mylonitic zones in the left slope, particularly a mylonitic zone below the mouth of the Massalezza at an approximate elevation of 625 m, together with the rock debris remaining on the right valley slope was considered by Giudici and Semenza as evidence of an ancient slide in the left slope. They pointed out that the whole mass below Pian del Toc, between Casera Pierin and Colomber, could slide if the surface of the prehistoric slide was inclined towards the lake. Furthermore, they indicated this movement could be produced by the reservoir filling.

July 1960 Dal Piaz submitted another geological report in which he reexamined the stability of the reservoir banks. He found no evidence of past movement in the rock of the left bank. A similar large occurrence in the future was not considered possible. The report mentioned the possibility of smaller slides developing in loose layers near the surface between Pineda and the Pian della Pozza only. Partial and localized detachments of

continued

level increased, the piezometer gradients towards the reservoir would tend to be maintained in such a manner as to transport the same amount of water through the bedrock. Therefore, as reservoir levels increase, the piezometer pressures should also increase, causing progressively smaller amounts of rain to produce unstable conditions.

Precipitation records from three stations, covering the period from 1960 through 1964, in the vicinity of the Vaiont Dam were examined. Two of the stations, Erto and Cimolais, are located east of the dam at el. 726 and 652 m, respectively. The third station at Longarone is at an approximate elevation of 474 m. A study of the precipitation records reveals rock "glebes and slices" along the edge of the Pian della Pozza, which would not extend to the Pozza itself, were predicted. "It was finally admitted that such detachments would help the area to reach a sure equilibrium" (p. 160).[20]

Summer 1960 Studies by E. Semenza were made to define the boundary of the old slide mass.

Sept. 1960 The dam was completed.

June - Oct. 1960 The reservoir level was raised from 595 to 635 m. Movements were recorded on the slope along the canyon wall from the dam to 350 m west of Massalezza Ditch, the region of the November 1960 slide noted below.

October 1960 The reservoir is filled to el. 635 m. Benchmark movements accelerated and a crack over 2 km long (see Figure 4) formed in the approximate location of the perimeter of the October 1963 slide. Approximately 500 mm of rain, the largest rainfall in the life of the reservoir, was measured at the Erto Station during this month. Cumulative movements of the sliding mass measured between the Massalezza Ditch and the dam exhibited an average of 1.0 m and a maximum of 1.4 m.[46]

Nov. 4, 1960 With the reservoir at el. 645 m, a 700,000 m^3 slide occurred on the left side of the valley just upstream from the dam (see Figures 4 and 20). This collapse produced a 2 m high wave in the reservoir.

Nov. 8 - 16, 1960 Müller, E. Semenza, Broili and others were called to Vaiont to investigate the movements of late October and early November 1960. In his Report No. 15, Müller outlined the nature of the movements, the various causes responsible for the movements and suggested a series of potential remedial measures.[41] He concluded that the sliding mass followed basically two types of movements: (a) a glacier-type movement that took place at the lower part of the slope between the dam and the Massalezza Ditch, and (b) a rigid block ("en block") type of movement that took place in the rest of the slide. He also concluded that it was not possible to stop the movements completely, and the only alternative was to maintain the slide under control by limiting the size of the sliding mass as well as the velocity of displacements. It was assumed that slow and controlled mass displacements would eventually build a passive resistance at the toe of the slide large enough to provide equilibrium. To gain control of the sliding movement, he recommended: (a) a slow and controlled lowering of the reservoir level, and (b) lowering and leveling of the phreatic level by means of two drainage tunnels driven underneath the sliding mass. These adits would start in the vicinity of the Massalezza Ditch at an approximate elevation of 900 m and run east and west, respectively. (Note, it is now known that the 900 m elevation was above most of the slide mass.) Other remedial measures — such as rock removal to reduce the weight of the "driving" mass, cementation of the sliding plane to improve the friction resistance along the sliding plane, and attempts to stop or considerably reduce the amount of water infiltrating the sliding mass — were considered either too expensive or be-

that the upstream stations of Erto and Cimolais (see locations in Figure 1) recorded much more precipitation that the station at Longarone. The records also show reasonably similar rainfalls at Erto and Cimolais. Since the Erto station was closest to the Vaiont Slide, its records were chosen to represent precipitation at the slide. However, actual precipitation on and above the slide very likely may have been higher than at Erto. Müller summarized the precipitation records in 10-day increments (shown at the top in Figure 36).[20]

In the winter months (November to March/April), the correlation between precipitation and slide movement would not be expected to be as reliable as when the precipiyond human endeavor.

Nov. - Dec. 1960 The reservoir is lowered from 650 to 600 m; slide movements were reduced.

Dec. 1960 Caloi completed a second seismic investigation. This investigation was more extensive than the first and included two traverses from an elevation of 750 m to the perimetral crack at the top of the slide. One traverse was about 200 m west of the Massalezza Ditch, the other about 400 m east of the ditch. This survey coincided with the 1959 survey in only one location along the 1.8 km length of the two traverses (see Figure 4). This time an upper layer of loose rock 30 to 50 m thick was found in the eastern part and a similar layer 70 to 150 m thick was found in the western part. Caloi concluded that there had been a deterioration in the rock quality since his first survey.[20]

Late 1960 Hydraulic model studies of slide induced reservoir wave phenomena were requested by C. Semenza.[12] Total slide movement ranged from .6 m to 1.5 m.

Early 1961 Exploration adits were driven in the Massalezza Ditch at about el. 920 to 950 m (see Figure 4).

April 1961 Broili and Weber visited exploration adits. They determined that the lower portion of the moving mass was at the contact between the Dogger and the Malm formations. They also determined that the movements did not take place along a single plane, but rather along a series of planes (passing through the fractured material) with clay layers sandwiched between solid pieces of rock.[46] Semenza indicated that, during the course of numerous visits to the adits, it was possible to determine that after a few tens of meters inside the underground openings, the loose materials present at the entrance changed into fractured rocks with folded stratification. Further on into the adit, after a section where a series of ultramylonitic facies were present, a sound uniformly bedded rock was found.[12] These strata dipped approximately 30° to 40° north and apparently represented the undisturbed beds beneath the zone of failure.

Early 1961 Bench mark system was extended over the total area included in the October 1960 movements.

Feb. - Oct. 1961 A bypass tunnel, shown in Figure 4, was constructed on the right bank to regulate the reservoir level in the Erto area in the event of a slide that would divide the reservoir. The reservoir was held down between el. 585 and 600 m during this period.

Sept. - Oct. 1961 Piezometers P1, P2, P3 and P4 were installed under the supervision of E. Semenza and F. Giudici (see Figure 4).

Oct. 1961 Carlo Semenza, designer of the dam, died.

Oct. 1961 - Feb. 1962 The water level in the reservoir was raised from 590 to 650 m. Mass movements during this period were almost negligible and the speed of movement remained below 0.1 cm/day.[46] The water level in the reservoir reached 635 m elevation in December 1961, the level at which the October 1960 movements and perimetral crack that outlined the 1963 slide developed. Movements were very small.

Oct. 1961 - Sept. 1963 Studies of

continued

tation was all rainfall. With much of the precipitation being snow, there would be almost no immediate infiltration; also, spring melting would cause large amounts of infiltration even though there might be no precipitation.

Graphical representation of rainfall and reservoir data is shown in Figure 37 on page 112. The water level in the reservoir is plotted against the amount of precipitation measured during the period 30 days preceding the arrival of the reservoir at those elevations. Similar plots were made for periods of 7, 15 and 45 days. It was believed that the "rain period" affecting the uplift pressures along the sliding plane would be bracketed between these intervals, although the slide were generally limited to routine monitoring of slide movements and observations of groundwater levels.

Feb. 1962 - Oct. 1962 The water level in the reservoir continued to rise from 650 to 695 m. Around the first of October, when the water level in the reservoir was at an elevation of 695 m, the maximum speed of movement was still below 1 cm/day.[46]

April 20, 1962 Dal Piaz died.

Nov. 1962 The water level in the reservoir was raised to el. 700 m. Records indicate heavy rainfalls, 414 mm, during this month (230 mm in the first ten days) and the rate of movement increased up to 1.2 cm/day.[46]

Dec. 1962 - March 1963 The reservoir level was lowered very slowly to an elevation of 650 m. By the middle of February 1963, the reservoir level was at an elevation of 675 m, and the maximum rate of movement was 0.3 cm/day.[46] By the end of March, the reservoir level was at 650 m and the movements were almost nil. At the end of this period, the slide between the Massalezza Ditch and the dam had moved approximately 2.3 m. Bench marks at points of maximum displacements indicated total cumulative movements approximately equal to 3 m.[46] East of the Massalezza, the magnitude of movements was smaller.

April - May 1963 The reservoir level was raised from an elevation of 650 m to 696 m. Bench marks indicated a slight increase in the rate of movement up to 0.3 cm/day.[46]

June - July 1963 The water level in the reservoir had reached an elevation of 705 m by the middle of July. The maximum rate of movement measured at this time remained below 0.5 cm/day.[46]

Aug. - Sept. 1963 The water level in the reservoir was raised from 705 to 710 m elevation between mid-August and early September. Heavy rainfalls were measured in the middle of August (close to 200 mm between August 10 and 20). Unusually heavy rainfall (200 mm) was also measured in the following 20 days.

Sept. 1963 The rate of movement increased during the first days of September, while the reservoir level was slowly rising to a level of 710 m. The rate of movement reached values similar to those reached in October 1960 and in November 1962. By the middle of September, the maximum rate of movement at the lower west portion of the sliding mass reached a value of 3.5 cm/day.

By the end of the month, the maximum rate of movement of 3.25 cm/day was measured at points located in both the upper and lower parts of the western portion of the slide mass.[46] A slow drawdown to minimize the rate of movement of the sliding mass was started during the last days of September. Rainfall records at Erto indicate 164 mm of rain during this month.

Oct. 1 - 9, 1963 A drawdown of the reservoir level continued at the rate of about 1 m per day. Records indicated relatively heavy rainfalls of 29 and 22 mm on October 3 and 4. The rate of movement increased during the first days of October. According to the Bozzi Commission, the rate of movement on October 9 reached a value of 20 cm/day.[45] The total movement of the slide mass at this time was reported

longer term climactic effects could also be significant. The solid and half-filled dots on Figure 37 correspond to those occasions where accelerating movements exceeded 0.5 cm/day. The solid line through the lower range of these points would represent a "failure envelope" corresponding to those combinations of water level and precipitation required for the slope to become unstable. The extremes of this failure envelope, if extended, would correspond to:

- the reservoir elevation that would develop enough uplift pressure to make the slope unstable without any rainfall or snowmelt (approximately 710 to 720 m) to have been between 3 to 4 m.

Oct. 9, 1963 A five-member board of advisors formed by the Italian Government in 1962 was evaluating conditions on a day-to-day basis. Prof. Penta, the geologist member, was scheduled to visit the slide area on Oct. 10 (Kiersch, personal communication to the authors).

At 10:39 p.m., with the reservoir level at el. 700.4 m, the Vaiont Slide took place.[45]

Oct. 10, 1963 The Minister of Public Works appointed an inquiry commission with Carlo Bozzi as chairman. The other members were: Engr. Giuseppe Merla, and Professors Livio Trevisan, Raimondo Selli and M. Viparelli. Their report was submitted January 16, 1964.[45]

E. Semenza made his first visit to the site after the slide. An extensive geological study of the slide mass and surrounding areas was undertaken by Semenza and Rossi for ENEL.

Oct. 23 - 27, 1963 Müller and Broili, together with Engr. H. Maier and Prof. G.A. Kiersch, made their first visit to the site after the slide. Extensive investigations for ENEL began, continuing into1964.

Nov. 1, 1963 A commission was appointed by ENEL to "ascertain the causes of the Vaiont disaster." The members of this commission were: Avv. Marcello Frattini, and Professors Filippo Arredi, Alfredo Boni, Costantino Fasso, and Francesco Scarsella. Prof. Filippo Falini, also a member of this commission, died in a helicopter accident in the Vaiont area while investigating the slide in November. The commission was commonly known as the "Frattini Commission" and submitted its report in January 1964.[39]

- the rainfall or snowmelt required to make the slope unstable without the reservoir present (approximately 180 mm/7 days, 350 mm/15 days, 700 mm/30 days and 1,100 mm/45 days)

Various çombinations of reservoir elevation and preceding precipitation that correspond to different situations during the lifetime of the reservoir (impoundments as well as drawdowns) are represented in Figure 37. As indicated in the figure, the combinations represented by open triangular points correspond to relatively stable conditions. Open circles indicate when the rate of movement is less than 0.5 cm/day. These points plot generally below the failure envelope and there is a tendency for the rate of movement (given by the number in the parentheses) to increase for those combinations closer to the failure envelope.

The two main variables affecting the stability of the slide were the reservoir level and the amount of precipitation in the preceding period. Figure 37 suggests that the slide would have failed with no rainfall or snowmelt when the reservoir levels reached the vicinity of the proposed full supply level, el. 722.5 m. The data also indicate that slide movements could be triggered by very high rainfalls or snowmelts, the magnitude of which were in the range of 130 to 200 percent of the 7- to 45-day precipitations recorded for the period from 1960 to 1964. Therefore, slope movements have most certainly resulted from the maximum precipitation occurring within 100-year to 1,000-year intervals in the past. Correlation with precipitation data would appear to provide quantitative verification of the stories attributed to the local inhabitants about the occurrence of slope movements from time to time.

Assumptions for Stability Analyses

The shear strength along the base of the slide was assumed to be related more to the residual shear strength of the multiple layers of clay found along the basal surface of sliding than to the higher shear strengths of the rock-to-rock contacts. This assumption represents a basic departure from previous stability analyses, such as those performed by Müller, Lo *et al.,* Chowdhury and others.[4,20,42,6] The bases for this assumption are the authors' field observations, summarized in Table 1, and the results of the laboratory shear strength and Atterberg limit tests, summarized in Tables 2, 3, 4 and 5, and in Figure 35.

Essentially, all peak strengths and most

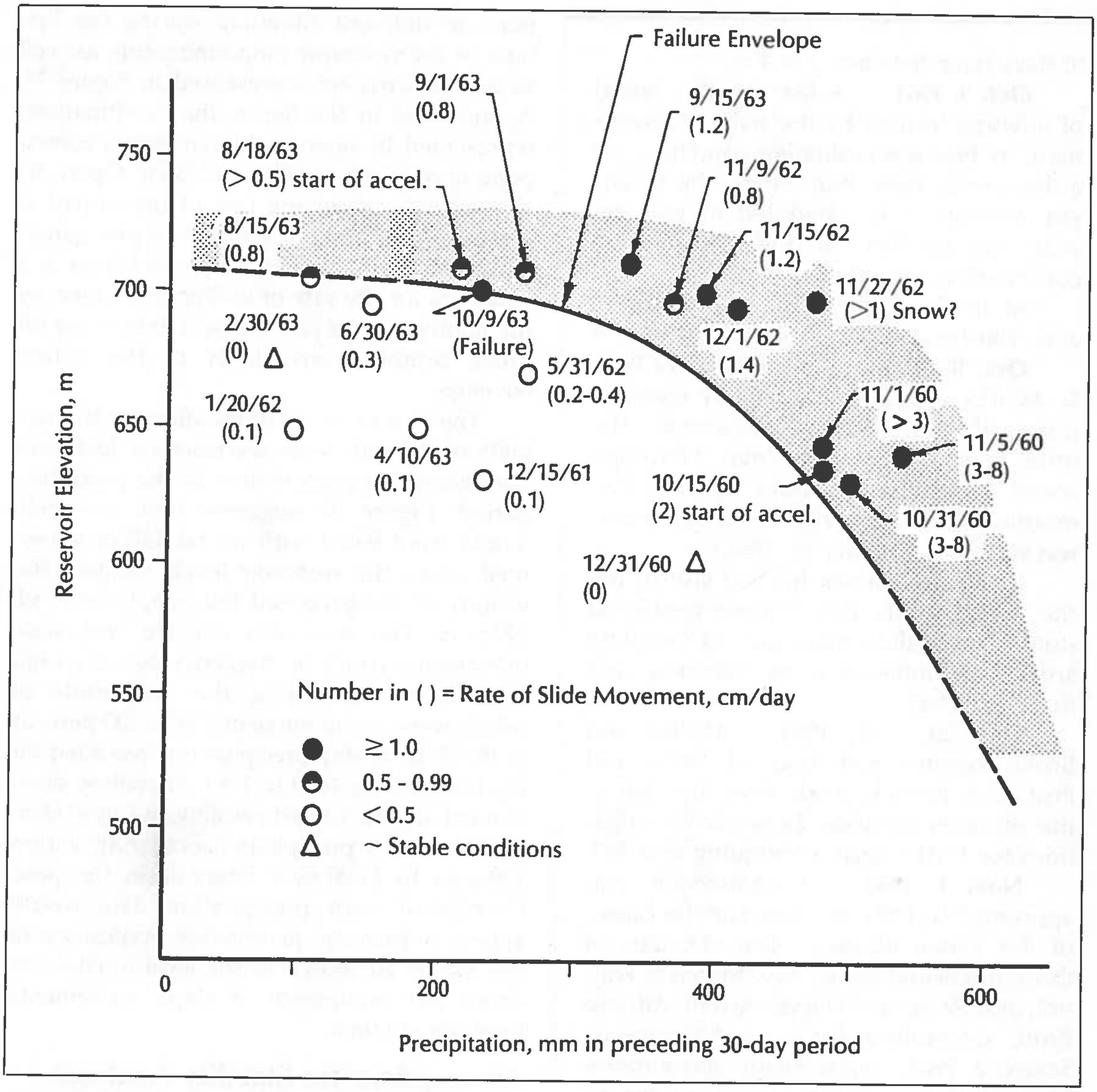


FIGURE 37. The stability of the Vaiont Slide for reservoir elevation *vs.* 30-day precipitation.

increases in strength caused by irregular geometric effects were assumed to have been lost because of prehistoric slide or tectonic movements. Thus, the residual strength, ϕ_r, of the basal failure plane materials was assumed to be the most significant factor in these analyses. However, modest strength increases, from those indicated by the results of laboratory residual strength tests of the weakest clays, could be expected because of some rock-to-rock contacts that occur along the basal sliding surface. These contacts occur because of the existence of:

- localized areas of shearing across bedding planes,
- areas where clays do not occur, and
- areas where rock beds are brought into contact because clays could be squeezed and forced to flow into voids that develop as a result of the displacement of adjacent irregular rock surfaces.

Also, small increases in shear strength could be expected as a result of the introduction of brecciated rock fragments into the clays along the surface of sliding.

The residual angle of shearing resistance, ϕ_r, of the clays as determined from the laboratory tests ranged from 5° to 16°. Most values fell within a range of 6° to 11°, and, for whole samples at high stress levels, the results were between 8° and 10°. However, because of the factors noted above, it seems quite reasonable to accept a mean value for ϕ_r along the basal surface of sliding of 10° to 12°. Cohesion is, of course, assumed to be essentially zero. The basal surface of sliding is assumed to correspond to the old rupture surface, as described by Semenza.[35] The surface of sliding may also be coincident with a tectonic thrust fault. Previous assumptions are in agreement with the occurrence of an uncemented basal fault or a pre-existing rupture surface.

In addition to the shearing that occurs along the slide's base, deformations occur within the slide mass as it moves over irregularities and across gross changes in inclination of the failure plane. In a highly disturbed rock mass, such as the Vaiont Slide, much if not all of these deformations will occur along pre-existing discontinuities, such as joints and faults. In this study, the angle of shearing resistance, β, acting along the discontinuities that cross bedding planes within the slide mass, was chosen on the basis of the authors' experience and field observations of the type of materials present. It was apparent that deformation along these planes would require shearing across thinly bedded limestones, cherts and clay interbeds of the Lower and Upper Cretaceous formations. On a large scale, these beds can deform locally and would be expected to develop an angle of shearing resistance, β, of 30° to 40°. This potential shearing resistance is not mobilized except where there is a tendency for adjacent slices to move relative to each other as described by Mencl.[47] With the geometry of the failure surface established, the largest amount of relative movement of slices would occur at the junction between the "back" that dips at 25° to 45°, and the nearly horizontal "seat" of the slide. Analyses have indicated that the stability of the slide is sensitive to the value of β.

Since there is no practical way to measure β in the field, the analytical procedure was arranged so that the effect of various assumed values of β could be determined. The β values along the discontinuities are assumed to be somewhat higher than the values of the residual shear strength along the basal surfaces due to the fact that these surfaces have undergone fewer differential movements than those occurring along the slide base. Therefore, some additional strength losses could presumably occur with continued displacement along the near-vertical surfaces.

In the three-dimensional analyses undertaken here, it is necessary to assume that differential movement may also occur between adjacent blocks. The angle of shearing resistance that can be mobilized along the sides of the blocks (those near-vertical planes oriented parallel to the direction of slide movement) within the slide mass is assumed to be similar to the values used for β since the materials are the same.

The frictional resistance of the steeply dipping planes forming the east end of the slide was assumed to be 36°. These values are in agreement with published data on the residual angle of shearing resistance for carbonate rocks.[40]

The piezometric head acting on the surface of sliding along its contact with the reservoir was assumed to be equal to the reservoir level. Away from the reservoir, the piezometric head was assumed to increase above reservoir levels due to an assumed groundwater flow system where water was moving from the mountain towards the valley. The initial water level recorded in drillhole P2 in October 1961 was over 90 m above the reservoir level. This reading is a control point on the fluid-pressure distribution curve for the "low rainfall" condition. For the sections without P2, an equivalent pressure difference was assumed at P2 than what was measured. For both low and high rainfall conditions, the difference between the assumed piezometric level at any point on the failure surface and the elevation of that point is gradually reduced to zero between the location of P2 and the southern extremity of the slide surface. The actual piezometric levels used in the analyses are given in a previous

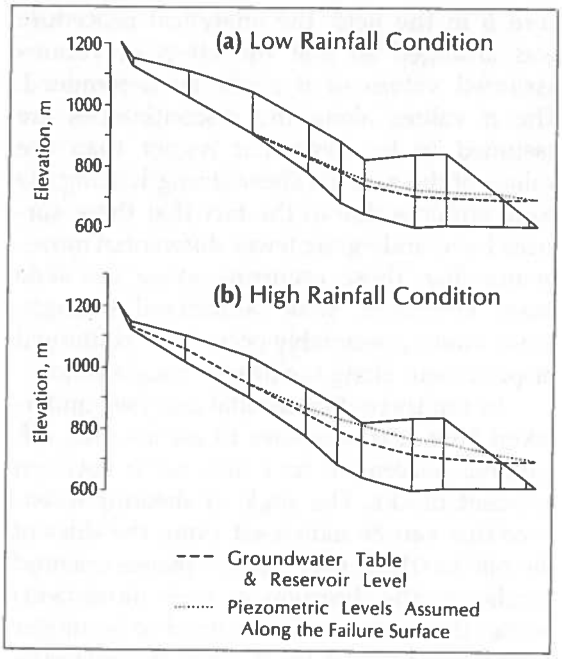


FIGURE 38. Piezometric levels used in stability analyses for Section 2, at a reservoir elevation of 710 m.

report.[18] An example of the actual piezometric levels used is illustrated in Figure 38 for Section 2 with a reservoir level of 710 m.

Each reservoir condition was analyzed for a low and a high piezometric pressure distribution corresponding to a low and a high rainfall condition. The actual pressure distributions would vary for intermediate rainfalls. For each reservoir level, the calculated factor of safety would be expected to differ from its real value. The amount of the correction from a known value, say at failure, would be an indication of the real fluid pressure distribution due to intermediate rainfalls, if other factors remained constant.

Figure 38 shows that the groundwater table above the clay layers was assumed to equal the reservoir level at the toe of the slide and to slope gently upwards to agree with the water levels measured in P1 and P3 (and in P2 after July 1962). The water pressure distribution on the ends of the vertical slices was assumed to be consistent with a hydrostatic increase in water pressure within the slide debris.

These interpretations of the water pressure distributions in the slide are in agreement with the only quantitative data available (*i.e.*, the water levels recorded in P1, P2 and P3) and account for the entire history of the water levels observed in P2.

The base of the slide has been assumed to correspond to a prehistoric slide surface. The position of the failure surface toe was assumed to agree with the contact along the Vaiont Canyon given by Giudici and Semenza, and Rossi and Semenza in their maps of the pre-slide geology.[7,26] The stratigraphic sequence of Rossi and Semenza was used to plot the base of the slide between exposures currently visible along the back of the slide and along the toe.[26] Location of the failure surface is further based on all available post-slide drillhole data including the interpretations by Broili, Rossi and Semenza, and more recently (by Rossi and Semenza) in the preparation of sections used in this study.[2,26] Although the core recovery was poor in the slide material and in the thinly bedded Lower Cretaceous and Malm units associated with the failure surface, it was generally possible to recognize the top of the Dogger formation with confidence. The failure surface was assumed to be located at a constant distance above the top of the Dogger formation, except near the eastern boundary. An offset distance above the top of the Dogger was similarly selected to establish the failure surface position along east-west sections (for example, see Figure 27).

The sections used for the two-dimensional analyses in the first stage of the overall reevaluation were drawn approximately parallel to the direction of the initial movement of the slide as determined by survey records. The orientation of these sections is shown in Figure 4.

The combination of low shear strength on the slide base and the pronounced eastward (upstream) dip of the failure surface along the base of the seat of the slide required that the shearing resistance developed along the east side of each north-south slice of the slide be considered in the analyses. In particular, this assumption was necessary to demonstrate the relative stability of the slide prior to reservoir filling. The step-like shape of the eastern side of the basal failure surface corresponds to surface observations of the tectonic fault at several locations. The base of the slide was assumed to be relatively continuous and sub-parallel to the bedding across the seat and the back of the slide, although the basal plane is assumed to step upwards as the eastern limit of the slide is approached.

Large movements were assumed to have occurred along a pre-existing surface of rupture. These movements occurred in an alignment sub-parallel to the direction of slide movement. Significant downhill movements along the failure plane are assumed to have occurred periodically during valley erosion and glacial loading and unloading in Pleistocene times. One of these movements was probably rapid and was responsible for the large remnant of slide material mapped by Giudici and Semenza on the right side of the valley prior to the 1963 slide (see Figures 4 and 7a).[7] Additional movements of the slide mass have occurred in post-glacial times with the erosion of the most recent Vaiont Canyon through the slide mass and the removal of support from the toe of the slide. These movements continued into historic times and are probably the source of the tales told by local residents about the instability of the slope and the name Mt. Toc, which is reported to mean "crazy" in the local dialect. Talus of various ages infills a large zone along the base of the top scarp of the slide, providing evidence of historic and prehistoric movements. Also, the aligned depressions and airphoto lineaments that can be noted along the perimeter of the slide and within the slide in the 1960 airphotos (see Figure 32) clearly reflect such prehistoric slide movements.

Most of the slide, including both sides of the Massalezza Ditch, is assumed to have moved as a unit to the northeast. Previous analyses have generally assumed a difference in slide movement and other factors on either side of the Massalezza Ditch.[4,20] The authors' field observations and interpretations of the pre-slide and post-slide mapping of Rossi and Semenza indicate that there was one general direction of slide movement and that the main slide mass did not undergo significantly different directions of movement.[26] This evidence also indicates that a much smaller slide from the east side came down onto the main slide. This secondary slide was probably triggered by loss of toe support produced by the movement of the main slide. However, consideration of this secondary slide is not necessary for an understanding of the main slide.

Sections 2, 5 and 10A (see Figure 4) were considered for analysis since they were in the approximate direction of the initial slide movement as determined by displacement vectors calculated from measurements of survey monuments.

Stability Analyses

The purpose in making stability analyses after a slide has occurred is to develop a more complete and more quantitative understanding of the factors that led to the slide. Such analyses also provide a check on the principal input parameters — including the shear strength along the slide surface, the geometry of the failure surface and the distribution of water pressures along the surface of failure — that had an effect on the slide. For stability analyses conducted after a slide, the geometry of the failure surface is determined by pre- and post-slide drillhole data and geologic mapping. Water pressure distributions may be estimated from pre-slide piezometric observations and geohydrologic interpretations. The shear strength data used may be based on laboratory tests or assumptions. In many cases, the shear strength is back-calculated for the failure condition, assuming a factor of safety of 1.0 at failure and assuming the geometry and pore pressures are known values.

Post-slide stability analyses are, in fact, a quantitative means of verifying the story developed to explain the slide. For example, when significant rates of movement were recorded at various times during the history of slide movement, various analyses should yield calculated factors of safety very near 1.0. It is equally important that the stability calculations yield factors of safety appreciably greater than 1.0 for those times in the slide history when the movements were known to be insignificant. If the results of the analyses do not agree with all the available data and

TABLE 7

Results of Previous Stability Analyses, from Müller[4]

Author*	Cross Section (See Fig. 34)	Reservoir Water Level	Inclination of the Water Level	$\phi_{req.}$	$tg_{\phi_{req}}$
Mencl (1966a)	2	700	—	18.75	0.339
Mencl (1966b)	2	700	—	20.5	0.364
				17.5	0.316
				18.5	0.325
Kenney (1967)	2	600	—	19.4	0.352
		650		20.1	0.366
		700		20.7	0.378
		600		21.8	0.400
		650		22.0	0.404
		700		22.2	0.408
Nonveiller (1965b)	2	590	~10°	22.1	0.406
		650	~4°	22.1	0.406
		700	2°	24.0	0.445
Nonveiller (1966a)	2 differing very much	700	2°	27.7	0.525
				27.0	0.510
				28.5	0.542
Müller (cal. according to Mencl [1966b])	2	600	—	21.0	0.384
		650		21.8	0.400
		700		22.5	0.414
(according to Kenney [1967])		600	—	20.4	0.372
		650		21.2	0.388
		700		21.9	0.402
(according to Nonveiller [1965b] but considering the actual shape of the slip surface accord. to Broili [1967])		600	~10°	18.8	0.340
		650	~4°	20.1	0.366
		700	2°	20.8	0.380

*References given in bibliography in Müller[4]. **Description of premises: (1) c =0; (2) tg ϕ has the same value along the whole slip surface (no zone has a higher shear resistance); (3) stiffness of the slip mass is not considered; (4) secondary failures are not considered; and (5) hydrodynamic pressure is not considered.

with the observed movement record, then the explanation developed is incorrect or at least incomplete. Because of the importance of the Vaiont Slide as a precedent, it is essential that stability analyses be in agreement with observed facts.

Stability analyses are a much more powerful tool when there has been a definite condition of failure or a significant rate of movement because the factor of safety can then be assumed to be 1.0 and various combinations of shear strength and pore pressure distribution can be investigated that will yield a factor of safety of 1.0. If several periods of movement have occurred under differing reservoir conditions, it is possible to further eliminate some of the ambiguity in the input to the stability analyses. Such is the case for the Vaiont Slide where four periods of movement have been identified. None of the analyses by Mencl, Kenney, and Nonveiller, which were summarized by Müller (see Table 7), or the later analyses by Kahn, Lo *et al.*, Jaeger, Trollope, and Chowdhury explain the known movement record for these periods.[47,14,16,17,4,48,42,49,5,6] Also, these analyses did not resolve the conflict between the unstable behavior observed in October 1960 when the reservoir was at el. 650 m with unstable behavior exhibited by the slope when the reservoir was at el. 650 m during January 1962.

The analyses performed for this study were designed to examine the equilibrium conditions of the Vaiont Slide for three periods when the factor of safety was near 1.0:

- prehistoric times, when geologic field evidence indicates that movement had occurred;

Calculation According to*	Assumed or Neglected	Premises Tacitly Assumed or Neglected**	Remarks
—	on secondary slip surfaces ϕ = 30° or 40° resp.; c = 50 t/m²	1 2 3 5	Prandtl's wedge
Petttersson		1 2 3 4 5	Prandtl's wedge
Mencl	(like Mencl [1966a])	1 2 3 5	Zone of arching
Mencl		1 2 3 5	
Janbu (1954)	—	1 2 3 4 5	Data taken from small drawings
Nonveiller (1965)	on the upper part of the slip surface is kept ϕ = 25° = constant	1 3 4	Assumptions of the slip surface position & form differ very much from the nature
Nonveiller (1967a)	same	1 2 3 4	
Pettersson	—	1 2 3 4 5	—
Janbu	—	1 2 3 4 5	—
Nonveiller	—	1 2 3 4	—

- October 1960, when the perimeter cracks developed; and
- the fall of 1963, when accelerating movements began just prior to October 9, 1963.

Two groundwater conditions were considered for each period, one representing periods of high rainfall and the other low rainfall. In addition, the case of a dry slide was included for control purposes. Differences in the behavior of the slide between October 1960 and January 1962 were expected to be explained by differences between the high and low rainfall groundwater conditions for a reservoir at el. 650 m.

Two-Dimensional Stability Analyses

The two-dimensional analyses conducted used a variation of the method of slices that is shown schematically in Figure 39. Developed at the request of the authors, this method is described by Anderson in Hendron and Patton.[50,18] The analyses of the three cross sections chosen as representative of the different portions of the slide were carried out by means of a computer program that calculated the factor of safety by considering the surface of sliding as a series of planes. Each cross section was subdivided into slices with vertical boundaries between slices as shown in Figure 39a.

Shear forces between slices were considered in these analyses. The maximum obliquity permitted for the resultant lateral force, *F*, acting on a vertical plane between slices is defined as β (Figure 39b) and is representative of the shearing resistance across strata of limestone, chert, siltstone and clay. The values of β used in these analyses

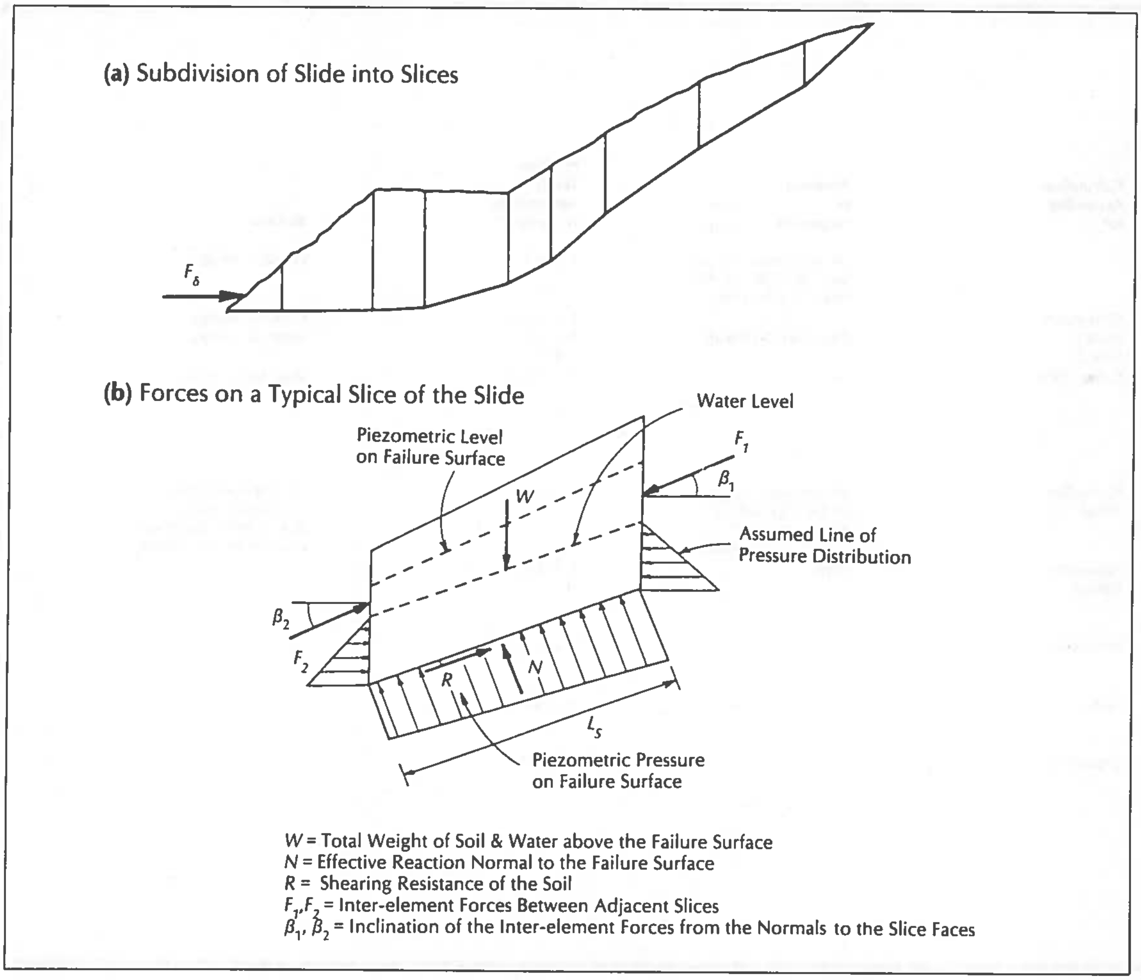


FIGURE 39. Selection of typical slices and forces acting on a typical slice.

ranged from 30° to 40°.

With the magnitude of the value β input to the program, the resultant effective forces between slices may be inclined at an angle β above or below the horizontal as shown in Figure 39b. The angle will depend on the relative changes in the slope of the base planes that support adjacent slices. The analyses satisfied the equations of horizontal and vertical equilibrium, but rotational equilibrium was not considered. The shear force resisting movement at the base of each slide, R, is formulated by:

$$R = \frac{(C' L_s + N \tan \phi')}{F.S.} \qquad (1)$$

where:

C' = cohesion (assumed to be zero in this analysis)

L_S = base length of the slice

N = "effective" normal base reaction

ϕ' = "effective" angle of shearing resistance

$F.S.$ = factor of safety

The computation involved the assumption of an initial factor of safety, and an iterative process was employed in which the factor of safety was changed until the slide mass was computed to be in equilibrium for all slices at the same factor of safety. The program also determined the horizontal force that would have to be applied to the downhill side of the lowermost slice to bring the slide to a factor of safety of 1.0. If the factor of safety

TABLE 8

Cases Analyzed for Sections 2, 5 and 10A

Case	Groundwater Level or Rainfall Condition	Reservoir Elevation, m
1	Low	None
2	High	None
3	Low	650
4	High	650
5	Low	710
6	High	710
7	No pore pressures on failure surface	

was less than 1.0, the force, designated as F_δ (Figure 39a), would be compressive. If the factor of safety was greater than 1.0, then F_δ would be a tensile force.

Cross sections 2, 5 and 10A were each analyzed for seven different cases that corresponded to different combinations of reservoir elevation and rainfall. These cases are summarized in Table 8 and include the case of no reservoir and instances when the reservoir elevation was at 650 and 710 m. For each reservoir elevation, both low and high groundwater levels in the slope are considered to account for low and high periods of rainfall. The low and high piezometric elevations along the failure surface were obtained from the piezometric elevations recorded in piezometer P2 in the fall of 1961. In addition, as a reference calculation for the cases cited in Table 8, each cross section was analyzed for the case of no pore pressure on the failure surface. The cross section and piezometric elevations considered for Section 2, cases 5 and 6, are shown in Figure 38.

The factors of safety calculated from the two-dimensional slope stability analyses for Sections 2, 5 and 10A are summarized in Table 9. For Sections 2 and 5, analyses were conducted for all seven water level conditions listed in Table 8 for ϕ values of 8°, 10° and 12°, and β values of 30° and 40°. For Section 10A, all seven cases were calculated for a ϕ value of 12° and β values of 30° and 40°.

An inspection of factor of safety values presented in Table 9 indicates that, even for no reservoir, the factors of safety are low for the shear strength used. If the values for ϕ = 12° and β = 40° are studied for the no reservoir case, Section 2 has a factor of safety ranging from 0.63 to 0.73, Section 5 has a factor of safety ranging from 1.04 to 1.18, and Section 10A has a factor of safety ranging from 0.51 to 0.57. In all cases, Section 5 is more stable than Sections 2 and 10A because Section 5 is closer to the Massalezza Ditch where the volume of material on the steep backslope is less than for Sections 2 and 10A.

It is also interesting to study the results for Section 5 for ϕ = 12°, β = 40° for cases 1 through 6. In comparing cases 1 and 2, the difference between high and low groundwater levels makes about a 14 percent change in the factor of safety for no reservoir. In comparing cases 1 and 5 with cases 2 and 6, there is a 12 to 14 percent change in the factor of safety caused by the reservoir changing from river level (450 m) to 710 m. A comparison of cases 5 and 6 shows that, at a reservoir elevation of 710 m, the difference in high and low rainfall could change the factor of safety by about 16 percent. Thus, it appears that for the unstable slope the changes caused by rainfall are just as significant as changes in the reservoir level.

Table 10 summarizes the calculated forces, F_δ, for Sections 2, 5 and 10A that are required to maintain the slide at a factor of safety of 1.0. The calculated forces, F_δ, are assumed to be applied horizontally to the lowermost slice.

Taken as a whole, the results of the two-dimensional calculations shown in Tables 9 and 10 indicate that the factors of safety are too low for the slide mass to have been stable over much of its history. Therefore, the shear strengths must have been higher, the pore pressures lower, or an important element has been omitted from the two-dimensional analyses. The pore pressure distribution assumed seems quite reasonable and the angle of shearing resistance of 12° is consistent with measured residual shear strengths, plus an increment to the angle of shearing resistance to account for local rock-to-rock contacts. It seemed reasonable, therefore, to check the effects of the three-dimensional nature of the

TABLE 9

Vaiont Slide, Calculated Factors of Safety

(a) Section 2

Case	ϕ = 12°		ϕ = 10°		ϕ = 8°		Reservoir	Groundwater
	β=30°	β=40°	β=30°	β=40°	β=30°	β=40°		
1	.651	.728	.540	.604	.431	.481	none	low
2	.562	.632	.466	.524	.372	.418	none	high
3	.627	.699	.520	.579	.414	.562	650 m	low
4	.540	.605	.448	.501	.357	.399	650 m	high
5	.560	.621	.465	.515	.371	.410	710 m	low
6	.469	.520	.399	.431	.310	.314	710 m	high
7	.714	.801					no pore pressure on failure surface	

(b) Section 5

Case	ϕ = 12°		ϕ = 10°		ϕ = 8°		Reservoir	Groundwater
	β=30°	β=40°	β=30°	β=40°	β=30°	β=40°		
1	.943	1.184	.782	.984	.624	.784	none	low
2	.838	1.038	.695	.863	.554	.688	none	high
3	.911	1.142	.756	.949	.602	.756	650 m	low
4	.801	0.991	.665	.822	.530	.656	650 m	high
5	.856	1.062	.711	.883	.566	.704	710 m	low
6	.738	0.899	.612	.746	.488	.594	710 m	high
7	1.144	1.505					no pore pressure on failure surface	

(c) Section 10A

Case	ϕ = 12°		ϕ = 10°		ϕ = 8°		Reservoir	Groundwater
	β=30°	β=40°	β=30°	β=40°	β=30°	β=40°		
1	.530	.574					none	low
2	.471	.514					none	high
3	.514	.557	Not Run		Not Run		650 m	low
4	.456	.496					650 m	high
5	.470	.508					710 m	low
6	.410	.445					710 m	high
7	.604	.655					no pore pressure on failure surface	

slide surface before abandoning the assumed values of shearing resistance and pore pressure distributions.

Three-Dimensional Nature of the Slide Surface

Figure 40 is a schematic diagram that illustrates the three-dimensional nature of the possible failure wedges resulting from the upstream dip of the failure surface at the base of the slide. In this figure, the plane *a-e-d* is taken as a vertical plane in the direction of movement and would be parallel to Sections 2, 5 and 10A. The surface *a-d-c-b* corresponds to the basal bedding plane failure surface, the trace *a-b* represents the outcrop of the bedding planes on the wall of the Vaiont Gorge, and the trace *b-c* represents the western extent of the slide. The shearing force, τ_1, is the shearing resistance mobilized on the base plane parallel to the direction of the movement and is the resisting force calculated in conventional two-dimensional analyses. The shearing force, τ_2, is the shearing resistance mobilized parallel to the direction of movement on the vertical plane *a-e-d* due to the normal force PN_2. PN_2 is the supporting force required on plane *a-e-d* to prevent movement upstream down the apparent dip of the bedding surfaces in a

TABLE 10

Vaiont Slide, Force Per Unit Width Required to Maintain Equilibrium of the Slide

units (N/lineal m of slide) x 10^7

(a) Section 2

Case	$\phi = 12°$		$\phi = 10°$		$\phi = 8°$	
	$\beta = 30°$	$\beta = 40°$	$\beta = 30°$	$\beta = 40°$	$\beta = 30°$	$\beta = 40°$
1	29.37	18.27	38.94	26.58	48.45	34.70
2	37.36	25.31	45.78	32.65	54.11	39.76
3	31.41	20.28	40.63	28.28	49.81	36.05
4	39.30	27.27	47.40	34.32	55.43	41.13
5	36.34	25.21	44.51	32.21	52.63	39.01
6	56.11	33.18	52.04	39.23	59.02	45.05
7	24.02	13.29	Dry Case		Dry Case	

(b) Section 5

Case	$\phi = 12°$		$\phi = 10°$		$\phi = 8°$	
	$\beta = 30°$	$\beta = 40°$	$\beta = 30°$	$\beta = 40°$	$\beta = 30°$	$\beta = 40°$
1	4.42	-10.10	16.68	0.86	28.73	10.61
2	12.74	-2.20	23.88	7.31	34.83	16.14
3	6.68	-7.63	18.24	2.52	29.60	11.60
4	15.12	0.53	25.71	9.26	35.94	17.41
5	10.26	-3.18	20.63	5.50	30.80	13.42
6	19.32	5.22	28.57	12.81	37.61	19.81
7	-11.04	-26.20	Dry Case		Dry Case	

(c) Section 10A

Case	$\phi = 12°$		$\phi = 10°$		$\phi = 8°$	
	$\beta = 30°$	$\beta = 40°$	$\beta = 30°$	$\beta = 40°$	$\beta = 30°$	$\beta = 40°$
1	62.26	47.65	—	—	—	—
2	70.82	55.24	—	—	—	—
3	63.12	48.53	—	—	—	—
4	71.42	55.98	—	—	—	—
5	66.65	52.23	—	—	—	—
6	75.52	60.30	—	—	—	—
7	52.39	38.44	Dry Case		Dry Case	

Note: $\beta = 0$ between the toe element & the next uphill element for all runs on Section 5.

direction perpendicular to plane *a-e-d*. The resisting force, τ_2, as shown schematically in Figure 40, is shown below to be significant and necessary for equilibrium of the slide at all times. This requirement would be true even before the filling of the reservoir, assuming the shear strength along the bedding planes was governed by the clays and was in the range of 8° to 12°. The angle of shearing resistance used along the base of the slide *a-b-c-d* was 10° to 12°. The angle of shearing resistance on planes parallel to plane *a-e-d* in Figure 40 was assumed to be ~ 36°.

Figure 41 illustrates a cross section taken at right angles to the two-dimensional sections identified by Sections 2, 5 and 10A. The triangular wedge *a-e-b* in Figure 41 corresponds to the east-west section shown as *a-e-b* in Figure 40. The surface shown as *b-a* in Figure 41 represents the eastward dipping failure surface as shown in Figure 27. The total horizontal normal force PN_2 required in section *a-e*, Figure 41, to prevent upstream (eastward) movement down the apparent dip of the bedding planes is formulated by:

$$PN_2 = W \tan \theta \qquad (2)$$

where:

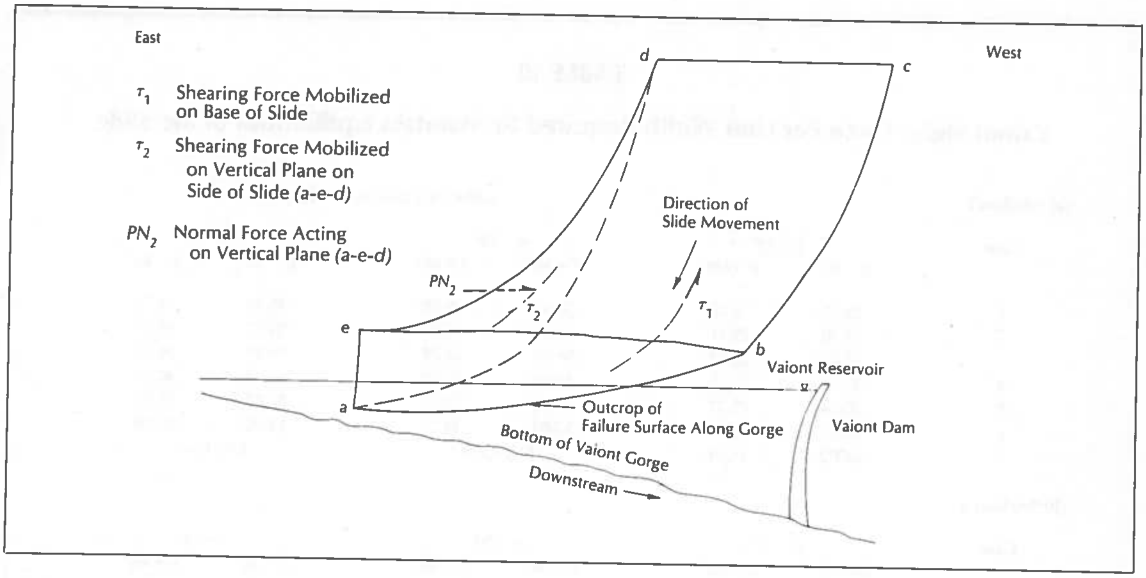


FIGURE 40. A schematic illustration of the three-dimensional nature of the Vaiont Slide mass.

W = weight of the slide mass to the west of the cross section being considered

θ = average upstream dip of the sliding plane in a direction perpendicular to planes containing Sections 2, 5 and 10A

The effective normal force $\overline{PN}_2$ is then equal to:

$$\overline{PN}_2 = PN_2 - U_h \quad (3)$$

U_h = hydraulic force against the face of the cross section

The frictional force acting parallel to the face of the cross section can then be calculated as:

$$\overline{PN}_2 \tan \phi_R \quad (4)$$

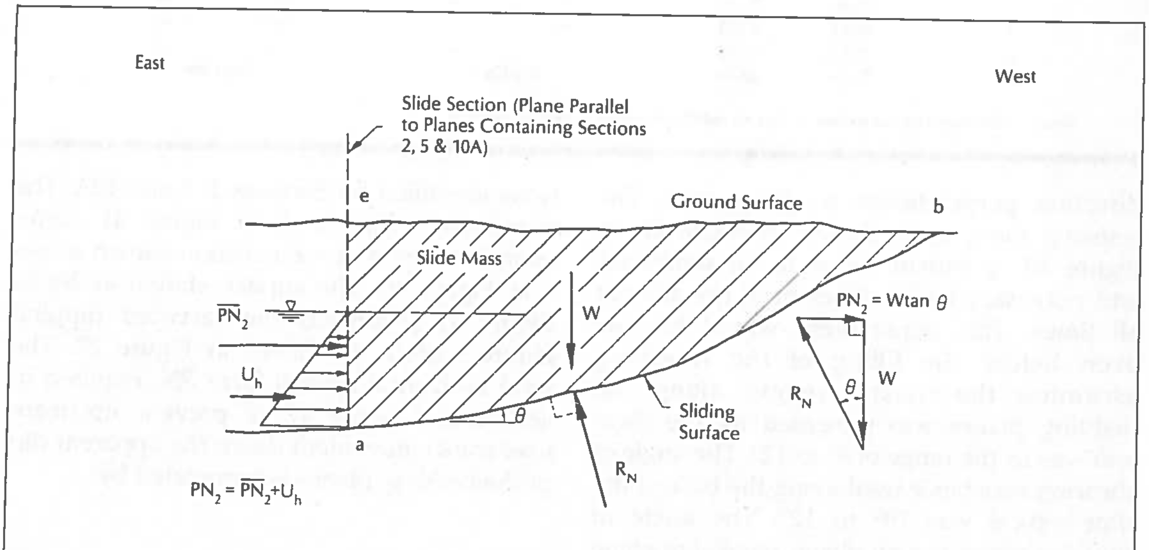


FIGURE 41. Representation of the normal forces on a slide cross section developed by the upstream dip of the sliding surface.

where:

ϕ_R = the friction angle along the vertical surface between adjacent cross sections

The frictional force on the slide plane *a-b* (Figure 41) does not have a component downhill along *a-b* perpendicular to Sections 2, 5 and 10A. The frictional force in the bedding plane base of the slide is parallel and opposed to the direction of movement; therefore, it is parallel to planes 2, 5 and 10A.

Factors of safety of the cross sections considered to be representative of the sliding mass under the seven different conditions investigated were calculated. Stability analyses of the three cross sections were carried out with the modified slice method described above. These analyses resulted in the factors of safety and equilibrium force, F_δ, per unit width of the slope given in Tables 9 and 10. The resisting force along the failure plane and the driving force acting on each unit width of slide represented by that particular cross section were then estimated as:

$$\frac{\text{Resisting force}}{\text{Driving force}} = \frac{\sum (N_i) \tan \phi}{\sum W_i \sin \alpha_i} = F.S. \qquad (5)$$

where:

W_i = weight of each slice in the cross section

α_i = angle of inclination of the bottom of the slice

ϕ = effective angle of friction along the failure plane.

N_i = effective normal force at the base of slice *i*

When the factor of safety is equal to 1.0 with the equilibrium force acting, Equation 5 becomes:

$$\frac{\sum (N_i) \tan \phi + F_\delta}{\sum W_i \sin \alpha_i} = 1.0 \qquad (6)$$

Equations 5 and 6 result in:

$$\frac{F_\delta}{\sum W_i \sin \alpha_i} = 1.0 - F.S. \qquad (7)$$

where the driving force is formulated by:

$$\sum W_i \sin \alpha_i = \frac{F_\delta}{1 - F.S.} \qquad (8)$$

and the resisting force along the failure plane is derived from:

$$\sum (N_i) \tan \phi = \frac{F_\delta}{\frac{1}{F.S.} - 1} \qquad (9)$$

Equations 8 and 9 were then used to calculate the resisting as well as the driving forces for various sections of the sliding mass. The total driving, resisting and restoring forces acting on the entire sliding mass were then obtained from the product of each force per unit width, times the width of the slope represented by the typical cross section where those forces were calculated. Factors of safety of the entire mass, including the frictional force along the eastern wall boundary, were then redefined as:

$$F.S. = \frac{\sum (N_i) \tan \phi + \overline{PN}_2 \tan \phi_R}{\sum W_i \sin \alpha_i} \qquad (10)$$

Calculated values of this redefined factor of safety of the entire mass were carried out in Hendron and Patton for the different water elevations considered in this study and are listed in Table 11.[18]

A friction angle of 12° along the failure surface was considered to be the most representative of the in-situ materials at the slip surface. The friction angle, ϕ_R, along the eastern wall boundary where displacements took place between rock surfaces (as indicated by the traces in the exposed wall) was estimated to be 36°. The friction angle, β, along vertical rock surfaces between slices used in the calculation of these revised factors of safety was taken as 40°.

As the values in Table 11 indicate, failure (factor of safety equal or near to 1.00) would occur under the combined effect of a heavy rainfall (developing a high groundwater level) and a reservoir elevation of 710 m. The slope

TABLE 11

Factor of Safety of Sliding Mass Calculated From Three-Dimensional Stability Analyses

Case No.	Description	Factor of Safety
6	710 m reservoir, high rainfall	1.00
5	710 m reservoir, low rainfall	1.10
4	650 m reservoir, high rainfall	1.08
3	650 m reservoir, low rainfall	1.18
2	No reservoir, high rainfall	1.12
1	No reservoir, low rainfall	1.21

would remain marginally stable (factor of safety of 1.10) during periods of high reservoir levels up to 710 m and low rainfall. Marginal slope stability (factor of safety of 1.08) would also develop if heavy rainfalls occurred at reservoir elevations near 650 m. The movements of October 1960, corresponding to a factor of safety of 1.0, may have developed because of the abnormally heavy rainfalls during this period. It is probable that the groundwater levels in October 1960 were above the levels considered as "high" groundwater levels in these computations.

The "high" groundwater levels were derived, in part, from the observation that piezometer P2 was 90 m above reservoir elevation at about October 20, 1961. Rainfall amounts for 7, 15, 30 and 45 days before October 20, 1961, were 59, 205, 208 and 246 mm, respectively. Rainfall amounts for 7, 15, 30 and 45 days before October 31, 1960, were 109, 170, 495 and 697 mm, respectively. The rainfall preceding October 31, 1960, was much heavier than the rainfall preceding October 21, 1961, when the P2 piezometer was operational and yielded data that were used in establishing the "low" and "high" groundwater elevations for these analyses.

If the groundwater elevations were adjusted to take into account the heavier rainfall in October 1960, the factor of safety of 1.08 would more appropriately be reduced to near 1.0. The factor of safety of 1.18 for the 650 m reservoir elevation and low rainfall (see Table 11) is indicative of the stable conditions that were observed in January 1962 when the reservoir was raised through el. 650 m and no movement was observed. Marginal slope stability (factor of safety of 1.12) was estimated for periods of heavy rainfall even without the presence of the reservoir. Over periods of several hundreds of years, periods of rainfall were likely in which raised piezometric levels were high enough to reduce the factor of safety from 1.12 to 1.0, making the slope, with no reservoir, unstable.

The factors of safety presented in Table 11 indicate that rainfall significantly influenced the stability of the Vaiont slopes for any reservoir level. The movement, or lack of, at any level of the reservoir was greatly influenced by the intensity of rain over the preceding 15 to 30 days.

The other process, discussed by Müller, in which it was inferred that new movements only occurred when the reservoir was raised to new elevations exceeding previous reservoir elevations, would appear to be a result of making interpretations from movement and reservoir data without attaching the importance to rainfall that calculations here would suggest.[4,20]

The schematic diagram in Figure 42 shows the three-dimensional nature of the blocks selected for the calculation of forces acting in the upstream (easterly) direction. These blocks are designated as Block I, Block I + II and Block I + II + III. In Appendix D of Hendron and Patton, the factor of safety of Block I (Figure 42a) is shown to be 1.07 for $\phi = 12°$, $\beta = 40°$, $\phi_R = 36°$ and high rainfall with reservoir elevation at 710 m.[18] The factor of safety of Block I + II is 1.31 (Figure 42b) and the factor of safety of Block I + II + III is 1.00 (Figure 42c). These three-dimensional analyses, which consider the shear forces between sections caused by the upstream dip of the strata, account for the fact that the entire slide came down at one time. This finding was not apparent from the two-dimensional analyses that yielded calculated factors of safety for Sections 2, 5 and 10A that were quite different

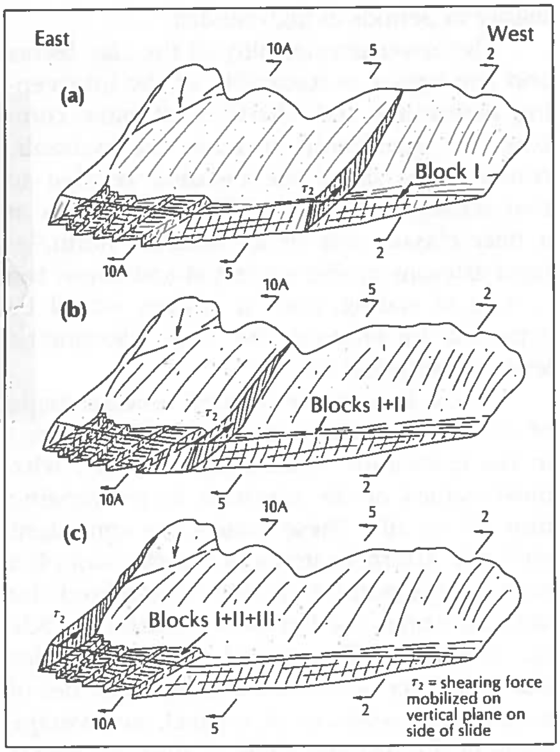


FIGURE 42. A depiction of the three blocks used in the three-dimensional stability analyses.

for each section.

The three-dimensional calculations also account for the fact that if the strength on the bedding planes were as low as 12°, the slide mass could have been stable, but not greatly above a factor of safety of 1.0, before the reservoir was built. However, this condition required large resistance along the eastern boundary of the slide. The epicenters of small tremors reported near the eastern boundary of the slide during the history of movement agree with the conclusion that significant resistance was developed at this boundary.

Conclusions

The 1963 Vaiont Slide was a reactivation of an old slide. Although the age of the old slide is not known, it probably occurred in post-glacial times, but before the period of recorded history of the Vaiont Valley. The evidence for an old slide includes: talus infilling a reoccurring crack at the headscarp where breccias occur with a variety of physical characteristics, the basal rupture plane and remnants of a previous slide mass or masses on the north side of the valley. Elements of surface morphology are also indicative of an old slide. These elements include deranged drainage, enclosed depressions, bulging slopes and other related alignments and patterns evident in the 1960 airphotos.

The slide mass moved on one or more clay layers that were continuous over large areas of the surface of sliding both east and west of the Massalezza Ditch. Multiple clay interbeds occur in the Malm and Lower Cretaceous stratigraphic units and were observed at many locations within the slide. Clays occur on the slide surface, below the slide surface and also form the matrix of the lower portions of the slide mass. Thick clay fragments and layers are abundant in the debris. Clay interbeds were found outside the slide area in stratigraphic positions corresponding to the surface of sliding of the 1963 slide. The field evidence for the presence of clay along the surface of sliding is compelling because of the number of locations where clays were noted on the failure surface and because of the details of the geology at these locations. Clays of predominantly calcium montmorillonite or a closely related clay mineral occur on the failure surface in many more locations than those cited in this study.

The lower portion of the failure plane, which is commonly seen as a near horizontal "seat" in cross sections of the Vaiont Slide, actually dips to the east (upstream) about 9° to 22°. This upstream dip is very significant in the stability analyses and is well documented by the geologic mapping of Giudici and Semenza before the slide and by drill-holes made after the slide.[7]

The eastern boundary of the slide appears to have been formed by one or more lateral faults. Such a lateral fault is shown on the geologic maps of Rossi and Semenza.[26,32]

The great majority of the slide both east and west of the central Massalezza Ditch moved as a unit. The evidence for this movement is the surface morphology of the slide and the geologic features of the area mapped before and after the slide by Rossi and Semenza. A secondary slide movement formed an area called the Eastern Lobe. This movement was presumably triggered by the loss of toe support caused by the movement of the main slide. The resulting unstable mass overran a large area on the uphill side of the eastern part of the slide. Therefore, an analysis of the main slide is not appreciably affected by omitting a consideration of the secondary slide. On this point, the authors differ with others who have suggested that the portion of the slide east of the Massalezza Ditch was fundamentally different from the portion to the west. As the main slide came to rest, differential movements developed within it as a result of differences in the geometry of the valley in the toe areas and differences in the momentum of various sections of the slide mass.

A significant area of pronounced karstic and/or combined karstic and glaciated terrain exists above the slide near the top of Mt. Toc. Evidence of minor and incipient karstic terrain is found just above the slide and on its western boundary. The bedding in those areas also dips towards the slide at angles of 13° to 45° or more. Solution features were observed at three areas immediately below the main surface of sliding. Undoubtedly, more solution features existed. This evidence strongly suggests that the conditions were present to enable the transmission of high water pressures developed due to infiltration from precipitation or snowmelt on the mountain above. These high water pressures could therefore develop along the surface of sliding.

High groundwater piezometric pressures with respect to the reservoir levels were measured in piezometer P2 in the vicinity of (probably just above) the failure surface. These measurements were taken prior to the slide and apparently before sufficient slide movement occurred to damage the piezometer. This water pressure fluctuated both with changes in the reservoir level and with rainfall. Initially, the piezometer level in P2 was 90 m above reservoir level. This level represents a water pressure difference that was probably lower than the real difference because the piezometer tip was not well sealed. Also, this 90 m difference was observed in a period of low to moderate rainfall and could have been higher in periods of high rainfall.

The lower permeability of the clay layers and the higher permeability of the intervening limestones and cherts must have combined to significantly increase the hydraulic conductivity along the bedding relative to that across the bedding. This effect results in a near classic case of an inclined multiple-layer artesian aquifer system at and below the surface of sliding. Such a system would be expected to produce the high piezometric levels observed at P2.

The values of the drained residual angle of shearing resistance of the clays measured in the laboratory varied from 5° to 16°, with most values of the clay-rich layers ranging from 6° to 10°. These values are consistent with the Atterberg limits of the clay sampled from a large number of areas throughout the slide and from the formation located outside the slide area. To account for irregularities along the clay layers and a limited number of rock-to-rock surfaces of contact, an average value of the residual angle of shearing resistance of about 12° would appear to be reasonable and consistent with laboratory test results.

Three-dimensional analyses were required due to the magnitude of the upstream inclination of the clay layers that form the slide base. These analyses reveal that a significant proportion, approximately 40 percent, of the total shearing resistance acting on the slide mass was supplied by near-vertical faces that formed the eastern boundary of the slide. This particular slide is especially sensitive to this three-dimensional effect because the clay layers along the base have a very low strength and the eastern boundary has a higher strength.

The history of slide movements, the record of reservoir levels, the shape of the failure surfaces and the assumed distribution of pore water pressures and water levels used in this study are consistent with the following shear strength values:

- residual angle of shear resistance (ϕ_r) on basal planes ~ 12°
- angle of internal shearing resistance (β) acting between slices on the slide ~ 40°

- angle of frictional shearing resistance acting along the eastern surface of the slide $\phi_R \sim 36°$

Only small variations in the parameters above appear to be possible for the results of the analyses to yield factors of safety consistent with the four periods of movement and the intervening periods of relative stability.

The 1963 slide occurred because of the combined effects of a rising reservoir and increases in piezometric levels as a result of rainfall. The reduction in the factor of safety caused by reservoir filling alone is calculated to be approximately 12 percent. The reduction in the factor of safety due only to a variation in rainfall and snowmelt is calculated to range from 10 to 18 percent.

Plots of cumulative precipitation against reservoir levels just prior to periods of movement have resulted in a well-defined "failure" envelope. This envelope indicates those combinations of reservoir and precipitation levels that yield a pore pressure distribution that would cause significant slide movement. The results of this correlation explain why the slide was observed to be stable at a given reservoir level and yet at a later date was unstable at the same reservoir level. The results of this correlation indicate that "prewetting" of the slide debris was not a significant factor in the slide behavior.

An extrapolation of the failure envelope enables an estimate to be made of:

- the rainfall that would cause failure without a reservoir
- the reservoir level that would cause failure with little or no rainfall on the Mt. Toc slopes

The cumulative 30-day rainfall that would cause failure without a reservoir would be about 700 mm. Since a monthly rainfall of almost 500 mm was recorded in the four-year period of record, it seems likely that the 700 mm rainfall has been exceeded during the post-glacial life of the slope. Therefore, significant movements must have occurred without a reservoir. The reservoir level that would cause failure without rainfall would be about 710 to 720 m. This reservoir failure level may be compared to the full supply level of the Vaiont Reservoir that was to have been 722.5 m. Therefore, had the reservoir been filled to its design level, the slide might have moved without any significant preceding rainfall. The results of the stability analyses are consistent with the conclusions that can be drawn from the precipitation against reservoir level correlations and the available movement record of the slide. A review of the accumulated evidence suggests that the slide could have been stabilized by drainage.

Casual studies of important precedent case histories, such as the Vaiont Slide, should not be accepted by the geological and geotechnical professions, especially when used for comparison purposes for proposed projects. Back-analyses and speculations on slide causes should not be made without a reasonably valid geologic, hydrogeologic and historic reconstruction of the significant events into a model. Because of the great diversity in geologic and hydrogeologic environments among projects, it is difficult, and perhaps misleading, to attempt to set rules for analyses and field exploration programs that would cover all landslide studies.

Any damsite investigation should include a detailed study of the proposed reservoir slopes. If old slides or areas susceptible to sliding are identified, a detailed evaluation of their relative stability under reservoir conditions should be required. The lesson afforded by Vaiont need not be relearned by another generation. However, it should not be a foregone conclusion that reservoir slopes will always be less stable with increased reservoir levels.

The analyses and evidence compiled indicate that the history of the sliding and the final collapse of the slope can be examined in quantitative terms. Conventional methods of analyses by limit-equilibrium techniques appear to be reliable if the input data are consistent with the geologic and hydrogeologic controls. The greatest gaps in the data accumulated on the Vaiont Slide involve the lack of substantive water pressure data and reliable movement records along the failure plane. Fluid pressure measurements taken from piezometers installed at multiple levels within and below the slide would have provided the essential data for correlation with slide movements and reservoir levels. Reliable measurements of the depth of the failure plane and the magnitude of displacements along it would have helped to confirm the depth and size of the slide mass and would have brought more reliability to the correlation studies.

In hindsight, it appears significant that an early (1960-61) diagnosis of the kinematics of the lower part of the slide as similar to that of some glaciers (having zero horizontal velocity at the base increasing to a maximum at the glacier's surface) led those involved to divert their attention away from the field exploration required to locate the failure plane, as well as away from instrumentation and analytical efforts. Subsurface borehole deformation measurements would have shown the error in this hypothesis.

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