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mind that Digests will have significant use only if they are lucid and succinct. The value of the original contribution will not be judged by the length of the Digest but rather by its directness and explicit description of the advancement wrought by the original paper, discussion, and closure. The Digest must not be a reconstruction of the original paper; it must be a perceptive analysis of the original contribution that is capable of standing alone.

This modification in the role of the *Transactions* of the Society, the result of several years of study, was developed to provide a *Transactions* that is of more use to members. The salient points brought out in the study are: (1) Papers are being published at an ever-increasing rate—the number of pages published has doubled in the past ten years; (2) it is not economically feasible to reprint all *Proceedings* papers in *Transactions;* (3) the subscription to the present *Transactions* indicates that it is in demand by less than 25 percent of the membership; and (4) it has been necessary to rely on *Proceedings* as a source for most papers since 1954 because *Transactions* has contained less than 40 percent of the material published in *Proceedings*.

The new form of *Transactions* will be a useful tool to the member because it will contain useful basic Digests of all the regular Society publications, that is, all *Proceedings* papers and Civil Engineering articles. Thus, within a single volume, a reader will be able to find the essential elements of all the technical papers published by the Society. The intention is to provide Digests of such a type that from them the majority of searchers can secure the information they require.

The new form of *Transactions* will continue many of the traditional features. It will contain an abstract of the President's Annual Address as well as abstracts of memoirs of deceased members; it will continue to be bound in the Society's official Royal Blue; and the volume numbering will be a continuation of present numbering. The cost for the new *Transactions* will be $4.50 to members, $7.25 to public and school libraries, and $9.00 to non-members.

All members will soon receive a direct-mail announcement concerning the new *Transactions*—a publication that will be the key to *all* regular Society publications in a useful and convenient form for instant referral. As usual and proper, the Society has taken the lead in our profession. We have recognized a need and, with the new *Transactions,* we have taken steps to fill it. —*W. H. W.*

VAIONT RESERVOIR DISASTER

Geologic causes of tremendous landslide accompanied by destructive flood wave

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Findings and views expressed here are those of the author, or as cited, and are not those of any board or organization or other person or persons. As a Senior Postdoctoral Fellow of the National Science Foundation, Professor Kiersch is on leave from his teaching post at Cornell University for special research in Europe on stresses in rock masses and how they affect conditions at the sites of high dams and open cuts. He is at the Technical University, Vienna, and was priviledged to study the Vaiont slide. His were among the first observations made outside of those by the authorities in immediate charge. CIVIL ENGINEERING is pleased to present this report for study as a means of reducing the danger of such disasters.

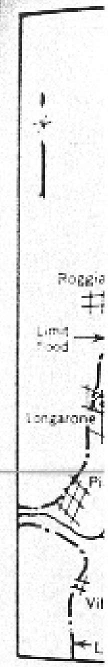
The worst dam disaster in history occurred on October 9, 1963, at the Vaiont Dam, Italy, when almost 3,000 lives were lost. The greatest loss of life in any similar disaster was 2,209 in the Johnstown Flood in Pennsylvania in 1899. The Vaiont tragedy is unique in many respects because:

- It involved the world's second highest dam, of 265.5 meters (875 ft).
- The dam, the world's highest thin arch, sustained no damage to the main shell or abutments, even though it was subjected to a force estimated at 4 million tons from the combined slide and overtopping wave,[1] far in excess of design pressures.
- The catastrophe was caused by subsurface forces, set up wholly within the area of the slide, 2.0 kilometers long and 1.6 km wide.
- The slide volume exceeded 240 million cu m (312 million cu yd), mostly rock.
- The reservoir was completely filled with slide material for 2.0 km and up to heights of 175 m (574 ft) above reservoir level, all within a period of 15 to 30 sec. (A point in the mass moved at a speed of 50 to 100 ft per sec.)
- The slide created strong earth tremors, recorded as far away as Vienna and Brussels.[2]

The quick sliding of the tremendous rock mass created an updraft of air accompanied by rocks and water that climbed up the right canyon wall a distance of 260 m (850 ft) above reservoir level. (References to right and left assume that the observer is looking downstream.) Subsequent waves of water swept over both abutments to a height of some 100 m (328 ft) above the crest of the dam. It was over 70 m (230 ft) high at the confluence with the Piave valley, one mile away. Everything in the path of the flood for miles downstream was destroyed (Fig. 1).

A terrific, compressive air blast preceded the main volume of water. The overtopping jet of water penetrated all the galleries and interior works of the dam and abutments. Air currents then acted in decompression; this tensional phase opened the chamber-locked safety doors of all the galleries and works and completed destruction of the dam installations, from crest to canyon floor.

This catastrophe, from the slide to complete destruction downstream, occurred within the brief span of some 7 min. It was caused by a combination of: (1) adverse geologic features in



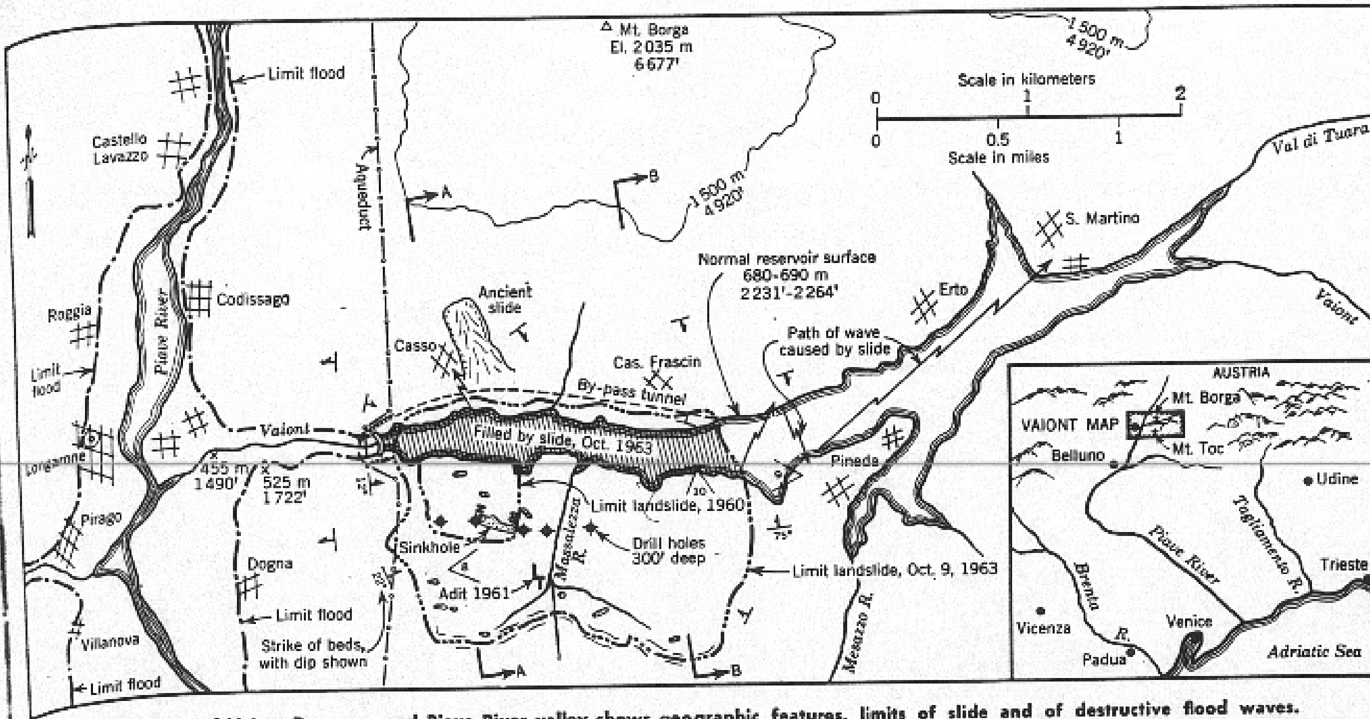


FIG. 1. Map of Vaiont Dam area and Piave River valley shows geographic features, limits of slide and of destructive flood waves.

the reservoir area; (2) man-made conditions imposed by impounded water with bank storage, affecting the otherwise delicately balanced stability of a steep rock slope; and (3) the progressive weakening of the rock mass with time, accelerated by excessive ground-water recharge.

On the day after the catastrophe, October 10, 1963, the Italian Government appointed a 15-man technical board to review the circumstances leading up to the slide and establish responsibility for preslide policies and actions. The report of this board was released on January 16, 1964, and cited a lack of coordination between the technical and governmental officials. Findings of another government board are scheduled for release some time in 1964. Understandably, this article omits reference to such aspects of the disaster, and is confined to an assessment of the geologic setting and the influence of engineering works on these conditions.

Design and construction

Vaiont Dam is a double-curved, thin-arch, concrete structure completed in the fall of 1960 (Fig. 2). The dam is 3.4 m (11.2 ft) wide at the top and 22.7 m (74.5 ft) wide at the plug in the bottom of the canyon. It has an overflow spillway, carried a two-lane highway on a deck over the crest, and had an underground powerhouse in the left abutment. Reservoir capacity was 150 million cu m (196 million cu yd, or 316,000 acre-ft).

The way in which the dam resisted the unexpected forces created by the slide is indeed a tribute to designer Carlo Semanza and the thoroughness of construction engineer Mario Pancini. The anchor tie-rods which strengthened the abutments were devised and supervised by the engineers, L. Muller and F. Pacher, of Salzburg, Austria.

Design and construction had to overcome some disadvantages both of the site and of the proposed structure. The foundation was wholly within limestone beds, and a number of unusual geologic conditions were noted during the abutment excavation and construction. A strong set of rebound (relief) joints parallel to the canyon walls facilitated extensive scaling within the destressed, external rock "layer." Excessive stress relief within the disturbed outer zone caused rock bursts and slabbing in excavations and tunnels of the lower canyon. Strain energy released within the external, unstable "skin" of the abutment walls was recorded by seismograph as vibrations of the medium. This active strain phenomenon in the abutments was stabilized with a grout curtain—to 150 m (500 ft) outward at the base—and the effects were verified by a seismograph record. Grouting was controlled through variations of the elastic modulus.[3,4]

The potential for landslides was considered a major objection to the site by some early investigators[5]; others believed that "the slide potential can be treated with modern technical methods."

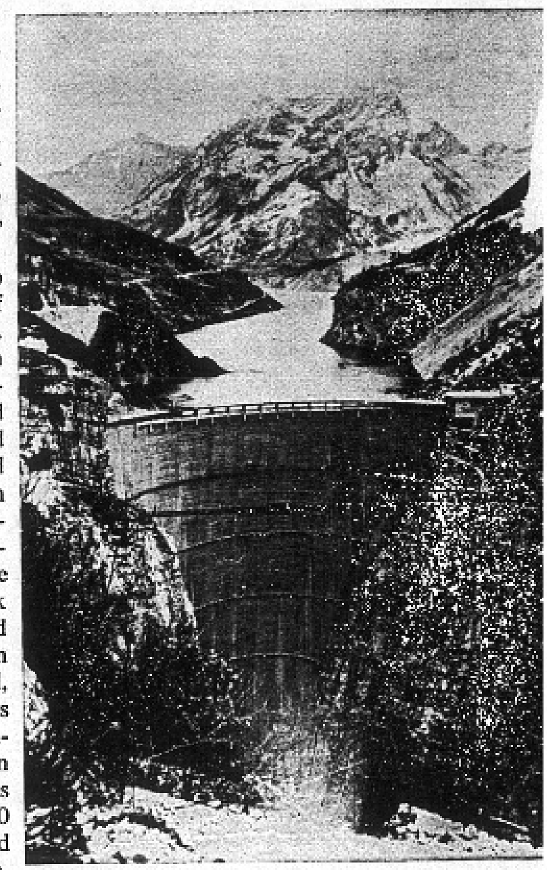


FIG. 2. Completed Vaiont Dam is seen with reservoir at about El. 680 m. On the right of the photograph, the white slope near the dam marks the 1960 slide. All the steep slope beyond was involved in the 1963 slide. (Wide World photo)

Vaiont Dam was constructed by SADE (Societa Adriatica Di Elettricita, Venezia) as part of its extensive hydroelectric system in northeastern Italy.[6,7] In 1962, the Italian national electric monopoly (ENEL) began to take over all of SADE's power facilities; during 1963 the operation of Vaiont Dam was under ENEL direction.[8]

The geologic setting

The Vaiont area is characterized by a thick section of sedimentary rocks, dominantly limestone with frequent clayey interbeds and a series of alternating limey and marl layers. The general subsurface distribution is shown in the geologic cross sections, Fig. 5. A brief description, progressing from the oldest to the youngest formations follows:

Lias formation, Lower Jurassic. Thin beds of gray limestone alternating with thin beds of reddish, sandy marl (shaly-sandy limestone). The soft beds aided fault movement in the overlying rock units (Fig. 5). **The Lias formation does not crop out in the Vaiont Reservoir, but underlies the region and is near canyon level at the dam site.**

Dogger formation, Middle Jurassic. Medium to thickly bedded gray, dense limestone; massive series over 300 m (1,000 ft) thick. Parting seams of clay are common. Upper part is thin bedded. Dissolved by solution action to produce some openings. **The dam foundation is wholly within Dogger beds and the series is well exposed in the walls of the canyon and on the slopes of Mt. Toc and Mt. Borga (Figs. 1 and 5).**

Malm formation (Titonico), Upper Jurassic. White to reddish, platy to very thin-bedded limestone with some siliceous beds. Clay seams are common along bedding planes and some claystone interbeds. Dissolved by solution action so that sinkholes, tubes, and openings are present. **This formation crops out in the walls of the reservoir (Fig. 3), mainly within 1 km (3,280 ft) of the dam; it was involved in the slides of 1960 and 1963.**

Lower Cretaceous formation. White, very thin- to medium-bedded limestone with some interbeds of siliceous limestone and claystone. Solutioning of the limestone has taken place and openings are common. **This formation crops out in the walls of the reservoir, mainly on the left bank and upper sector of the slide (Fig. 5, Section B-B); it was involved in the slides of 1960 and 1963.**

Upper Cretaceous formation (Senon). Red, thin beds of marl alternating with light red, thin beds of limestone. There is one zone of grayish marl with red to gray clayey sandstone. **This formation crops out in the upper part of reservoir on the left bank and channel; it had a strong influence on the slide plane in 1963 (Fig. 5, Section B-B).**

Glacial debris, Pleistocene. Irregular boulders and gravels, largely limestone with sand and silt, morainal remnants deposited on the floor of the glacial valley. **This material occurs as a thin mantle overlying bedrock on the sides of the outer valley (Fig. 5); it was involved in the slides of 1960 and 1963.**

Slide debris, Recent. Irregular blocks of talus, slope wash and old landslide material. **This material occurs as a thin to thick mantle overlying the bedrock of both the outer and the inner valleys (Fig. 5); it was involved in the slide of 1963.**

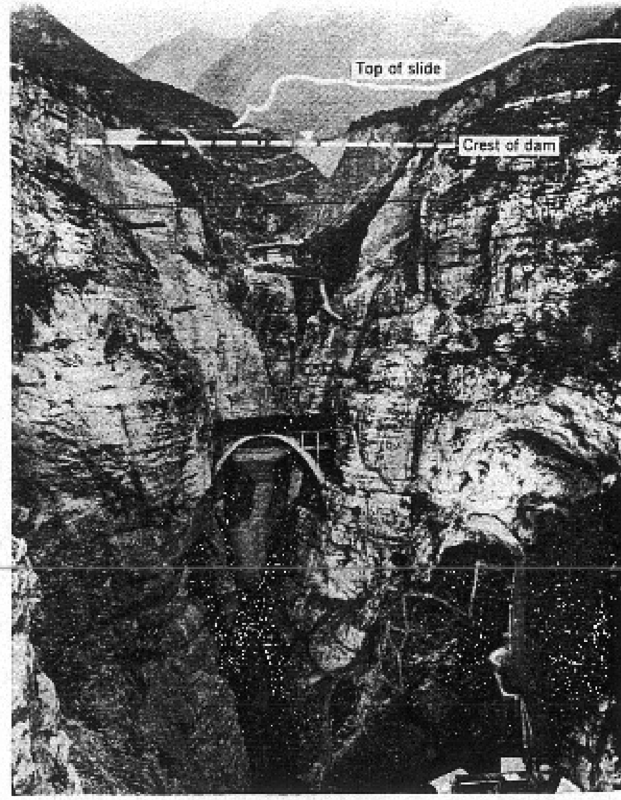


FIG. 3. Vaiont canyon is seen looking toward the reservoir site during early construction and stripping of abutments. Terrain of 1960 and 1963 slides is shown at right, with the steep cliff of Malm formation. The overtopping flood wave scoured the abutments above the dam, destroying the aqueduct and bridge (black) and stripped away the highway, lower right. Photo courtesy of Water Power.

Retained stress

The young folded mountains of the Vaiont region retain a part of the active tectonic stresses that deformed the rock sequence. Faulting and local folding accompanied the regional tilting along with abundant tectonic fracturing. This deformation, further aided by bedding planes and relief joints, created blocky rock masses.

The development of rebound joints beneath the floor and walls of the outer valley is shown in Fig. 4. This destressing effect creates a weak zone of highly fractured and "layered" rock, accentuated by the natural dip of the rock units. This weak zone is normally 100 to 150 m (330 to 500 ft) thick. Below this a stress balance is reached and the undisturbed rock has the natural stresses of mass.

Rapid carving of the inner valley resulted in the formation of a second set of rebound joints—in this case parallel to the walls of the present Vaiont canyon. The active, unstable "skin" of the inner canyon was fully confirmed during the construction of the dam.[3,4]

The two sets of rebound joints, younger and older, intersect and coalesce within the upper part of the inner valley (Fig. 4). This sector of the canyon walls, weakened by overlapping rebound joints, along with abundant tectonic fractures and inclined bedding planes, is a very unstable rock mass and prone to creep until it attains the proper slope.

Causes of slide

Several adverse geologic features of the reservoir area contributed to the landslide on October 9:

Rock units that occur in a semicircular outcrop on the north slopes of Mt. Toc are steeply tilted. When deformed, some slipping and fault movement between the beds weakened frictional bond.

Steep dip of beds changes northward to Vaiont canyon, where rock units flatten along the synclinal axis; in three dimensions the area is bowl-shaped (Fig. 5). The down-dip toe of the steep slopes is an escarpment offering no resistance to gravity sliding.

Rock units involved are inherently weak and possess low shearing resistance; they are of limestone with seams and clay partings alternating with thin beds of limestone and marl, and frequent interbeds of claystone (Fig. 5).

Steep profile of the inner canyon walls offers a strong gravity force to produce visco-elastic, gravitational creep and sliding (Fig. 4).

Semicircular dip pattern confined the tendency for gravitational deformation to the bowl-shaped area (Fig. 1).

Active solutioning of limestone by ground-water circulation has occurred at intervals since early Tertiary time.

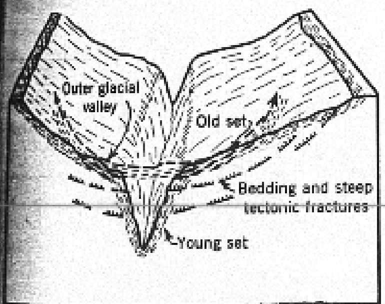


FIG. 4. On sketch of inner Vaiont canyon and remnants of the outer glacial valley, are shown rebound joints—old and young set—from stress relief within the walls of the valley to depths of 100 to 150 m (330 to 500 ft).

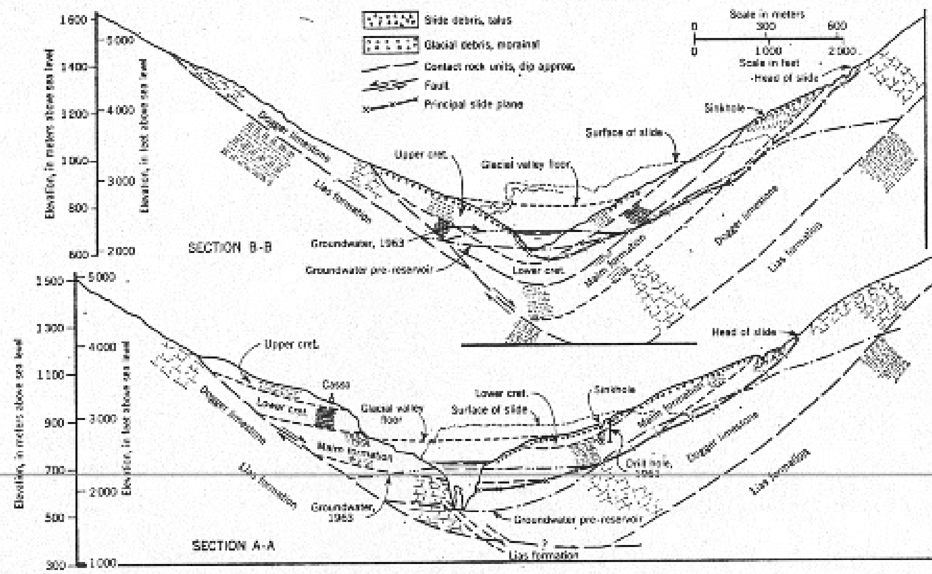


FIG. 5. On geologic cross-sections of slide and reservoir canyon, running from north to south, principal features of the slide plane, rock units and water levels are shown. For location of Sections A-A and B-B, see Fig. 1.

The result has been subsurface development of extensive tubes, openings, cavities and widening of joints and bedding planes. Sinkholes formed in the floor of the outer valley (Fig. 1), particularly along the strike of the Malm formation on the upper slopes (Fig. 5); these served as catchment basins for runoff for recharge of the ground-water reservoir. This interconnected ground-water system weakened the physical bonding of the rocks and also increased the hydrostatic uplift. The buoyant flow reduced gravitational friction, thereby facilitating sliding in the rocks.

Two sets of strong rebound joints, combined with inclined bedding planes and tectonic and natural fracture planes, created a very unstable rock mass throughout the upper part of the inner canyon (Fig. 4).

Heavy rains for two weeks before October 9th produced an excessive inflow of ground-water from the drainage area on the north slopes of Mt. Toc. This recharge raised the natural ground-water level through a critical section of the slide plane (headward part) and subsequently raised the level of the induced water table in the vicinity of their junction (critical area of tensional action). The approximate position of both water levels at the time of the slide is shown in Fig. 5.

Excessive ground-water inflow in early October increased the bulk density of the rocks occurring above the initial water table; this added weight contributed to a reduction in the gross shear strength. Swelling of some clay minerals in the seams, partings and beds created additional uplift and contributed to sliding. The upstream sector (Fig. 5, Section B-B) is composed largely of marl and thin beds of limestone with clay partings—a rock sequence that is inherently less stable than the downstream sector (Fig. 5, Section A-A).

The bowl-shaped configuration of the beds in the slide area increased the confinement of ground water within the mass; steeply inclined clay partings aided this containment on the east, south, and west.

The exploratory adit driven in 1961 reportedly exposed clay seams and small-scale slide planes. Drill holes bored near the head of the 1960 slide (Figs. 1 and 5, Section A-A) were slowly closed and sheared off. This confirmed the view that a slow gravitational creep was in progress following the 1960 slide and probably even before that—caused by a combination of geologic causes. Creep and the accompanying vibrations due to stress relief were later described by Muller.[9]

Effects of man's activities

Construction of Vaiont Reservoir created an induced ground-water level which increased the hydrostatic uplift pressure throughout a triangular subsurface mass (Fig. 5) aided by fractures and the interconnected system of solution openings in the limestone.

Before April 1963, the reservoir was maintained at El. 680 m. In September, five months after the induced water table was raised 10 m (33 ft), the slide area increased its rate of creep. This action has three possible explanations: (1) a very delicate balance existed between the strength of the rock mass and the internal stresses (shear and tensile), which was destroyed by the 10-m rise of bank storage and accompanying increase in hydrostatic pressure; (2) the same reaction resulted from the large subsurface inflow in early October due to rains; or (3) the induced ground-water level from the reservoir at El. 680 m during 1961-1962 did not attain maximum lateral infiltration until September 1963, when creep accelerated. In any case, the rate of ground-water migration into bank storage is believed to have been critical. To ascertain which condition actually prevailed, observation wells would have been needed for measurement of the transmissibility factor.

Evidence indicates that the immediate cause of the slide was an increase in the internal stresses and a gross reduction in the strength of the rock mass, particularly the upstream sector where this mass consists largely of marl and alternating thin beds of limestone and marl. Actual collapse was triggered by an excess of ground water, which created a change in the mass density and increased the hydrostatic uplift and swelling pressures along planes of inherent weakness, combined with the numerous geologic features that enhanced and facilitated gravitational sliding.

The final movement was sudden—no causes from "outside" the affected area are thought to have been responsible.

GEOLOGIC CHANGES IN THE AREA

The Vaiont area has been modified by the following series of geologic events (oldest to youngest), which weakened the reservoir rocks in some manner;

1. The thick section of sedimentary rocks (Fig. 5, Section A-A) underwent initial attack by erosion and solutioning throughout early Tertiary time. The relief became unstable and later, some 40 million years ago (Eocene time), sands, clays, and marls of the Alpine flysch were deposited over the region as a covering blanket.

2. Beginning some 25 million years ago (mid-Tertiary time) the region underwent strong mountain-building forces. A series of regional folds developed with accompanying thrust faults running generally east-west. The Erto synclinal axis is followed by the present Vaiont channel, while to the north an anticlinal axis runs through Mt. Borga and a second anticline runs just south of Mt. Toc (Fig. 1).

Later the large fold that crests just west of Vaiont Dam was formed at right angles to the Erto synclinal axis. This fold tilts all the beds to the east at the dam and along the synclinal axis in the reservoir. Beds on the north and south banks dip toward the synclinal axis to form a bowl-shaped structure (Figs. 1 and 5).

3. The Erto synclinal sag became the natural site for the ancient Vaiont River; carving of the outer valley was initiated before late Tertiary time. Erosion removed much of the flysch cover and the solutioning of the underlying limestone was accelerated, particularly along the flanks of the outer valley.

4. Beginning a million years ago (in Pleistocene time), glaciers were active in scouring the outer valley (Fig. 5). This scouring along with preglacial stream erosion, removed a thick section of the former rock column. The rapid unloading affected the balance of stresses within the rocks; adjustment resulted in the progressive formation of a strong set of rebound (relief) joints roughly parallel to the walls and later the floor of the outer canyon (Fig. 4).

5. Within the past 18,000 years, the glaciers have withdrawn from the outer Vaiont valley. Since the ice disappeared, erosion by the Vaiont River has been rapid; the present channel has cut down from 200 to over 350 m (650 to 1,150 ft) below the glacial valley—an unusually fast rate of erosion. The inner canyon was carved so rapidly that inherent stresses in the rocks were not fully adjusted by stress relief, giving rise to the imbalance of stress in the walls of the inner canyon (Fig. 4) which still exists.

6. The change in the natural ground-water level, from the outer to the inner valley stream level, further aided the subsurface solutioning of the limestone and marl beds. As the canyon deepened and the ground-water gradient became steeper, solution action was accelerated.

7. In prehistoric time, a large landslide occurred in the Pineda sector of the Vaiont inner valley and distorted rocks within the uppermost part of the 1963 slide. The stream channel apparently was closed off much as it is today. Water was impounded behind the constriction formed by the slide until the debris was overtopped and the former stream channel dug out, a condition faced by the Vaiont River today. But now it lacks an outlet with a steep gradient downstream for removing debris.

Sequence of Slide Events

Large-scale landslides are common on the slopes of Vaiont Valley; witness the ancient slide at Casso and the prehistoric blocking of the valley at Pineda. Movement at new localities is to be expected periodically because of the adverse geologic setting of the valley. The principal events preceding the movement on October 9 were:

In 1960, a slide of some 1 million cu m (1.3 million cu yd) occurred on the left bank of the resevoir near the dam. (See Figs. 1, 2, and 3.) This movement was accompanied by creep over a much larger area; a pattern of cracks developed upslope from the slide and continued eastward.[10] These fractures (Fig. 1) ultimately marked the approximate limits of the October 9 slide. The slopes of Mt. Toc were observed to be creeping and the area showed many indications of instability.[9]

In 1960-1961, a bypass tunnel 5 m (16.4 ft) in diameter was driven along the right wall of the reservoir for a distance of 2 km (6,560 ft), (Fig. 1) to assure that water could reach the outlet works of the dam in case of future slides.[6]

As a precaution, after the 1960 slide the reservoir elevation was limited to a maximum of 680 m and a grid of geodetic stations on concrete pillars was installed throughout the potential slide area extending 4 km (2.5 miles) upstream, to measure any movement.[3]

The potential slide area was explored in 1961 both by drill holes to a depth of 90 m (300 ft) and by a man-sized adit. Reportedly, no confirmation of a major slide plane could be detected in either drill holes or adit.[10] An analysis now indicates that the drill holes were too shallow (Fig. 5, Section A-A) to intercept the major slide plane of October 9, and what was in all probability the deepest plane of gravitational creep started by the 1960 slide and active thereafter.

Gravitational creep of the left reservoir slope was observed during the 1960-1963 period, and Muller[9] reports "movement of 25 to 30 cm (10 to 12 in.) per week (on occasion) which was followed in close succession by small, local earth tremors due to stress relief within the slope, centered at depths of 50 to 500 m (164 to 1,640 ft). The total rock mass that was creeping was about 200 million cu m (260 million cu yd)."

During the spring and summer of 1963, the eventual slide area moved very slowly; scattered observations showed a creep distance of 1 cm. (3/8 in.) per week, an averge rate since the 1960 slide.

Beginning about September 18, numerous geodetic stations were observed to be moving 1 cm a day. However it was generally believed that only individual blocks were creeping; it was not suspected that the entire area was moving as a mass.

Heavy rains began about September 28 and continued steadily until after October 9. Excessive runoff increased ground-water recharge and surface inflow; the reservoir was at El. 690 m or higher, about 100 ft below the crest.

About October 1, animals grazing on the north slopes of Mt. Toc and the reservoir bank sensed danger and moved away. The mayor of Casso (Fig. 1) ordered townspeople to evacuate the slopes, and posted notice of an expected 20-m (65-ft) wave in the reservoir from an anticipated landslide. (The 20 m was also the estimate of engineers for the height of the wave that would follow such a slide, based on experience of the slide at nearby Pontesi Dam in 1959.)

Movements of geodetic stations throughout the slide area reported for about three weeks before the collapse were:

Date	Rate of Creep (approx.)	Type of Creep
Sept. 18 to 24	1 cm (3/8 in.) per day	Transient creep
Sept. 25 to Oct. 1	10 to 20 cm (4 to 8 in.) per day	Quasi-viscous creep
Oct. 2 to 7	20 to 40 cm (8 to 16 in.) per day	Quasi-viscous creep
Oct. 8	40 cm (16 in.)	Creep to failure
Oct. 9	80 cm (2.64 ft) (before collapse)	Creep to failure

About October 8, engineers realized that all the observation stations were moving together as a "uniform" unstable mass; and furthermore the actual slide involved some five times the area thought to be moving and expected to collapse about mid-November.

On October 8, engineers began to lower the reservoir level from El. 690 m in anticipation of a slide. Two outlet tunnels on the left abutment were discharging a total of 5,000 cfs but heavy inflow from runoff reduced the effectiveness of this measure. The reservoir contained about 135 million cu m of water at the time of the disaster.

On October 9, the accelerated rate of movement was reported by the engineer in charge. A five-member board of advisers were evaluating conditions, and authorities were assessing the situation on an around-the-clock basis. Although the bypass outlet gates were open, verbal reports describe a rise in the reservoir level on October 9. This is logical if lateral movement of the left bank had progressed to a point where it was reducing the reservoir capacity. These reports also mention difficulty with the intake gates in the left abutment (El. 591 m) a few hours before the fatal slide.

Movement, flood and destruction

Those who witnessed the collapse included 20 SADE technical personnel stationed in the control building on the left abutment (Fig. 2) and some 40 people in the office and hotel building on the right abutment. But no one who witnessed the collapse survived the destructive flood wave that accompanied the sudden slide at 22 hours 41 min 40 sec (Central European Time).[2] However, a resident of Casso (Fig. 1) living over 260 m (850 ft) above the reservoir, and on the opposite side from the slide, reported the following sequence of events:[10]

- About 10:15 p.m. he was awakened by a very loud and continuous sound of rolling rocks. He suspected nothing unusual as talus slides are very common.
- The rolling of rocks continued and steadily grew louder. It was raining hard.
- About 10:40 p.m. a very strong wind struck the house, breaking the window panes. Then the house shook violently; there was a very loud rumbling noise. Soon afterward the roof of the house was lifted up so that rain and rocks came hurtling into the room (on the second floor) for what seemed like half a minute.
- He had jumped out of bed to open the door and leave when the roof collapsed onto the bed. The wind suddenly died down and everything in the valley was quiet.

Observers in Longarone reported that a wall of water came down the canyon about 10:43 p.m. and at the same time a strong wind broke windows, and houses shook from strong earth tremors. The flood wave was over 70 m (230 ft) high at the mouth of Vaiont canyon (Fig. 1) and hit Longarone head on. Everything in its path was destroyed. The flood moved upstream in the Piave valley beyond Castello Lavazzo, where a 5-m (16-ft) wave wrecked the lower part of Codissago. The main volume swept downstream from Longarone, hitting Pirago and Villanova (Fig. 1). By 10:55 p.m. the flood waters had receded and all was quiet in the valley.

The character and effect of the air blast that accompanied the main flood wave at the dam have been described in the introduction. The destruction wrought by the blast, the jet of water, and the decompression phase are difficult to imagine. For example, the steel I-beams in the underground powerhouse were twisted like a corkscrew and sheared; the steel doors of the safety chamber were torn from their hinges, bent, and carried 12 m (43 ft) away.

Seismic tremors caused by the rock slide were recorded over a wide area of Europe—at Rome, Trieste, Vienna, Basel, Stuttgard, and Brussels. The kinetic energy of the falling earth mass was the sole cause of the seismic tremors recorded from Vaiont according to Toperczer.[2] No deep-seated earthquake occurred to trigger the slide. The seismic record clearly demonstrates that surface waves (L_1 = 3.26 km per sec, or about 730 mph) were first to arrive at the regional seismic stations, followed by secondary surface waves (L_2 = 2.55 km per sec, or 570 mph). There was no forewarning in the form of small shocks and no follow-up shocks—which are typical of earthquakes from subsurface sources. No *P* or *S* waves were recorded.

Pattern of sliding

The actual release and unrestricted movement of the slide was extremely rapid. Seismological records show that the major sliding took place within less than 30 sec (under 14 sec for the full record of the L_1 wave) and thereafter sliding ceased. The speed of the mass movement (50 to 100 ft per sec) and the depth of the principal slide are strikingly demonstrated by the preservation intact of the Massalezza River canyon (Fig. 1) and the grassy surface soil with distinctive "fracture" pattern (Fig. 7).

A study of the slide mass correlated with the geologic circumstances suggests that the eastern or upstream sector (Fig. 5, Section B-B) moved first by a few seconds, followed by the downstream part (Fig. 5, Section A-A). This sequence is substantiated by the following facts:

1. The thickest section of weak rocks crop out over the upper area (all possess clay interbeds, seams) and continue beneath the reservoir channel (Fig. 5, Sect. B-B). Similarly these rock units were more highly saturated and weakened by ground-water.

2. The deepest and widest zone of deformation is in the upstream sector where the head of the slide is nearly 200 m (650 ft) higher up the slopes of Mt. Toc (Fig. 1) and sliding occurred beneath the floor of the canyon (Fig. 5, Section B-B).

3. At the upper end, the principal mass moved northwesterly (Fig. 8) to lower slopes where the trend changed to northward across Vaiont canyon. This pattern would have been impossible if the slide mass on the west had already moved into place or was moving contemporaneously with the upper sector.

4. The wall of water that swept over the dam had so great a volume that the reservoir adjacent to the slide was literally displaced downstream. This hinge-like motion by which the water was displaced confirms the suggested pattern of the slide mass and is in conformity with the distrbution of the weaker rock units. The path of the waves generated in the reservoir upstream from the slide (Fig. 1) indicates that they were due to a tangential force, which pushed the first wave against the shore opposite Pineda.

Wave action due to slide

Sketchy reports from observers at Erto described the first wave by stating that "the entire reservoir for 2.0 km (1.2 miles) piled up as one vast curving wave" for a period of 10 sec. The strong updraft of air created by the rapid slide was confined in movement by the deep Vaiont valley encircled by high peaks (Fig. 4). The updraft within the confined outer valley sucked the water, accompanied by rocks, up to El. 960 m (885 ft or more above the original reservoir level) and accounted for part of the force possessed by the initial wave.

At the dam, the initial wave split on hitting the right canyon wall, after demolishing the SADE hotel building at El. 780 m (300 ft above the reservoir surface). Some of the water followed the canyon wall downstream and moved above and around the dam. The major volume, however, seems to have bounced off the right wall, swept back across the canyon to the left abutment and moved upslope and around the dam to at least El. 820 m (460 ft above the reservoir level).

The overflow waves from the right and left abutments (Fig. 1) were joined in the canyon by the main surge, which overtopped the dam, and together these constituted the flood wave that hit Longarone. Water overtopped the dam crest on the left side

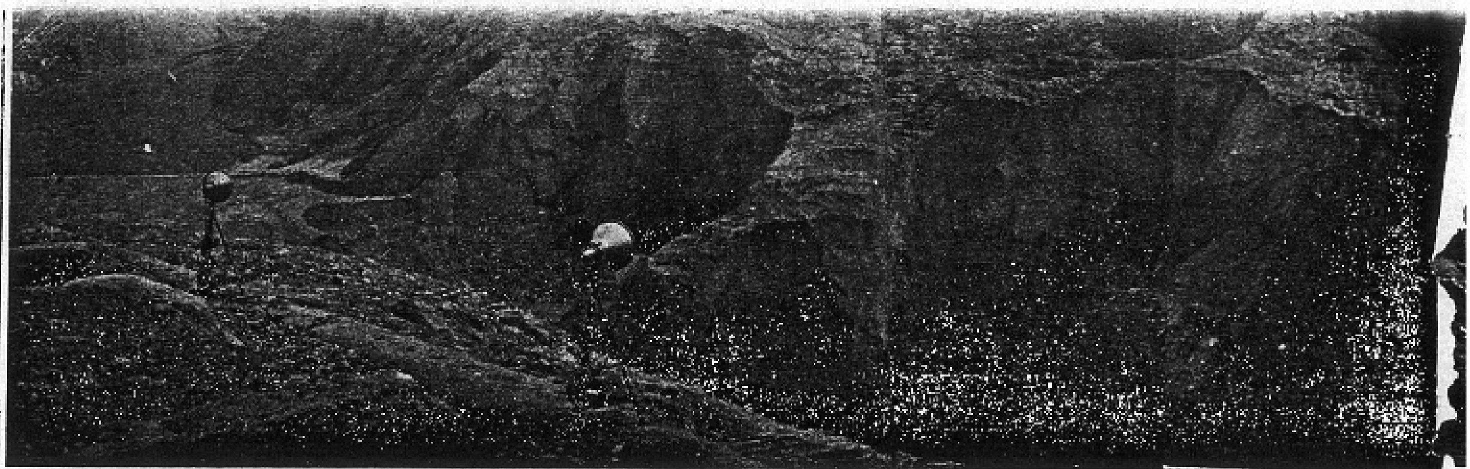


FIG. 6. Slide area following the disaster is seen from right dam abutment. Note wave-scoured area at right. Holes, or funnel-like craters, appeared in the slide as it underwent adjustment. Damaged

(Fig. 6) for some hours after the slide, strongly the next morning, and during this time also displaced water drained from pools scattered over the slide surface.

Upstream the wave generated by the slide moved first into the area opposite Pineda, where it demolished homes, bounced off the canyon wall and moved southward, hitting the Pineda peninsula. On receding from there, the wave moved northeastward across the full length of the lake and struck San Martino (Fig. 1) with full force, bypassing Erto, which went unharmed.

Conditions since the slide

The water level just behind the dam dropped at the rate of 50 to 80 cm (20 to 32 in.) per day during the first two weeks after the slide. This loss is believed due in part to leakage through the intake gates for the bypass aqueduct and powerhouse conduits. Geologically, there was a substantial loss due to the new conditions of bank storage, subsurface circulation and saturation of material filling the canyon.

A pond that formed at the Massalezza River canyon, along the foot of the slide plane, dropped in level rapidly and was dry on Ocrober 24, confirming the idea of ground-water recharge to slide material and the establishment of a water table within the newly formed mass. Smaller ponds initially formed upstream from the dam along the zone of contact between the slide and the right reservoir bank (Fig. 6). These likewise dried up by October 24 as a result of ground-water recharge and a readjustment in the water table within the slide mass.

The lake level behind the slide dam (Fig. 9) rose steadily from the inflow of tributary streams. For example, two weeks after the slide, the reservoir was 13 m (43 ft) higher than the water level at the dam—a major problem in the future operation of Vaiont Dam.

Strong funneling craters developed during the first days after the slide in the soil and glacial debris concentrated near the toe of the slide (Fig. 6). This cratering was of concern to some as indicating large-scale movement to come, but other conditions are the probable causes of the surface subsidence. Large blocks of rock, with some bridging action, fill the canyon and create much void space in the lower mass. Some of these spaces are filled by normal gravity shifting of fines, and ground-water circulation also distributes fines into these void spaces. Formation of craters is restricted to the section of the slide that fills the former canyon, and craters appear at intervals along its entire length. They are most extensive in the slope behind the dam.

Numerous small, step-like slide blocks occur at different levels on the

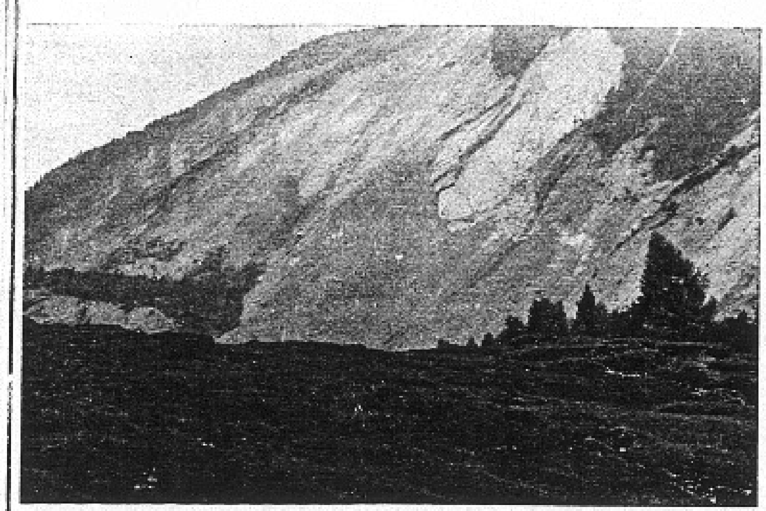


FIG. 7. Top of main slide is seen along cross section A-A of Fig 5. Typical talus runs and step-like blocks are shown moving down the surface of the slip plane. The coherent grass and soil, characteristic of a large part of the surface of the slide mass, appear in foreground.

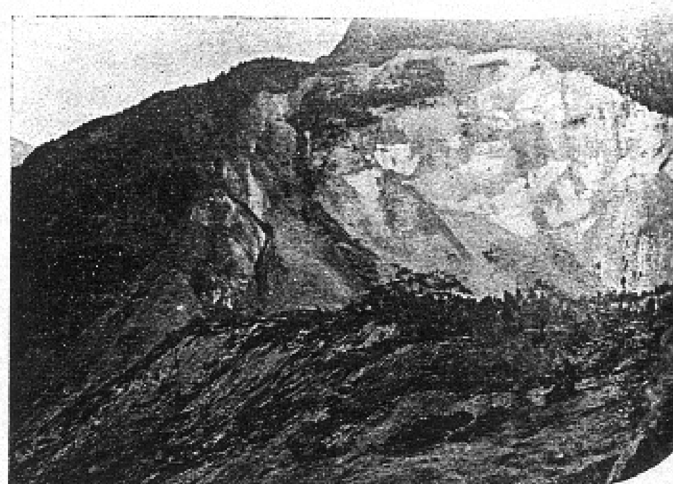
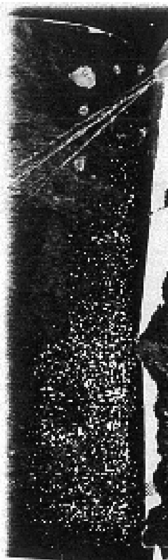
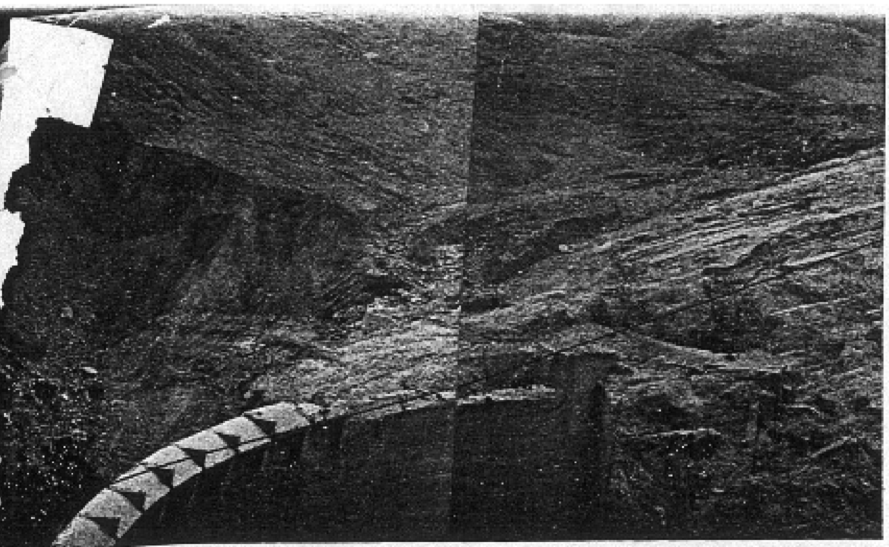


FIG. 8. Slip plane and eastern limit of the slide are seen looking south from a point above the former reservoir. A typical slide mass is in foreground, with talus runs and step-like blocks moving down the slip plane.





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crest, from which the roadway was torn away, is the only apparent structural damage to the dam. Front of slide (see Fig. 8) is the high cliff on the left, extending into the distance.

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main slip plane (Fig. 8). These blocks were loosened by the movement on October 9 and have since moved slowly down the slip plane, some to the bottom of the escarpment. Talus runs are common from small V-notched canyons along the edge of the steep eastern sector of the slide.

Future of the reservoir

The steeply dipping beds along the head of the slide will undoubtedly fail from time to time as a result of gravitational creep. Ultimately the uppermost part of the slip plane (Fig. 8) will be flattened and thereby will attain a stable natural slope.

The Italian Ministry of Public Works has announced that Vaiont Dam will no longer be used as a power source. The cost of clearing the reservoir would be prohibitive because of the volume involved, the distance of 4 or 5 km (3 miles) that waste material would have to be hauled to the Piave valley, and the 300-m (1,000-ft) lift required to transport the waste over the divide west of the dam.

The bypass tunnel in the right wall of the reservoir could be ultimately used to pond water behind the dam for release through the existing outlet works. Another alternative would be to divert the reservoir water southeastward to the Cellina River drainage by a tunnel driven from the upper end of the lake. Such diversion would develop the upper catchment area of Cellina and utilize Vaiont storage, behind the slide dam, as a multi-seasonal storage astride the Piave and Cellina catchments.[7]

Vaiont in retrospect

Vaiont has tragically demonstrated the critical importance of geologic features within a reservoir and in its vicinity—even though the site may be otherwise satisfactory for a dam of outstanding design.

In future, preconstruction studies must give thorough consideration to the properties of a rock mass as such, in contrast to a substance, and particularly to its potential for deformation with the passage of time. An assessment that is theoretical only is inadequate. The soundest approach is a systematic appraisal that includes:

An investigation of the geologic setting and its critical features

An assessment of past events that have modified features and properties of the site rocks

A forecast of the effects of the engineering works on geologic features in the area and on the strength of the site rocks

The geologic reaction to changed conditions in the process of time

Project plans should set forth a system for acquiring data on the interaction between geologic conditions and changes induced by project operation.

Time, in terms of the life of the project, is a key to safety and doubtedly was a controlling factor at Vaiont. Since 1959, eight major dams around the world have failed in some manner. It seems imperative that the following factors be recognized:

1. Rock masses, under changed environmental conditions, can weaken within short periods of time—days, weeks, months.

2. The strength of a rock mass can decrease very rapidly once creep gets under way.

3. Evidence of active creep should be considered as a warning that warrants immediate technical assessment, since acceleration to collapse can occur quickly.

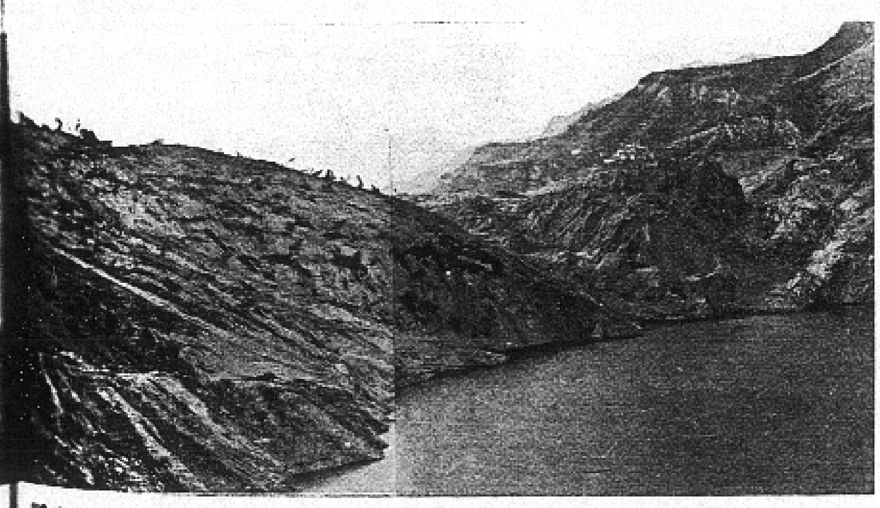

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FIG. 9. Upstream side of slide "dam" and impounded reservoir are seen looking westward from near Pineda. Note village of Casso at upper right corner (El. 960 m). Low "rift" valley in center of photo is due to settling and lateral slipping of slide mass within the reservoir canyon.

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