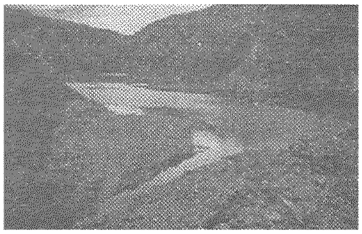


Figure 17. Outflow from the excavated channel over the dam crest.

Numerical, physical and statistically-based simulations permitted the definition of a risk scenario with the prediction of a total volume of 177 × 10⁶ m³ of released water and a peak discharge ranging between 2 000 and 16 000 m³/s, depending on the grain-size distribution of the dam material. At about 0700 hrs on 1 May 1993, the dam started to breach when the lake had reached a maximum storage of 210 × 10⁶ m³. In 24 hours, about 185 × 10⁶ m³ of water were released, with an overflow peak discharge of about 10 000 m³/s (Figure 18) (Canuti *et al.*, 1994). The flood from the rupture caused serious damage, especially for the first 20 km, destroying property, productive activities, infrastructures and services. However, thanks to the emergency measures put into effect, no human lives were lost and the Amaluza dam, despite being overtopped, did not suffer significant damage.

The work of the international scientific commission in this case was of fundamental importance in transferring the know-how and the technical support to the decision makers for the successful implementation of the emergency plan.

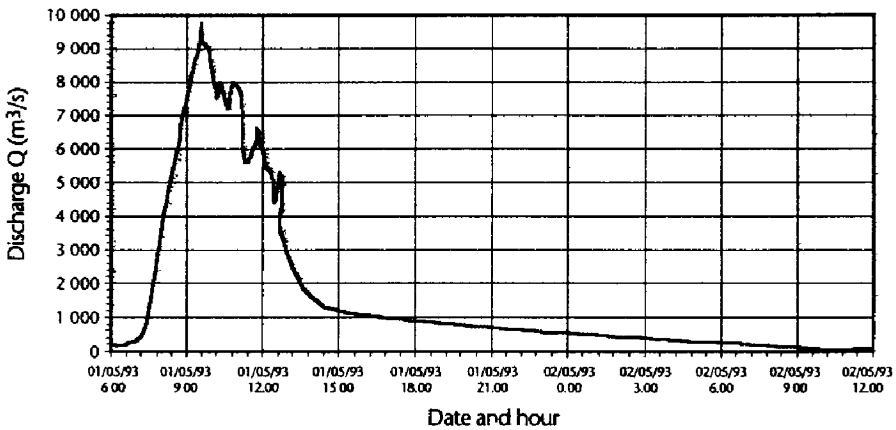


Figure 18. Hydrograph of the flood wave originated by the dam breaching (after Canuti *et al.*, 1994).

4.2 THE VAIONT SLIDE: AN EXAMPLE OF POOR MANAGEMENT LEADING TO A CATASTROPHE

The 1963 Vaiont event in northeastern Italy represents the most disastrous landslide in Europe since historic times. On 23 October 1963, a rockslide of 270 × 10⁶ m³ fell from the northern flank of Mount Toc (Figure 19), with a peak velocity estimated at 20-30 m/s, into the 150 × 10⁶ m³ reservoir of the Vaiont dam, the then highest arch dam in the world (Figure 20). The slide displaced over 50 × 10⁶ m³ of water, which overtopped the dam causing huge losses downstream in the Piave valley (Figure 21). Five villages were destroyed and 1 759 lives were lost. The total direct cost of the loss of property and services (excluding the value of the lives lost) was estimated to 600 × 10⁶ US $ (1990 value).

The presence of a prehistoric dormant slide on the northern slope of Mount Toc was first recognized by Giudici and Semenza (1959), two years after the construction of the dam was started. The inadequacy of the geological and geophysical investigations, mainly due to the limited technological development of applied geosciences at that time, did not permit those involved to draw conclusions of the seriousness of the situation. The dam was completed and started to impound water in February 1960.

A first global re-activation of the slide occurred on 4 November 1960, three years before the catastrophe, when a crack suddenly appeared bordering the entire landslide body, thus confirming the Giudici and Semenza hypothesis (Figure 22). In the following three years, the technical commission in charge of the reservoir readied and implemented different strategies to manage the emergency situation. The scenario defined by the commission was based on the principle that the reactivation of a pre-existing slide of such relevant size would occur gradually, with progressive limited displacements and slow rates. Within this framework, Müller proposed to induce the progressive, slow mobilization of the entire mass by alternately filling and drawing down the reservoir (Muller, 1964). A bypass tunnel was excavated within the opposite bank with the aim of maintaining the reservoir functionality after the landslide (Figure 22). During the third filling phase, in October 1963, the slide velocity overcame the warning thresholds fixed by the

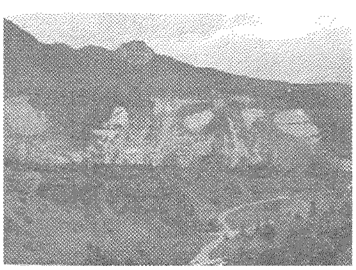


Figure 19. The Vaiont landslide: in the foreground the foot of the displaced mass and behind it the scar.

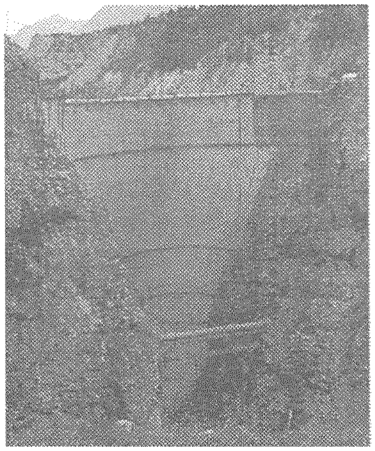


Figure 20. The Vaiont dam seen from downstream.

technical commission and a rapid draw down of the reservoir level was initiated. This triggered the sudden rapid mobilization of the entire landslide mass and caused the Vaiont catastrophe.

In the 36 years since the disaster, the scientific community has developed and disseminated knowledge which today would suggest a completely different management of the situation. The main points which can, in part, be considered as lessons learned from that disaster, are the following:

(a) studies and analyses of the stability of slopes on reservoirs are now routinely carried out in the preliminary design of dams;
(b) the dual effect of raising the external water level on a potentially unstable slope is now fully clarified and has lead to the development of the "critical pool level" concept;
(c) the decrease of the safety factor during rapid drawdown phases has been understood and can be adequately predicted;
(d) the fact that the re-activation of a pre-existing shear surface can produce large displacements and high velocities has been demonstrated by a series of case histories.

Despite advances in scientific research on the mechanisms of large landslides in rock, the Vaiont event remained poorly understood for many years and still cannot be considered fully explained today. The first studies on the Vaiont failure (Müller, 1964, 1968; Kenney, 1966, Novellier, 1967 Mencl, 1967) did not provide a satisfactory explanation of the movement mechanism. Only with the study of Hendron and Patton (1985), 22 years after the event, was a fully convincing interpretation of the landslide mechanism provided. In particular, the main points of their work can be summarized as follows:

(a) comprehension of the coupled effect of external water level and antecedent rainfall;
(b) identification of the presence of sheared argillitic inter-layers (at residual strength) within the calcareous sequence;
(c) presence of a confined aquifer under the slip surface and consequent new interpretation of the piezometric readings made before the landslide;
(d) additional friction provided by the sub-vertical fault plane on the western margin which makes a three-dimensional stability analyses necessary;
(e) the sudden acceleration is explained with a 50 per cent drop in strength caused by the generation of pore water pressure on the shear surface by frictional heating.

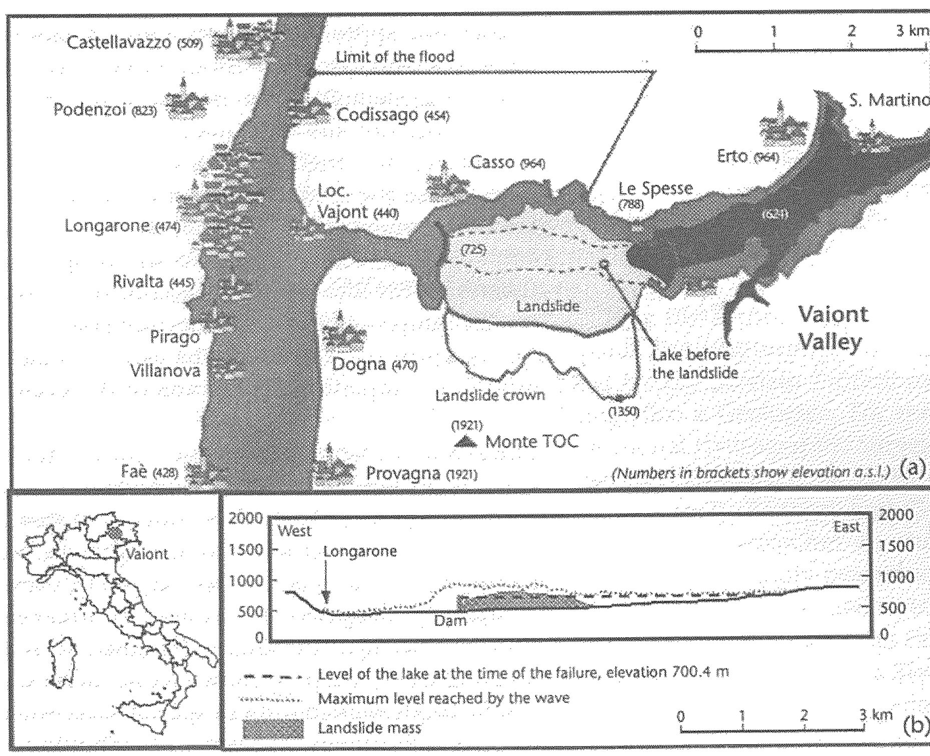
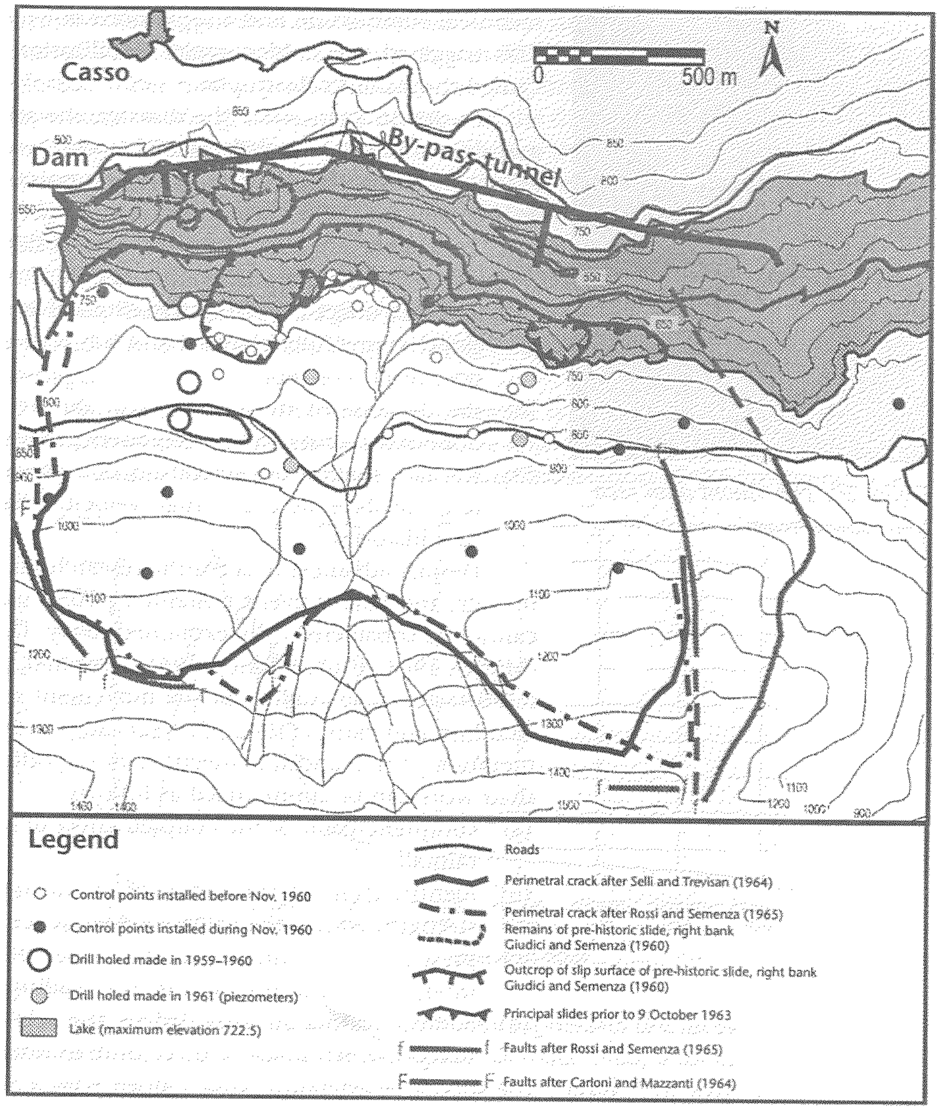


Figure 21 General plan showing the Vaiont landslide and the limit of the flood (a); schematic longitudinal section showing the original lake level and the elevation of the flood wave (b). After Selli and Trevisan (1964) and Kiersch (1964).

Figure 22. General plan of the Vaiont valley before the slide (after Hendron and Patton, 1985).



The last point is perhaps the weakest of the Hendron and Patton study, since it does not appear to be sufficiently documented nor supported by thermodynamical modelling. Hutchinson (1987) offered an alternative explanation of the sudden acceleration. The markedly non-circular shape of the slip surface (in section) did not allow the mass to slide without triggering internal deformations or ruptures. The high strength and brittleness of the Cretaceous limestone could have caused the accumulation of strains with a sudden drop in strength following the development of internal shear zones. A further decrease in strength is attributed by Hutchinson (1987) to the drop in residual strength caused by rapid shearing. This idea seems to be confirmed by high-speed ring shear tests carried out on samples from the slip surface (Tika and Hutchinson, 1999) that showed a loss of up to 60 per cent of the slow residual strength. Thirty-six years after the disaster a complete interpretation of the event seems to be close.

5. CONCLUSIONS

The actions to be carried out for coping with landslide hazard can be divided into three main phases: prediction, prevention, and emergency management In the prediction phase, it should be considered that landslides are complex phenomena caused by many factors, such as intrinsic ground conditions, geomorphological, physical and man-made processes. All of these factors interact and can rarely be completely recognized before the occurrence of an event. Therefore the prediction, in particular the temporal prediction, is difficult and complex and can only be obtained by keeping these factors under control by monitoring systems. This can be implemented only in special cases where the value of the elements at risk justifies the expense. Particular care should be used when the territory has been strongly modified by human activity, which frequently disturbs the pre-existing conditions of natural equilibrium. Spatial hazard prediction is usually more feasible since the integrated analysis of slope stability factors, such as lithology, morphology and hydrogeology, makes landslide-prone areas readily identifiable. Landslides are dynamic processes that, in most cases, show evident traces of their presence before occurring. This is obvious in re-activations of pre-existing events, but it is also frequently true in first-time failures characterized by precursory symptoms that, if promptly detected with detailed geomorphic investigations, are of invaluable help in landslide hazard zoning. These considerations point out how landslide inventory mapping can be a powerful predictive tool. The Emilia-Romagna case is an excellent example of how the systematic collection of geologic and geomorphic data, with the aid of modern geographic information systems, can be successfully employed in the regional assessment of landslide risk. Unfortunately, man is still confronted with situations that are difficult to predict, such as in the Versilia example, that show how extreme events can escape the prediction techniques currently available and cause huge unexpected losses.

Regarding landslide risk prevention, success is linked to a clear spatial and typological prediction: when the phenomena are clearly spatially delimited and their mechanism is fully described, risk mitigation actions can be successfully implemented. Therefore prevention can be pursued, on one hand, through the mitigation of hazard, following the identification of precursory symptoms and of preparatory casual factors and, on the other, through a correct management of human activities and land use. With the combination and coordination of these actions, the success rate of preventive measures becomes satisfactory. Careful land and urban planning is of paramount importance in countries exposed to landslide hazard and the cases illustrated in this paper have shown two different approaches. These can either lead to effective slope stabilization, even promoting the re-beautification of a landscape such in the San Miniato hill example, or to a major catastrophe such as in the Sarno event where incomplete geologic and geomorphic knowledge was combined with uncontrolled urban development.

For effective management, an emergency should be accurately planned and defined before hand, integrating both elements of prediction and prevention. The implementation is usually carried out in rapid succession and under conditions of great stress. It is in this phase that the scientific community can play a fundamental role, transferring to the decision makers the necessary knowledge for successfully overcoming a crisis. The comparison between La Josefina and the Vaiont examples points out how the development of investigation and simulation techniques can help define reliable scenarios, with functional warning systems, that permit us to correctly manage emergency situations.

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