About deterioration in the abutment rocks of some large dams in Northern Italy

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Riassunto

Si espongono i dati sperimentali riguardanti le velocità delle onde elastiche longitudinali ottenute nelle rocce d'imposta di alcune grandi dighe del Nord Italia e se ne studia la variazione nel tempo. Sulla base della trattazione di O'Connell e Budiansky sulla velocità delle onde sismiche in solidi fratturati asciutti, si è poi stimata la densità di frattura nei vari casi.

Lo studio eseguito ha permesso di evidenziare una diminuzione nei valori di velocità e un conseguente aumento della fratturazione da imputarsi dapprima all'azione dirompente dell'esplosivo (nella fase di costruzione) e poi alla microsismicità provocata nei sistemi rocciosi di spalla dalla dinamica del manufatto. La fenomenologia si presenta diversa nei vari casi; l'effetto, comunque, è per lo più consistente.

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Abstract

Experimental data concerning to the velocities of longitudinal elastic waves obtained in abutment rocks of some large dams in North Italy are considered; also the time variation of values is studied. In the different cases, crack density has been then estimated, on the basis of O'Connell and Budiansky' paper, regarding the seismic wave velocities in dry cracked bodies. Study carried out a decrease in the values of velocity and a consequent increase of crack density caused, at first, by the breaking of explosive, and then by the microseismicity due to the dynamic of structure in abutment rocks. Phenomenology is different in the various cases; however, the effect is generally strong.

1. Introduction

Starting 1949, various large dams in Northern Italy along with sustaining rocks underwent geodynamic controls. Some of these results have already been published. Herewith some data are given which for the most part are inedited and adjourned up to 1973 (after that year it has been impossible to continue these specific geophysical studies) concerning the velocity of longitudinal elastic waves within the abutment rocks of certain dams; further on their elaboration results are discussed.

2. Description of main experience and characteristics of the dams under observation

In correspondence to the dam crowns — on rock systems building up their downward side — tape recordings were made of waves produced by blastings on the valley bottom. These experiments were carried out over the years, during the same seansons and along the same portion of rock. Every time precise sights made it possible to reproduce exactly sources and stations. The distances between sources and stations were determined by means of precision topographic levels; the uncertainty does not exceed 1%. A scheme of the stations and the sources for a dam is shown in fig. 1, and explored abutment rock is pointed out too.

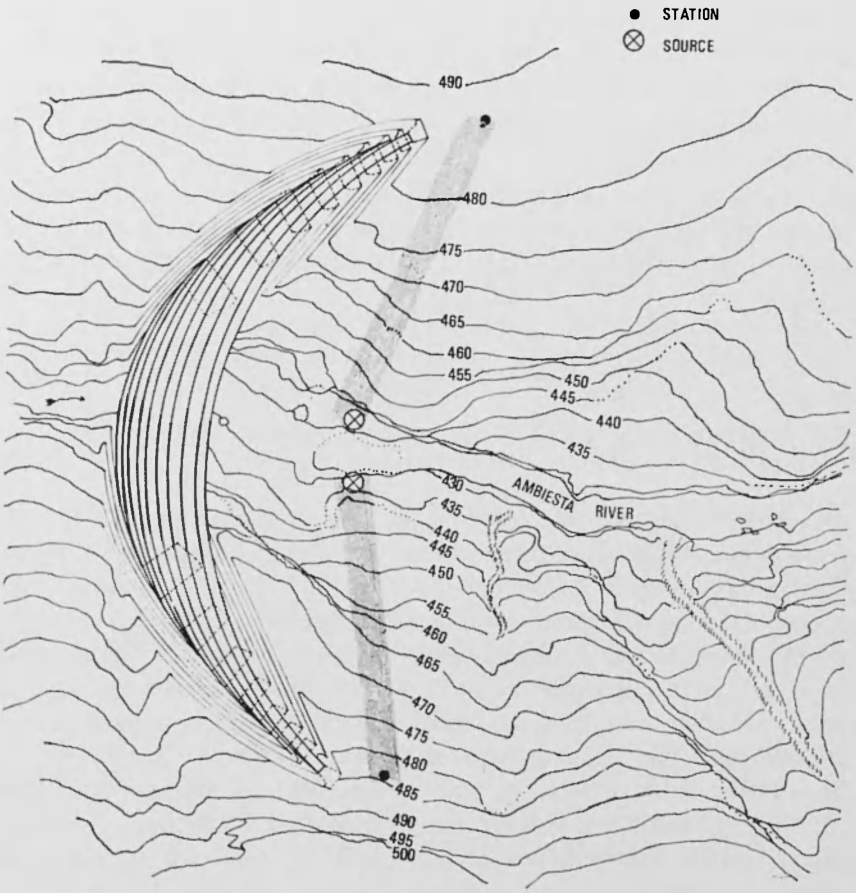

Fig. 1 - Ambiesta dam. Scheme of the stations and the sources in left and right abutment. The hatching points out the portion of the explored abutment rock.

During the first years, an Askania vibrometer with optical recordings and incorporated time signal was used. Later on, an Hellige vibrometer with three indipendent components was used and recordings were made on heat-sensitive paper. In all cases the origin time was obtained by an electromagnetic impulse via cable. Recordings were made at an average speed of 10 cm/s (tape speed); thus it was possible to evaluate the velocity of the longitudinal waves with a uncertainty of about 2%.

The dams considered in this report, are those whose data had been gathered methodically enough to permit the elaboration of this information.

Table I refers to the main characteristics of the dams under study; the relative longitudinal sections are in diagrams in figure 2, with the indication of the lithology of the abutment rocks.

3. Experimental results and elaboration of the data

The values of the velocity on the abutment rocks which were obtained in the course of the following years are different: for the most part it was possible to verify a specific trend toward a reduction of the same. This can be explained as a consequence of the force of the explosive used in the construction phase and later on, as a consequence of a microseimicity produced in the rock, whereby the dam is anchored to, by the constant movements that the construction undergoes when it is subject to variations of the reservoir water load, and by variations of the outside temperature due to daily insolation and change of seasons. Lastly, the velocity decrease which has been observed is to be attributed to the increased crack density in the rock.

The study on the connections between these factors has been carried out by many authors. During the last few years, R.J. O'Connell and B. Budiansky have statistically obtained the following equations (values with index « o » refer to rocks which are not cracked) in the hypothesis of dry circular cracks:

$$\sigma = \sigma_o \left(1 - \frac{16}{9} \varepsilon \right) \qquad [1]$$

$$\frac{K}{K_o} = 1 - \left(\frac{16}{9} \frac{1 - \sigma^2}{1 - 2\sigma} \right) \qquad [2]$$

$$\frac{v_p}{v_{po}} = \left[\frac{(1 - \sigma)(1 + \sigma_o)}{(1 + \sigma)(1 - \sigma_o)} \frac{K}{K_o} \right]^{\frac{1}{2}} \qquad [3]$$

σ, being Poissons's report, ε the density of the cracks, K the bulk coefficient and v_p the velocity of the longitudinal waves. From previous formulae it is possible to obtain ε as a function of $\frac{v_p}{v_{po}}$ (if $\sigma = 0.25$). The calculation was done giving v_{po} as the value obtained during the first study carried out for each dam. The experimental values of the velocity and the corresponding values of ε are listed in table II. Data from table II are plotted in figures 3-6. In the various cases the distribution of the points with higher probability is linear. Fit's equations are indicated in the figures.

4. Discussion of the results

4.1 *Vajont dam*

As it is known, on October 9, 1963, about one year after the dam entered into operation a big landslide broke away from Mount Toc, on the left side of the dam causing tragic consequences.

Much has been written on the causes of this event; in this report we are going to limit ourselves to illustrate the pertinent results to the velocity's values and to the consequent crack density within the abutment rocks.

Geophysical studies in the narrow of the Vajont began in 1953, that is to say, three years before construction began. As

TABLE I

Name	Period of construct.	Enter into operation	Type	Maximum height (m)	Lenght of the crest (m)	Total storage capacity ($10^6 m^3$)	Catchment area (sq Km)
Ambiesta	1957-1959	1960	Single curvature arch in concrete	59.2	144.6	3.9	9.1
Maina di Sauris	1942-1947	1952	Double curvature arch	136.2	138	73	59
Pieve di Cadore	1946-1949 In 1964, (the) right abutment was consolideted with cement injections	1950	Concrete arch gravity	112	410	68.5	818
Vajont	1956-1960	1962	Double curvature arch	261.6	190.5	168.8	62

TABLE II

AMBIESTA DAM

YEAR	LEFT ABUTMENT		RIGHT ABUTMENT	
	$(v_p \pm \Delta v_p)$ in Km/s	ε	$(v_p \pm \Delta v_p)$ in Km/s	ε
1960	1.8 ± 0.1	0	5.0 + 0.1	0
1964	1.63 ± 0.06	0.08	4.2 ± 0.1	0.14
1966			3.17 ± 0.03	0.31
1972	1.78 ± 0.07	0.01	2.6 ± 0.1	0.39

MAINA DI SAURIS DAM

YEAR	LEFT ABUTMENT		RIGHT ABUTMENT	
	$(v_p \pm \Delta v_p)$ in Km/s	ε	$(v_p \pm \Delta v_p)$ in Km/s	ε
1952	6.9 ± 0.2	0	6.7 + 0.2	0
1956	6.7 + 0.3	0.03	6.1 ± 0.5	0.08
1959	6.4 ± 0.1	0.06	5.7 + 0.1	0.09
1962			5.9 ± 0.1	0.10
1965	6.1 ± 0.2	0.10	5.9 ± 0.2	0.10
1970	5.8 ± 0.1	0.14	5.8 ± 0.2	0.11
1973	5.7 + 0.2	0.15	5.6 + 0.3	0.14

Cont. table II PIEVE DI CADORE DAM

YEAR	LEFT ABUTMENT $(v_p \pm \Delta v_p)$ in Km/s	LEFT ABUTMENT ε	RIGHT ABUTMENT $(v_p \pm \Delta v_p)$ in Km/s	RIGHT ABUTMENT ε
1949	3.2 ± 0.1	0	4.3 ± 0.1	0
1952			3.9 ± 0.1	0.08
1953			3.9 ± 0.1	0.08
1955	2.93 ± 0.06	0.07	3.83 ± 0.08	0.09
1957			3.65 ± 0.03	0.13
1959	2.97 ± 0.06	0.06	3.41 ± 0.03	0.18
1960	2.98 ± 0.06	0.06	2.88 ± 0.06	0.28
1961	2.65 + 0.04	0.15	1.86 ± 0.04	0.44
1964	2.69 ± 0.05	0.14	3.28 ± 0.03	0
1970	2.53 ± 0.05	0.18	2.84 ± 0.04	0.11
1973			2.34 ± 0.04	0.25

VAIONT DAM

YEAR	LEFT ABUTMENT $(v_p \pm \Delta v_p)$ in Km/s	LEFT ABUTMENT ε	RIGHT ABUTMENT $(v_p \pm \Delta v_p)$ in Km/s	RIGHT ABUTMENT ε
1953	5.6 ± 0.2	0	5.1 ± 0.2	0
1954	5.4 ± 0.2	0.03	4.9 ± 0.2	0.03
1956	5.5 ± 0.2	0.02	4.9 ± 0.1	0.03
1957	5.1 ± 0.1	0.08	4.6 ± 0.2	0.09
1959	4.44 ± 0.05	0.18	4.1 ± 0.2	0.17
1961	3.40 ± 0.07	0.33	3.63 ± 0.07	0.25
1963	2.80 ± 0.07	0.40	3.0 ± 0.1	0.34

fig. 6 shows, following the initial period whereby values remain practically constant, the velocity in both abutment rocks drops abruptly in time with a consequent 35-40% increase of the crack density. This effect is more evident in the left and it is no doubt the result of the disruptive force of the explosive, of the structure's construction and of the preliminary operations of hollowing and stemming. The excessive speed of the phenomenon seems, at any rate to point out a certain tendency (referred as "latent microseismicity" by P. Caloi) of the rock to deteriorate whenever subject to perturbing causes, both natural or artificial.

4.2 *Pieve di Cadore dam*

First tests were made in 1949 after the construction was completed. As far as the left hand abutment rock is concerned, fig. 5a shows a gradual and modest decrease of the velocity values which has brought an increase of about 18% of the crack density, over the period of time during which these observations were made.

The condition of the right hand abutment rock is different. The trend of the obtained points (fig. 5b) has permitted to point out three distinct phases: the first goes to about 1960, the second which ends around 1963-1964, the third being underway during the last study. During the first period, the about 18% increase of the crack density indicates the structure's tendency to reach a new equilibrium, first as a result of alterations caused by the ground removal and by dam's construction, and later, by micromovements of the structure.

The second phase, characterized by a sudden increase of the crack density which in two year's time has reached 45%, is probable cause by the increase dynamic of the dam following increased water supplies consequent to completion of the Piave-Boite-Mae-Vajont's system (fig. 7) to which the dam belongs.

One should not be surprised for the lack of a similar difference of phases on the left, considering the considerable asymmetry of the structure (fig. 2c) whereby its left abutment rock bears the burden of the efforts connected to the dynamic of the dam. Later, a similar phenomenon occurs again despite reinforcement's work although it is resulted considerably slower in the time. must be noted however that following the Vajont's incident, system's production was reduced to that of the years preceding 1960.

4.3 *Ambiesta dam*

The various geophysical studies were carried out after the dam entered into operation. Figure 3 shows in this case too, that the two abutment rocks took a different course; while velocity's values in the left were practically constant in time, the velocity's values in the right shwed a considerable decrease with a consequent 40% increase of the crack density. This can be possible attributed to the different consistency of the dolomite's limestone and not to asymmetry in the structure. Because of the scarse rigidity of the left rocks, the right abutment rock, as a hinge, bears the highest weight as to the dynamic of the dam. This asymmetry is also likely responsible for a transverse fracture of a lateral section which we noticed during the last geophysical testing.

4.4 *Maina di Sauris dam*

As in the previous case, there are no available experimental data obtained during the construction. In effect, the first tests were carried out the year the dam entered into operation. At any rate, the velocity's values which have been obtained during a 20 year's period show that both abutment rocks have a similar trend (fig. 4): i.e. a slight decrease and a crack density's increase of about 15%. This phenomenon, quite unlike the preceeding ones, is justified by the symmetrical construction of the dam (fig. 2b) and by the same high rigidity of the massive limestone of the two abutment rocks, whereby obtained velocity's values, since from the beginning, have been the highest among all those obtained in several parts of the Alps for rock formations of the same lithology.

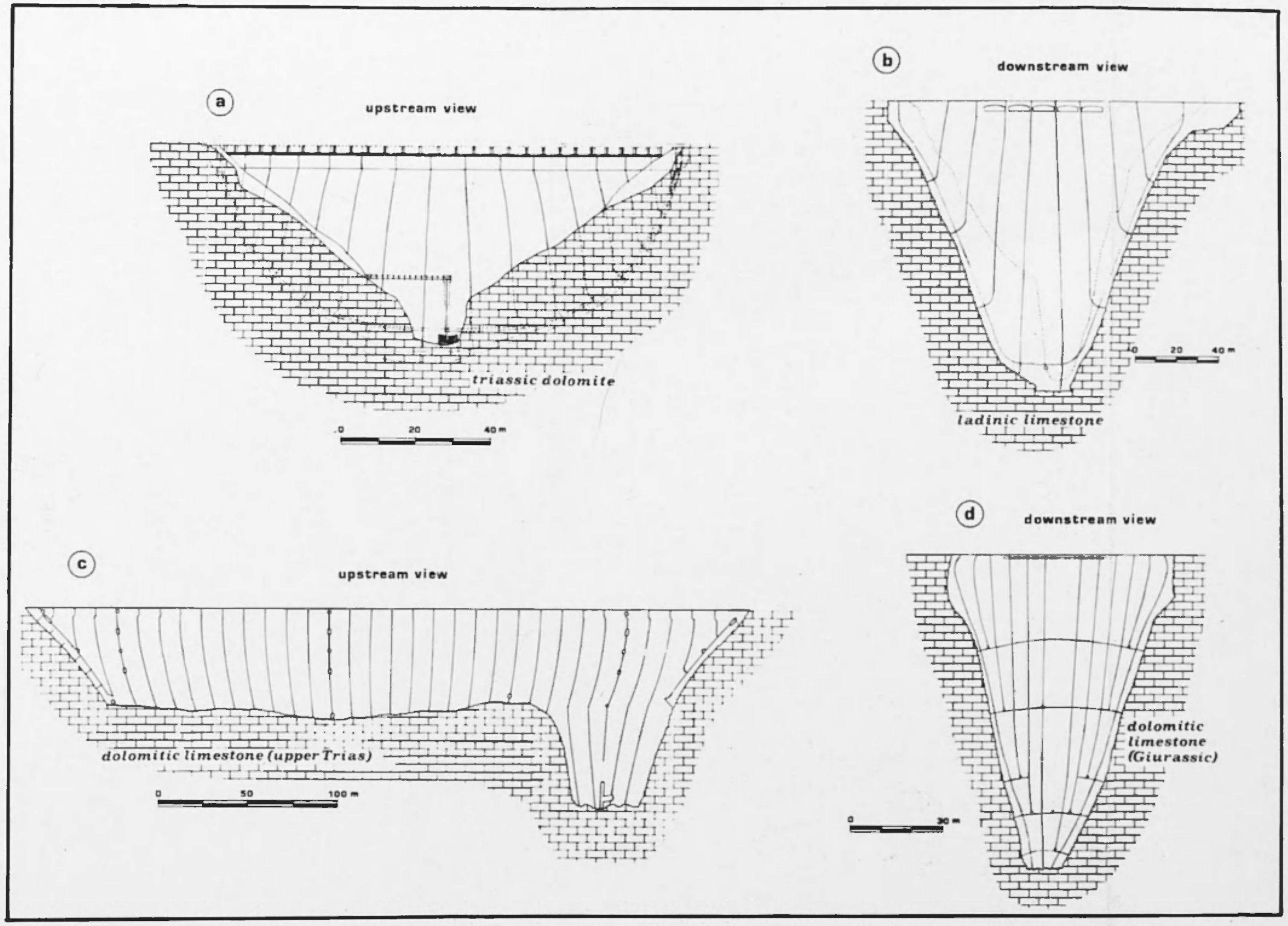

Fig. 2 · Longitudinal section of considered dams.

a) Ambiesta dam

b) Maina di Sauris dam

c) Pieve di Cadore dam

d) Vajont dam.

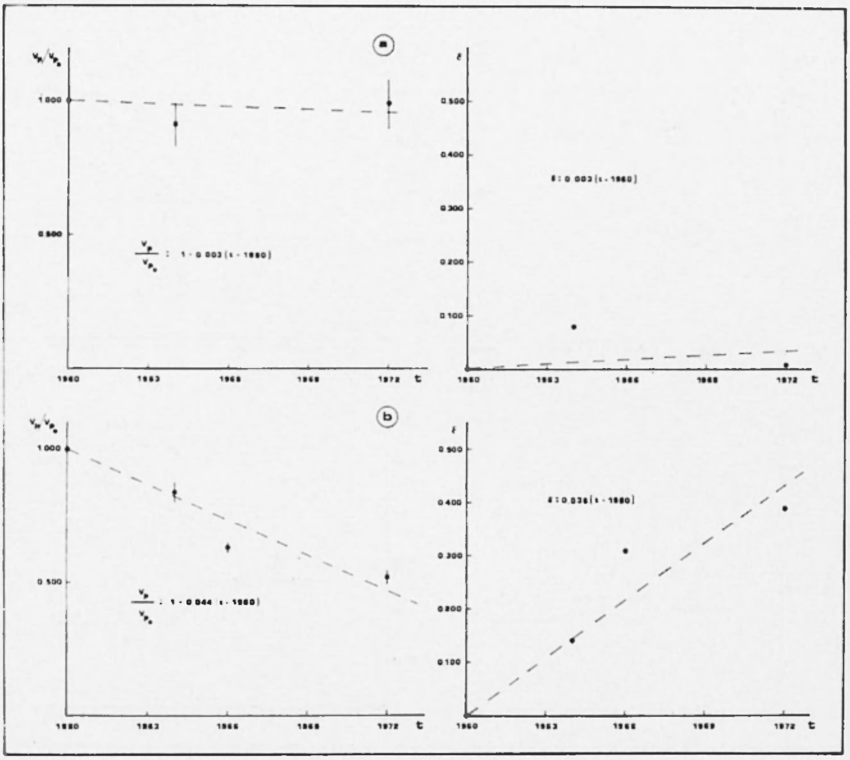

Fig. 3 - Ambiesta dam. Representation of v_P and ε value versus time (in years), with indication of most probable trends.

a) left abutment

b) right abutment.

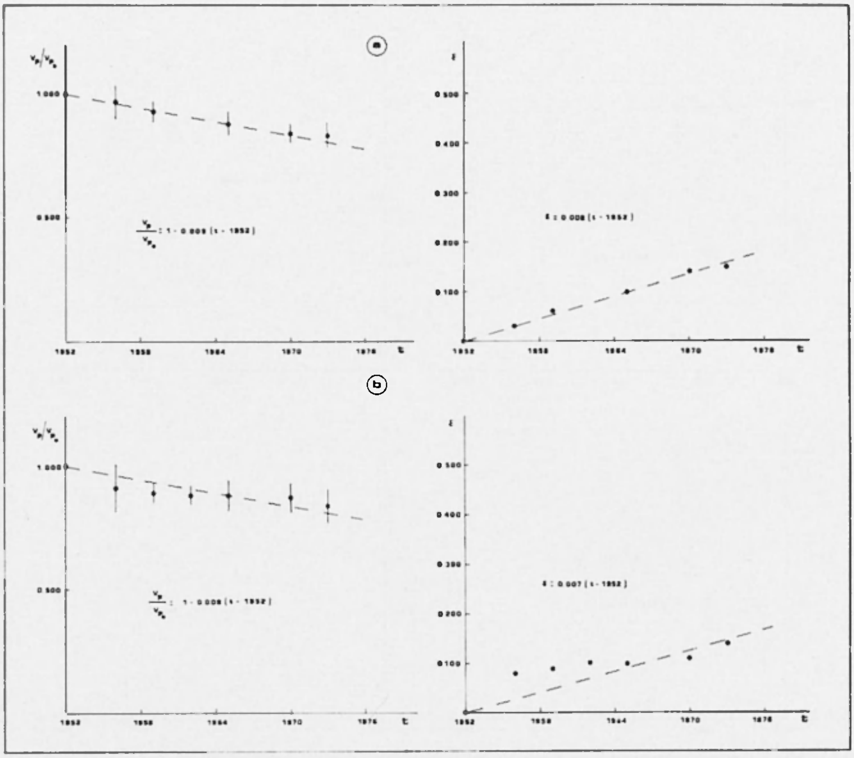

Fig. 4 - Maina di Sauris dam. Representation of v_p and ε values versus time (in years), with indication of most probable trends.

a) left abutment

b) right abutment.

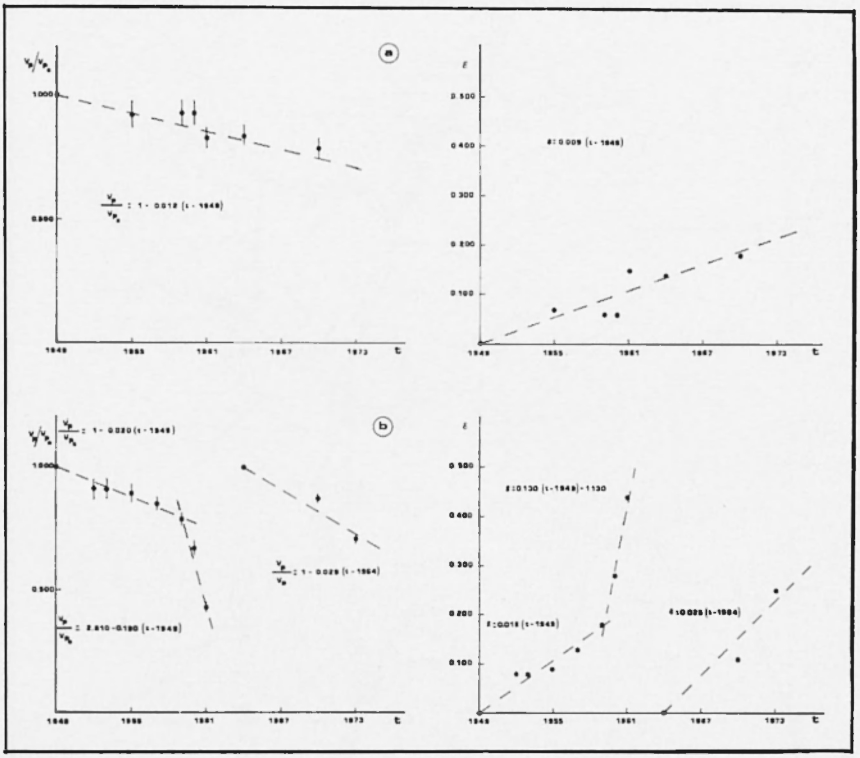

Fig. 5 - Pieve di Cadore dam. Representation of v_P and ε values versus time (in years), with indication of most probable trends.

a) left abutment

b) right abutment.

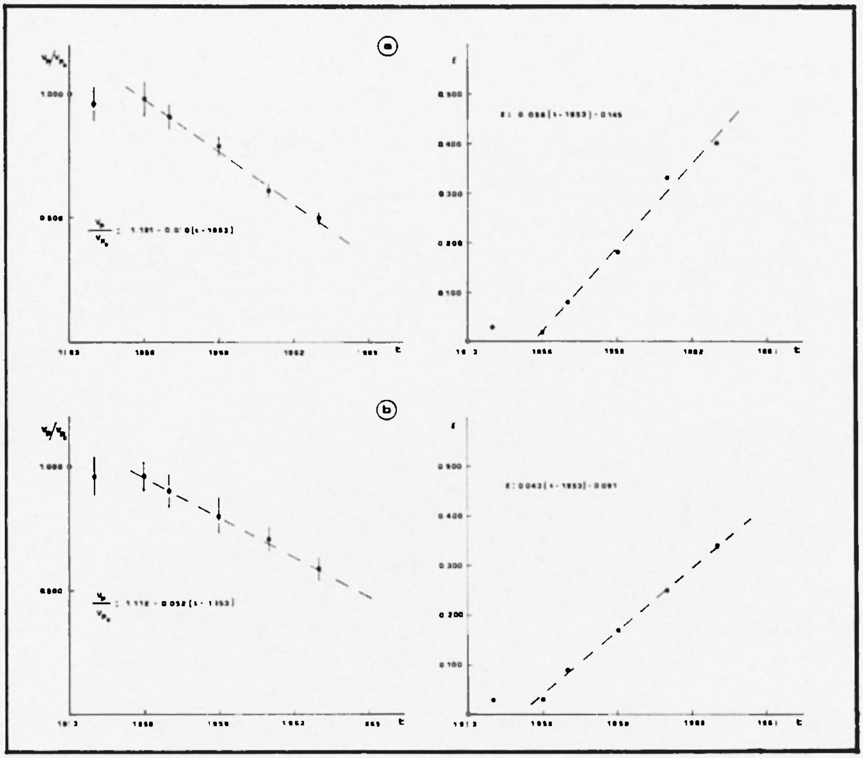

Fig. 6 - Vajont dam. Representation of v_P and ε values versus time (in years), with indication of most probable trends.

a) left abutment

b) right abutment.

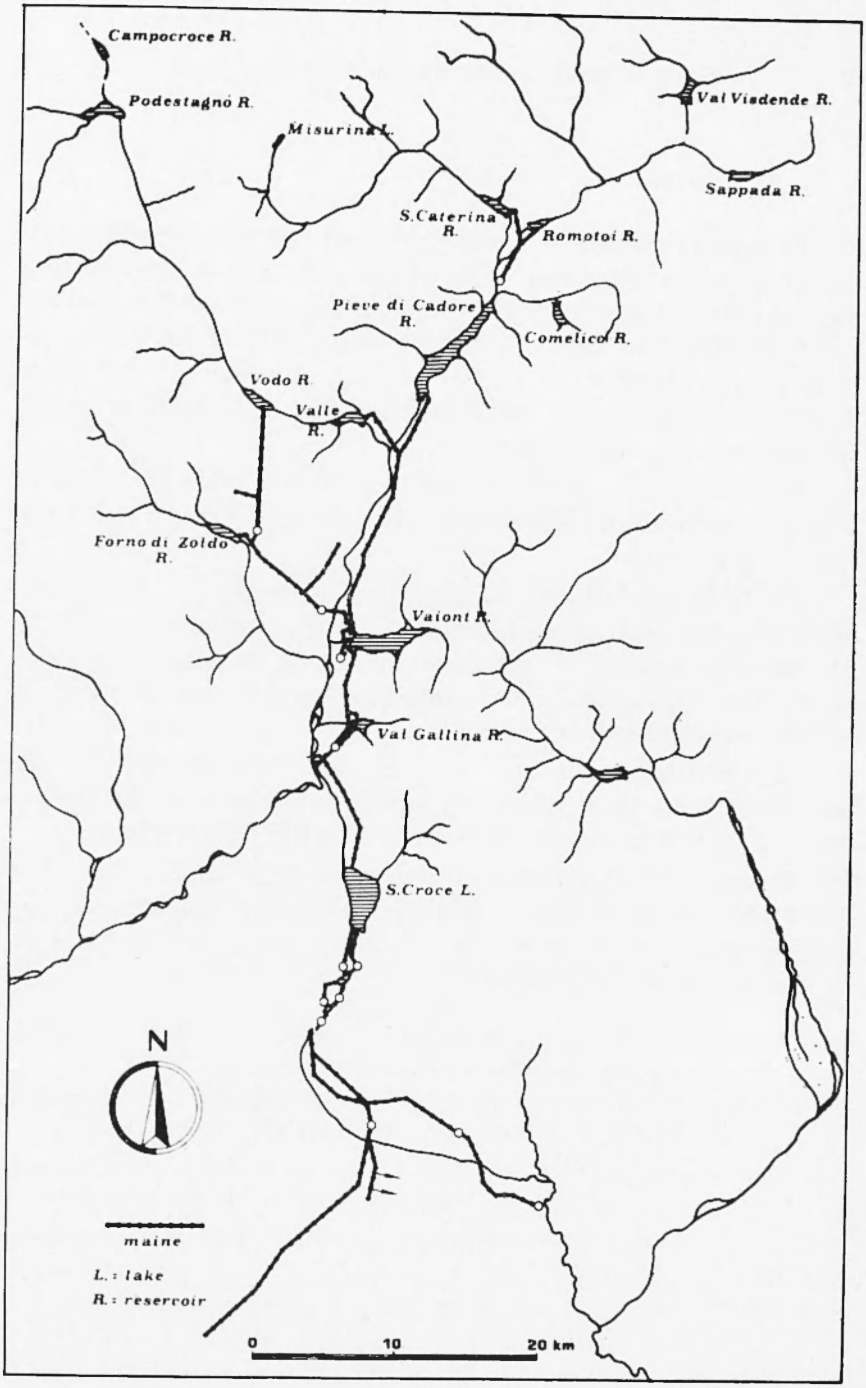

Fig. 7 - General planimetry of Pieve's hydroelectric plants (North-Eastern system).

5. Conclusions

In view of the above, cases pertinent to the velocity's variations within the abutment rocks of the dams are in effect rather different. In some cases there is a slow and gradual decay of the values during the time, in others there is a sudden change; at times the situation is similar in both abutment rocks, while in others the decrease is differentiated due to intrinsic or estrinsic causes to the structure.

Reinforcement operations do somewhat enable the rock to regain something of its elasticity without preserving them from further variations.

The theoretical handling of the crack density to which one attributes the decreasing of velocity's values has enables us (for dry circular cracks) to estimate the crack density in various cases. The maximum values obtained indicate an increase of 40-45% compared to initial value.

In conclusion, studies indicate that deterioration in the abutment rocks of some large dams is generally a strong phenomenon; therefore, a constant control must be taken place.

At any rate, it is possible (in some large dams) that this effect reduces the average life span of the plant remarkably. The average life span is generally calculated only on the basis of the silting up of the reservoir.

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