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ANALYSIS OF DAM BEHAVIOUR AFTER EIGHTY YEARS OF SERVICE

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ABSTRACT

The paper reports on the behaviour of a masonry dam built in the Italian Alps in the early twenties of the last century and still in operation for electric power supply. The dam is 31 m high and its waterproofing is ensured by a multi-layered impervious facing, a concrete cut-off and a grout curtain protruding into the foundation soils. The geological location of the dam is rather complex, because its left abutment is located on a rock formation while the right one rests on a thick moraine deposit. Since its first impounding, large downstream water flows and significant movements of the dam and of its moraine abutment were observed. A comprehensive investigation has thus been conducted in order to understand the overall behaviour of the reservoir, after eighty years of service. For this purpose, historical documents have been first reviewed in order to reconstruct the design assumptions, construction operations and early observations on site. Experimental investigations of the moraine deposit have then been conducted, in order to estimate the subsoil properties. Seepage flow rates and reservoir impoundment levels, recorded for more then twenty years, have also been analysed, showing the correlation existing between these two variables. More recently, a system for monitoring the displacements of the dam and the moraine has been implemented and the recorded data have been examined. All the available observations have been evaluated and a reasonable interpretation of the coupled hydraulical-mechanical behaviour of the dam and of its moraine abutment has been inferred. Numerical calculations have finally been conducted, in order to verify such explanation.

INTRODUCTION

At the beginning of the twentieth century, several dams were built in the Italian Alps with the aim of providing water reservoirs for electrical supply. Most of these dams are still on service, even though they were designed and constructed following out of date concepts and techniques. It is general opinion that their safety should then be assessed by means of modern investigation methods.

One of such cases is the Alpe Cavalli dam, built in the 1920's, in the north-western Italian Alps. The dam is located in a very peculiar geo-morphological environment. In particular, while the right abutment and the foundations are located on a moraine deposit, the left abutment rests on a mass of metamorphic rocks. The reservoir has been effectively operating for about eighty years. However, since its first impoundment, relevant seepage has been observed downstream and large water flows have been continuously recorded from then on, in spite of several waterproofing treatments. Significant movements have also been observed on the dam and on the moraine abutment producing localised deformations on the downstream face of the dam.

A thorough assessment of the safety conditions of this old dam has recently been attempted. For this purpose geological and geotechnical investigations have been performed, in order to clarify the subsoil conditions. Systematic topographical measurements are also available but only for few years.

Moreover a large amount of observations, covering a time period of about twenty years, has been collected and analysed. These data concern water level fluctuations in the reservoir, water losses losses through the moraine deposit, minimum and maximum daily temperatures at different depth in the reservoir and in the atmosphere, rainfall and ice thickness.

In the following, a brief description of the reservoir features and of the dam history is provided first. Results of the recent geotechnical investigations and monitoring are presented next. The seepage data are then analysed and the flow regime is simulated by numerical calculations together with the cyclic displacements of the moraine deposit, induced by the water level fluctuations in the reservoir. This analysis is aimed to provide a logical explanation of the dam movements and of the observed cracks on the downstream abutment.

DAM FEATURES

The reservoir of Alpe Cavalli, with a full capacity of 8,35 millions of cubic meters, is located in the basin of an old glacial lake, 1500 meters above see level (Fig.1). The dam height, computed from the bottom of its foundation is 41.60 m, and the crest is 165 meters long. The barrage is made of masonry and is waterproofed, on its up-hill side, by a composite multi-layered facing of cement mortar, reinforced concrete, bitumen and bricks (Fig.2). The dam foundation is made of a continuous masonry layer, about 1.30 meters thick, cemented by hydraulic mortar and is provided with a concrete vertical cut-off reaching the maximum depth of 10 meters.

The geo-morphological conditions of the dam site are quite peculiar since the reservoir location coincides with an ancient natural lake of glacial origin which was probably emptied after the last glaciation, when the front moraine was eroded by the Loranco river and a deep narrow cut was eventually opened through the valley. The fluvio-glacial deposit fills all the valley and overlaps a metamorphic formation (schist) which outcrops on the left shoulder of the dam. This rock mass is highly fractured and cleaved, due to intensive tectonic forces. Since the early design studies, performed before the first world war, the engineers were puzzled by the large extension and the depth of the fluvio-glacial deposit and by its hydro-mechanical behaviour, with particular reference to the stability and the water-tightness of the foundations and of the right shoulder of the dam. In particular, the first design question concerned the extension and the depth of the alluvial deposit located below the embankment. The second one was related to the waterproofing capacity and the overall stability of the right abutment formed by the moraine deposit. However, the dam was finally located at the bottom of this valley resting its right shoulder on the moraine, its central body on the river bed alluvial deposit and its left shoulder on the metamorphic rocks (Fig.3). The works started in 1922 and the dam was completed in 1926. During the construction of the dam, further doubts arose on the soundness of the rock formation, located below the left shoulder of the dam, which appeared highly fractured and affected by the presence of cavities.

Concerning the river bed alluvial deposit, ten years after the completion of the dam, an extensive campaign of ground improvement was undertaken, consisting of several injections of grout. Each injection, which protruded into the lower rock stratum, was performed with a 30 bars pressure in order to fill the alluvial deposit. This measure proved to be effective since it resulted in a water flow reduction in the drainage tubes of about 60 %.

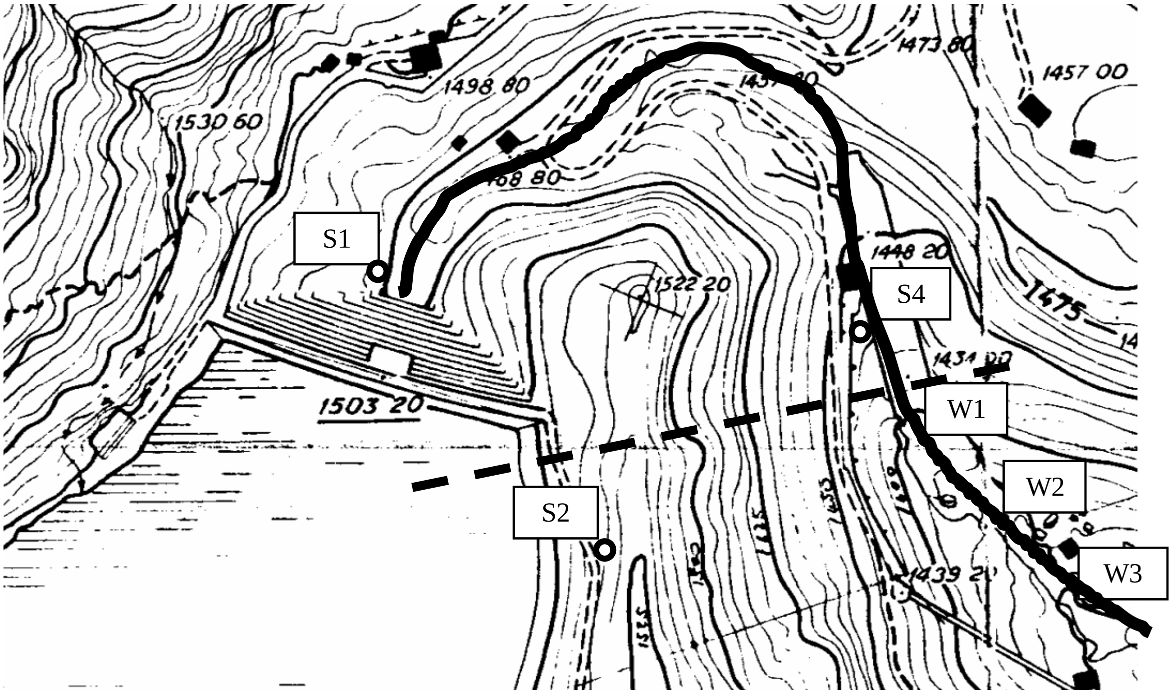
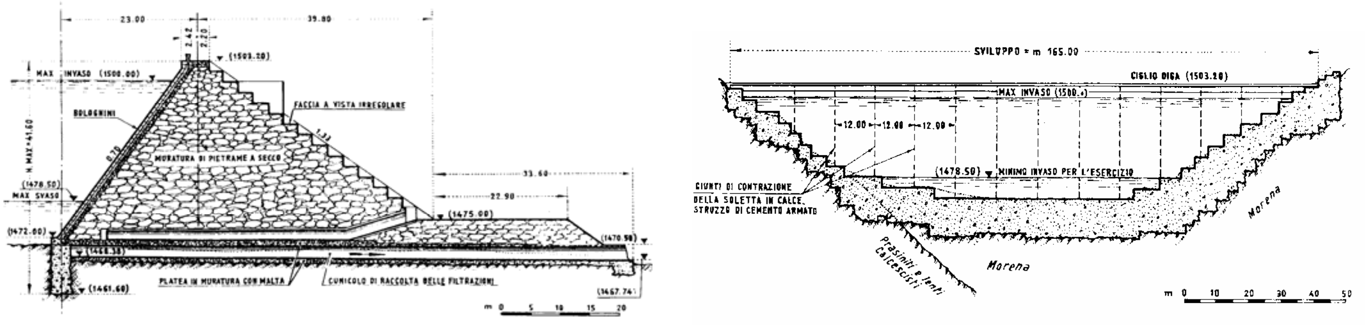


Fig. 1. Plan view of the Alpe Cavalli dam with the locations of the intercepted water springs (W_1, W_2 and W_3) and of the continuous borings (S1, S2 and S4); the Loranco River is indicated by the thick continuous line and the trace of the analysed cross section through the morain deposit is indicated by the dotted line.



(a) (b)

Fig. 2. Cross section (a) and front view (b) of the masonry dam (ANIDEL, 1953)

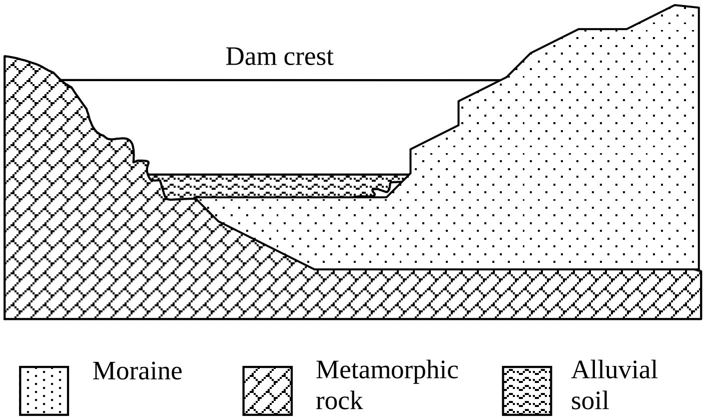


Fig. 3. Longitudinal geo-morphological pattern at the Alpe Cavalli dam.

A similar subsoil treatment was also performed in order to reduce the water loss in the fissured rock mass of the left shoulder. However, although a reduction was obtained, still significant water losses were observed (Gignoux e Barbier, 1955).

However, the most difficult problem detected during the first years of reservoir operation was the seepage observed through the moraine deposit of the right shoulder, which raised serious concern also on its stability and thus on the overall safety of the reservoir. In fact, this moraine deposit may be considered as the natural extension of the dam. In particular, as written in one of the original design report, even before the construction of the dam, several water springs had been observed at the downstream foot of the moraine deposit and local debris slides were also recorded downhill. After the construction of the dam, the water flows became quite large and three most significant springs were collected to be pumped back into the reservoir (W_1, W_2 and W_3 in Fig.1).

During all the operation period substantial movements of the dam have also been observed-and vertical cracks were observed on the downhill abutment, close to the left shoulder (Fig.4). This last observation suggested to monitor the dam movement with systematic topographical surveys.

Fig. 4. Down stream abutment of Alpe Cavalli dam with indication of the observed vertical crack.

GEOTECHNICAL INVESTIGATIONS

Due to the lack of modern tools, geotechnical investigations of the moraine deposit could not be performed at the time of construction and thus the extension and the mechanical characteristics of the deposit were largely unknown. Three continuous boring were recently performed in different locations (see Fig.1). A 60 meters deep borehole was first performed starting from 1475 m a.s.l. close to the downhill toe of the embankment. A second borehole, 80 meters deep was then accomplished in the middle of the moraine deposit, at 1506 n meter a.s.l.. The last borehole, 40 meter deep, was performed at 1447 meters a.s.l., near the toe of the moraine on the opposite side of the reservoir. Visual inspection of the samples retrieved from all the borings showed an alternation of dark-red gravel layers immersed in a sandy silt to silty-gravelly sand matrix. Undisturbed samples could not be retrieved but several remolded samples were recovered by the three continuous borings at different depths in order to detect their grain size distribution. Typical results of these analysis are summarised in Fig. 5 where the soil composition observed at boring S2 is reported as a function of depth.

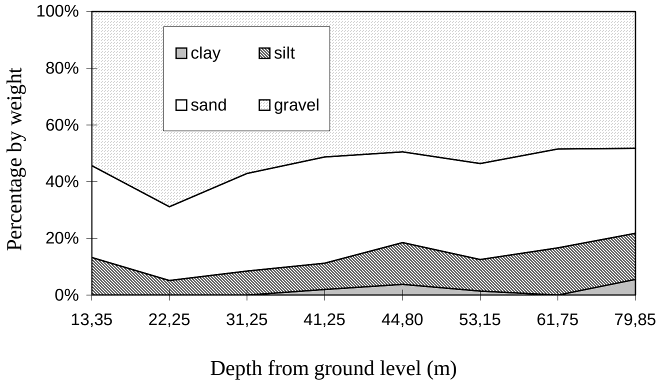


Fig. 5. Grain size composition of the moraine at boring S2.

As a general comment the soil forming the moraine deposit is rather homogeneous with depth and in the different borings. It can be broadly classified as a well graded coarse grained material, being gravel and sand the predominant fractions, with a low but not negligible portion of fine grained soils made of silts and clays. Although it is not shown from the grain size analysis the presence of large blocks in the moraine was also detected.

In situ permeability Le Franc tests were also performed at different depth. The permeability coefficients obtained from such tests are summarized in Fig.6, together with a broad estimation of the Darcy's coefficient provided by the Hazen correlation based on grain size distribution (Hazen, 1911). Generally a scatter of three orders of magnitude can be observed from all the reported data but, when looking only at the Le Franc tests, the permeability coefficient ranges from 2×10^{-4} to 3×10^{-3} cm/s, which is typical of a fine sand.

With regard to the mechanical properties, it is recalled that the deformation and strength characteristics of fluvio-glacial soils are generally very difficult to evaluate. In fact undisturbed sampling is not possible due to the large size of the soil particles. Furthermore soil is very heterogeneous at the scale of typical situ tests, due to the occurrence of large blocks and thus the meaning of these tests results is very low.

For such reasons the compressibility of glacial origin soils has been evaluated by Croce et al. (1963) back analyzing the settlements measured at the foundation base of three dams built in the Italian Alps. In the hypothesis of linear elastic response, a Young modulus ranging between 30 and 160 MPa was obtained from such study.

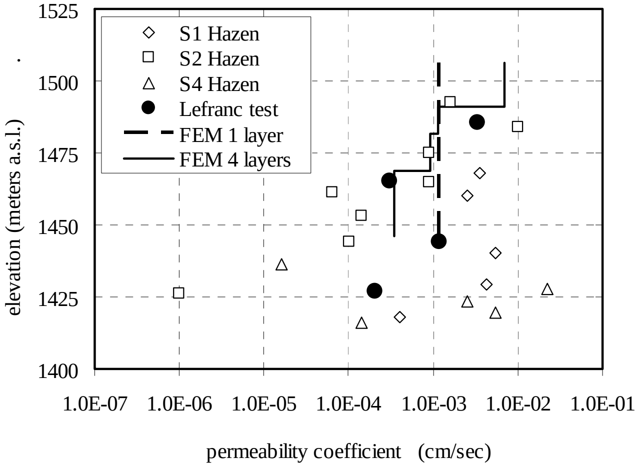


Fig. 6. Permeability coefficients of the moraine.

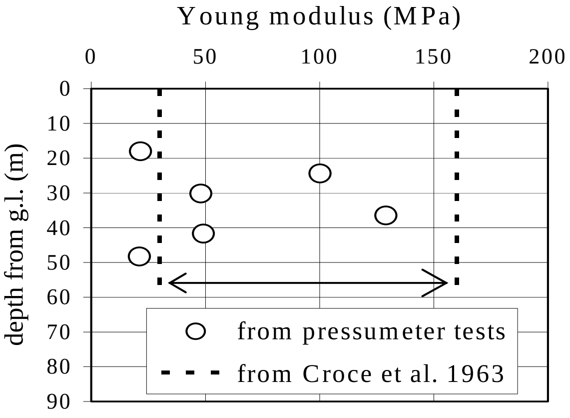


Fig. 7. Young moduli obtained from pressumeter tests.

In the present case, a rough estimate of the Young's modulus is provided by the results of several pressumeter tests (Menard, 1975), performed along the three boreholes at different depths. As reported in Fig.7, the values of the Young moduli E calculated from the pressumeter tests are quite variable, ranging from a minimum of 21 to a maximum of 129 MPa and there is not a clear dependence on the depth. The observed values are however consistent with the ones previously quoted from the literature.

SEEPAGE THROUGH THE MORAINE

Soon after the first impoundment of the reservoir, significant water losses were observed and then monitored through the embankment and the moraine body, being these latter the most relevant. In particular, the water emerging from three of the most plentiful springs located at the toe of the moraine (W_1, W_2 and W_3 in Fig.1) was collected and pumped back into the reservoir.

Such a procedure allowed for a continuous record of the water flow trend through the moraine during the period 1980-1998 As an example, the collection of daily measures for the period 1982-1984, together with the simultaneous measures of water level in the reservoir, is reported in Fig. 7. A seasonal cyclic trend can be observed from both series of data, with minimum values occurring during spring and maximum values in autumn. Such a trend is fully consistent with the hydrological features of the Italian Alps, where snow typically falls during winter. The time offset between the water reservoir level and the snow fall can be explained by considering the reservoir as mainly feeded by the water coming from spring melting and transported by the Loranco River. The level in the reservoir is the result of the balance between the amount of water coming from the Rio Loranco and the one discharged for electric supply.

The similitude of the two curves of Fig.8.a is the most clear sign of the correlation existing between reservoir level and seepage through the moraine. A quantitative evaluation of the time delay existing between these two quantities has been obtained by relative shifting of the two curves reported in Fig.8.a by a period T and evaluating the corresponding cross correlation factor defined in Fig.8.b. The results of such analysis clearly show that the best superposition of the two curves is obtained with a practically nil delay, accordingly with the high permeability of the moraine.

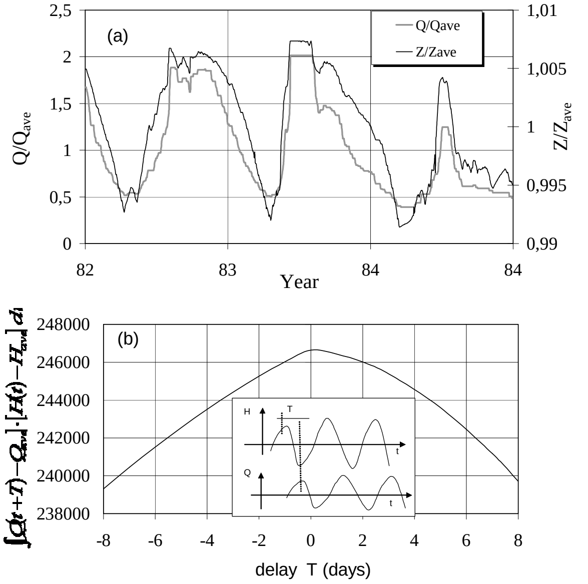


Fig. 8. Reservoir level and water loss in the period 1982-1984 (a) (Q_{ave}=0.165 m^3/s ; Z_{ave}=1488.4 m a.s.l.) and cross correlation among the two series (b).

The total amount of water collected at the three springs (Q) and the reservoir level H are directly compared in Fig.9, scaling both of them by their maximum observed value. The plot confirm the strong correlation between the two variables. However it is also seen that there is a non negligible amount of flow rate (more than 10% of the maximum value), not directly related to the water level in the reservoir. It is inferred that such portion of water comes from natural flows through deeper water bearing strata.

One final important question regards the stability of such correlation along with time, which could be a sign of potential erosion through the moraine. It is easy to argue from Fig.10, where the water flows corresponding to fixed impounding levels are reported as a function of time, that the average flow rate is almost constant throughout the years, thus confirming that the permeability of the moraine mass is substantially constant.

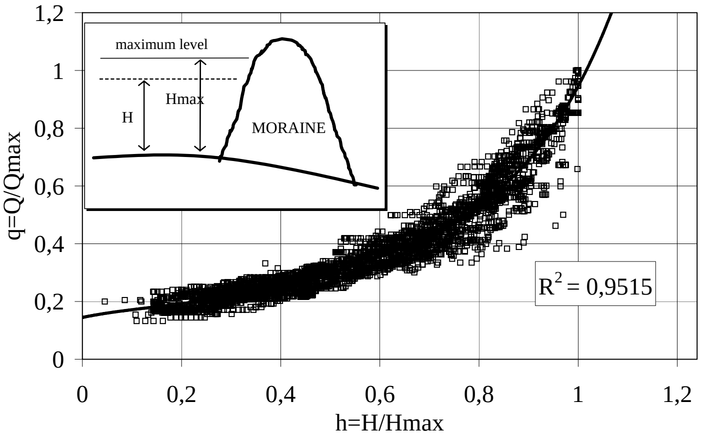


Fig. 9. Water loss versus reservoir level in the Alpe Cavalli moraine (period of observation 1980-1998).

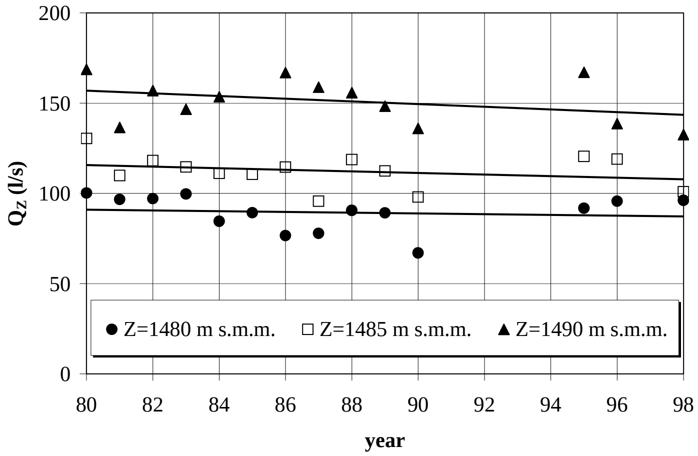


Fig. 10. Progression with time of water losses measured at three different reservoir levels.

DAM AND MORAINE DISPLACEMENTS

The dam movements have been monitored by a multiple topographical survey system (Fig.11). Alignment measurements are available since the beginning of 1998 for two points of the dam body (A' and C') from two stations (A and C) located on the metamorphic rock at the left of the dam. Triangulation measurements are available from the period 2001-2002 for one target on the moraine, taken from a station located on the metamorphic rock (B).

The comparison between the displacements recorded on alignments A-A' and C-C' (Fig. 12) provides basic information on the deformation mechanisms of the dam. In fact, while the position of point C' located close to the right dam shoulder is almost stable (the recorded displacements are less than 1 mm), the point A' located at the centre of the dam shows every year cyclic movements with a double amplitude equal to about 6 mm. In the long period this latter movements provide also a permanent displacement increasing with an average rate of 1.6 mm/year. It can be inferred that this trend is strictly related to the response of the moraine deposit on the right dam shoulder to the cyclic loading produced by the water level excursion in the reservoir.

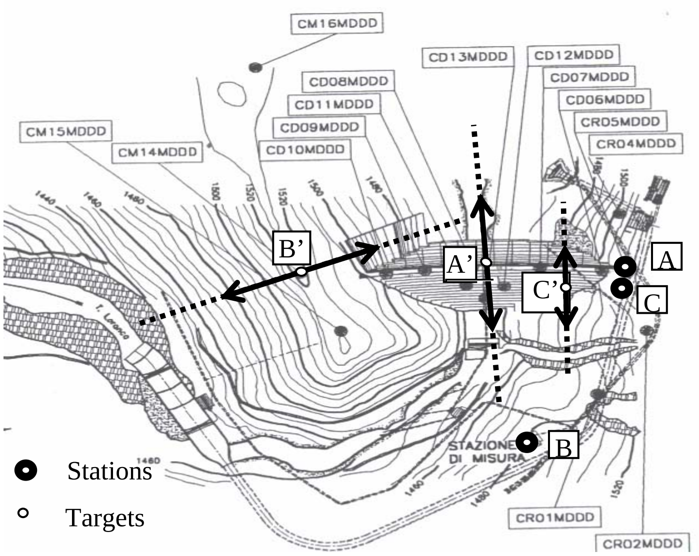


Fig. 11. Topographical survey system installed at Alpe Cavalli.

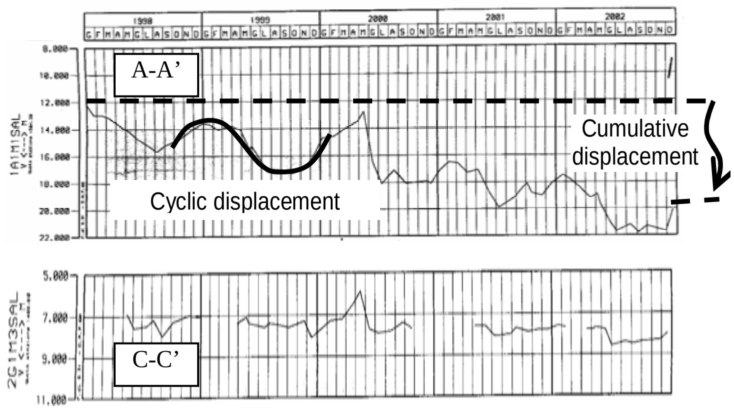


Fig. 12. Alignment measurements recorded on A-A' and C-C'.

The horizontal displacements recorded at point B of the moraine in the two years 2001 and 2002 have been composed on the alignment orthogonal to the moraine crest (see Fig.11) and related to the water level in the reservoir (Fig. 13).

Even these measurements show the close relation existing between the deformation in the moraine body and the reservoir level. In particular the observed double amplitude of the cyclic displacement at the top of the moraine is equal to 13 mm. In such short measurement period the accumulated displacements are rather low and thus the moraine stress strain behavior is almost reversible.

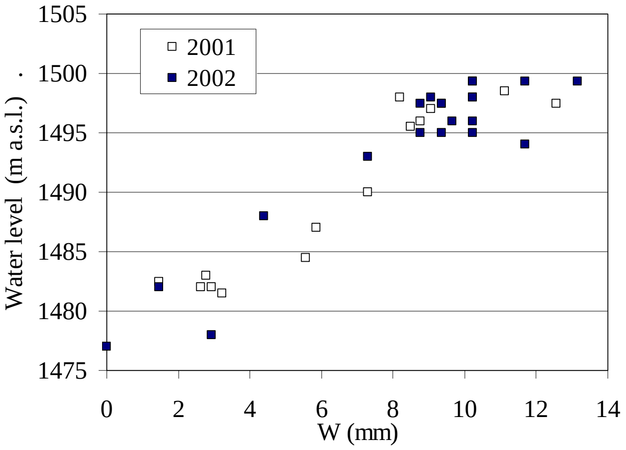


Fig. 13. Recorded horizontal displacements at point B (a) and reservoir impounding level (b).

NUMERICAL ANALYSIS

A numerical simulation of the observed phenomena has been performed by means of a finite elements code (Plaxis vers. 7.0, 1998) in order to analyse the response of the moraine with regard to seepage and the stress-strain behaviour of the moraine deposit. A two-dimensional model (Fig.14) has been implemented at the cross section reported by the dotted line in Fig.1 (i.e. close to the point B', where measurements of displacement were available). In the model, the moraine body is superimposed to a thick layer of metamorphic rocks whose position has been estimated based on the results of the subsoil investigations supported by geological considerations.

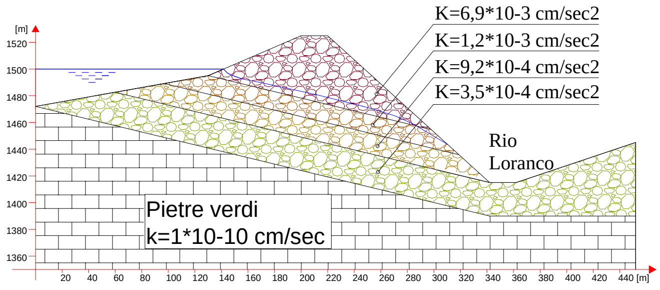


Fig. 14. Two-dimensional model of the moraine at cross section reported by dotted line in Fig.1.

The seepage conditions through the moraine have been initially simulated by supposing the whole moraine body as having a unique constant permeability coefficient ($k=1.16*10^{-3}$ cm/s) equal to the mean value of the data obtained by the results of permeability tests (see Fig.6). This analysis has been performed for different reservoir levels and its results are compared with the experimental ones (previously reported in Fig. 9) in the non dimensional plot of Fig. 15. In this plot, the measured and computed flow rates have been divided by their maximum values and the water level has been scaled by the minimum and maximum levels in the reservoir. The different shape of the theoretical and experimental curves can be explained considering that the assumed two-dimensional scheme may not be fully representative of the entire moraine deposit and that the moraine permeability may not be constant. Concerning this latter issue, a possible variation of permeability with depth has been considered. Four different layers, parallel to the bedrock, have thus been introduced in the numerical model and different permeability coefficients have been assigned to each of them (Fig. 14). The most appropriate values of k (see Figs. 6 and 14) have been established by a trial and error procedure. It can be seen that by assuming these coefficients increasing from the bottom to the top of the moraine a better simulation of the observed experimental trend is obtained (Fig.15).

Under these seepage conditions, a numerical analysis has then been performed on the displacements induced by the water fluctuation in the reservoir. For this purpose, the soil has been modelled as a linearly elastic material and the horizontal displacements at the top of the moraine deposit (Fig.16.a) have been computed at several impounding levels for different Young's moduli. A comparison of simulated displacements with those observed at point B' (Figs. 11 and 13) is reported in Fig. 16.b.

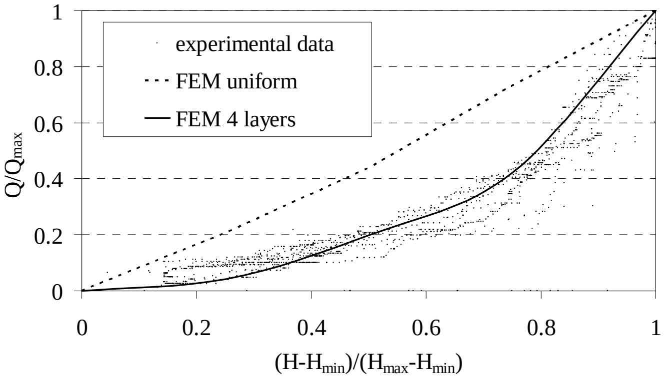


Fig. 15. Simulation of seepage through the moraine deposit.

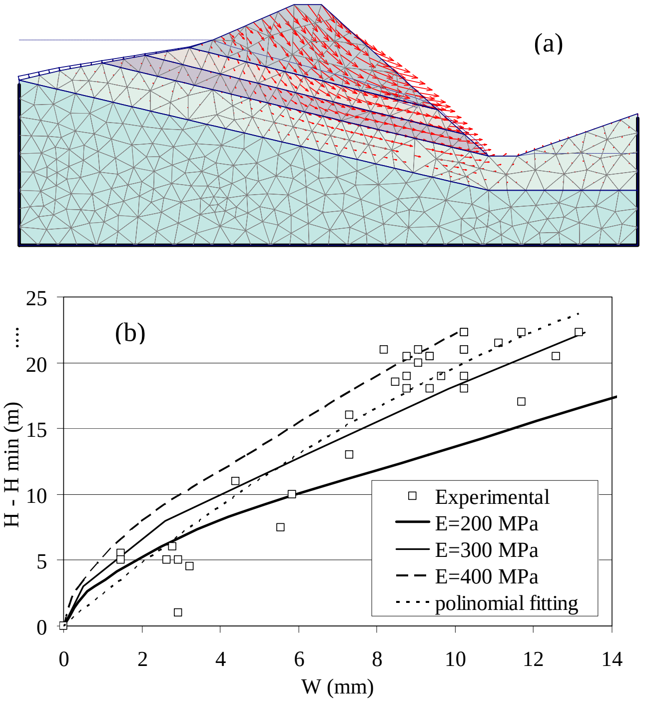


Fig. 16. Pattern of calculated displacements (a) and comparison between measured and calculated horizontal displacements at point B' (b).

This analysis shows that the elastic modulus of the soil model necessary to simulate the observed displacements of the moraine is larger than those evaluated by the pressumeter tests (Fig.7). Furthermore, all the simulation curves show a larger curvature and a rightward bending compared to the polynomial fitting curve of the experimental data. It is worth observing that such divergence with measured data would be more pronounced if plasticity were introduced in the soil model and that a non linear elastic model with increasing stiffness would be more appropriate to fit the experimental curve. Such observation is fully consistent with the stress-strain response observed from laboratory experiments on gravels repeatedly subjected to large amplitude loading cycles (Anh Dan and Koseki, 2004; Modoni et al., 2006). In particular, the plot of Fig.17 clearly shows the change of the stress-strain response due to repeated cyclic loading, with a marked increase of stiffness.

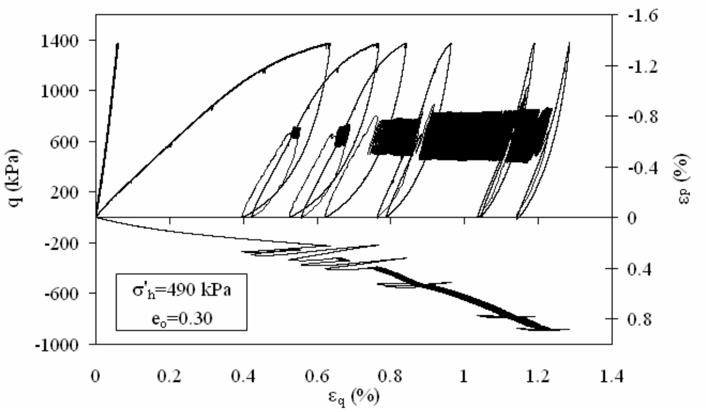


Fig. 17. Cyclic triaxial shearing of gravel (from Modoni et al. 2006).

In the left part of the plot, the deviator stress is also reported versus the elastic distortional strains, these latter calculated by performing small strain unloading-reloading cycles (Tatsuoka and Shibuya, 1992). It is seen that the soil response at the end of the test (i.e. after a large number of loading cycles) becomes similar to the elastic response, with an inversed convexity of the stress strain curve compared to the initial loading. As a further consequence of such strain accumulation, the post cycles stress-strain response of soil becomes more brittle, but with a noticeable increase of the soil stiffness and strength (see Modoni et al. 2006). These results suggest that cyclic loading produced on the moraine by the seasonal excursion of water level in the reservoir should have a positive effect in terms of stiffening and strengthening of the soil response but with the negative effect represented by the progressive strain accumulation (Fig.11). This latter effect should be carefully controlled by continuously monitoring the movements of the dam and of the moraine.

CONCLUSIONS

The case reported in the present paper has regarded a masonry dam built in the Italian Alps in the years 1922-1926. This dam has been continuously in operation for electrical purposes, and still is, even though large seepage flows and significant dam movements have been recorded along the years. Due to the limited knowledge of the subsoil properties and to the lack of well established calculation methods, at the beginning of the last century, the design was carried out mostly based on empirical rules. The present work has been aimed to analyse the present working conditions of the dam by combining the results of a geotechnical investigations campaign, a monitoring plan and different numerical analyses. The most peculiar aspect observed in this case is the complex interaction between the reservoir, the dam body and the different subsoil formations. In particular, a predominant role is played by the moraine deposit forming a natural prolongation of the dam along its right shoulder. Geological studies and geotechnical investigations have provided basic information on this deposit but the grain size composition of the moraine, consisting mainly of coarse grained material, has limited the geotechnical information which could be retrieved by laboratory and site investigations. This gap has then been filled by direct observations and by complementary numerical analyses. The former has provided a logical correlation between reservoir level excursions, water seepage and movements of the moraine and of the masonry dam. In particular, this latter is partly founded on moraine and alluvial soil, partly resting on a metamorphic rock formation. Such difference is responsible for a significant strain concentration on the right shoulder of the dam. The results of numerical back analysis have also shown that the soil response is much stiffer than estimated by pressumeter tests and similar to a non linear elastic medium. Such response is consistent with laboratory observation on gravelly soils subjected to a large number of loading cycles.

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