

GEOTECHNICAL ANALYSIS OF AN ANCIENT DAM BUILT IN UNFAVOURABLE GEOLOGICAL CONDITIONS

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ABSTRACT

The paper reports on the behaviour of the Alpe Cavalli dam, built in the Italian Alps between 1922 and 1926 and still in operation for electric power supply. The dam, which is 31 m high, made by dry masonry, is waterproofed by a multi-layered impervious facing, a concrete cut-off and a grout curtain in the foundation soils. The geological conditions of the dam site are quite peculiar since the reservoir location coincides with an ancient natural lake of glacial origin which was emptied, probably after the last glaciation, when the front moraine was eroded by the emissary river and a deep narrow cut was opened on the left side of the valley. For such reason the right shoulder of the dam rests on the moraine deposit, its central body is placed on the river bed alluvium while its left shoulder stands on a metamorphic formation composed of highly fractured rocks.

A comprehensive investigation has been conducted in order to understand the overall behaviour of the reservoir, after about ninety years of service. For this purpose, historical documents have first been reviewed for reconstructing the design assumptions and the building operations. Experimental investigations of the moraine deposit have then been conducted, in order to estimate the subsoil properties. Seepage flow rates and reservoir impoundment levels have been thoroughly analyzed, showing a strong correlation between these two variables. The displacements of the dam body and of the moraine deposit have also been examined in de-

tail. The available observations have been evaluated in order to gain an over all interpretation of the reservoir behaviour, with particular reference to the moraine deposit. Stability analyses have finally been performed to check the safety level of the reservoir.

KEY WORDS: dam, moraine, seepage, displacements, monitoring, back-analysis

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 Most of these dams are still on service, even though they were designed and constructed following out of date concepts and techniques. Moreover, the locations chosen for such dams would often be questionable, from the geological and geo-morphological stand point, according to present safety criteria. The overall safety of such dams and reservoirs 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 (Fig. 1). The dam is located in a very peculiar geomorphological environment. In particular, while the right abutment is located on a moraine deposit the dam foundations are placed on the fluvio-glacial deposit and the left abutment rests on a cliff of metamorphic rocks.1

The reservoir has been effectively operating for

about ninety years so far. 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 localized deformations on the downstream face of the dam.

A thorough assessment of the safety conditions of this old dam has already been attempted (CROCE & MODONI, 2008a; 2008b). However, the critical geological factors deserve some further explanation which is provided in the present paper. 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 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 analyzed 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.

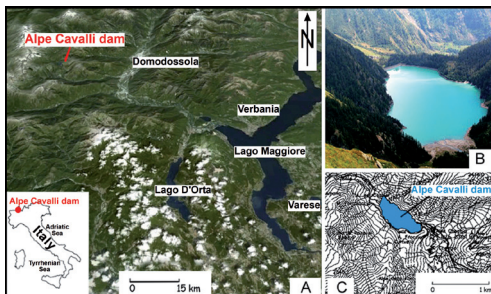


Fig. 1 - Partial overview of western Alpine sector between Domodossola and Varese (A), Alpe Cavalli reservoir (B), topographic sketch of Alpe Cavalli lake, scale 1:50.000 (C)

GEOLOGICAL SETTING

The Loranco stream, left tributary of Ovesca river, is located in the north-western Alpine sector. Its evolution is conditioned by morphoclimatic and structural features, developed in a fluvial-glacial environment. A sharp change of direction in its course (from ESE-WNW to NW-SE) is due to the different erosion rate among the outcropped bedrocks. Glacial proofs have been recognized in lateral and front moreins, partially covered by talus and localised on the bottom of the main valley. Moreover hanging valleys are present on the left side. Because of a transition from glacial to fluvial condition, the front moraine has obstructed the river valley thus creating a paleolake. The fluvio-glacial deposit, interbedded with talus, fills all the valley and lies on the metamorphic rockmass. Paleozoic ortogneiss and granite of "Monte Leone" are overlapped on mesozoic schists, belonging to the piedmontese "Pietre Verdi" series, by means of a regional thrust (SCHMID, 2004). Surveys on "Pietre Verdi" have revealed schistosity planes dipping approximately 335.50 nearby the left shoulder. Perpendicular to the stratification, another schistosity set has been recognized with a 110.35 trend. The "Pietre Verdi" series is characterized by "prasinitic", amphibolitic and calcareous schists, permeable for cracking. From an hydrogeological point of view, the circulation scheme of the area can be divided in two different paths respectively for the metamorphic complex and the moraine deposit. In particular, the discontinuities of the metamorphic layers are filled and covered by eluvial clays, whereas the glacial-karst process is barely visible in the calcare-

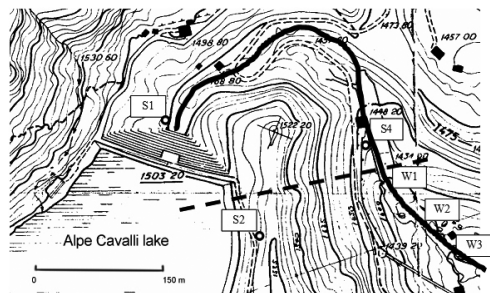


Fig. 2 - Plan view of the Alpe Cavalli dam with the locations of the intercepted water springs (W1, W2 and W3) and of the continuous borings (S1, S2 and S4); the Loranco River is indicated by the thick continuous line and the trace of the analysed cross section through the moraine deposit is indicated by the dotted line

ous schists. Weathered rocks underlying the morain deposit are fairly impermeable thus representing an acquiclude for the morainic aquifer

DAM FEATURES

The Alpe Cavalli reservoir, with a full capacity of 8,35 millions of cubic meters, is located in the basin of the previously mentioned paleo- lake, 1500 meters above sea level (Fig. 2). The reservoir feeds the ground water seepage mainly through the morain body. 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. 3).

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.

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

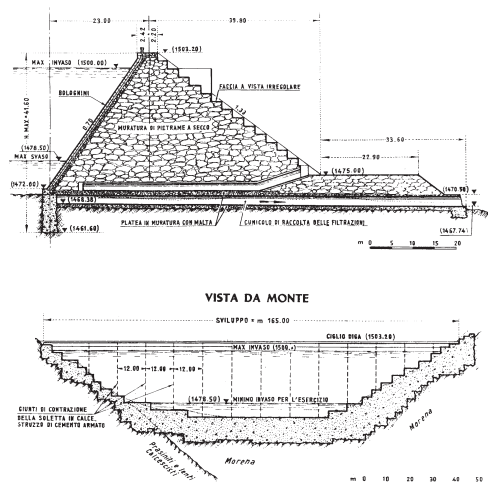


Fig. 3 - Cross section (a) and front view (b) of the masonry dam (ANIDEL, 1953)

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 fluvio-glacial deposit and its left shoulder on the metamorphic rocks (Fig. 4). 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 %. 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 & BARBIER, 1955).

In fact, 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. 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 had also been recorded downhill. After the construction of the dam, the water flows became

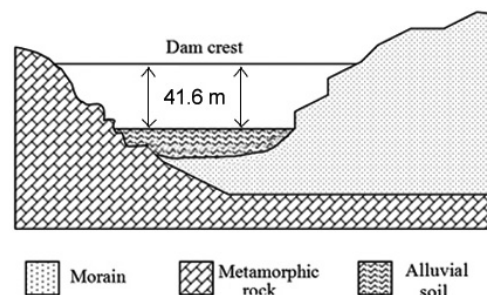


Fig. 4 - Longitudinal geo-morphological pattern at the Alpe Cavalli dam

quite large and three most significant springs were collected to be pumped back into the reservoir (W1, W2 and W3; Fig. 2).

During all the operation period significant movements of the dam body have also been recorded and vertical cracks were observed on the downhill abutment, close to the left shoulder (Fig. 5). This last observation suggested to monitor the dam movement with systematic topographical surveys.

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 (Fig. 2)

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 res-



Fig. 5 - Down stream abutment of Alpe Cavalli dam with indication of the observed vertical crack

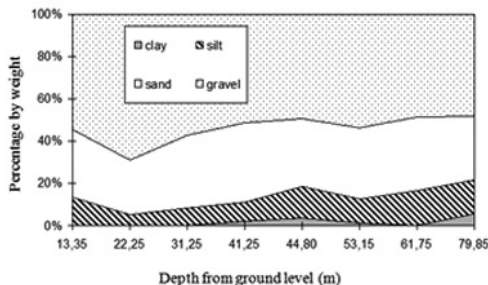


Fig. 6 - Grain size composition of the moraine at boring S2

ervoir. 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 summarized in Fig. 6 where the soil composition observed at boring S2 is reported as a function of depth. The soil 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. However, considering the large extension of the moraine deposit, the soil can be considered to be practically homogeneous.

Le Franc tests were also performed at different depth along the bore holes. The permeability coefficients obtained from such tests are summarized in Fig. 7, together with a broad estimation of the Darcy's

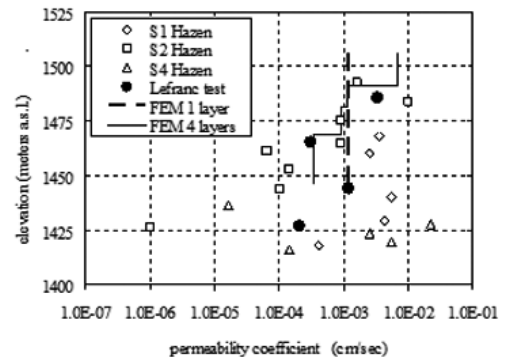


Fig. 7 - Permeability coefficients of the moraine

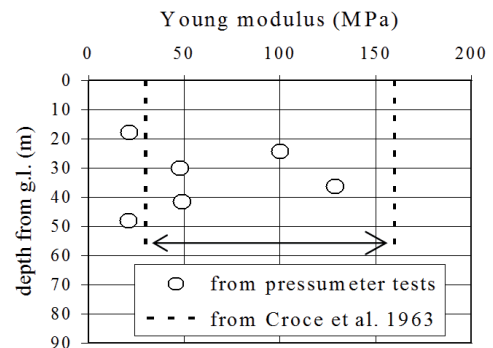


Fig. 8 - Young moduli obtained from pressurometer tests

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 alii.* (1963) back analyzing the settlements measured at the foundation of three dams built in the Italian Alps after the Second World War. In the hypothesis of linear elastic response, a Young modulus ranging between 30 and 160 MPa was obtained from such study.

In the present case, a rough estimate of the Young's modulus is provided by the results of several pressuremeter tests (MENARD, 1975), performed along the three boreholes at different depths.

As reported in Fig. 8, the values of the Young moduli E calculated from the pressuremeter 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 both the dam 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 (W1, W2 and W3 in Fig. 1) was collected and pumped back into the reservoir.

Such a procedure allowed for a continuous recording 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. 9. 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 fed 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. 8a 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. 9a by a period T and evaluating the corresponding cross correlation factor defined in Fig. 9b. 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.

The total amount of water collected at the three springs (Q) and the reservoir level H are directly compared in Fig. 10, scaling both of them by their maxi-

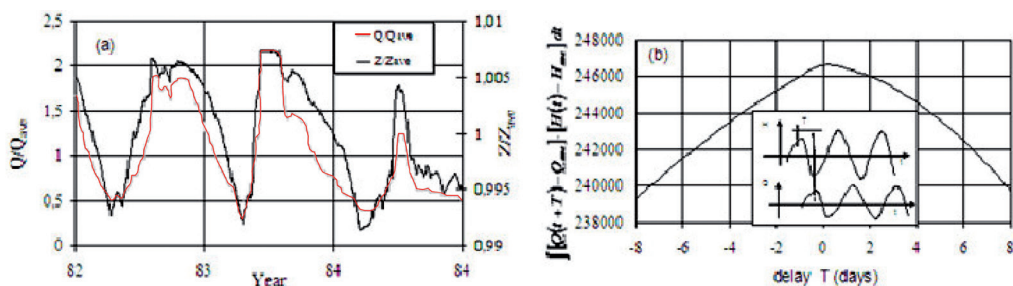


Fig. 9 - Reservoir level and water loss in the period 1982-1984 (a) ($Q_{ave}=0.165$ m³/s ; $Z_{ave}=1488.4$ m a.s.l.) and cross correlation among the two series (b)

mum 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. 11, 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.

DAM AND MORAINES DISPLACEMENTS

The dam movements have been monitored by a multiple topographical survey system (Fig. 12). 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 metamor-

phic 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. 13) 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.

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 (Fig. 12) and related to the water level in the reservoir (Fig. 14).

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.

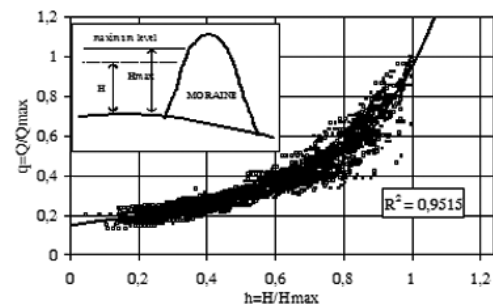


Fig. 10 - Water loss versus reservoir level in the Alpe Cavalli moraine (period of observation 1980-1998)

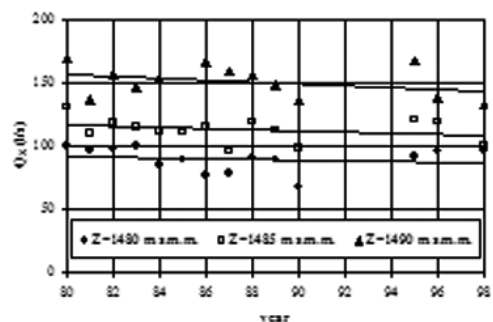


Fig. 11 - Progression with time of water losses measured at three different reservoir levels

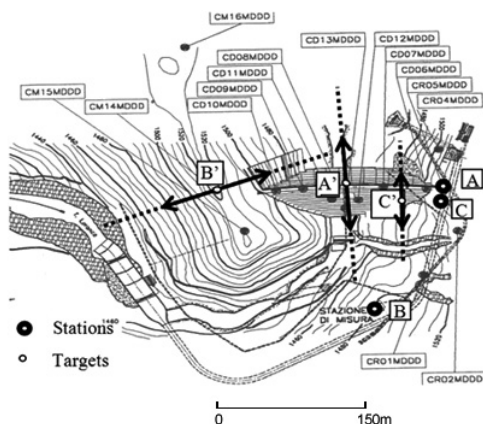


Fig. 12 - Topographical survey system installed at Alpe Cavalli

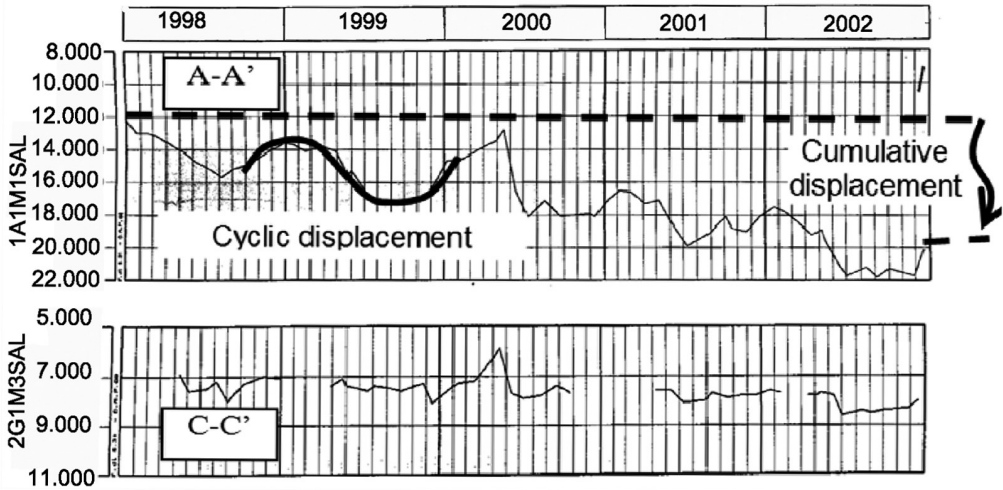


Fig. 13 - Alignment measurements recorded on A-A' and C-C'

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. 15) has been implemented at the cross section reported by the dotted line in Fig. 2 (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.

The seepage conditions through the moraine have been initially simulated by supposing the whole moraine body as having a unique constant permeability coefficient ($k=1.16 \cdot 10^{-3}$ cm/s) equal to the mean value of the data obtained by the results of permeability

tests (Fig. 7). This analysis has been performed for different reservoir levels and its results are compared with the experimental ones (previously reported in Fig. 10) in the non dimensional plot of Fig. 16. 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

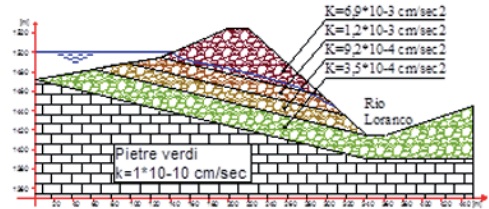


Fig. 15 - Two-dimensional model of the moraine at cross section reported by dotted line in Fig. 2

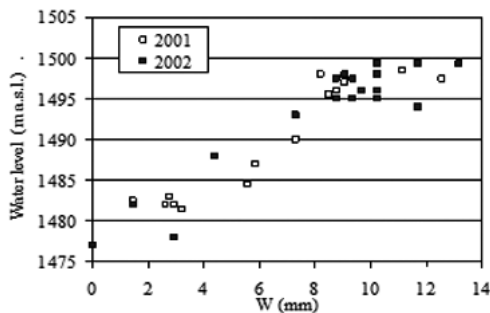


Fig. 14 - Recorded horizontal displacements at point B (a) and reservoir impounding level (b)

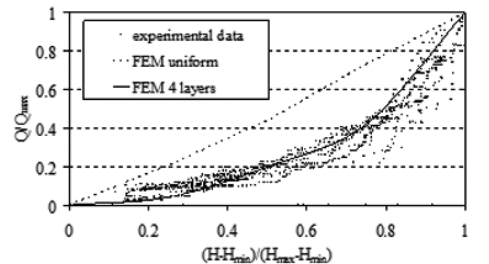


Fig. 16 - Simulation of seepage through the moraine deposit

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. 15). The most appropriate values of k (Figs. 7 and 15) 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. 16).

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. 17a) have been computed at several impounding levels for different Young's moduli. A comparison of simulated displacements with those observed at point B' (Figs. 12 and 14) is reported in Fig. 17b.

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 pressuremeter tests (Fig. 7). Furthermore, all the simulation curves show a larger

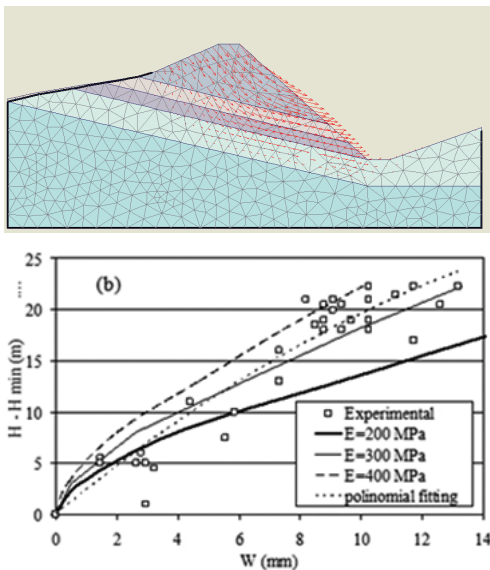


Fig. 17 - Pattern of calculated displacements (a) and comparison between measured and calculated horizontal displacements at point B' (b)

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 & KOSEKI, 2004; MODONI *et alii*, 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.

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 & 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 inverted 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 (MODONI *et alii*, 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.

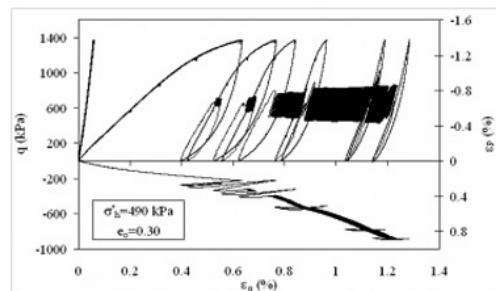


Fig. 18 - Cyclic triaxial shearing of gravel (MODONI *et alii*, 2006)

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 paper provides an updated analysis of 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 which have resulted in visible cracks on the downstream facing. The results of numerical back analysis have also shown that the soil response is much stiffer than estimated by pressuremeter 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.

With regard to the stability of the moraine, a parametric analysis has been carried out by CROCE & MODONI (2008b). Considering the experience so far cumulated on materials having the same grain size composition and density as those of the morainic deposit, this analysis suggests that deep instability mechanisms are unlikely to occur, while some concerns may arise with respect to shallow sliding surfaces. Such interpretation is supported by the evidence that the moraine as a whole has never shown any signs of instability. On the other hand, shallow mechanisms confined to the top cover of the morainic deposit had already been observed by the designers along the Loranco river downstream of the dam: much lower than the "piano dei Cavalli", to the right of the course of Loranco river ... a large landslide named "Rovina" is taking place (NOVARESE & STELLA, 1919). Still visible landslides have been more recently reported (FAITELLI, 1999) as shown in the schematic geological map (Fig. 4).

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