1st IMEKO TC-4 International Workshop on
Metrology for Geotechnics
Benevento, Italy, March 17-18, 2016

Geotechnical investigation and field performance of a zoned earth dam in Italy

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***Abstract* – The Farneto del Principe dam in southern Italy is a critical infrastructure, equipped with a complete monitoring system. Over the years, the effectiveness of this system has been drastically reduced, mainly due to a consistent number of malfunctioned piezometers. A substantial geotechnical investigation campaign was performed in 2015, and new piezometers installed. They are beneficial for supplementing monitoring data and enhance the reliability of the old monitoring system.**

This paper describes the results from standard geotechnical laboratory and chemical-physical tests, as well as first measurements from the new piezometers. The first insights from these investigations are: (1) the hydraulic conductivity in the core did not increase over time, (2) the seepage flow discharge is relatively low, and (3) the water analyzed does not show critical chemical-physical changes. Combining this information, it is possible to anticipate that the first results of the 2015 campaign show a good static behavior of the dam and exclude possible water tightness problems.

I. INTRODUCTION

A large number of Italian dams can be classified as old structures, being in operation for several decades [1]. It has been extensively demonstrated for these structures that damage under static conditions occurs immediately after the end of construction, or several years later, owing to ageing effects [2]. These observations, with the need of owners to ensure complete dam functionality, suggest that the monitoring of their behavior over the years is fundamental.

The hydraulic behavior of a zoned dam is strictly related to the evolution of seepage flow within the embankment, and to possible changes in the pore water pressure. The monitoring and the analysis of these variations is very important for old dams that are suffering ageing effects. These analyses are vital for those dams in which ageing effects are combined to a complicated construction phase. In this case, practical issues related to the model used for measurement interpretation, are amplified by the possible low long-term reliability of the monitoring system. The mechanical characterization of the dam materials, performed before and during the construction of the dam, is usually insufficient to estimate the parameters required by modern advanced prediction models [3]. Furthermore, the properties of the dam materials could have been modified by ageing effects and possible transformations occurred over the years. Thus, the current characteristics of the dam materials can be remarkably different from those estimated during the construction of the structure.

The Farneto del Principe dam is a zoned earth dam located in southern Italy. A substantial geotechnical investigation campaign started in the fall of 2015. The main scope of the new investigations is to obtain a reliable characterization of the dam materials. We anticipate that this information will be used for evaluating the performance of the dam under seismic excitation. This paper shows the first results of the new investigation campaign. In the first part, we examine monitoring system data with focus on hydraulic aspects. We seek to analyze the reliability of the monitoring instruments and to infer the overall static behavior of the dam. In the second part we show the geotechnical characterization of the dam materials, comparing current values with those obtained during the construction of the dam.

ISBN: 978-92-990075-0-1

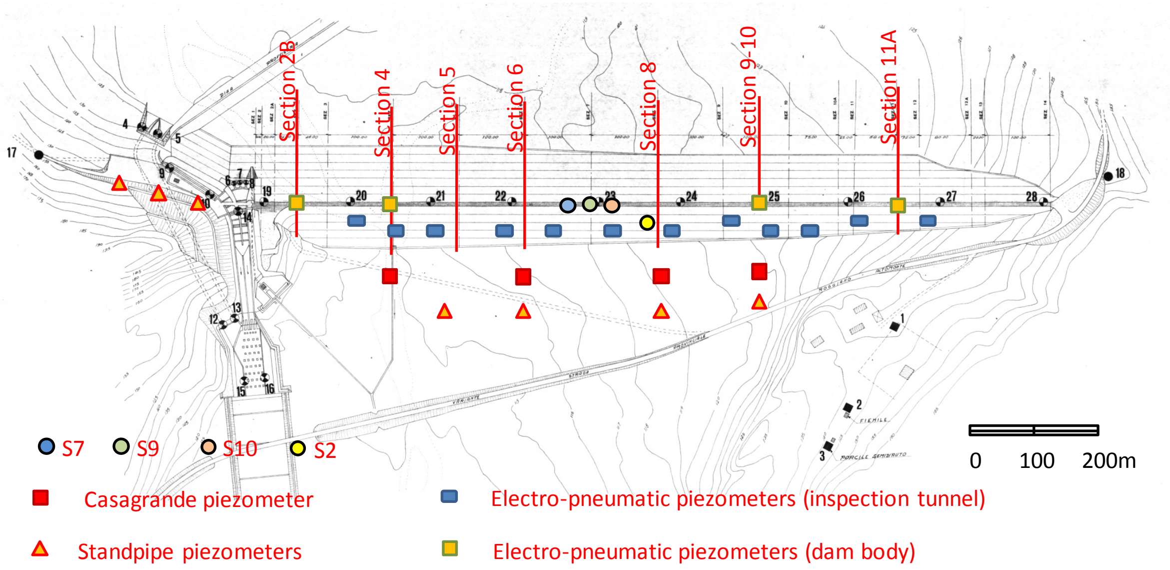

Fig.1. Planimetric view of the dam monitoring system

II. THE FARNETO DEL PRINCIPE DAM

A. Dam description

The Farneto del Principe dam is located in the Calabria region, not far from the city of Cosenza. This dam was designed at the beginning of the ’60s, it was built between the end of the ’70s and the beginning of the ’80s, and it is in operation from 1989. It is a zoned dam, characterized by a central impervious core (mainly made up clay and silt), used for irrigation purposes and flow balancing. The maximum normal operating water surface level is 136.30 m above sea level (a.s.l.), the crest elevation is 144.40 m a.s.l. and the maximum allowable level of the reservoir is 141.70 m a.s.l. The height of this dam is about 30 m, while its length is more than 1200 m. (Figure 1). Table 1 shows a summary of the main geometrical characteristics of the dam.

Table 1. Main geometrical characteristics

Geometrical property	**Value**
Water storage volume	46 Mm^3
Average height (above the foundation)	27.7 m
Crest length	1240 m
Crest width	7 m
Freeboard (max level of the reservoir)	2.7 m
Current freeboard	8.1 m
Upstream face slopes	1:2.5, 1:3, 1:3.5
Downstream face slopes	1:1.185, 1:2.25

The dam core is constituted of low permeability clay, while alluvial materials (gravel with sand and sandy gravel) with a high permeability were used for both upstream and downstream shells (Figure 2). The dam core is protected on both sides by two filters (with a thickness of 2 m in total) formed by sand on the core side and by sand and gravel on the shells sides. The dam is founded on alluvial material (with permeability and deformability properties similar to those characterizing the shells), that overlay a very stiff clay bed. Beneath the core and for the whole length of the dam, a cut-off wall was built, in order to avoid a potential ground water flow under the dam body (possible due to the presence of surficial pervious materials). The cut-off wall was realized using two construction strategies: (1) two slurry walls formed by panels excavated in presence of the bentonite mud, and (2) a double line of close piles with half meter diameter, without injection of waterproof material. The cut off wall is embedded for 3 m into the clay bed for the whole longitudinal extension of the dam. An inspection tunnel, also used for seepage collection, is located on the downstream side of the core base.

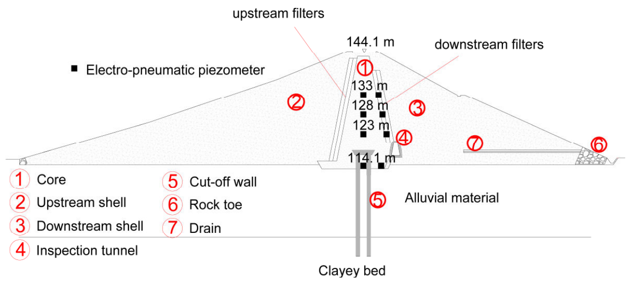

Fig.2. Instrumented cross section 4 of the dam

B. Geotechnical characterization

During the design phase of the dam several laboratory tests, such as direct shear, triaxial and oedometric tests, were performed on undisturbed and/or reconstituted samples of the foundation materials (both clay bed and alluvium) and on materials which were candidates for the construction of the dam. During the construction phases, additional laboratory tests were performed on the materials used for the dam body. Table 2 shows the mean values of various geotechnical parameters of the foundation and of the dam body materials.

The core material, after a period of exposure to natural weathering, was compacted in 30 cm thick layers by means of six runs of a 60-ton dump truck and additional runs of a 35-ton smooth roller. The continuity of the layers was ensured by a scarification of the current compacted surface prior to the placement of a new layer. Water contents were accepted in a relatively narrow range (-3% to +2% around optimum). Construction logs show values (obtained by means of oedometric tests) of the hydraulic conductivity ranging from 1 x 10^{-7} to 4 x 10^{-9} cm/s.

Table 2. Summary of the mean properties of the dam materials

Symbol	Description	Mean value			
		Foundation		Dam body	
		Alluvium	Clay bed	Core	Shells
c' (kPa)	Cohesion	0	180	80	0
φ' (°)	Friction angle	37.5	24	18	40
s_u (kPa)	Undrained strength	/	450	202	/
γ (kN/m^3)	Unit weight	24.1	21.12	21.31	25.1
γ_d (kN/m^3)	Dry unit weight	/	17.98	18.07	24.04
γ_S (kN/m^3)	Particles unit weight	/	27.3	27.3	27
n	Porosity	/	0.36	0.33	0.11
S (%)	Degree of saturation	/	97.2	95.6	96.7
e	Void ratio	/	0.54	0.51	0.123
PI	Plasticity index	/	18.26	26.16	
w (%)	Water content	7.5	19.54	17.88	4.42
w_L (%)	Liquid limit	/	41.51	45.4	/
w_p (%)	Plastic limit	/	18.26	19.18	

The material used for the shells comes from a borrow area along the riverbed. The shells and the filters were built by compacting this material in 80 to 100 cm thick layers, using an 8-ton vibratory roller with frequency of 1500 to 2000 vpm (vibrations per minute). Permeability tests show that typical hydraulic conductivity values for the shells material are 1.5 to 2.5 x 10^{-2} cm/s.

C. Monitoring system and data interpretation

The Farneto del Principe dam is equipped with a well-conceived mechanical and hydraulic monitoring system (Figure 1). In the remainder of this section we present a description of the piezometers data and their interpretation. Four cross-sections (2B, 4, 9-10 and 11A) are instrumented with 32 electro-pneumatic piezometers. Each cross section is instrumented with eight piezometers: four within the dam core, and four in the downstream filter on the core side. Figure 2 provides a better understanding of the positioning of these piezometers, showing the instrumented cross-section 4, which can be considered representative of the other 3 sections.

In the inspection tunnel, 24 electro-pneumatic piezometers (intended to be used for the ground-water flow control) are present. Four Casagrande piezometers (sections 4, 6, 8, 9-10) and four standpipe piezometers (sections 5, 6, 8, 9-10) are located outside the dam body, on the downstream side (not far from rock toe) and three open-tube piezometers are present in the right abutment area.

Currently, several piezometers do not work anymore. A critical analysis of the available data shows that: (1) only seven (of the 32 originally installed) electro-pneumatic piezometers within the dam body are currently in operation, and (2) 14 of the 24 piezometers located in the inspection tunnel work fine. Starting from the beginning of the operation of the dam, the electro-pneumatic piezometers did not work as expected. As a result, it is not easy to interpret the scarce and sparse data available from these piezometers. This issue does not allow for performing a reliable evaluation of the ground-water flow within the dam body [4]. In order to overcome this problem, and to better characterize the hydraulic behavior of the dam, it is necessary to install a new piezometer system. This system will provide new useful data as well as a powerful tool for calibrating the old piezometers.

The data from the Casagrande and the standpipe piezometers located in different positions outside the dam body give very important information about the ground-water flow under the dam body. An analysis of these data shows that the piezometers outside the dam body are not affected by the variation of the water level in the reservoir. This consideration excludes significant ground-water flows under the dam because of two main reasons: the core materials have low permeability, and the cut-off wall is likely undamaged. Zimmaro [5] speculates that the variations with time observed in the Casagrande and standpipe piezometers can be attributed to the rainfall events seasonality that probably produces the variation of the water level outside the dam body.

III. THE 2015 GEOTECHNICAL INVESTIGATION CAMPAIGN

Despite extensive investigation campaigns performed before and during the construction of the dam, the mechanical characterization of the foundation and dam body materials is not sufficient. The characterization of parameters for advanced prediction models requires further and more detailed investigations. In this context, in the fall of 2015, a new substantial investigation campaign has been performed. It consists of the following: (1) boreholes with continuous sampling, (2) static and dynamic laboratory tests on undisturbed specimens, (3) down-hole and cross-hole tests, and (4) seismic tomography. In this section we provide an overview of some of these investigations, as well as insights from the first measurements of the new piezometers.

A. Geotechnical index properties

Sieve and sedimentation analyses were recently performed on samples from the dam core [6]. Figure 3 shows the comparison between the grain size distribution curves from the 2015 investigations and those obtained during the construction of the dam. It can be noted that the curves are practically identical, thus that the groundwater flow within the dam body did not alter the core particle size distribution. This result suggests that neither internal erosion, nor migration of soil particles took place.

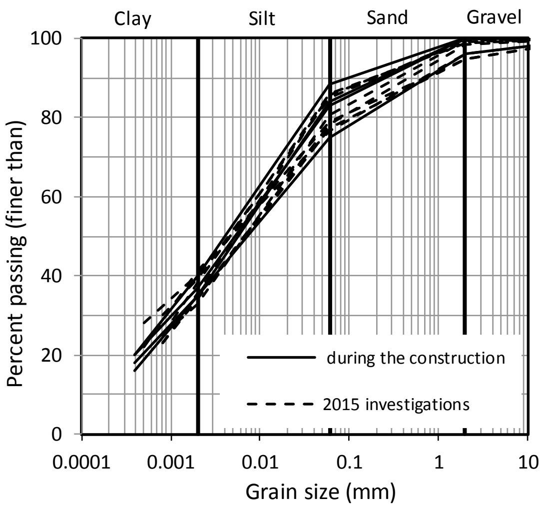

Fig.3. Grain size distribution curves for the dam core

Laboratory index tests were also performed. Figure 4 shows the trend of the water content with the depth in the central core. The water content has a mean value of 20.5%. This value is slightly higher than the mean water content measured during the construction of the dam (17.88%). Figure 4 also shows the trend of the plastic and liquid limit in the dam core. This plot provides also a visualization of the trend of the plasticity index with depth. It assumes values ranging from 24.7% to 32%, with a mean value equal to 28.56%. The mean value of the plastic limit is equal to 20.8%, similar to the value measured during the construction phase, equal to 19.18%. The mean values of liquid limit are 49.36% and 45.4%, as measured during the 2015 campaign and the construction phase, respectively. Figure 4 shows that the natural water content is close to the plastic limit. Accordingly, the core material at the natural moisture content, assumes a behavior between the semi-solid and plastic states.

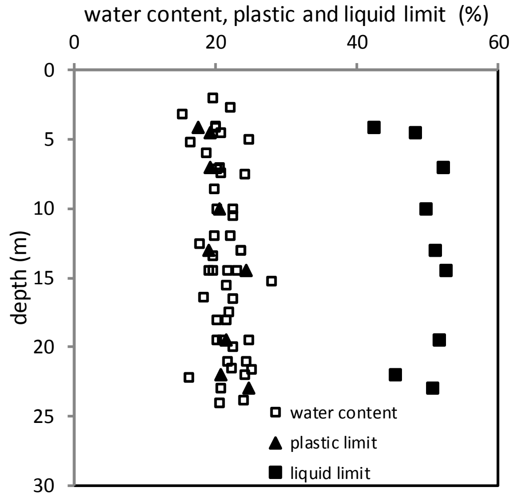

Fig.4. Water content, plastic limit and liquid limit versus depth

B. Spatial variability of the hydraulic conductivity

The likelihood of failure in an embankment dam depends on the degree of control over internal erosion and piping in the dam body. These phenomena can induce an increase in permeability, and thus an increase in seepage, over time. Accordingly, the possible variation of the permeability is a critical factor for the stability of the dam. The scope of this section is to analyze the hydraulic conductivity measurement performed on undisturbed samples of the core materials, during the recent geotechnical investigation campaign. We measured the vertical coefficient of hydraulic conductivity (k_v) by means of oedometer tests. Test results show that k_v values fall within the range of acceptability defined during the construction of the dam. Figure 5 shows vertical hydraulic conductivity versus void ratio, at different depths. It can be noted that k_v increases with void ratio. Figure 6 shows vertical hydraulic conductivity values with depth. The two curves refer to two different vertical effective stress levels used in the oedometer tests, a lower bound (σ'_v = 196 kPa) and an upper bound characterized by σ'_v = 3138 kPa. As expected, the vertical hydraulic conductivity decreases with increasing depth. We performed additional measurement of the coefficient of hydraulic conductivity, by means of a falling head test carried out in the oedometer cell for two selected depths (4.0 m and 10 m). The results of these tests show that the vertical hydraulic conductivity values, estimated using the falling head tests (open triangles in Figure 6), are consistent with those obtained by using the oedometer test at the same depths.

The hydraulic conductivity measurements are extremely important for a good characterization of the geotechnical model for static and dynamic analyses, as well as for the evaluation of possible water-tightness problems. In the core of the Farneto del Principe dam, the hydraulic conductivity did not increase over time, being the values obtained during the construction phase actually larger than those measured during the 2015 geotechnical investigation campaign. These results show a good performance of the hydraulic behavior of the core. Generally, the hydraulic conductivity measured in the core of an earth dam right after the compaction, all other things being equal, is expected to increase over time. It takes several months for the water, after the construction, to flow within the core; as a result, during this period, significant thixotropic effects can occur [7].

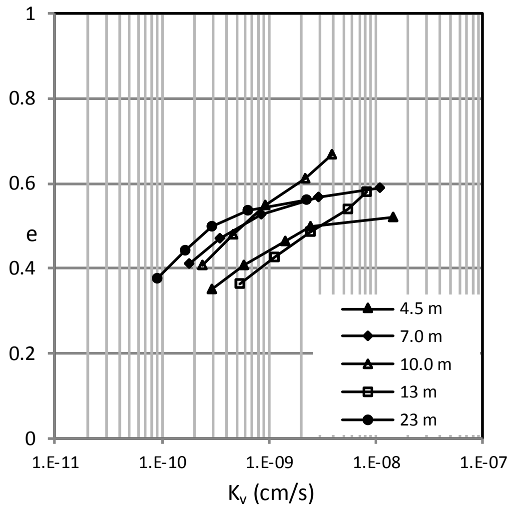

Fig.5. k_v against void ratio for various depths

We also evaluated the influence of permeability anisotropy in the core, through the investigation of the coefficient of horizontal hydraulic conductivity (k_h), normal to the direction of compaction forces. Figure 6 shows k_h measured by using the falling head test in the oedometer cell, for various stress levels and for a sample taken at a depth of 22 m (red diamond). The horizontal hydraulic conductivity is slightly greater than k_v, providing a confirmation that the core material, compacted at the optimum water content, shows a partially-oriented structure, thus influenced by the water flow direction [7].

C. Groundwater flow analysis and properties of the flowing water

The hydraulic performance of the dam can be assessed by measuring the seepage water collected, through a channeling and collection system, in the inspection tunnel, along the longitudinal axis of the dam. Inconsistency between measured seepage water and the reservoir level evolution can be related to a progressive reduction of the dam water-tightness [8]. Figure 7 shows values of discharge seepage water (i.e. drained water collected in the inspection tunnel) in the period January 2013 – December 2015. Ausilio et al. [4] show that, in the previous period of observation 1991 – 2012, the maximum measured seepage was 0.53 l/s. The new data suggest the following important considerations: (1) the seepage values measured in the last three years are consistent with those collected in the past; (2) the seepage is hardly influenced by the water level in the reservoir, and (3) the seepage can be considered low enough to ensure stability to the embankment, because these values are relative to the whole dam, demonstrating its efficient water-tightness.

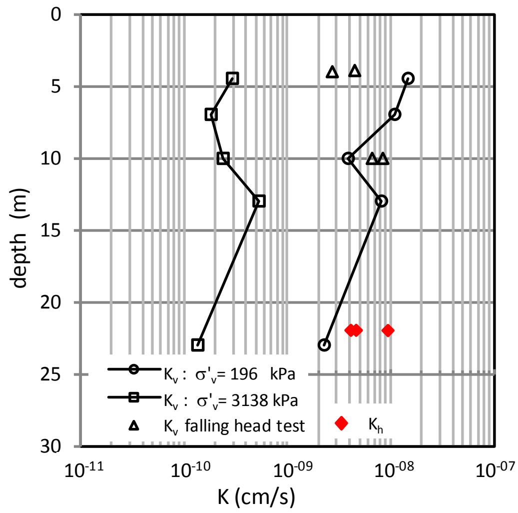

Fig.6. Hydraulic conductivity variation with depth

Previous studies show that chemical reactions (e.g. sulphide oxidation) can be detrimental for dam stability due to a possible reduction in the embankment shear strength parameters [9-11]. In order to evaluate whether the flowing water of the reservoir undergoes some chemical-physical change, a water sample taken in the reservoir and another one collected in the drainage tunnel were subjected to chemical-physical tests. Table 3 shows the results of these tests. The water in the tunnel presents higher values of conductivity, alkalinity, and magnesium ions. Furthermore, the water taken in the reservoir presents a larger quantity of calcium ions. This result is counterintuitive, but can be explained because calcium ions precipitate, forming calcium formations (stalactites) that are visible in the inspection tunnel (Figure 8).

D. New piezometers: installation procedure and first measurements

During the new investigation campaign, new piezometers have been installed. In particular, 5 new Casagrande type piezometers are distributed in the core as follows: (1) at depths 21 m (123 m a.s.l.) and 16 m (128 m a.s.l.) from the crest elevation in boring S7; (2) at depths 15 m (129 m a.s.l.) and 11 m (133 m a.s.l.) in boring S9; (3) at depth 7 m (138 m a.s.l.) in boring S10. These depths are practically identical to the piezometers installed in the sections: 2B, 4, 9-10, 11A and shown in Figure 2. Other 2 new piezometers are installed in the boring S2 with measuring tips located in the downstream blanket drain and in the alluvial foundation. The first measurements, performed after flushing operations and a period of about three months, show the absence of water in the piezometers with depths less than 16 m. Instead, the piezometer positioned 21 m deep shows the presence of water, suggesting the location of the ground water table at depth of 18.35 m (126.05 m a.s.l.). This measurement should be further verified and confirmed in the future, because, given the low permeability of the core and the response time of the piezometer, the current water level measurement can be biased.

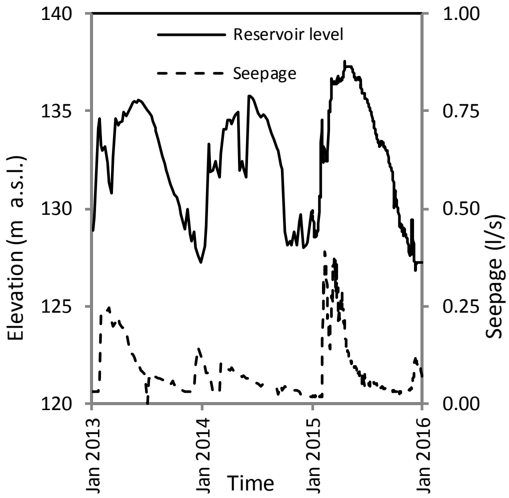

Fig. 7 Reservoir level and seepage flows in the period 2013-2015

Table 3. Chemical-physical test

Parameter	Water (reservoir)	Water (tunnel)
PH	8.1	8.09
Conductivity (mS/cm)	437	534
Total Hardness (°f)	21.2	23.8
Calcium Hardness (°f)	12.3	9.8
Magnesium Hardness (°f)	8.9	14
Ca^{2+} (mg/l)	49.3	39.28
Mg^{2+} (mg/l)	21.63	34.03
Alkalinity (mg/l $CaCO_3$)	190	225

IV. DISCUSSION AND CONCLUSIONS

The Farneto del Principe dam in Calabria (southern Italy) is a zoned earth dam characterized by a central impervious core (mainly composed by clay and silt). The new investigation campaign performed in the fall of 2015 has allowed us to determine some geotechnical parameters of the dam materials. The comparison between these measures and those obtained during the construction are useful for making considerations about the static behavior of the dam. The grain size distribution curves of the core materials are practically unchanged, thus the ground-water flow within the dam body did not alter the core particle size distribution. This result suggests that neither internal erosion, nor migration of soil particles took place. Useful considerations can be derived comparing values of the water content with plasticity and liquid limits. The values obtained in 2015 are consistent with those measured during the construction of the dam. We found that the natural water content is close to the plastic limit: as a result, the core material assumes a behavior between the semi-solid and plastic states. Furthermore, the permeability of the core material has been measured by means of oedometer tests, and falling head test carried out in the oedometer cell. Test results show that k_v values fall within the range of acceptability defined during the construction of the dam. The horizontal hydraulic conductivity, k_h, is slightly larger than k_v.

Fig.8. Photo of the calcium formations present in the inspection tunnel of the Farneto del Principe dam

In order to investigate the hydraulic behavior of the dam, the seepage water collected in inspection tunnel has been analyzed. We found that the seepage is not influenced by the reservoir level, and it can be considered low. The water collected in the inspection tunnel was also subjected to chemical-physical tests. These tests show that no critical reactions or changes took place in the dam body.

We analyzed the monitoring system of the dam. The data from the electro-pneumatic piezometers inside the dam body are sparse and not sufficiently reliable to carry out an analysis on the ground-water flow within the dam body. The situation is better for the Casagrande and the standpipe piezometers whose data exclude potential underseepage issues.

During the recent investigation campaign, new

Casagrande piezometers were installed in the core of the dam. The first measurements do not provide enough data for evaluating the current flow rate within core. Thus they should be analyzed in a longer time interval. Surely these piezometers will provide useful data to be used for assessing the efficiency of those still in operation and possibly to calibrate them.

Combining the results presented in this paper, it is possible to highlight that the Farneto del Principe dam has a good static behavior, and that possible water-tightness problems are unlikely to happen. We anticipate that these results will be verified over time and new tests will be carried out, providing further insights into the current behavior of the structure.

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