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Rockfill dam monitoring through ground-based and remote sensing techniques

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***Abstract* – The paper describes the preliminary results of ground-based and remote sensing techniques applied to monitor the displacements and seepage flow of a bituminous faced rockfill dam located on the Aspromonte mountain in southern Italy (Menta Dam). The analysis and interpretation of the seepage flow highlighted the overall good performance of the dam during the first impoundment. Moreover, the application of Differential Interferometric Synthetic Aperture Radar technique for measuring the dam's displacements produced fairly good results, highlighting the effectiveness of remote sensing techniques for geotechnical infrastructures.**

I. INTRODUCTION

Monitoring of large scale civil infrastructures is of vital importance for avoiding casualties, deaths, injuries and property damages. Among the geotechnical infrastructures, dams must be carefully monitored because of the potential damage caused by their possible collapse. The primary function of monitoring is to ensure the longevity and safety of a dam. Monitoring must enable the timely detection of any behavior that could deteriorate the dam, potentially resulting in its shutdown or failure, in order to implement corrective measures. Monitoring also plays a fundamental role during construction. It enables the verification of design hypotheses and may affect the construction rate of certain works. Monitoring is particularly crucial during the initial filling of the reservoir, a critical phase in the life of a dam, and in case of seismic events [1].

Means and methods available to monitor physical phenomena that can lead to a dam failure include a wide spectrum of instruments and procedures ranging from very simple to very complex. Any program of dam safety instrumentation must involve proper design, consistent with other project components, and must include consideration of the hydrologic and hydraulic factors both present before and after the project. Instrumentation designed for monitoring potential deficiencies at existing dams must take into account the threat to life and property that the dam presents. Thus, the extent and nature of the instrumentation depends not only on the complexity of the dam and the size of the reservoir, but also on the potential for loss of life and property downstream.

There are many conventional ways to monitor the static and dynamic behavior as well as the seepage flow of structures like dams and embankments. Regarding the displacements, over the traditional geodetic surveying techniques, Satellite Synthetic Aperture Radar Interferometry (InSAR) techniques and, specifically, Differential InSAR techniques (DInSAR) are becoming a powerful tool for the investigation of ground [2] and structure deformations [3]. The DInSAR technique has the potential for monitoring millimeter-scale ground motion in an accurate and cost effective manner.

In this paper, we describe the first results of an application of ground-based and remote sensing techniques to monitor a Bituminous-Faced Rockfill Dam (BFRD) located in southern Italy. Moreover, measurements of pore water pressures and seepage flow have been collected during the first impoundment of the reservoir. The integration of such measurements allowed assessing the overall static performance of the dam.

II. THE CASE STUDY

The “Menta Dam” is a rockfill dam with an impervious bituminous concrete lining on the upstream side.

The barrage closes a complex section formed by two distinct gorges, a left one whose bottom (1343 m a.s.l.) hosts the former bed of the river and a right one having the bottom located at an upper level (1418 m a.s.l.). These two gorges are divided by a massive rocky spur steeply emerging in the middle of the section up to an altitude of 1433 m a.s.l. (Figure. 1a). Such a peculiar section is filled with an irregularly shaped embankment made of rockfill quarried from a nearby hill of metamorphic rocks. The embankment has a curvilinear plan trend of the crest developing for about 450 m, a total

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volume of about 2.1 x 10^6 m^3 and a maximum height of about 90 m (Figure 1b). It includes a central core of coarse grained material (zone 3 in Figure 1b), a layer of finer soil placed below the upstream face as a foundation of the waterproofing lining (zone 1), a transition zone with particles having intermediate size (zone 2) and a composite cliff made of boulders which covers the downstream face (zone 4).

The zone 2 is extended all over the dam basement, with a thickness ranging between 1.5 m and 3.0 m, as a safety layer to prevent the rise of water inside the dam body. This layer plays a relevant role in the water flow involving the dam.

The bituminous concrete facing on the upstream side of the dam is made by the superposition of six layers of different permeability. The facing is placed on a regularly packed basement of compacted sandy gravel and is anchored to the reinforced concrete tunnel running along the inner perimeter of the dam. The upstream face of the dam is divided into seven drainage sectors.

Metamorphic rocks belonging to the "Calabrian complex" constitutes the foundation of the dam. The rock is fractured in the upper part because of the weathering effect. At depth, the rock is more compact, therefore, a reduction of the coefficient of permeability of the rock mass with increasing absolute depth has been observed during the investigations performed by means of several Lugeon tests. The measured hydraulic conductivity ranges between $3x10^{-6}$ m/s and $1x10^{-9}$ m/s.

In order to reduce the hydraulic conductivity of the rock mas under the upstream side of the dam foundation, a grout curtain has been made. Cement-water injections were executed along the perimeter and auxiliary galleries (Figure 1a), reaching a depth of about 50 m and 2.5 m spacing. Drainage pipes of the same depth and spacing were also installed along the gallery, as a safety measure

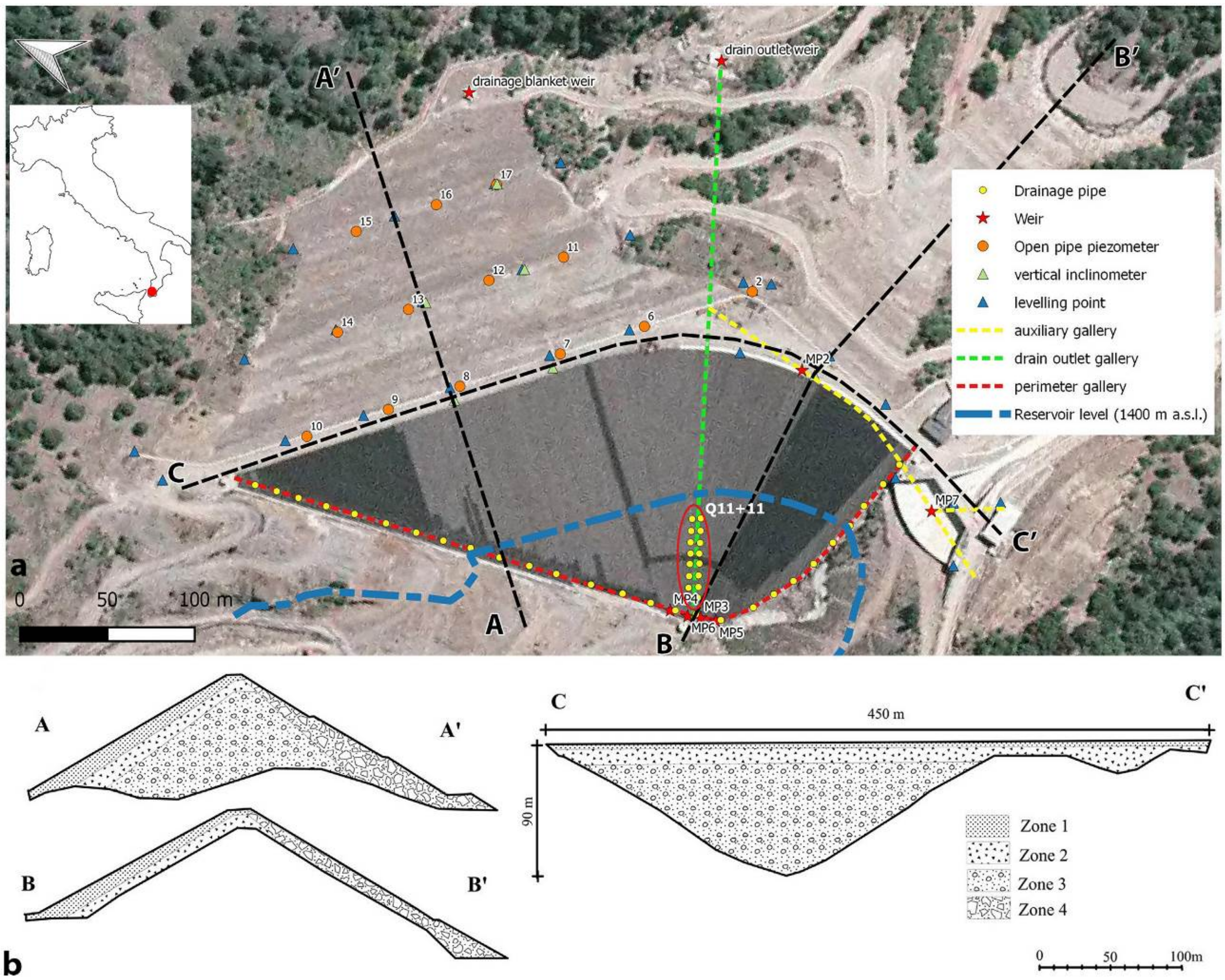

Fig. 1. (a) Location, plan view and monitoring instruments of the Menta dam;(b) relevant cross sections of the dam's body (traces in panel a).

to eventually reduce the water pressures under the embankment.

III. MONITORING EQUIPMENT

A. Ground-based monitoring

The displacements and the seepage flow of the dam are monitored through a series of ground-based instruments. The displacements are monitored with vertical inclinometers placed along the crest and the downstream slope. The displacements of the downstream slope are also monitored through topographic measurements at selected points (Figure 1a).

A series of Casagrande and open pipe piezometers, placed at different depth inside the dam body, monitors the water level inside the embankment and the foundation rock. Water leaks below and inside the dam body are measured with a series of weirs installed along the perimeter and drain outlet galleries and at the toe of the downstream slope (MP 2-7, drainage blanket and drain outlet weirs in Figure 1a).

B. Satellite monitoring

The deformations of the dam body during the first impoundment of the reservoir have been monitored through remote sensing techniques. A series of SAR images taken from the ENVISAT satellites have been collected and processed in order to retrieve the temporal displacements. The SAR sensor has a so called Line Of Sight (LOS) of the scene characterized by an off nadir angle of 23° and a looking direction of -77° (about North-East) with respect to the geographic north, i.e., on a descending orbit. We used a dataset acquired in the time span from April 2005 to September 2010.

IV. DISPLACEMENT MONITORING

We processed the SAR data with the multi-baseline GAMMA IPTA technique [4] that allows exploiting the properties of both PS [5] and SBAS [6] approaches.

The maximum perpendicular and temporal baseline have been set to 280 m and 600 days, respectively. The 90 m DEM provided by the SRTM mission has been used to remove the topography in the interferometric phase.

Due to the lack of coherence of the investigated area, we applied a Goldstein filtering and a low coherence threshold of 0.35. The processing returned more than 100 interferograms but many of them were discarded in a second step because of unwrapping, atmospheric and coherence lacking problems. At the end, we used 38 interferograms to retrieve the displacement time series of the dam body during the observed time interval.

The processing has provided the time series of displacement for points where high reflectivity and high coherence are maintained during the whole observation period. Unfortunately, the detected coherent pixels are limited, because of the particular topographic and morphological features of the investigated area, characterized by the presence of high reliefs, vegetation, and snow during winter. Indeed, high coherent pixels are only preserved in non-vegetated areas, such as man-made constructions (dam, buildings and roads) or bare surfaces, while interferograms degrade faster in vegetated areas, which characterize most of the slopes around the reservoir.

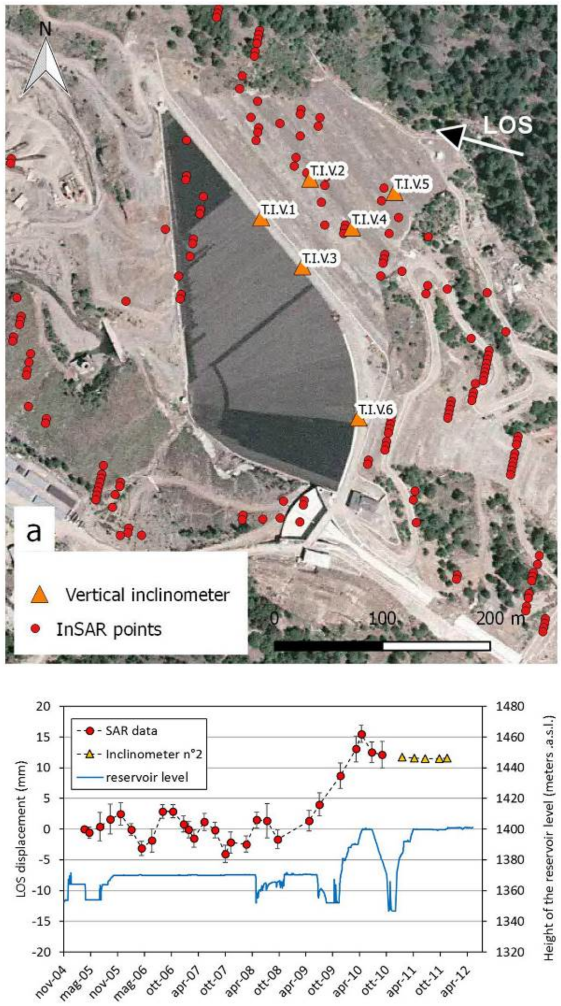

Fig. 2. (a) Detected coherent pixels on the dam body; (b) Comparison among the reservoir water level change and the displacements from ground-based and satellite measurement.

Despite the low coverage, some points are available on the downstream face of the dam (Figure 2a). The observed LOS displacement time series are consistent with the reservoir level rise between September 2009 - July 2010 (Figure 2b). A positive LOS displacement increment means that the coherent pixels are moving towards the satellite sensor, i.e. the dam is deforming to the North-East. This result is consistent with the load produced by the reservoir impoundment.

A direct comparison with ground-based measurements has not been possible because of the lack of measurements from inclinometers and topographic measurements in the same observation period of SAR data. The available measures from vertical inclinometers cover the period January-December 2011. Despite that, the measured horizontal displacements at the inclinometer n°2, projected along the satellite LOS, seem to be in agreement with the displacements observed with SAR data (Figure 2b).

V. SEEPAGE FLOW MONITORING

BFRD are designed so that the dam body must be completely dry during the operational life. The uncontrolled seepage flow inside the embankment body may provoke severe damages as well as the collapse of the structure. The water flow behind and inside the Menta dam has been monitored during the controlled filling of the reservoir to verify the functionality of the dam as hydraulic barrier. Water flows are monitored by means of v-notch weirs with automatic acquisition, placed at different points along the tunnel network (Figure 1a). Each weir measures the water leaks through specific parts of the dam: the bituminous concrete facing (right side MP5, left side MP6); the drainage pipes along perimetric gallery (right side MP3, left side MP4) and along secondary galleries (MP2 and MP7). All of these water leakages are conveyed at the end of the drain outlet gallery (Figure 1a).

Along the drain outlet gallery are present other 22 drainage pipes (Q11+11 in the Figure 1a) which drain the water coming from the drainage blanket at the bottom of the dam body. This water amount is measured together with all the other water flow contributions at the end of the drain outlet gallery.

Another v-notch weir, placed at the foot of downstream slope of the embankment (drainage blanket weir in Figure 1a), measures the amount of water flow within the drainage blanket that has not been captured by the drainage pipes along the drainage gallery (Q11+11).

The flow rates measured at the drain outlet gallery weir and the drainage blanket weir have been reported for the period April 2011 – November 2011, when the water height in the reservoir was maintained at 1440 m a.s.l.. (Figure 3a). The average water flow at the drain outlet gallery is about 31 l/s while the average water flow pertaining to the drainage layer weir is about 8 l/s. Such measures correspond to the operational condition of the dam, with all the drainage pipes along the tunnel network opened.

In order to verify the efficiency of the drainage blanket, we closed progressively all the drainage pipes along the perimetric gallery and the drain outlet gallery (drainage pipes in Figure 1a). In this way, the water flowing below the dam is captured only by the drainage blanket at the dam's base. We contextually measured the water flowing

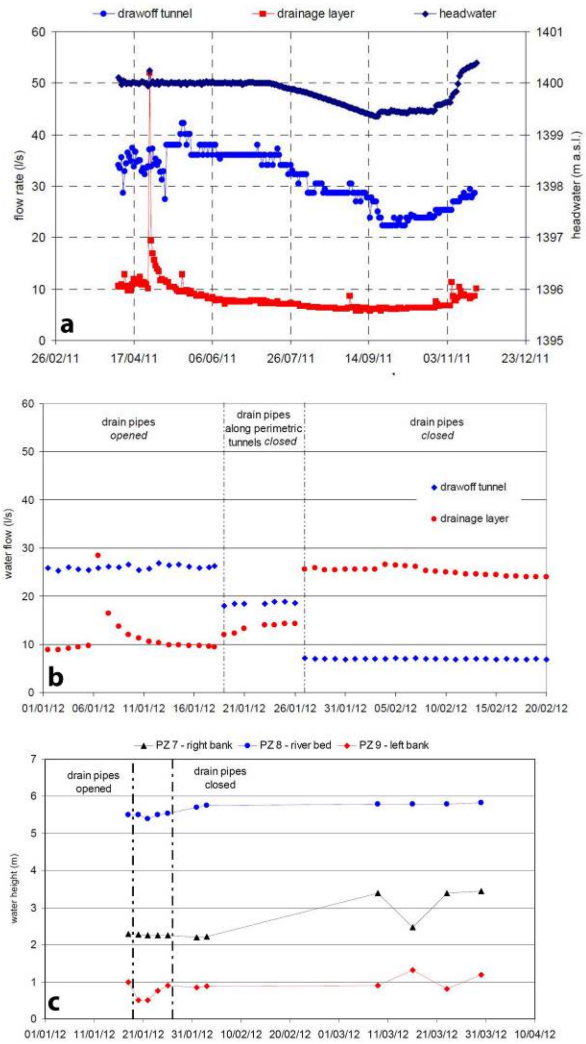

Fig. 3. (a) Flow rates measured during 2nd impounding cycle; (b) water flows corresponding to different hydraulic operating conditions of the dam (c) measurements at the of open pipe piezometers n. 7, 8 and 9 (Figure 2a).

to the drainage blanket weir and the water height at the open pipe piezometers.

The closing procedure has been performed in two phases: 1) closure of the drainages along the perimetric gallery (red dotted line in Figure 1a); 2) closure of the drainages along the drain outlet gallery after about eight days (Q11+11 in Figure 1a). The water flows measured by the drain outlet gallery weir and by the drainage blanket weir are reported in Figure 3b. When all drains are opened, the average water flows are aligned with those showed in Figure 3a for the period April 2011 – November 2011. It is noteworthy the relevant dependence of the water flow in the drainage blanket on the rainfall intensity (first part of January in Figure 3b) with a rapid increase because of an intense rainfall event.

After the first phase, a reduction of the flow rate is measured at the drain outlet gallery, together with an increase of the flow within the drainage blanket, as a consequence of the increase of the piezometric head induced by the closure operations.

The transfer of the water flow from the drain pipes to the drainage blanket is confirmed by the further increase of water flow measured at the drainage blanket weir (reaching about 25 l/s) after the complete closure of drainage pipes (phase 2); and the consequent flow reduction at the drain outlet gallery (about 7 l/s).

The water flow measured for this hydraulic conditions allows to quantify the seepage interesting the dam for a reservoir level of 1400 m a.s.l.. The body of the dam is interested by a negligible flow as evidenced by the constant and low water flow measured at the drain outlet weir after the drains closure. Moreover, a quote of the measured flow of about 2 l/s is associated to the leaks of the bituminous facing. The major amount of seepage pertains to the measured water flow within the drainage blanket and within the rock mass under the dam foundation, which is not quantifiable. The results of the performed test highlight the efficiency of the drainage layer, which represents a safety measure to prevent increasing positive water pressure within the embankment.

A confirmation of the efficiency of the drainage blanket is given by the measurements of the water level performed at the n. 12 new open pipe piezometers installed along the crest and the downstream face of the dam (Figure 1a).

Each piezometer has been installed by reaching the rocky foundation of the dam, crossing the variable thickness of the drainage blanket. In Figure 3c data referring to the water level (from the base of the open piezometer) measured in three piezometers along the dam crest (namely piezometers n.7, n.8 and n.9) have been represented during the period January 2012 – April 2012. The different hydraulic operating conditions did not affect relevantly the measured water heights, and the values showed that water flow line falls within the thickness of the drainage blanket, also for the piezometer n.8, whose base is about 3.9 m under the rock foundation level.

VI. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this paper, the Menta Dam has been described in detail with reference to its monitoring system.

We monitored the displacements and the seepage flow during the first impoundment by means of ground-based and remote sensing techniques. In particular, the interpretation of water leakages and the piezometric water levels inside the dam body confirmed the correct functioning of the dam and the fundamental role played by the drainage blanket at the dam’s bottom. It has been evidenced that the drainage layer is capable of conveying the water flowing under the dam foundation for all the hydraulic operating conditions, although the water discharge can be relevant.

Regarding displacements, the lack of ground-based measurements during the reservoir impoundment has been covered through remotely sensed data. The results of a multitemporal analysis of SAR data produced a discrete picture of the displacements of the downstream slope, in agreement to subsequent ground-based measurements performed by means of vertical inclinometers. Further analyses are currently under development with reference to a 2D and 3D numerical models of the dam and the rock mass in order to predict its behaviour in terms of displacements and seepage flow for different reservoir levels.

In the next future, the InSAR analyses will be integrated with more data coming from the most recent COSMO-SkyMed mission and the new SENTINEL-1 mission, which is able to provide data with high spatial resolution, high displacement accuracy and high temporal sampling rate. Furthermore, the installation of a series of Corner Reflectors on the downstream slope of the dam will contribute to improve the InSAR analysis.

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