The safety assessment of Campotosto Lake dams following 2016-2017 seismic sequence in Central Italy. Focus on Poggio Cancelli embankment dam

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ABSTRACT
The Campotosto Lake is one of the biggest reservoirs of Europe, with a storage capacity exceeding 200 million of m^3. The natural original lake was confined with three large dams owned by Enel.

In the recent past, the lake and the dams have been subjected to a series of seismic events known as the seismic sequence of L'Aquila in 2009 and the seismic sequence of Central Italy in 2016-17. Following the last one, Enel promptly decided to temporarily lower the water level to carry out surveys, measurements and automatic monitoring activities. Based on available data, in order to verify, ensure and asseverate the safety conditions of the dams and the lake's slopes, a series of multi-disciplinary studies and in-depth analysis were specifically conducted.

Detailed studies were developed for the Poggio Cancelli embankment dam: geotechnical surveys, geophysical in situ tests and "advanced" laboratory tests in order to define at best the foundation soil characteristics, thus reasonably excluding the liquefaction risk applying sophisticated methods of analysis. Moreover, InSAR analysis allowed to retrieve the displacement history of the sites and confirmed the topographic measurements taken before and after the earthquakes. Displacement data, together with the real accelerograms recorded at the dam toe were used for a back analysis of the settlements by means of a FEM model of the dam. With this validated model, it was possible to simulate the seismic response of the embankment in the catastrophic scenario represented by the worst expected earthquake at the site. However, recent and important research contributed to establish the position and associated potential magnitude of the Campotosto fault. They indicate that the seismic scenario adopted by our analysis is precautionary, therefore our results are conservative.

Seismic assessments on the other dams and InSAR analysis of the slopes surrounding the reservoir were also carried out.

All these studies were concluded in 2020 showing good results and satisfactory safety factors, allowing Enel to set up again Campotosto reservoir to normal water levels.

1 CAMPOTOSTO LAKE AND DAMS

1.1 *The Campotosto Lake*

The Campotosto basin was the site of an ancient lake, used as a mine of peat for fuel since 1800s. Peat digging continued until 1924.

The reservoir for hydroelectric purpose was built in 2 phases. In the first one (1940-1951), it was subdivided in two parts, one contained by the Poggio Cancelli dam, the other barred by the Rio Fucino dam and Sella Pedicate dam, for a storage capacity of 153 million cubic meters and a maximum water level of 1310.50 m asl.

Figure 1. The Campotosto Reservoir, Dams and Hydro Power Plants.

Afterward (1964-1971), the dams were raised and the two reservoirs connected. The total capacity increased to 218 million m^3, with an accepted maximum water level of 1317.50 m asl.

The Campotosto lake is located in two regions, between the provinces of L'Aquila, Rieti and Teramo. It extends for 14 sq km within the Gran Sasso and Laga Mountains National Park. The reservoir is the uppermost basin of a complex system of Hydro Power Plants, with two Pumped Storage schemes (Figure 1). The lake is also used for water supply, irrigation, fishing and fish farming and tourism.

1.2 *The Dams - Main technical characteristics*

The Rio Fucino Dam (Figure *2*) is a 37 m high concrete gravity dam, with right abutment in stones. The dam has a straight planimetric course with a total crest length of 154 m. All the outlets of the reservoir are located here, with a typical morning glory spillway.

The Sella Pedicate Dam (Figure *2*) is a 21 m high concrete dam, with a 14 m high embankment dam in the left final part. The dam has a broken line planimetric trend, with a total crest length of 816,5 m.

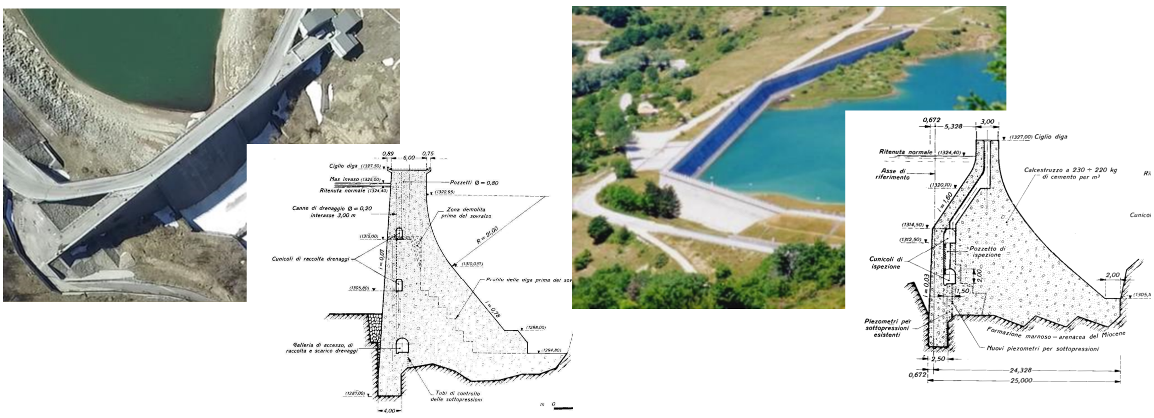

Figure *2.* Rio Fucino gravity dam (on the left) and Sella Pedicate gravity dam (on the right)

The Poggio Cancelli Dam (Figure 3) is a 27 m high embankment dam, with clay core and underlying concrete diaphragm wall. The dam has a straight planimetric course with a total crest length of 500 m. In the upstream part of the embankment, the old earthfill dam has been incorporated; the dam is equipped with transition zones and filters in a modern set-up, and a culvert for inspection and leak collection is located in the downstream nail. An accelerometer station is also installed at the toe of the dam, which has been in operation since 2009 and has recorded almost every earthquake that has occurred in recent years. More details about that were discussed in par. 4.1.

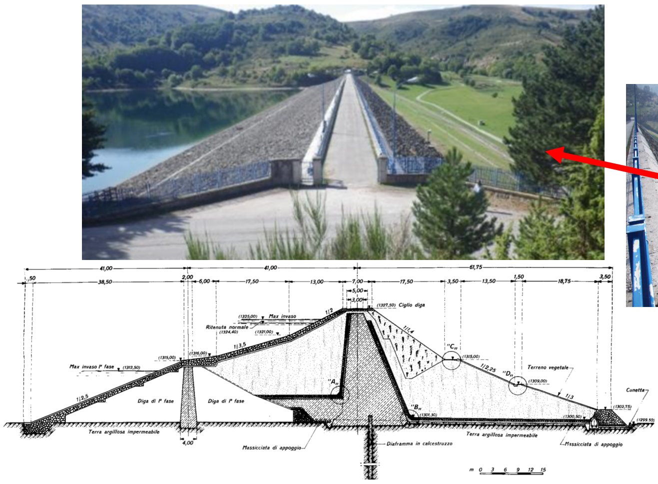

Figure 3. Poggio Cancelli embankment dam. The accelerometric station is shown on the right.

2 SISMOLOGY OF THE SITE

2.1 *Seismic Hazard and seismogenic faults*

In the last decade, central Italy was struck by devastating seismic sequences resulting in hundreds of casualties (i.e., 2009-L'Aquila moment magnitude [Mw] = 6.3, and 2016-2017 Amatrice-Visso-Norcia Mw max = 6.5). The Campotosto lake is located within a sector between the capable seismogenic sources (Paganica and Monte Vettore faults) of the described seismic sequences. This high-level hazard seismic zone was particularly activated in the last part of the 2016-2017 sequence (par. 2.2.). These seismogenic faults, historically connected to the Campotosto area, have long been debated by the scientific community and reviewed recently by an important research carried out by the University of Camerino, that has identified a linkage transfer zone in this Laga Mountains sector (Figure 4).

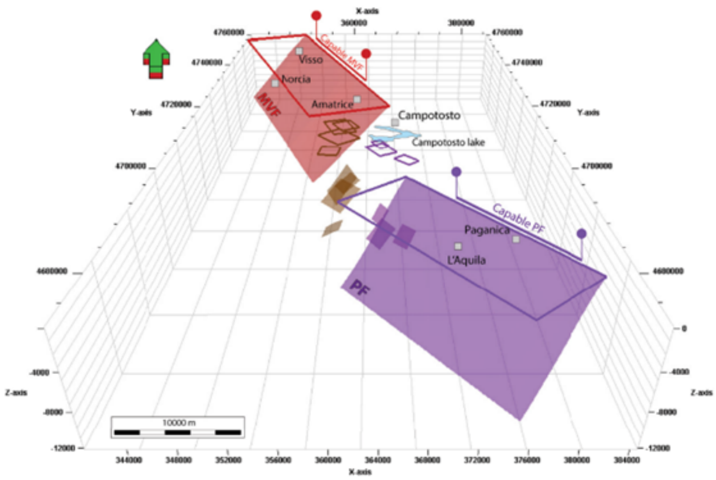

Figure 4. The linkage Campotosto seismogenetic source between two main seismogenetic ones associated to the 2009 "L'Aquila" and 2016-2017 "Central Italy" last seismic sequences (Tondi et alii, 2020).

The research was developed through a multidisciplinary approach combining paleoseismological shallow trench analysis, epicentral relocations of the whole 2017 seismic sequence, deep and shallow reflection and refraction seismic lines interpretation, geological and geomorphological surveys and finally seismogenetic deep model evaluations allowed to investigate about evidence of the fault activity, its deep geometry, its seismogenic potential and its exact position. Finally, the Mw of the fault was established in the order of M_w=6.0 and it was located at enough safety distance of the damage zone from the dams, according to the latest italian microzonation criteria.

2.2 *Seismic Sequence of 2016-2017*

Between August 2016 and January 2017, four major earthquakes occurred in Central Italy. The first event, with M6.0, took place on 24th August 2016, the second one (M5.9) on 26th October, the third one (M6.5) on 30th October 2016 and the fourth one (M5.5) on 18th January 2017.
As shown in Figure 5, this earthquake sequence occurred in a space gap between two earlier damaging events, the 1997 "Colfiorito" earthquake in the north-west and the 2009 M6.1 "L'Aquila" earthquake in the south-east, both of moment magnitude greater than 6.

These events took place along the NW-SE direction of the Apennine Chain with tensors corresponding to normal faulting focal mechanisms. Each of these events produced substantial damage to local towns and villages.

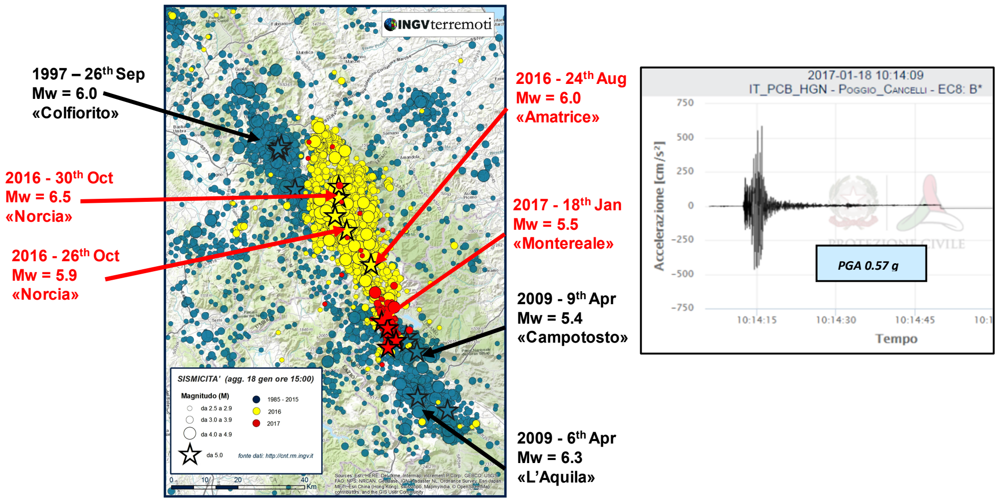

Figure 5. Seismic main events in the last 25 years in the interested area.

During these important seismic sequences, the dams didn't show any effects nor on the works and slopes, neither on the measurements. The only evidence of the action of the earthquakes was observed after the main shocks at Poggio Cancelli dam, with a centimetric settlement of the dam embankment body (Figure 6).

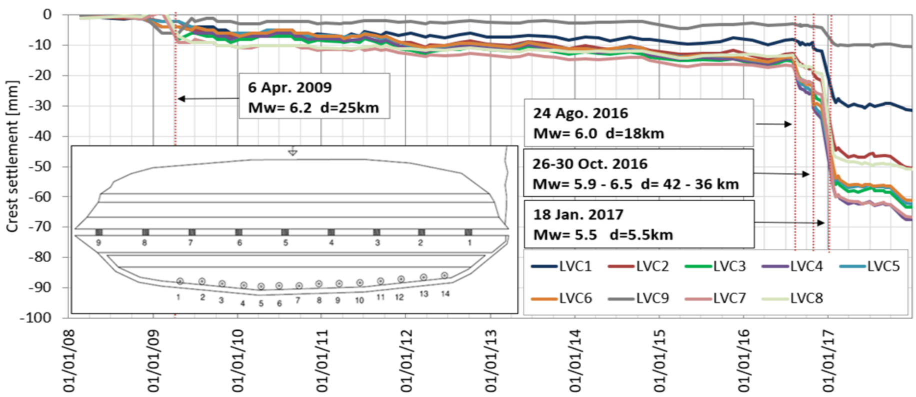

Figure 6. Displacements trends of the Poggio Cancelli embankment crest before and after the seismic sequences 2009 and 2016-2017.

No significant increase was observed in the seepages nor piezometric measurements, both in the dam body and foundation. As a precaution an immediately water level limitation has been applied to the basin and the frequency of measurements increased.

3 POST SEISMIC ACTIVITIES

3.1 *Seismic geotechnical investigation and monitoring upgrade*

Since the last seismic sequence Enel carried on an intensive geotechnical exploration activity on Campotosto dams focused to an upgrade of the structural, geotechnical and geomechanical parameters of dam bodies and foundations. In detail, more than 1250 m of boreholes were drilled, more than 500 m of geomechanical borehole televiewer surveys scanned, around 164 geotechnical in situ test executed, more than 290 samples subjected to lab soil, rocks and concrete tests and many kinds of geophysical in situ tests energized (Cross-hole, down-hole, seismic refraction lines, HVSR tests). More details about the in-depth Poggio Cancelli geotechnical exploration (Figure *8*) are in par. 4.1.

After the earthquakes, automatic monitoring systems were installed in several dams, in order to measure the most important static magnitudes in real time and remotely, as laser sensor to measure downstream-upstream displacement of the pendulum weirs, magnetostrictive level sensors for seepages and pressure sensors for uplift.

3.2 *Seismic Assessment*

By using the big data obtained from surveys, monitoring system and seismogenic review, all the dams were re-assessed through analysis that took into account the seismic aspects. As an exceptional precaution, Enel in agreement with Dam Authority adopted a seismic input with maximum magnitude associated at the unique fault (Mw = 6.7±0.3), despite the results of the Camerino University research indicating Mw = 6.0, as shown in par. 2.1. All the seismic assessments, carried out from 2019 and 2021, had positive results in terms of tensile stresses and expected displacements, even against the catastrophic scenario imposed by the Italian Law. Additional details about Poggio Cancelli Dam analysis are pointed out in Cap. 4.

3.3 *InSAR analysis*

Synthetic aperture radar interferometry (InSAR) is a remote sensing technique that can measure small (mm to decimeter) displacements of the earth surface. It is based on the principle of using two SAR scenes to form an interferogram with each pixel containing displacement information as difference of phase.

We used a modified small baseline approach (Hooper, 2008) to retrieve displacement information for pixels that maintain coherence during the analysis period. Interferograms associated to large temporal (> 6 months) and spatial baselines (> 100 m) were discarded to reduce noise contributions. This selection involves trying different interferogram networks and introduces some subjectivity. However, it helped significantly to improve the results.

We also used standard two-pass interferometry in order to maximize the territorial coverage of our results and verify the presence of interferometric signals possibly related to ground displacements. In this case, the quality of interferograms is crucial (Handwerger et a., 2013). Therefore, we privileged short duration, high-quality interferograms (Squarzoni et al., 2020) to detect possible movements of the slopes surrounding the reservoir.

Figure 7 reports the results of the standard (RAINS) and multi-temporal (MT-SBA) InSAR analysis for the reservoir and surrounding slopes. RAINS results are obtained by stacking selected, high-coherence interferograms covering the entire analysis period (October 2014 to April 2020). The value of each pixel corresponds to the mean displacement rate along the Line Of Sight (LOS) of the satellite, in descending geometry. The territorial coverage is good, except for densely vegetated areas associated to very low coherence values and, therefore, masked. Occasional displacement signals can be detected in single interferograms near the lake shores. Such signals appear periodically as the consequence of the reservoir level fluctuations, maintain a very limited areal extension and are likely associated to the presence of compressible soils. No interferometric displacement signals potentially associated with gravitational processes acting along the slopes surrounding the reservoir were detected.

MT-SBA results (Figure 7) show mean LOS-displacement rates (October 2014 to April 2020), for each stable reflector, by means of the color scale. The data appear slightly noisier than the

RAINS results, because of the higher sensitivity of the technique. However, they confirm that no significant deformation process has been acting along the slopes.

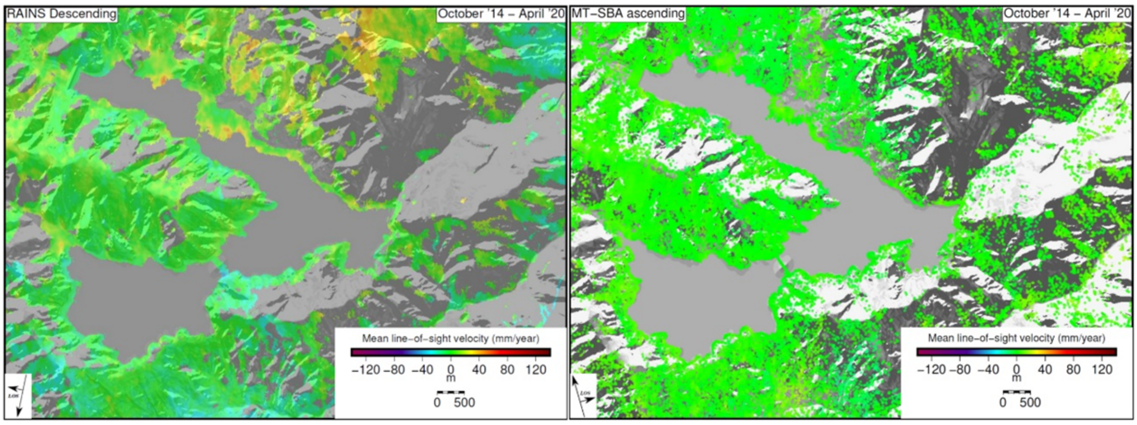

Figure 7. Results of the areal InSAR analysis for the entire analysis period (October 2014 to April 2020). The interferometric stack on the left shows the results of the standard two-pass interferometric analysis (RAINS) obtained for the descending geometry. The results of the multi-temporal analysis (MT-SBA) are shown on the right by means of stable reflectors obtained for the ascending geometry.

4 FOCUS ON POGGIO CANCELLI DAM

4.1 *Geotechnical characterization*

The geotechnical characterization was the result of four investigation campaigns conducted in 1997, 2009, 2017 and 2019. Exploration locations are shown in plan view in Figure *8*.

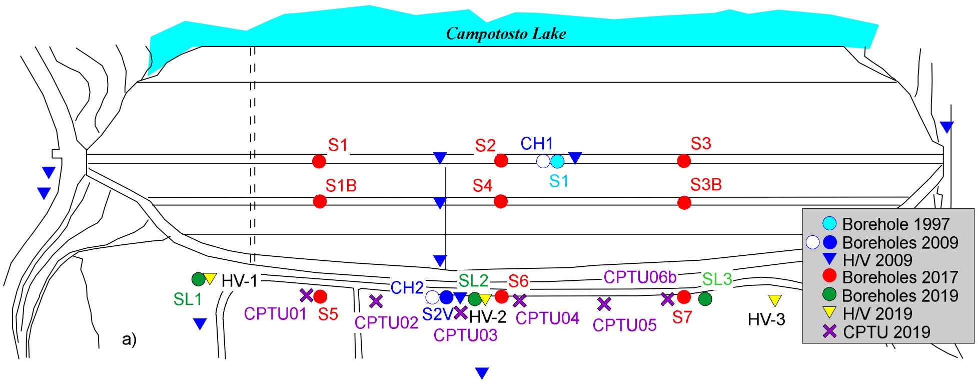

Figure 8 Plan view of Poggio Cancelli dam showing exploration locations.

Boring logs were performed through the dam and immediately downstream along the dam toe. Extensive field (SPT, CPTU, cross-hole, down-hole, ambient vibration measurements H/V, etc.) and laboratory testing (standard physical and mechanical tests, advanced cyclic simple shear tests) were used to develop a geotechnical model of the dam-foundation system. The latter campaigns (2017 and 2019) were essentially aimed at defining dynamic soil properties for the seismic assessment and liquefaction potential evaluation of the dam and foundation soils.

We can identify three layers of the alluvium deposit: an upper zone, which is a complex interlayered mix of silty sands and sandy silts with gravel and clay; a fine-grained intermediate zone, made of clayey silt, and a deeper zone, of similar characteristics of the upper one, resting above the seismic bedrock.

4.2 *Accelerometric recordings and back analysis*

A comparison was made between the spectra of the earthquakes recorded in 2009, 2016 and 2017 at the PCB station of the Italian national network installed at the toe of the dam and the UHRS spectra (uniform hazard response spectra) evaluated for Return Period (Tr) of 101 yrs (Damage Limit State, DLS) and Tr=475yrs. Since the probabilistic spectra refer to the rock site, in order to compare them with the spectra of the recorded signals, a local seismic response analysis (LSR) was performed using PSHAKE software. It is observed that the spectral ordinates calculated for the DLS earthquake agrees with those of the spectra of the signals recorded on 9 and 13 April 2009. Furthermore, the magnitude (M_w) and epicentral distance (R_{epi}) values of the two records (respectively M_W=5.4; D=7.7 km and M_W=5.0; D=7.4 km) agrees with the values evaluated with disaggregation for Tr=101yrs (Mw= 4.9±0.3;. D=10km). Therefore it is reasonable that the two seismic events of 9 and 13 April 2009 are compatible with earthquakes Tr=101yrs, (DLS), as shown in Figure 9. Confirmation is obtained from the analysis of the settlements recorded by the monitoring system which have shown maximum settlements of about 1.0 cm; these correspond with the values calculated numerically (see par 4.3).

The events recorded in January 2017 could instead be compatible with earthquakes having Tr=475yrs (Figure 1); the disaggregation analysis for this return period provides Mw-D equal to Mw=5.6±0.3 D= 10 km while the earthquake of 18 Jan 2017 has Mw=5.5 and D=5.5 km.

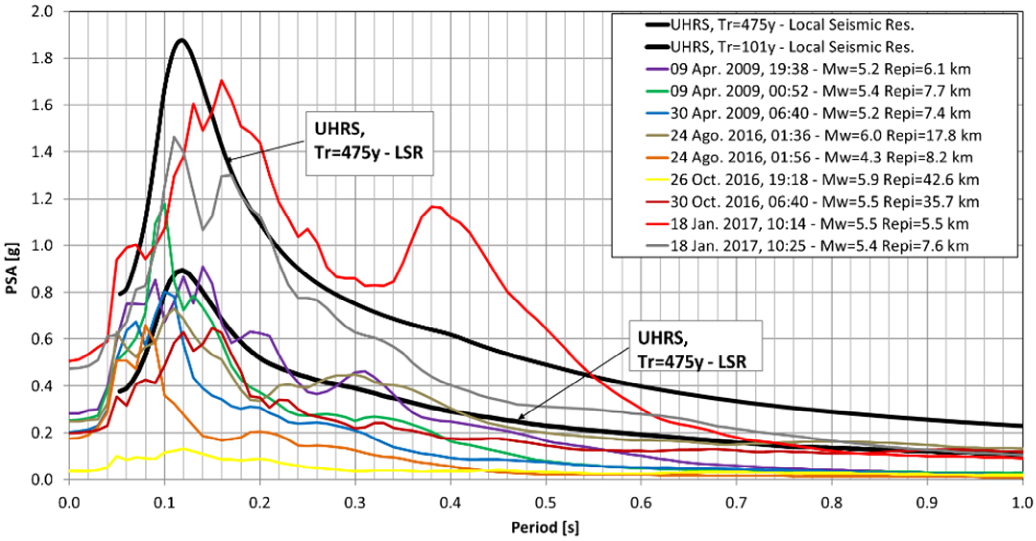

Figure 9: Response spectra of the accelerometric components (average between EW and NS directions) recorded at the PCB station and reference spectra calculated with LSR analysis (solid black line).

4.3 *InSAR Monitoring and back analysis*

The InSAR analysis of Poggio Cancelli dam was aimed at: i) extracting dense displacement information on the dam and ii) achieving accuracies comparable to those obtained by ground-based topographic instruments. To pursue these objectives, we designed a site-specific multi-temporal analysis which uses a reference area located at short distance from the dam and ad-hoc parameters for removing atmospheric and topographic noises. Interferograms (6 to 24 days) were selected on the base of their coherence in the vicinity of the dam. Since the dam is clearly visible, in terms of amplitude, in Sentinel SAR images, we adopted an innovative approach for the selection of stable reflectors which makes combined use of multi-temporal pixel coherence and phase amplitude.
Results are reported in Figure 10 showing the ascending and descending dataset are similar. While the dam abutments are stable (green colors), range-increase displacements (warm colors) indicate the settlement of the dam embankment. The labelled blue rectangles in the maps identify groups of reflectors whose averaged cumulative displacements are reported in the charts, as vertical components. They are shown in Figure 10 and reach maximum values of about 4.5 cm which compare well with ground-based topographic measurements (dashed lines in Figure 10).

The time-series of vertical displacement illustrate that the Poggio Cancelli dam was subject to a small settlement induced by the Amatrice earthquake of August 2016 which mainly affected the mid and southern portion of the embankment. The slow settlement continued during the following months with a total displacement not exceeding 10 mm through December 2016. Following the January 2017 Campotosto earthquake, the dam suffered a larger episode of settlement, again more intense in C3 to C6 areas where we measure 25 to 30 mm of settlement. Close to the dam abutments, the settlements are noticeably smaller, close to the detection limit of the MT-SBA technique. Our analysis does not detect noticeable displacements downstream of the dam.

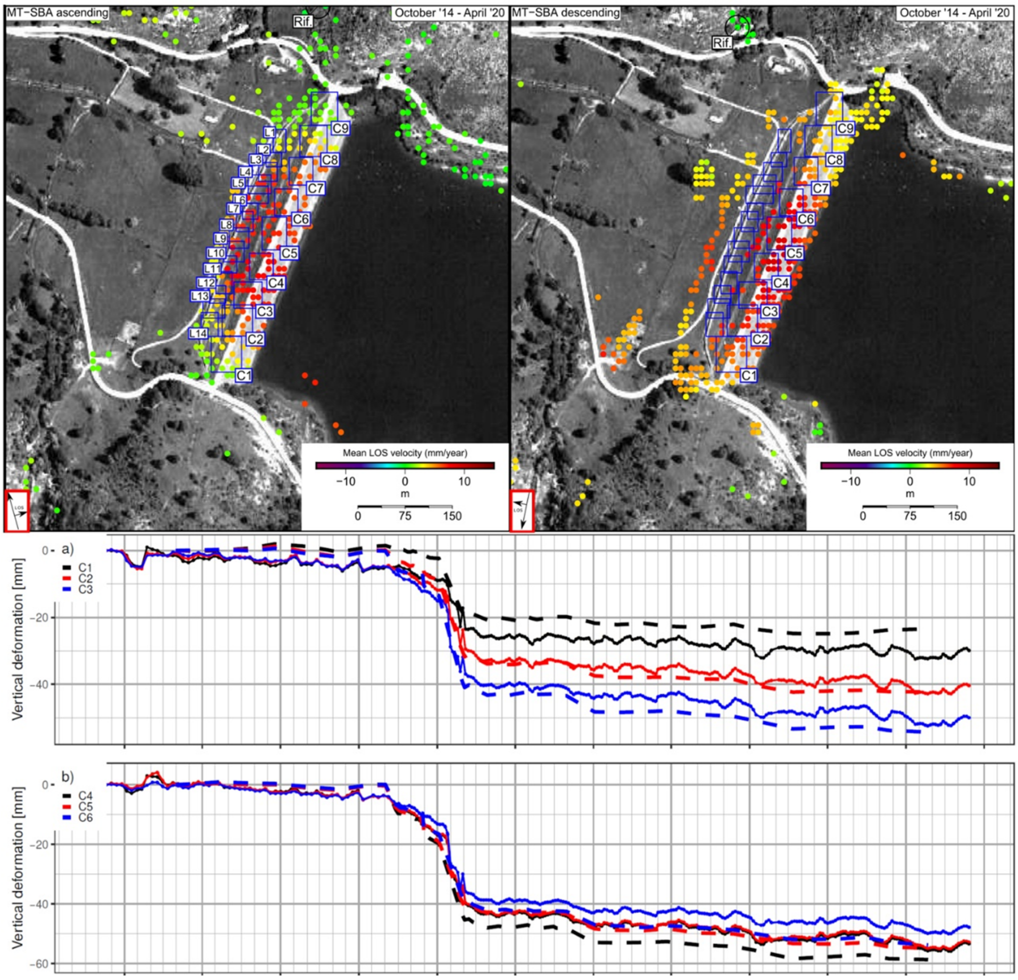

Figure 10. Results of the site-specific InSAR analysis of the Poggio Cancelli dam. The upper aerial photog raph reports the pixels corresponding to stable reflectors and their average displacement rates during the analysis period. The graphs report the cumulative vertical displacements (ground measurements vs. InSAR)

4.4 *Seismic assessment and back analysis*

The seismic assessment of the dam was first performed for the DLS (Tr=101yrs) in accordance with the Italian code for dams (D.M. 26/06/2014). A back analysis of the main seismic events in terms of calculated displacements vs. measurements was also carried out.

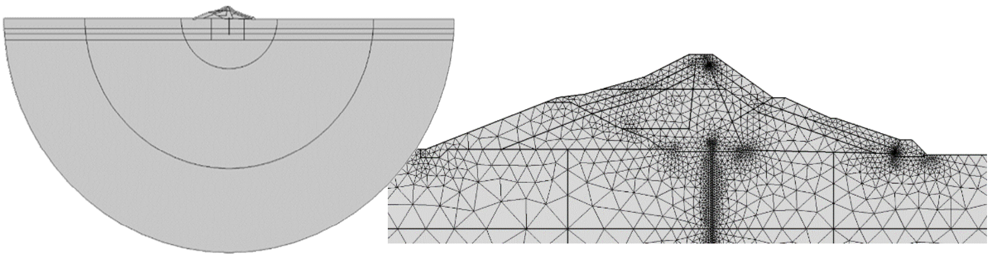

Figure 11. Geometric model and FEM

An explicitly dynamic analysis with the EF COMSOL Multiphysics software was carried out. The analysis was conducted via a decoupled approach, based on the independent evaluation of the seismic response and the expected permanent displacements (with Newmark method). The seismic response was evaluated on the highest central cross section ((Figure 11), using the linear-equivalent method; the foundation is provided with mass and equivalent viscous dampers on the contours. The damping effects were simulated with the Rayleigh method. The static and dynamic properties of the soils were evaluated from the results of the 1997, 2009 and 2017 surveys; in particular the dynamic properties were obtained from geophysical tests (cross-hole and down-hole) and from laboratory tests (resonant column) which allowed to define the normalized modulus reduction (G/G0- γ) and damping ratio (D- γ) curves, and the volumetric shear strain thresholds (γ_{tv}). The piezometric line was defined from monitoring data and steady state flow analysis. The dynamic calibration of the FE model was performed starting from vibration tests results.

Seven natural accelerograms selected and scaled to match the target spectrum (UHRS) were used. Accelerograms were evaluated with a probabilistic approach by adopting the parametric catalog of Italian earthquakes (CPTI15) and a new seismogenetic zonation evaluated by the National Institute of Oceanography and Applied Geophysics (OGS).

Maximum shear strains (average of the contours of 7 analyses) are maintained in the non-linear stable field. The maximum values in the foundation are γ_{max}=0.014% (in the fine-grained soil layer), and for the embankment γ_{max}=0.010% at the base of the central core. The values are always lower than those of the volumetric deformation γ_{tv}; therefore the development of excess pore water pressures that can affect the strength reserve of the structure is not expected. This is also confirmed by the absence of effects observed in the dam and in the foundation following the seismic events of 09 and 13 April 2009. The damping values vary from 1.5% to 6% (Figure 12). The average reduction of the first natural frequency is equal to 7%; the reductions of the shear modulus G_0 are equal to 20%. The maximum accelerations at the top vary between –4.5 m/s^2 (upstream) and 5.6 m/s^2 (downstream); the maximum amplifications at the crest reach 3.5.

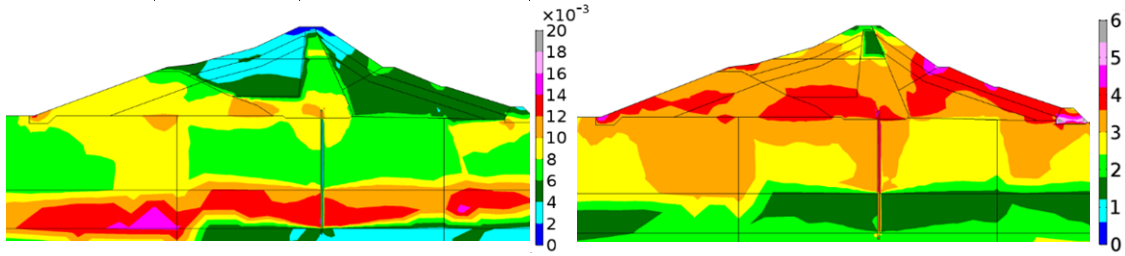

Figure 12. Contours of shear strain (left) and damping (right) - average of 7 earthquakes.

The irreversible displacements calculated with the Newmark method were evaluated from the acceleration histories obtained in the center of the potentially unstable masses. The maximum irreversible displacements occur on the downstream surfaces with maximum values less than 1.5 cm, in a very good agreement with the measurements after the 2009 main shock (Figure 6).

Furthermore, it's important to notice that this value of 1.5 cm (calculated for a DLS analysis) is less than 2017 main shock measurements, in a good agreement with the larger magnitude recorded by the accelerometric station and evaluated in term of spectrum associated to an event with a Return Period around 475yrs, as shown in Figure 9.

4.5 *Evaluation of liquefaction hazard*

As mentioned, the upper alluvium layer consists of chaotically distributed mixtures of silty sands and sandy silts. The first step in evaluating the liquefaction potential of this layer was to identify the "sand-like" versus the "clay-like" behavior. Data suggests that these soils can be largely split into two sub-units: the first predominantly sandy near the right abutment while the second, near the dam centerline and the left abutment, is mainly silty (FC> 35-40% and average plasticity index PI≅8). These latter soils fall into the category of "transition" (or "intermediate") soils.

Liquefaction susceptibility of transition soils was analyzed based on the results of monotonic triaxial and cyclic simple shear tests which provide indications of a primarily clay-like behavior.

Liquefaction potential of the sand-like portions of the alluvium was analyzed using CPT-based methods. A back analysis of liquefaction was performed along selected verticals at the dam toe during the seismic event of 2017, January 18 (Mw=5.5, R_{epi}=5.4 km). At the time of the earthquake, no evidence of liquefaction at the ground surface was observed. The CSR induced by the seismic event was determined by 1D ground response, total stress, equivalent linear analyses. For this purpose the seismic acceleration history recorded at PCB station was deconvoluted to obtain the bedrock motion. CSR was compared with the CRR calculated by the "standard" Boulanger and Idriss (2015) liquefaction triggering procedure. The effects of liquefaction were also calculated using integral parameters such as the Liquefaction Potential Index (LPI), the Liquefaction

Severity Number (LSN) and the post-earthquake reconsolidation settlements (S_{V1D}). Figure 13 illustrates the implementation of the procedure for the calculation of the FS_{liq} and the profiles of the integral parameters. The standard CPT-based method have resulted in liquefaction overprediction, with integral parameters corresponding to “moderate-to-high” liquefaction.

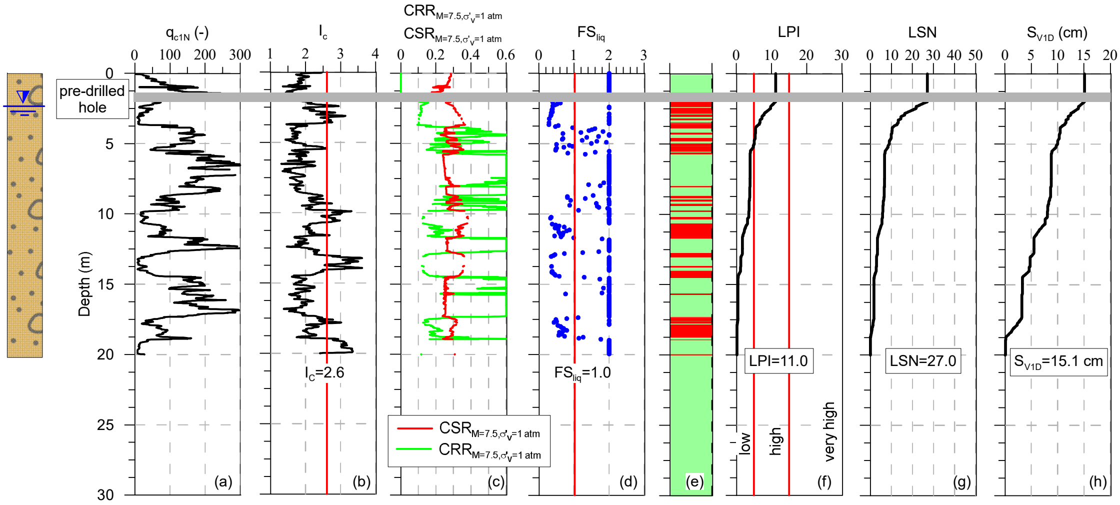

Figure 13. Results of the Idriss and Boulanger (2015) liquefaction procedure for estimation of safety factor against liquefaction (FS_{liq}) and integral parameters LPI, LSN and S_{V1D} (red bars indicate zones with FS_{liq}<1)

Therefore, back analysis was examined for the 2017 seismic event of 2017 by means of 1D effective stress analyses. To this aim, the DEEPSOIL (Hashash et al., 2017) and CYCLIC1D (Elgamal et al., 2002) codes were used. The calibration of the codes was carried out thanks to the cyclic strain-controlled tests. The numerical analyses allowed to estimate the liquefaction triggering through the calculation of the excess pore water pressure ratio (r_u) and the calculation of S_{V1D}. For all the investigated verticals both codes predict no liquefaction, as the results indicate maximum values of r_u below 0.4 and maximum reconsolidation settlements of about 3 cm. These numerical results are in fairly good agreement with observations.

Based on the above results, the occurrence of liquefaction was investigated for the MCE scenario earthquake (Mw=6.6, R_{epi}=10 km) using the 1D effective stress dynamic analyses. In this case large generation of pore water pressures ratios, ranging between 0.4 and 0.8, were calculated within the sandy deposits but liquefaction was not predicted. The post-earthquake reconsolidation settlements provided average values of the order of few tens of centimeters (10-30 cm).

5 CONCLUSIONS

Following the 2016-2017 Central Italy seismic sequence, Enel decided to lower Campotosto reservoir and carry out the re-assessment of the three dams (Rio Fucino, Sella Pedicate, Poggio Cancelli) that enclose it, maintaining the water level limitations meanwhile.

Detailed studies were developed for the Poggio Cancelli embankment dam: geotechnical surveys, geophysical in situ tests and “advanced” laboratory tests in order to define at best the foundation soil characteristics, thus reasonably excluding the liquefaction risk applying sophisticated methods of analysis. Moreover, InSAR analysis allowed to retrieve the displacement history of the sites and confirmed the topographic measurements taken before and after the earthquakes. Displacement data, together with the real accelerograms recorded at the dam toe were used for a back analysis of the settlements by means of a FEM model of the dam. With this validated model, it was possible to simulate the seismic response of the embankment in the catastrophic scenario represented by the worst expected earthquake at the site. However, recent and important research contributed to establish the position and associated potential magnitude of the Campotosto fault. They indicate that the seismic scenario adopted by our analysis is precautionary, therefore our results are conservative.

Seismic assessments on the other dams and InSAR analysis of the slopes surrounding the reservoir were also carried out. All these studies were concluded in 2020 showing good results and allowing Enel to set up again Campotosto reservoir to normal water levels.

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