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The 2016 October 30th earthquake effects on cultural heritage in Rome: The Necropoli Ostiense case study

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ABSTRACT: The 2016 October 30th Central Italy earthquake (Mw 6.5) was the largest event occurred in Italy after the 1980 Irpinia event. The epicenter was located near Norcia and the shaking was clearly felt all around Central Italy and even in Rome, despite the considerable distance. Highest damages were located in the southern area of the city centre: particularly the San Paolo basilica was closed to assess damages, after the opening of cracks and fall of cornice's pieces. Immediately after the earthquake, ISPRA experts were claimed to implement a damage assessment in the Necropoli Ostiense, located next to San Paolo basilica. The whole archaeological site was affected by a set of N-S trending parallel cracks induced by the earthquake. The relationship between Necropoli and the neighboring Tiber's valley has been also investigated. Active and passive seismic surveys, as well as a GPR surveys, helped in clarifying the local stratigraphic setting and its influence on local effects.

1 INTRODUCTION

The Mw=6.5 earthquake, occurred on 30th October 2016 in Central Italy at the boundaries among Lazio, Marche, Abruzzo and Umbria regions, has been the major seismic event of a ~ 6 months-long seismic sequence starting on 24th August 2016 at 2.44 a.m. The first main shock (Ml=6.0; Mw=6.2), with epicenter near Accumoli village and focal depth of about 8 km, caused more than 300 casualties and very large damage in Amatrice and surrounding villages (MCS epicentral intensity = X, with peaks of X-XI; Galli et al., 2016). It produced strong damage (intensity > VIII) in an area of about 100 km^2 and it was clearly felt even in Rome, but did not produce significant damage to buildings in the city. During the following weeks, the seismic sequence was characterized by thousands of aftershocks, including more than ten events with M>4, that culminated with three major shocks occurred at the end of October. In particular, two strong events occurred on 26th October (Mw= 5.4 and 6.1) with epicenter located near Visso, causing additional damage especially in the northern sector. This event was followed by the abovementioned 30th October event (see next for details). In the subsequent months the seismic sequence was progressively attenuating in terms of frequency and magnitude. However, a new peak of the seismic sequence was recorded on 17th January with four shocks (5.1 < Mw < 5.5). Concerning specifically the 30th October event (Mw=6.5), it occurred at 7:40 a.m. with hypocenter 9 km deep and epicenter near Norcia. It did not cause additional casualties since it was not unexpected, like the 24th August event. Nevertheless, it had a disruptive impact affecting a very large area (MCS intensities > VIII in an area larger than 400 km^2), causing the collapse of several buildings that were able to resist to the previous shocks (e.g. the San Benedetto Church in Norcia). The final damage scenario resulted in 36 villages with intensity > 9 MCS, 29 of which suffered an intensity > 10 MCS, and 5 reached intensity = 11 MCS (Galli et al., 2017). The different impact of the two major shocks is clearly recorded also in the landscape, in terms of surface faulting extent: in fact, evidence of 24th August surface faulting was found only in the Vettoretto – Cordone del Vettore area, for an end-to-end rupture length of at least 4.5 km and surface displacement up to 25 cm. Instead, the 30th October event caused the surface reactivation of the entire Vettore-Bove Mt. fault system, from Arquata del Tronto to Ussita for an end-to-end rupture length of about 28 km and maximum surface displacements up to 2 m (see Figure 1).

The 30th October event was clearly felt in Rome at a linear distance of about 130 km, causing several local damages, especially to historical buildings, and threatening the stability of some infrastructures. Every district of the city was shaken, so that in a few hours more than 185 surveys were conducted with the aim to verify fissures and cracks on both historic and modern buildings. Strongest damages were located in the southern area of the city centre: in particular, the San Paolo basilica was closed to assess damages, after the opening of cracks and fall of cornice's pieces. Similar damages were also observed at Porta Portese gate, Sant'Ivo alla Sapienza church and San Lorenzo and Santa Maria Maggiore basilicas. Since long time ISPRA cooperates with archaeological *superintendences* in the field of protection and conservation of Cultural Heritage against geo-hazards. Thus immediately after the earthquake, ISPRA experts were claimed to implement a damage assessment in one of the most affected site: the Necropoli Ostiense, located next to the San Paolo basilica (Figure 2).

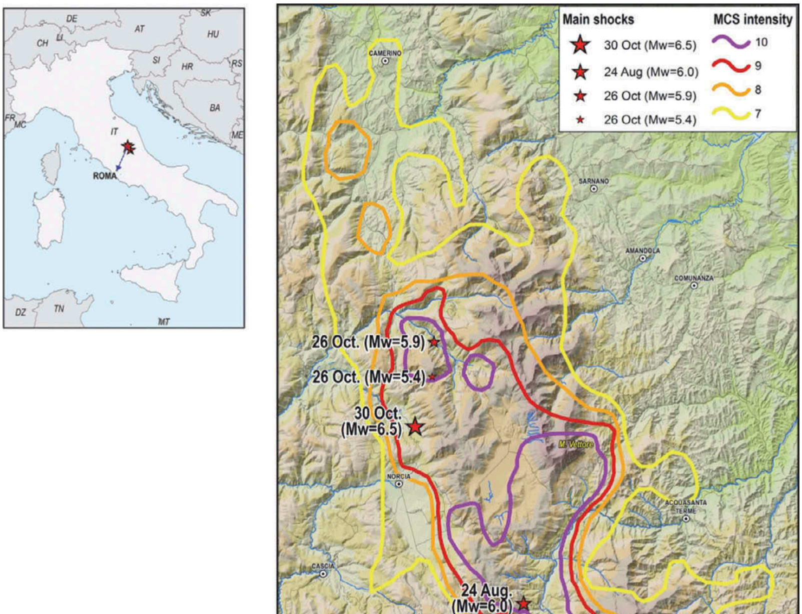

Figure 1. - MCS intensity map for the 2016 Oct. 30 earthquake. Red stars locate the epicenters of major shocks characterizing the seismic sequence

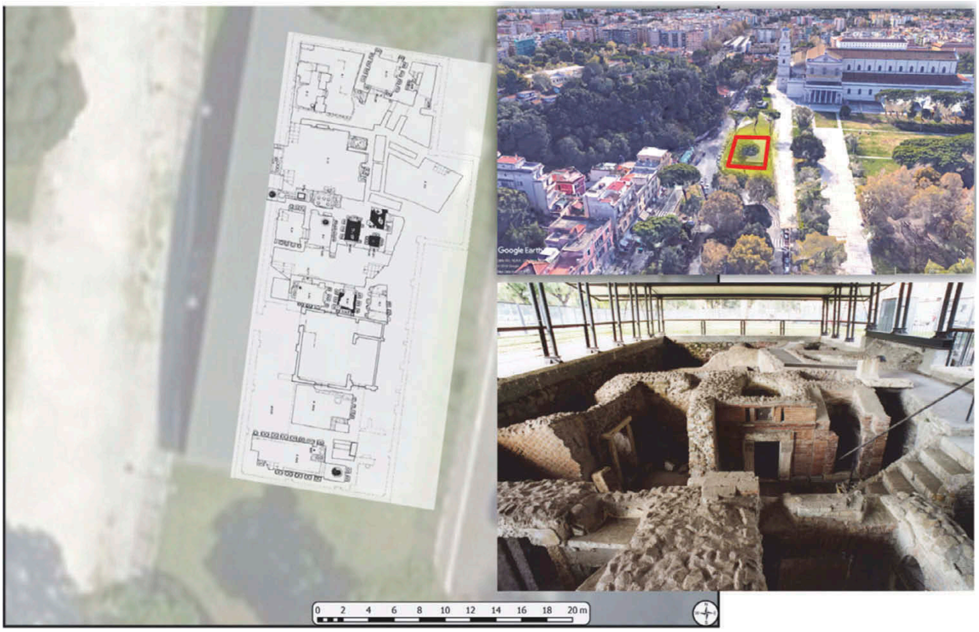

Figure 2. General view of the Necropoli area affected by the 30Th October earthquake.

2 ARCHAEOLOGICAL AND GEOLOGICAL SETTING OF THE INVESTIGATED AREA

2.1 *The Necropoli Ostiense archeological site*

The archaeological site of the cemetery along the Via Ostiensis is the best-preserved part of a vast necropolis, flanking the eastern side of the ancient via Ostiensis, that led from Rome to Ostia, covering a distance of 18 miles. The road originated from the Porta Trigemina of the Servian wall, by the Aventine Hill, and in the 3rd century AD, crossed the Aurelian walls under Porta Ostiensis (today called Porta San Paolo). Via Ostiensis was bordered by an intensive cemetery, consistent remains of which are still visible near San Paolo basilica.

According to tradition and archaeological data, the apostle Paul was buried in one of these graves and, in the 4th century, the first Christian basilica was built above it. Some aristocratic monumental tombs grew up along the road, like the Pyramid of Caius Cestius and the mausoleum of the Gens Claudia. Several tombs were discovered by chance during the 18th and 19th centuries, but the greatest sector came to light in 1898 AD, during the excavation of a new sewer channel, testifying the large uninterrupted extension all along the road. The currently visible sector was exposed during road works in 1917 (Figure 2).

At the end of the 1917 survey, directed by Giuseppe Lugli, a small part of the funerary area was restored and opened to the public. A general restoration work was made for the 2000 Jubilee. The tomb monuments, following the north-south orientation of the Via Ostiensis, were used continuously since the 1st century BCE until 4th century CE, highlighting the switch in burial custom from cremation to inhumation. The most common typology is a small familiar building ("columbarium" type) with no more than 30–40 urns; nice paintings with natural and mythological elements decorate the walls and pavements are usually in black white mosaic. In many cases, when all the niches were full, new spaces for urns were obtained under and over the pavement. Tombs' typology and the articulation of the

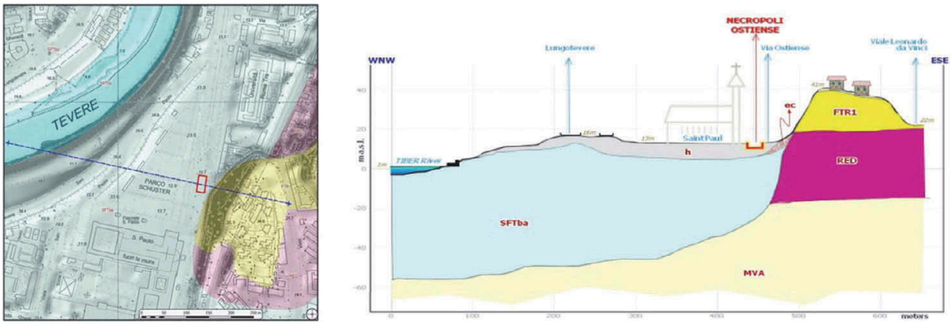

Figure 3. Geological map and section of the investigated area.

cemetery are comparable to those of the Via Triumphalis, Portus and Ostia. Then, after the 2nd century, inhumation burials sunk directly in the earth or cut the floors and the walls of the previous buildings. New types of inhumation tombs – so-called "ad arcosolium" and "formae" - spread.

2.2 *Geological setting*

The Necropoli Ostiense is located in the alluvial plain of Tiber river and it lays at the foot of a 20 meters high cliff, made with pyroclastic deposits. The archaeological site, built next to the ancient Via Ostiense, nowadays lies about 3 meters below the ground level (12.7 meters a.s.l.). The flood plain is made of an about 50 meters thick fining-upward succession of alluvial sand and clay, from the postglacial (Holocene) continental filling of the ancient Tiber River valley ("SFTba" in Figure 3 map). The hill's cliff is cut in a thick-layered volcanoclastic unit (*Conglomerato Giallo*., "FTR1", about 20 m thick always in Figure 3 map) laying over a massive pyroclastic unit (*Pozzolane Rosse*, about 35 m thick). Both volcanic units are Middle Pleistocene in age. Alluvial and pyroclastic deposits lay over a Pliocene bedrock made of marine sand and overconsolidated clay (Monte Vaticano Unit, "MVa" in Figure 3 map). While the alluvial plain fills an ancient 60 meters deep valley excavated by the Tiber during last glaciation, the volcanic hill covered an ancient preexisting highland, which top is now at about 20 meters below actual sea level. At the foothill is preserved a debris deposit ("ec" in Figure 3 section), spanning from blocks to sand, highly weathered to soil. Flat areas are covered by an irregular layer of made ground ("h" in Figure 3 section), that is thin at the top of the hill, but thick up to 10 meters in the plain, due to the anthropogenic settlement.

3 MONITORING SYSTEM IMPLEMENTATION AND GEOPHYSICAL SURVEY

3.1 *Crack gauges manual monitoring system*

After a preliminary survey (November 2016), according to the above evidences and to the original hypothesis that the observed crack pattern are co-seismic effects induced by the 30 October seismic shaking, a simple manual crack gauge network on 5 main discontinuities was implemented and installed (Figure 4). The monitoring system was designed and installed since June 2018. The first three lectures (including the zero lecture) provide a general stability of the whole structure: none fracture seems active so far; however at least one year will be necessary in order to exclude the impact of seasonal effects affecting the structure. The general stability of the cracks seems to confirm the hypothesis of a single shock due to the earthquake's dynamic input.

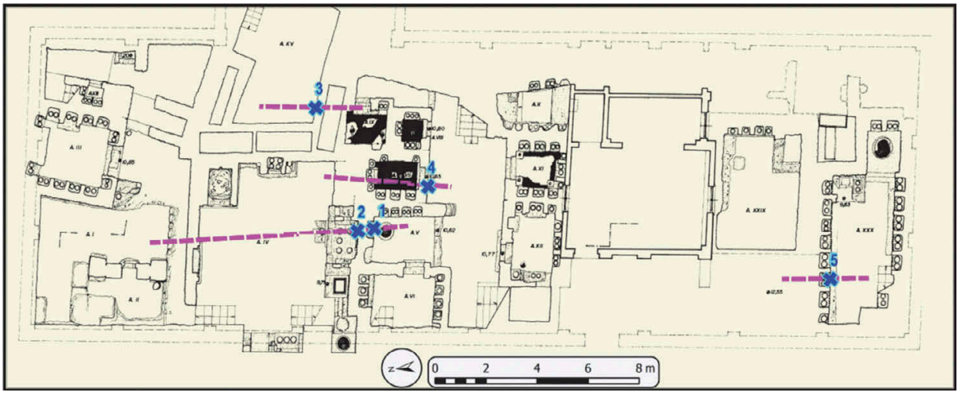

Figure 4. Manual crack gauge monitoring system location (blue) and fractures pattern (pink).

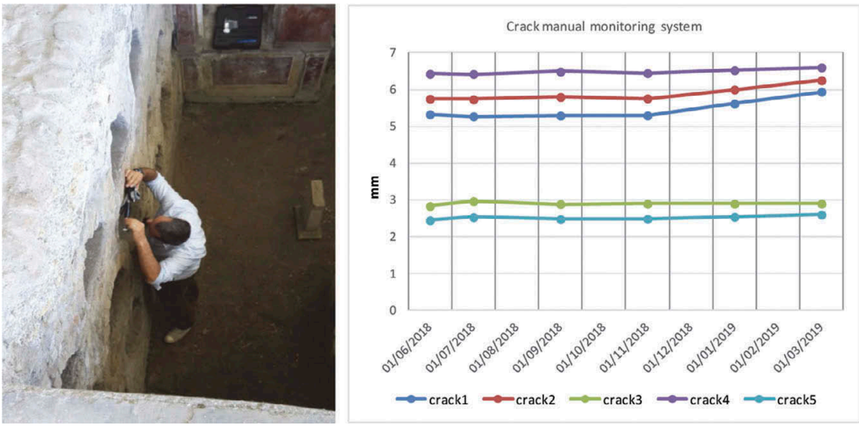

Figure 5. Plot of the manual monitoring and first measurements.

3.2 *Geophysical survey*

In order to verify geological and stratigraphic effects, an active seismic survey was carried out in the archaeological site, by using the surface-waves method (Spizzichino et al.2012), aimed at the characterization of alluvial deposits in terms of shear waves velocity (Vs), that is a parameter directly related to stiffness of buried materials. For the data acquisition, a MSOR multi-channel simulation with one receiver was implemented (e.g. in Lin & Ashlock, 2016) using the Moho 3C velocimeter Tromino (http://moho.world/) and 19 shot points, with a 2.5m spacing, along a straight profile. The surface waves were produced by vertically striking an instrumented 8kg sledgehammer on a metal plate coupled to the ground and adopting a minimum offset of 5 meters. To better constrain the shear-wave velocity model in depth, a 30 minutes recording of ambient vibrations was performed, using the same velocimeter, in order to retrieve the corresponding HVSR curve (Nakamura 1989). Surface waves dispersion was analyzed by using the winMASW® software by Eliosoft (http://www.winmasw.com/) and the phase velocity spectrum was inverted jointly with the HVSR curve (Figure 6).

The inversion routine implemented in the software is based on a multi-objective evolutionary algorithm that exploit a Pareto-based ranking system to identity the fittest models and proceed with the optimization procedure (e.g. Dal Moro, 2014; Dal Moro & Pipan, 2007; Dal Moro & Ferigo, 2011). Data interpretation was accomplished following

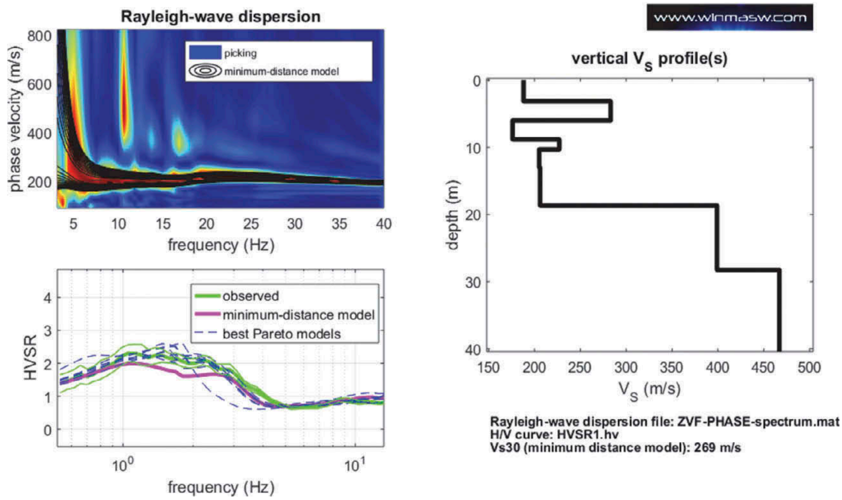

Figure 6. Results of the joint inversion of dispersion and HVSR data.

the FVS-Full Velocity Spectrum approach (Dal Moro, 2014) avoiding possible interpretative issues linked to the interpretation of velocity spectrum in terms of modal curves. Figure 6 shows the results of the geotechnical characterization in terms of the vertical shear waves (Vs) profile. The HVSR curve used to constrain the shear-wave velocity values for the deepest layers shows a very broad frequency range of possible amplification, with a peak around 1 Hz. This value was confirmed by a second test performed just few tens of meters apart from the Necropoli site. Furthermore, in terms of Vs values, the presence of a velocity inversion within the first 5–7m in depth is clearly worth of attention, since the anthropogenic layer thickness is of about 4–5 meters and therefore further investigations will be needed to clarify the 2D geotechnical setting of the area. Below 7 meters in depth the Vs values are very low, not exceeding 210 m/s up to about 20 meters in depth where they reached 400 m/s. The Vs values retrieved seem to be reliable for characterizing the Tiber alluvial sequence in this sector since they are in good agreement with those obtained by Bozzano et al. (2008) by means of a DH test located few hundreds of meters far from the Necropoli, closer to the Tiber river course. In order to further investigate the subsoil close to the Necropoli Ostiense site, a total of 7 GPR ground probing radar profiles were also performed during October 2018, using a MALA 100 MHz shielded antenna and their processing and interpretation is still ongoing.

4 CONCLUSION, REMARKS AND FUTURE INVESTIGATION

The 2016 October 30th central Italy earthquake affected even Rome's Cultural Heritage. Damage was recorded at the basilicas of San Paolo, San Lorenzo and Santa Maria Maggiore, the Porta Portese gate and Sant'Ivo alla Sapienza church. The present study summarize the analysis carried out in the Necropoli Ostiense archaeological site, following the *Soprintendenza di Roma* request of support. The whole area has been indeed affected by a set of fractures, thus the site was investigated from geological, geomorphologic and geophysical point of view in order to verify the presence and amount of co-seismic site effects. Aiming at understanding trend, type and triggering mechanism of the damage a simple manual monitoring system has been implemented, but any active deformation was detected during the first months. Moreover a geophysical survey pointed out that the Vs values retrieved seem to be reliable for characterizing the Tiber alluvial sequence in this sector. In fact obtained measures are in good agreement with previous investigations at short distance from the studied site (Bozzano et al, 2008). Further investigations will be addressed to the definition of a 2D subsoil model for the whole archeological site, possibly by means of direct shallow investigations, at least within 10–15 meters, where a remarkable difference in stiffness between anthropogenic layer and the underlying alluvial deposits has been detected. While these latter are mainly silty and clayey, the former is mostly heterometric, eventually mixed to coarse debris coming from the cliff, therefore a non negligible difference in terms of dynamic behavior between them can be hypothesized yet at this preliminary stage. It must be also underlined that a Vs inversion occurs at the same depth of the bottom of the Roman age anthropogenic layer, likely as a consequences of the reclamation works necessary for the construction and the subsequent use of the Necropolis during Roman age. The proximity of the city to the Tiber river, as potential concentration channel for the waves propagation, and the peculiar geological settings seem to have played an important role for the site effects along the Necropoli. Further geophysical surveys will allow to better define the interaction between archeological structures and underground setting. These actions are needed to characterize the impact of strong earthquakes from Central Apennines on cultural heritage in Roma in order to identify proper mitigation measures.

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