Geotechnical Engineering for the Preservation of Monuments and Historic Sites III – Lancellotta, Viggiani, Flora, de Silva & Mele (Eds)

Cultural Heritage sites conservation and management: The case of the Circus Maximus in Rome

L.M. Puzzilli, G. Delmonaco, F. Traversa, V. Ruscito, F. Ferri, E. Mariani & C. Quadrozzi
Department of Geological Survey of Italy, Italian Institute for Environmental Protection and Research, Rome, Italy

P. Clemente, G. Bongiovanni & V. Verrubbi
Casaccia Research Centre, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Rome, Italy

M. Buonfiglio & F.M. Rossi
Superintendency of Cultural Heritage of Rome, Rome, Italy

ABSTRACT: The Circus Maximus in Rome (Italy) is the most famous ancient Roman chariot-racing circus, built along the alluvial valley between Palatine and Aventine hills, in the hearth of the historical city centre. Thanks to its exceptional size, it still represents the largest structure ever built in the history for entertainment. As soon as the Roman empire fell, the area suffered spoilation and disuse, changing the original use several times through the centuries. Starting from 2009, the site has been involved into a restoration and conservation project which includes multidisciplinary studies based on geophysical surveys, geotechnical investigations and instrumental monitoring of potentially vulnerable structures. The present experimental campaign, based on additional geophysical surveys, boreholes and geotechnical tests, will produce a systematic and detailed analysis of the underground conditions of the Circus Maximus area. The new findings will be used to support policies for a sustainable use of the area.

1 INTRODUCTION

Rome is a unique city in the world that can boast such a high number of cultural heritage and archaeological sites located in the heart of its historical area. A significant part of this heritage is certainly represented by the remains belonging to the Roman Age, some of which with imposing size (e.g. Colosseum, Pantheon, Basilica of Maxentius) and/or large extension (e.g. Palatine Hill, Caracalla Baths, Roman Forum and Circus Maximus) that caused the city to develop around them over the centuries and incorporated them into the present urban fabric. The Circus Maximus, a structure intended to host chariot races and religious celebrations, played a significant role for the life of Roman citizens up to the end of the Roman Era. Built along a small tributary valley of the Tiber River called "Murcia", between Palatine and Aventine hills (Figure 1), when fully developed, the Circus Maximus became a "model" throughout the Roman Empire for such kind of structures created for mass events. Unfortunately, an almost-complete burial of the entire monumental area took place already a few centuries after its abandonment and this had hampered its effective knowledge till today. Not surprisingly, to date, some considerations about its architectures as well as the spatial relationships between its architectonic elements (e.g. dimensions of the track and the middle barrier called "Euripus", position of holy temples etc.) are inferred based on studies

 DOI 10.1201/9781003308867-40

Figure 1. Location of the Circus Maximus area in Rome (Italy) between the Palatine and Aventine Hills. The study area is enclosed in the dotted rectangle and includes the Archaeological Park Area (A), freely accessible for entertainment and social events, and the Archeological Area (B) with limited access (satellite image available at http://www.pcn.minambiente.it/ mattm/servizio-wms/, accessed on 25 September 2021).

in Roman circuses outside of Italy. Today, this monumental area is separated into two distinct sectors: the Park and the Archaeological Area (Figure 1). The Park occupies about two-third of the site extension and is granted for use of social events; this area contains most of the archaeological heritage buried in the subsoil. The Archaeological Area is separated and protected with a fence and includes Roman and medieval remains that can be visited by the public. The site is under the supervision and protection of the Superintendency of Cultural Heritage for the City of Rome; nevertheless, it maintains its character as a recreational and cultural area for many citizens and tourists who also enjoy the Park daily. The Park also hosts yearly many social events ranging from pop-music and opera concerts to sport celebrations and cultural exhibition, often with a very large audience. Just to give examples, in 2007 the English band Genesis performed a concert before hundreds of thousands of people (https://www.bbc.co.uk/programmes/b00bbxxv) while in 2014 the Rolling Stones played in front of about 71,500 fans. Also, sport celebrations were hosted as in 2001 after the A.S. Roma victory of the Football Italian championship and few years later after the Italian victory of the 2006 Football World Cup. Since May 2019, just within the Archaeological Area, a new virtual and augmented reality experience, the "Circo Maximo Experience", has been opened, taking visitors on a journey through the site and its history. The Circus Maximus represents an example of cultural heritage site prone to anthropic and environmental stress that needs policies for a rational and sustainable use to be adopted; this implies an adequate detail of knowledge as a fundamental base to address mitigation actions for its maintenance and preservation. Starting from 2009, the Superintendency of Cultural Heritage of Rome coordinated multidisciplinary studies primarily aimed at providing a more exhaustive knowledge and revealing the uses of this site throughout the centuries. To support this ambitious project, a series of scientific activities have been carried out, including geophysical surveys, geotechnical investigations, instrumental monitoring of some structures during social events. In this paper, the main archeological features and the geological setting of the site are first introduced, then the ongoing multidisciplinary experimental campaign is described. The field investigations are based on geophysical surveys (concluded at the end of October 2021), boreholes and geotechnical tests. Some preliminary outcomes are eventually described and briefly discussed, along with the main results of the vibration monitoring campaign performed in 2019 during a concert attended by 40,000 people in the park area.

2 ARCHAEOLOGICAL CONTEXT

The Circus Maximus was the first and largest building dedicated to the Roman "ludi", the public games connected to Roman's religious festivals. The Romans built a structure of a truly exceptional size: this large oval-shaped hippodrome could accommodate about 220,000 spectators in its fully developed form (about 600 m long and 140 m wide) becoming a model all over the Roman Empire. The present archaeological knowledge of this area is mainly due to researchs studies started at the beginning of last century by Bigot (Bigot 1908) and continued till present days by many institutions and researchers throughout excavations, drillings campaign and, more recently, using geophysical methods (e.g. Brandizzi Vittucci 1991; Buonfiglio 2018; Canciani et al. 2013; Carpentieri et al. 2015; Ciancio Rossetto 2002; Ciancio Rossetto & Buonfiglio 2007; Mancini et al. 2018; Marra et al. 2016, 2018, 2021; Pietrangeli 1940). The first masonry works were made under Caesar and after numerous vicissitudes (fires and restorations) the Circus was rebuilt and enlarged under the Emperors Domitian and Trajan, remaining active as such until the 549 B.C when the Ostrogoth king Totila organized the last games. After the 6th century, the area has fallen into progressive disuse suffering spoliation and becoming a quarry for building materials. The lower levels became again prone to flooding and were gradually buried under alluvial soil and accumulated debris so that the original track is now buried up to 10 meters beneath the present surface. Throughout the centuries, the intended use changed many times: agricultural area (in Middle Ages), Jewish cemetery (17th century), district of industrial settlements (19th–20th century). At the end of 1800s, this area became a target for industrial purposes: a gasometer was installed here and, in turn, warehouses, factories, cottage industries, even houses were established here. In the middle of the Fascist era, however, the area was used by the regime for trade fairs and exhibitions such as the Textiles Show (1934) and the Exhibition of Italian Autarkic Mineral (1939) and converted into a park, in the shape of the original form of the Circus. Finally, by the mid-20th century, to institute the Circus Maximum Monumental Area protecting the remains, the valley floor was freed from preexisting industrial buildings; massive excavations were also carried out, mainly concentrated in the south-eastern sector. The works uncovered the lower parts of a seating tier and outer "portico" and subsequent excavations exposed further sections of the seating and hemicycle. Those can be admired today along with the medieval structure called "Torre della Moletta", a square tower with battlements erected by the Frangipane family. In 1998, archeological excavations took place through large diameter wells (2 m) in correspondence with the present central barrier where some remains of Roman age were previously logged by one drilling. These investigations have reconstructed the detailed sequence of the archeological layers as well as the analysis of the remains of different ages included therein (Ciancio Rossetto 2002), extending the observations up to the depths corresponding to the Circus track. It was possible, for the very first time, to visually inspect the skeleton of the "euripo" and determine that in-place Roman remains pertaining to this structure could be found in the Park area within a depth ranging between 8 ÷ 11 m (i.e. corresponding to 10.5 ÷ 7.5 m a.s.l.). Two different anthropic layers progressively embedding the remains were also classified according to the different age of the remains; the most superficial, related to modern era, has a maximum thickness of about 4 meters along the whole area (14.5 ÷ 18.5 m a.s.l.).

3 GEOLOGICAL SETTING OF THE STUDY AREA

From a geological point of view, the "Murcia" valley is carved into the Plio-Pleistocene clays known as "Mount Vaticano" Formation (Funiciello & Giordano 2008), hundreds of meters thick, that represents the geological bedrock of the whole area of Rome. According to recent studies (Marra et al. 2021), during Middle-Late Pleistocene and Holocene the sedimentary processes over the whole Rome area were strongly controlled by sea-level changes related to glacio-eustatism. This strongly influenced the sedimentary processes that led to the progressive infilling of all the Tiber River tributary valley by a fining-upward sequence: from fine gravels with intercalations of clay at the bottom to silty clay and organic and peaty clay on top, closed by a heterogeneous anthropogenic layer (historical backfilling). While during the Roman Ages the entire valley was transformed into the largest monument of antiquity ever built, after the fall of the Roman Empire this area suffered the abandon, experienced frequent floods and finally become a swamp. Waterlogged sediments belonging to this period were interposed by progressively increasing volumes of anthropic backfilling, accumulated during almost two-thousand years of human activities, including the complete urbanization and occupation with industrial plants at the beginning of 1900s. Stratigraphic and hydrogeological data have been derived from the current research activities during which the available information referred to the subsoil (scientific reports, studies, publications, archeological report and drawings, borehole logs etc.) have been collected, reviewed and georeferenced in a geodatabase referred to the whole monumental area.

3.1 *Stratigraphic setting*

The first investigation campaign took place here in 1939 through the drilling of a 1,330 meters deep borehole by Azienda Generale Italiana Petroli (AGIP), aimed at the improvement of the geological knowledge of the entire Rome subsoil. However, it also provided the first information about the infilling of the valley. More detailed investigations were carried out only in the early 1980's by means of 16 deep boreholes (up to 62 m in depth) commissioned by the Rome's Superintendency of Cultural Heritage (Geosonda 1983). This investigation reconstructed the geological and hydrogeological setting at site scale and was aimed at supporting the archaeological surveys performed few years later (see e.g. Ciancio Rossetto & Buonfiglio 2007). Additional investigations, consisting in shallow boreholes and in-situ tests were also performed in 2003 and 2005 in the surrounding of the medieval remains (i.e. at the south-eastern end and close to the "Torre della Moletta") thus providing geotechnical parameters of the soils. In Figure 2a the locations of the available boreholes in the area are shown; the stratigraphic setting referred to two main sections crossing the archeological site are depicted in Figure 2b and 2c. The surface layer is represented by a heterogeneous and poorly graded deposit, from sandy gravel to gravelly silty sand to clayey silt, often brown color, stiff to very stiff, containing in some cases potteries and even fragments of concrete. It mostly consists in anthropic backfills and waterlogged deposits accumulated here during almost 1,500 years of human activities, including the complete urbanization and occupation with industrial plants at the beginning of 1900s, with an overall thickness of 10 m and rather continuous along the whole site. Deeper, a very thick geological body made of fluvial and fluvial-marshy environments deposits follows. It consists of clays, silts and clayey silts, from dark brown to dark grey and grey, soft to very soft, generally containing abundant organic matter (with peat levels). These alluvial deposits,

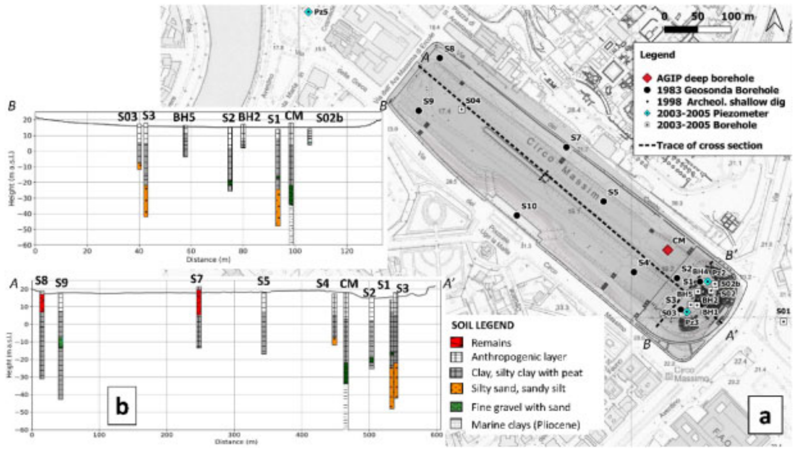

Figure 2. Location of available boreholes (a) with the correspondent stratigraphic logs projected along the A-A', (b) and B-B', (c) cross sections. AGIP deep borehole (CM) is located according to Argentieri et al. 2020.

as reported in geotechnical borehole logs, are slightly coarser at greater depth, ranging from fine sands to sandy silts. Since, to date, no drillings have passed through the entire fine-grained geological body, the Valle "Murcia" Quaternary sequence resting above the geologic substratum is supposed to be closed at the bottom by coarse deposits according to Mancini et al. 2018.

3.2 *Hydrogeologic setting*

At present, the hydrogeologic setting of the area is still poorly reconstructed; no detailed study has been undertaken to date, therefore only basic information can be deduced from general studies concerning the nearby Tiber and its small tributaries (e.g. Funiciello et al. 1995). To fill the data gap on the hydrogeological setting, some piezometers have been installed inside and outside the Circus area during the 2003 and 2005 geotechnical campaigns, located as shown in Figure 3a. Monthly measurements of water levels have been performed, from November 2003 to July 2004, determining the presence of groundwater resting few meters below the ground surface. The groundwater table is somewhat superficial along the whole valley up to Tiber River, with limited seasonal variations along all measurement points as in Figure 3b. The same picture shows a remarkable difference between the piezometers installed inside the study area and the piezometer (n. 310) close to the Tiber River. It suggests the presence of a possible complex hydrogeological setting as the water level drops more than 6 m from piezometer n. 304 to n. 310 (only 275 m away), thus requiring further investigations and groundwater levels monitoring. As a matter of fact, no measurements have been performed after 2004 and, to date, all piezometers are lost. Only during the 2015 works inside the archeological area, the groundwater level has been observed almost constantly at 13.5 m on shallow excavations. New piezometers should be installed during the next drillings campaign.

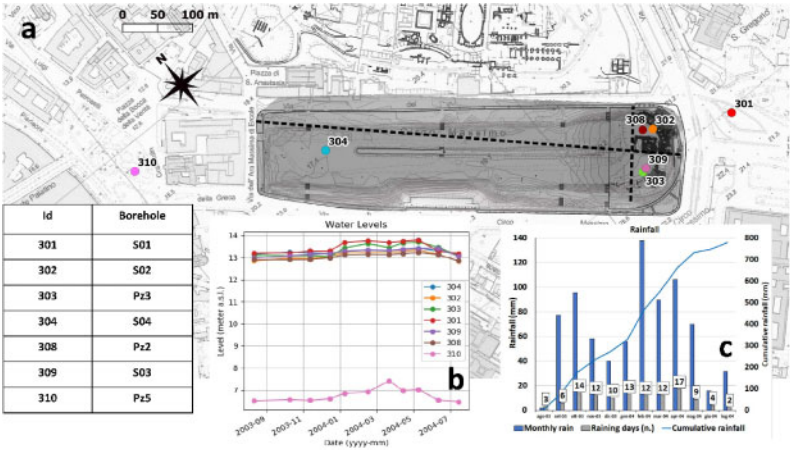

Figure 3. Location of piezometers along the study area (a). Results of the 2003–2004 groundwater monitoring (b) and rainfall data during the monitoring period (c). Each instrument is identified by a Id number that refers to a borehole code in Figure 2.

4 GEOPHYSICAL INVESTIGATIONS

The Circus Maximus is an illustrative example of a still partially buried archaeological site on which it is highly recommendable to conduct indirect investigations before considering new and expensive excavations, as most of the remains lie many meters below the surface. Different geophysical methods and survey techniques, 2D and 3D, have been adopted here: electrical resistivity tomography and Ground Probing Radar for archaeological purposes, Noise recordings and Surface Wave (SW) tests to obtain estimates of the fundamental frequency of resonance of the site and the shear-waves velocity profile respectively. In addition, vibrations of the "Torre della Moletta" and the surrounding Roman ruins have been recorded during a concert, in May 2019, to analyze the effects induced on the structures by anthropic noise.

4.1 *Electrical Resistivity Tomography*

The first campaign consisting in 21 electrical resistivity profiles has been conducted in 2015 and focused on the characterization of the longitudinal central axis of the Circus. Based on the obtained results the ERT survey has been extended more recently to the whole area (Figure 4) for different aims such as: 1) to estimate the depth range of the buried Roman remains vs. those of later periods; 2) to constrain the size, position and orientation of the "euripo", the central barrier of the track, with respect to other structures of the Circus and Palatine Hill; 3) to extend spatially information derived from boreholes, e.g. by correlating ranges of resistivity values with lithological units. A high resolution geoelectrical resistivity surveying has been designed and performed using the X612EM resistivimeter (M.A.E. – www.mae-srl.it) with a multi-electrode acquisition system, using 30 to 96 electrodes along 68 profiles. Measurements have been taken by using at least two different arrays (wenner, wenner-schlumberger, dipole-dipole) along each profile, exploiting the different sensitivity of each one (see e.g. Dahlin & Zhou 2004) to achieve good resolution in both vertical and horizontal directions, thus increasing the quality of the survey. The 2D data inversion process has been carried out after the quality check and data filtering using the Res2DInv software (Loke & Barker 1996) obtaining a 2D model to be interpreted. The data are currently being used for 3D resistivity modeling extended to the entire study area.

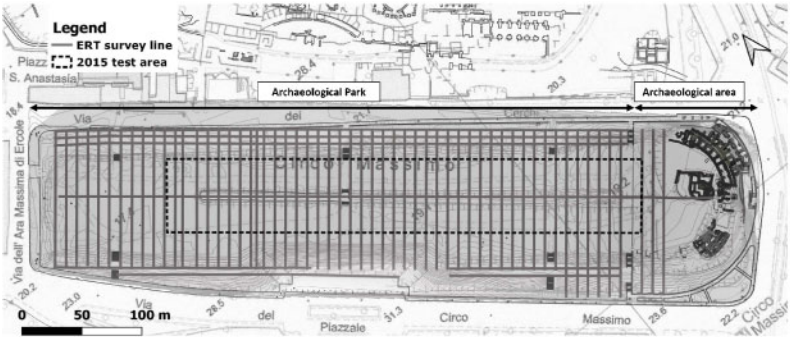

Figure 4. Location of ERT profiles within the Circus Maximus along with the test area surveyed in 2015.

4.2 *Ground Probing Radar*

The GPR method has been used to couple ERT survey lines to obtain detailed information of shallow subsurface useful to constrain the resistivity models. Radar data have been collected along 7 profiles by means of a MALÅ bistatic antenna emitting a frequency band centered at 100 MHz. After some preliminary field tests, this low frequency system has been chosen as a compromise between need of resolution and depth of investigation in such geological environment dominated by conductive soils. The surveys with 100 MHz antenna have been performed fixing the sample frequency at 1100 MHz, the time window equal to 100 ns and recording one trace every 0,02 m in profiling direction, stacking each sample 16 times. Along the central axis of the Circus, 5 parallel radar profiles (0.50 m equally spaced) have been recorded using a MALÅ bistatic 250 MHz antenna; a 3D processing has been implemented to possibly evaluate the buried geometry of some superficial remains, made of concrete, related to 1900s structures.

4.3 *Ambient noise recordings*

The first noise recordings were performed during the experimental campaign conducted in 2019 within the archeological sector in the framework of the vibration monitoring experiment conducted during a social event and following described. Data were recorded using three-axial Tromino velocimeters (5 sites) and SARA SL06 three-axial seismometers (3 sites) deployed as in Figure 5. The duration of the noise recordings ranged from 20 to 245 min, using sampling frequencies equal to 128 Hz (Tromino) and 200 Hz (SARA SL06). The procedures proposed in SESAME 2004 have been implemented for the processing and the statistical validation of the horizontal–vertical spectral ratio (HVSR) curves: recorded signals were divided into time windows with a fixed length of 60 sec and the transient parts of the signals have been excluded (since possibly associated to close sources). The signal pertaining to each time window was cosine tapered (5%) and the Fourier spectrum has been calculated. Smoothing has been applied using the Konno–Ohmachi function with a constant bandwidth coefficient "b" ranging from 25 to 35 (Konno & Ohmachi 1998). According to Nakamura's procedure the spectral ratio curve has been calculated between the two horizontal components and the vertical one, obtaining for each time window a HVSR function within the 0.20 ÷ 20 Hz frequency interval. Processed data have been used to infer the fundamental frequency value (F_0) at each recording site, considering the frequency peaks with a spectral ratio value greater than 2 along each curve. To date, aiming to possibly characterize the whole monumental site in terms of seismic site amplification phenomena, a total of 38 single-station ambient vibration recordings have been performed. Based on the retrieved HVSR curves (not shown here), the F_0 values for the study area vary in a narrow range around 1.35 Hz, without significant differences across the site, also in accordance with Di Luzio et al. 2014.

4.4 *Surface-waves analysis*

Surface-waves surveys have been conducted in the Archaeological area to retrieve a reliable seismic characterization of the soils in terms of shear-waves velocity (Vs) being the main parameter affecting the site amplification of seismic motion. For this purpose, a 57,5-m-long seismic profile has been used deploying 24 geophones equally spaced of 2.5 m oriented as in Figure 5. The compliance of the site conditions with the hypothesis of horizontally layered medium under the seismic profile has been checked via HVSR results, also considering the stratigraphic setting of the cross-section BB' shown in Figure 2b. Vertical and horizontal geophones, both with a nominal frequency of 4.5 Hz, have been used to achieve dispersion data, referred to Rayleigh's (both vertical and radial components were acquired) and Love's waves respectively. Seismograms have been recorded with different offset distances, using an 8-kg sledgehammer as a waves source, striking it vertically over a steel plate to generate Rayleigh's waves dispersion or over a wooden beam firmly fixed to the ground to generate Love's waves dispersion. Due to the traffic, the site is always noisy so that a very different number of recordings have been stacked at each shot position to achieve acceptable signal-to-noise ratio. According to Park et al.1998, the recorded seismic traces at each shot point have been transformed into the velocity–frequency domain so to obtain the corresponding phase velocity spectrum. The shear wave velocity (Vs) profile of the investigated site has been obtained according to the full velocity spectrum approach as described in Dal Moro 2014.

5 GEOTECHNICAL INVESTIGATIONS

Although this area has been investigated many times through the last decades, few geotechnical tests have been performed as main investigations were primarily focused on the reconstruction of the local geology, or rather driven by archaeological needs (shallow excavations and/or large diameter digs). During the 2003 and 2005, as part of the design activities for the new visitor area hosting the Circus Maximus Experience, the area close to the "Torre della Moletta" has been interested by several geotechnical investigations as follows:

- n. 5 shallow boreholes, 20 m deep each;
- n. 11 in-hole Standard Penetration Tests – S.P.T.
- n. 4 in-hole Flat Dilatometer Tests – M.T.D.
- n. 8 Dynamic Probing Super Heavy Tests-DPSH

Laboratory tests were also conducted on 8 undisturbed core samples, to retrieve parameters descriptive of soils shear strength and consolidation behavior. A critical revision of the available geotechnical data is ongoing aiming at using these values as a preliminary reference to design a new geotechnical investigation campaign on soils and structures to be performed during early 2022.

6 VIBRATION MONITORING

On 7th September 2019 about 40,000 people attended a pop concert hosted at the Circus Maximus, in the Park area. This event had been exploited to possibly analyze the effects on both Roman and Medieval remains in the south-east side of the Circus by monitoring the vibrations induced to the structures. Experimental data were recorded between 6 PM of 7 September and 8 AM of 8 September 2019, thus including three periods, before, during, and after the concert, respectively. Eleven SARA SL06 three-axial seismometers were used, deployed both on remains and on the ground as depicted in Figure 5, namely:

- one at the west side of the area (S05);
- three at the east side of the area (S09, S10, and S11);
- three on the “Torre della Moletta” (S02 on the ground very close to the entrance, S03 and S04 at two opposite corners at the top floor).

Additional seismometers (CM5, CM6, and CM7 in Figure 5) and velocimeters (CM1, CM2, CM3 and CM4 in Figure 5) were placed on the ground, far from the structures. All instruments were deployed having the same orientation, i.e. the y direction was parallel to the major axis of the Circus, the x direction was orthogonal to it, and the z direction was the vertical one for each location. Time series obtained on the “Torre della Moletta” and on the archaeological ruins have been analyzed in the frequency and time domain. An analysis has been carried out on the behavior of the monitored structures and soils under the stresses produced by traffic-induced vibrations before the concert, by the presence and the behavior of the audience during the concert as well as by ambient noise after the concert.

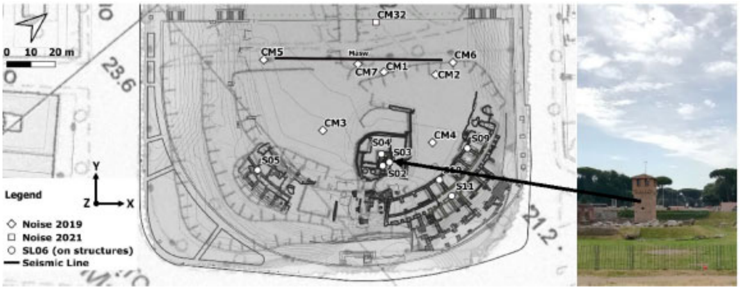

Figure 5. Sensors deployment within the archeological area (see text for details) and a photo of the “Torre della Moletta” medieval structure.

7 PRELIMINARY OUTCOMES

The reconstruction of the subsoil setting has been undertaken first, as essential support for the geotechnical modelling and to constrain and interpret the geophysical models. On this regard, it is to note that, to date, only the drilling from AGIP has intercepted the entire fine-grained geological body. Based on revised stratigraphic logs projected along the cross sections, these coarse deposits should be reinterpreted. Indeed, they have been intercepted mostly along the north-eastern flank of the valley, whereas, at the same depths, fine-grained deposits clearly prevail in the middle of the “Murcia” valley (Figure 3b). This is also suggested by 2D resistivity models along the central axis of the Circus (not shown here) where low resistivity values are found at depth almost corresponding to the bottom of the buried valley. Conversely, assumptions on the near-surface geological setting have been determined not only by means of boreholes logs but also by information coming from archeological investigations and historical maps. These allows the 2D/3D geophysical models derived from ERT and SW technique to be interpreted, at least for some tens of meters in depth within which the geological and geotechnical constraints play a key role. In the following Figure 6 the XY slice (2 m in depth) from the 3D resistivity modeling is shown, referred to the central area of the Park, obtained by using ERTLab inversion software (https://www.mptech3d.com/software). The base map used to interpret the resistivity distribution consists of a historical map with the footprints of early 1900s industrial buildings. The result of the modeling is rather satisfactory as the shallow resistivity distribution correlates with many perimeters (e.g. gas storage in Figure 6b indicated by the grey arrow) thus suggesting pronounced effects on soils. Also the 2D resistivity modelling of 2021 data has proven to be efficient in defining buried resistivity anomalies of potential archeological interest. In Figure 6c the 2D ERT model of the profile running for 200 meters along the central barrier is shown. Based on the calibration of the model through boreholes data (not presented here), the thickness of the most superficial archeological layer referred to the 1900s industrial period has been estimated along the profile (black lines in Figure 6c). In addition, resistivity anomalies within the depths range of in-place Roman remains (see ch.2) have been identified as e.g. the "A" one in Figure 6c that is suspected to belong to the "euripo" structure.

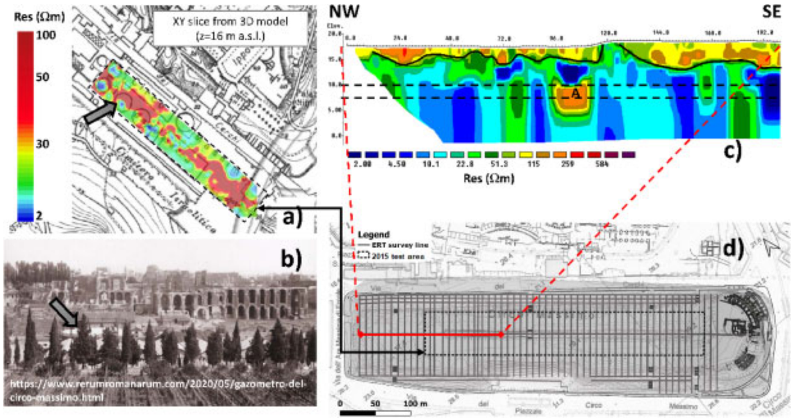

Figure 6. Example of results obtained from 3D processing of 2015 data (a) interpreted by using archeological map and photo (b) and from 2D processing of new data (c) to investigate the buried Roman remains along the central axis of the Circus (d).

The preliminary results of the seismic tests conducted on archeological area and of the vibration monitoring during a social event have been used to address the geotechnical investigations aimed at analyzing the local seismic response and soil–structures interaction (see Puzzilli et al. 2021 for details). From the active seismic survey, some geotechnical complexity in the subsoil emerged due to significant Vs velocity inversions detected near surface, at the contact between superficial backfilling and the underlying clayey deposits. Incidentally, note also that Mancini et al. 2014 included the whole "Murcia" valley in the Seismic Microzonation study of the Palatine Hill. To compare the two seismic characterizations, the acronyms used in Mancini et al. 2014 for the same soils have been reported on the right column in Figure 7 (please refer to that paper for acronyms) in which the soils have been tentatively classified according to the USCS Unified Soil Classification System (ASTM D2487).

The experimental data obtained during the vibrations monitoring on structures and remains performed in 2019 have been divided into three time intervals to better analyze induced effects, namely:

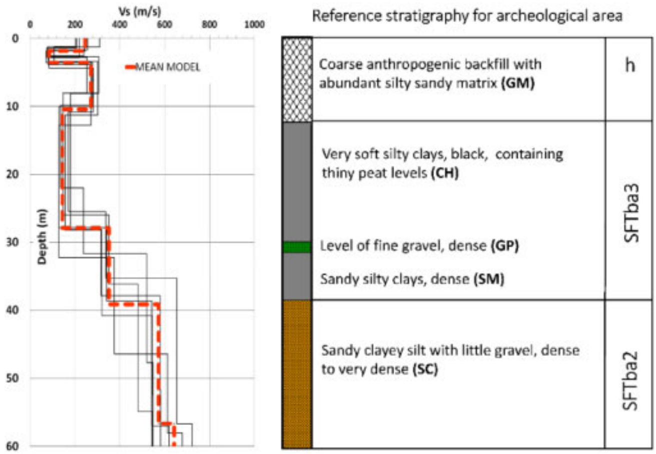

Figure 7. Velocity profiles referred to the subsoil of archeological area (a) compared to the reference stratigraphy.

- a time interval with the presence of traffic-induced vibrations (T), which occurred in the evening before the concert, from 6 PM to 9 PM of 7 September;
- a time interval from 9 PM to midnight, approximately, which includes the entire concert (C);
- a time interval from midnight to 8 AM of 8 September, with the presence of low ambient noise only (N), which occurred after the concert.

Attention has been devoted to the analyses of the velocities recorded in the three directions (x, y and z) during the three intervals (T, C, and N) at locations on the "Torre della Moletta" and the archaeological remains (see Figure 6.1.1). While the amplitudes during T were 2 ÷ 3 times those during N, the amplitudes recorded during the concert (C) exceeded by ten times those after the concert in the presence of ambient noise only (N). On the remains, also the amplitudes during the concert (C) were much higher than that during T and N (Puzzilli et al. 2021 for further details). In Table 1, the maximum values of velocity have been reported to ease the comparison with limit values suggested by UNI-9916 for historical buildings and by SN640312 for traffic-induced vibrations, also reported following.

Table 1. Maximum values of velocity (mm/s) measured ad each recording site.

Location	x	y	z
S02	0.67	1.09	1.10
S03	4.01	4.20	5.18
S04	3.85	3.65	1.35
S05	0.38	0.47	0.17
S09	0.54	0.69	0.71
S10	0.43	0.94	0.46
S11	0.75	0.61	0.36

UNI-9916 velocity limits for historical buildings are:
Short-term vibrations: V = 3.0 mm/s at the foundation and V = 8.0 mm/s at the top;
Permanent vibrations: V = 2.5 mm/s;
Building floors: V = 10 mm/s (no historic buildings).

SN640312 velocity limits for traffic induced vibrations are:
Permanent vibrations: V = 1.5 ÷ 3.0 mm/s;
Frequent vibrations: V = 3.0 ÷ 6.0 mm/s;
Occasional vibrations: V = 7.5 ÷ 15 mm/s.

The major evidence is that, in some cases, the registered values are very close to the limit ones: this is even more significant if one considers that limits are introduced for non-damaged historic buildings, otherwise lower values should be considered in a precautious manner. The results of vibration monitoring pointed out also differences in terms of preferred vibration directions (not shown here).

8 DISCUSSION AND CONCLUSIONS

Still after about 2000 years and many vicissitudes, the Circus Maximus in Rome plays every day the role of recreational and cultural area for tourists and citizens. The area must be preserved from the enormous anthropic and environmental pressure through mitigation and preservation actions. To support these actions, all available information on subsoil have been collected and critically reviewed to design new geophysical surveys and direct investigations on soil and structures. The preliminary results obtained through 2D and 3D resistivity modeling on restricted areas encourage the 3D modeling extended to the whole monumental area. Evidence from vibration monitoring during social events, to our knowledge the first ever performed in this site, highlighted potentially dangerous conditions for some particularly vulnerable portions, such as remains of the vaults. Direct investigations to be conducted in early 2022 will be used to calibrate geophysical models and to test areas of potential archaeological interest identified through them. Also, to sample soils for laboratory testing and create a baseline to standardize lithological descriptions of soils in borehole logs through the years. In the Archaeological area, non-destructive tests will be also performed, to assess the mechanical quality of different archaeological structures (i.e. walls, vaults) and built with upon different type of masonry. This will be supported by means of a suitable model of the "Torre della Moletta" to be set up with the aims of directing experimental analysis and in the interpretation of experimental results.

REFERENCES

Argentieri, A., Capelli, G., Mazza, R. 2020. The "Circo Massimo" borehole (Rome 1939), a site of the geological memory. *Italian Journal of Groundwater*. 8. Doi:10.7343/as-2019-444.

ASTM D2487. 2020. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). American Society for Testing and Materials, U.S.A.

Bigot, P. 1908. Circus Maximus. *Mélanges d'archéologie et d'histoire*. 28: 229–231. Doi: 10.3406/mefr.1908.6980.

Brandizzi Vittucci, P. 1991. L'emiciclo del Circo Massimo nell'utilizzazione post classica. *Melanges de l'Ecole Francaise de Rome* 103(1):7–40. Doi: 10.3406/mefr.1991.3150

Buonfiglio M. 2018. La definizione di uno spazio urbano: nuovi elementi sulle fasi di formazione e sviluppo del Circo Massimo alla luce delle recenti indagini (2009–2016). *Bullettino della Commissione Archeologica Comunale* CXIX:123–166.

Canciani, M., Falcolini, C., Buonfiglio, M. et al. 2013. A method for virtual anastylosis: the case of the arch of Titus at the Circus Maximus in Rome. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*. II5(61).

Carpentieri, E., De Rita, D., Della Monica G. 2015.Geology of the Murcia Valley and Flood Plain Modifications in the Construction of the Circus Maximus, Rome, Italy. *Geoarcheology.* 30(6): 483–494.

Ciancio Rossetto, P. 2002. Risultati delle indagini archeologiche nell'area centrale, *Bullettino della Commissione Archeologica Comunale* CIII: 186–189.

Ciancio Rossetto, P. & Buonfiglio, M. 2007. Circo Massimo: rifiessioni e progetti. *Orizzonti:rassegna di archeologia* VIII:19–41.

Dahlin, T. & Zhou, B. 2004. A numerical comparison of 2D resistivity imaging with 10 electrode arrays. *Geophysical Prospecting,* 52: 379–398. Doi:10.1111/J.1365-2478.2004.00423.X

Dal Moro, G. 2014. *Surface Wave Analysis for Near Surface Applications*; Elsevier: Amsterdam, The Netherlands.

Di Luzio, E., Fazio F., Imposa, S., Rannisi, G. 2014. Ambient Noise Recordings in the Circo Massimo and Vallis Murciae Areas: Main Results Compared with the Dynamic Response of the XII Cen. AD Torre Della Moletta. *Engineering Geology for Society and Territory*. 8:399–403. Doi:10.1007/978-3-319-09408_69.

Funiciello, F. et al. 1995. La Geologia di Roma. Il centro storico. *Memorie Descrittive della Società Geologica.* 50.

Funiciello, R. & Giordano, G. 2008. La nuova carta geologica del comune di Roma: litostratigrafia e organizzazione stratigrafica. In Renato Funiciello, Antonio Praturlon, Guido Giordano (eds) *La geologia di Roma dal centro alla periferia. Parte Prima. Memorie Descrittive della Carta Geologica d'Italia*. LXXX: 39–85.

Geosonda 1983. Indagini geognostiche per scavi archeologici al Circo Massimo – 3° lotto – Perizia 213/82. Archive of the Superintendency of Cultural Heritage of Rome (in Italian).

Konno, K & Ohmachi, T. 1998. Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. Bulletin of the Seismological Society of America. 88(1): 228–241.

Loke, M.H. & Barker, R.D. 1996. Rapid Least-Squares Inversion of Apparent Resistivity Pseudosections by a Quasi-Newton Method. *Geophysical Prospecting*. 44:131–152. Doi:10.1111/j.1365-2478.1996.tb00142.x.

Mancini, M., Marini, M., Moscatelli, M., Stigliano, F. et al. 2018. Stratigraphy of the Palatine Hill (Rome, Italy): a record of repeated middle Pleistocene-Holocene paleovalley incision and infill. *Alpine and Mediterranean Quaternary*. 31 (2): 171–194.

Mancini, M., Marini, M., Moscatelli, A., Pagliaroli, A. 2014. A Physical Stratigraphy Model for Seismic Microzonation of the Central Archaeological Area of Rome (Italy), *Bulletin of Earthquake Engineering*. 12: 1339–1363.

Marra, F., Florindo, F., Anzidei, M., Sepe, V. 2016. Paleo-surfaces of glacio-eustatically forced aggradational successions in the coastal area of Rome: Assessing interplay between tectonics and sea-level during the last ten interglacials. *Quaternary Science Reviews*. 148: 85–100.

Marra, F., Motta, L., Brock, A. L., Macrì, P. et al. 2018. Rome in its Setting. Post-glacial Aggradation History of the Tiber River alluvial Deposits and tectonic Origin of the Tiber Island, *PLoS ONE*, 13(3).

Marra, F., Buonfiglio, M., Motta, L. 2021. Holocene aggradation history of the Murcia alluvial valley: insights on early Rome paleoenvironmental evolution. *The Olocene* (submitted).

Pagliaroli, A., Lanzo, G., Tommasi, P. et al. 2014. Dynamic characterization of soils and soft rocks of the Central Archeological Area of Rome. *Bulletin of Earthquake Engineering*. 12: 1365–1381. Doi: 10.1007/s10518-013-9452-5.

Park, C.B., Miller, R.D., Xia, J. 1999. Multichannel analysis of surface waves. *Geophysics* 64: 800–808. Doi:10.1190/1.1444590.

Pietrangeli, C.1940. Circus Maximus. *Bullettino della Commissione Archeologica Comunale* CIII:186–189.

Puzzilli, L.M., Bongiovanni,G., Clemente, P., Di Fiore, V., Verrubbi,V. 2021. Effects of Anthropic and Ambient Vibrations on Archaeological Sites: The Case of the Circus Maximus in Rome. *Geosciences*. 11, 463. Doi: 0.3390/geosciences11110463.

Signorini, R. 1939. Risultati geologici della perforazione eseguita dal A.G.I.P alla Mostra autarchica del Minerale nel Circo Massimo di Roma. *Boll. Soc. Geol. It.* LVIII(2–3).

SESAME 2004. Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations-Measurements, processing and interpretation. SESAME European research project, WP12-Deliverable D23.12. Project No. EVG1-CT-2000-00026 SESAME, 62 pp.

SM Working Group. 2015. Guidelines for Seismic Microzonation. Rome: Conference of Regions and Autonomous Provinces of Italy – Civil Protection Department (ed).

SN 640312. 2013. Vibrations—Vibration Effects in Buildings; Swiss Standards: Zürich, Switzerland.

UNI 9916. 2004. Criteria for the Measurement of Vibrations and the Assessment of Their Effects on Buildings; Italian code; UNI: Milan, Italy.

UNI EN ISO 22476. 2012. Geotechnical investigation and testing. Field testing Dynamic probing; Italian code; UNI: Milan, Italy.