

Local seismic response of the Quadriportico of the Basilica of Saint Paul Outside the Walls in Rome

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ABSTRACT

The Basilica of Saint Paul Outside Walls is one of the four papal basilicas in Rome, the largest after Saint Peter's in the Vatican. The facade of the church is preceded by a large Quadriportico, designed and built in the thirties of the last century. The *Quadriportico* is a monumental architectural structure, measuring 70 m on each side. The Basilica and the *Quadriportico* stand on a flat area on the left bank of the Tiber River. This area has been affected by several earthquakes throughout history, notably those in 442, 801, and 1351 AD, which caused significant damage to the Basilica. More recently, the Central Italy mainshock of 2016 (Mw=6.5) caused slight damage to the *Quadriportico*. Over the years, several geotechnical investigations have been conducted to characterize the subsoil characteristics and determine its main geotechnical properties. As part of a national research project, a recent investigation focused on defining the dynamic soil properties through both laboratory and in-situ testing. The data collected was used to develop a geotechnical model for seismic response analyses, carried out using one-dimensional (1-D) numerical code. The results of these analyses were then compared with code-based response spectra at the ground surface. The findings and their implications for the seismic protection of the monuments are examined and discussed.

Keywords: Basilica of Saint Paul Outside the Walls, Quadriportico, Rome, Dynamic Soil Properties, Seismic Protection of Monuments, Local Seismic Response

INTRODUCTION

The protection of architectural heritage is a fundamental issue in the cultural identity of contemporary societies. In Italy, and in the city of Rome in particular, the huge and rich heritage of great historical and artistic value is characterized by a significant vulnerability and constantly subject to natural risks. This makes it especially susceptible to potential earthquakes, even if Rome's overall seismic hazard can be regarded as moderate. The awareness of this susceptibility to seismic risk has stimulated several studies aimed at investigating the potential ground motion and dynamic response of historic buildings in the city of Rome (e.g., [Bozzano et al., 2008](#); [Pagliaroli et al., 2014](#)). These studies have demonstrated the strong correlation between the distribution of damages, typically concentrated in some sectors of the urban area, and the subsoil conditions, which govern the local amplification of seismic motion.

The Basilica of Saint Paul Outside the Wall is, after Saint Peter's Basilica, the second most important place of worship in Rome. The Basilica is completed by the Quadriportico, an architectural structure of significant historical and artistic value. According to historical sources, this monumental complex has experienced earthquake ground motion in the past which caused slight to significant damages.

In this paper, the local amplification phenomena in the *Quadriportico* area are investigated through numerical seismic response analyses, based on extensive *in situ* and laboratory investigations. The final goal is to improve our understanding of the seismic motion at the site, thereby supporting possible effective strategies for its protection. This research work has been conducted in the framework of a national research project "GIANO – Geo-Risks Assessment and Mitigation for the Protection of Cultural Heritage" funded by the *Ministero dell'Istruzione, dell'Università e della Ricerca* (MIUR) in 2020.

BRIEF HISTORY AND PERFORMANCE IN PAST EARTHQUAKES

The Basilica of Saint Paul Outside the Walls is one of the four papal basilicas in Rome and, in terms of size, is second only to St. Peter's in the Vatican. The structure ([Figure 1a](#)), located in the southern district of Rome's urban area, is built in a flat area on the left bank of the Tiber River. Since the 1st century BC, the area has been used as a burial site. In fact, it is believed that the apostle Paul, martyred in 67 AD, was buried in this area. His remains were temporarily moved to the Appian Way around the middle of the 3rd century, but were only brought back permanently around 336 AD.

The current building is the third to be erected on the site of the apostolic burial. The first church, built by Constantine, was soon replaced by a grandiose structure, much larger and with a different orientation than the previous one, commissioned in 384 by the emperors Valentinian II, Theodosius I, and Arcadius. This basilica remained virtually unchanged until the fire of 1823, which destroyed much of it. The Basilica was rebuilt in its current form starting in 1825.

There is no certain information as to whether the facade was preceded by a Quadriportico from the outset. The oldest evidence of this structure can be found in a passage from the *Liber Pontificalis*, which mentions the existence of an "atrium" paved by Pope Hadrian I as it was in a state of complete abandonment (772-795). In the centuries following the construction of the Basilica, several buildings were constructed around its walls, such as rural buildings, small baths and secondary basilicas. This aggregation led to the creation of a large village, named Giovannipoli in honor of Pope John VIII (872-882). After 880 AD no further mention of Giovannipoli is available, and it had already almost completely disappeared by the 14th century due to the effects of the earthquake occurred in 1349. To date, the only reliable sources on the original appearance of the portico are ancient roman engravings dating back to the 16th century. The construction of the Quadriportico in its current configuration was started in 1899 and completed in 1929 ([Figure 1b](#)). The portico, composed of 150 white marble columns, features a row of columns at the entrance (West), double on either sides (North and South) and triple on the opposite side (East). The sides of the portico are 70 meters long, and both the north and south sides are enclosed on the outside by a travertine-clad wall. The west side, to allow a view of the façade, is colonnaded. At the center is a colossal statue of Saint Paul.

Over the centuries, the city of Rome has been affected by several seismic events ([Galli & Molin, 2013](#)). The Authors reported that the occurrence of strong far-field earthquakes generated along the Apennine faults has undoubtedly caused considerable damage to the ancient building stock and specifically to the St Paul's Basilica and its Quadriportico. The earthquake of 443 AD caused the collapse of some statues and porticoes, while that of 801 caused the collapse of the roof of the basilica and some beams. However, the most damaging effects on the structure were caused by the 1349 earthquakes, which is the strongest shaking ever felt in Rome. This seismic sequence caused the collapse of part of the roof and the bell tower; further, most of the colonnades of the Quadriportico collapsed. The earthquakes that occurred in 1812, 1915 and 2016, although they did not seriously damage the basilica, still caused minor damages.

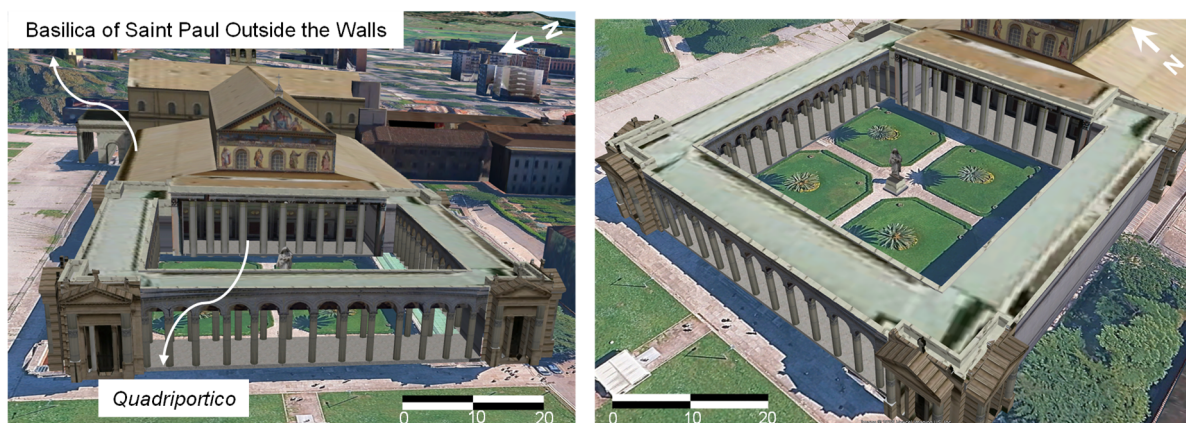


Figure 1: Aerial view of the Basilica of Saint Paul Outside the Walls with the Quadriportico (left); view of the Quadriportico (right)

Finally, during the 2016–2017 Central Italy seismic sequence, and in particular following the October 30, 2016 event—the strongest shock ($M_w=6.5$)—a pronounced crack opened in the pediment of the Quadriportico (Figure 2). Moreover, numerous cracks developed in the Basilica of Saint Paul, and several cornices collapsed.



Figure 2: Crack opened in the pediment of the Quadriportico following the 2016, October 30th event

GEOLOGICAL OUTLINES

The geological setting of Rome consists of plio-pleistocene marine sediments known as the *Monte Vaticano* Formation (MVA), which represent the geological bedrock of the area, overlain by fluvio-lacustrine deposits associated with the paleo-Tiber River. These sedimentary units are capped by volcanoclastic deposits, both fallout and flow, sourced from the *Colli Albani* volcanic district and the *Sabatino* volcanic complex.

An excerpt of the geological map of the Rome municipal area, highlighting the Basilica area, is presented in Figure 3 (Funiciello & Giordano, 2008). The main geological units outcropping in this area are: (i) *Fiume Tevere* Synthem, consisting of sand, silt and clay with organic component, specifically the alluvial deposits within the river channels (SFT_{bb}) and the alluvial deposits (SFT_{ba}) sedimented in the plains of the river; (ii) *Fosso del Torrino* formation (FTR₁) made of fluvial-lacustrine polygenetic conglomerate, sand and silt dominated by volcanoclastic debris; (iii) Red *Pozzolane* (RED), a massive and chaotic pyroclastic unit. Finally, although of lesser relevance, there are: (iv) *Valle Giulia* formation (VGU), composed of travertine incorporating lenses of volcanoclastic sands and gravels and (v) *Pozzolanelle* pyroclastic deposits (VSN₂), consisting of massive deposits containing scoria, lapilli, and lava blocks.

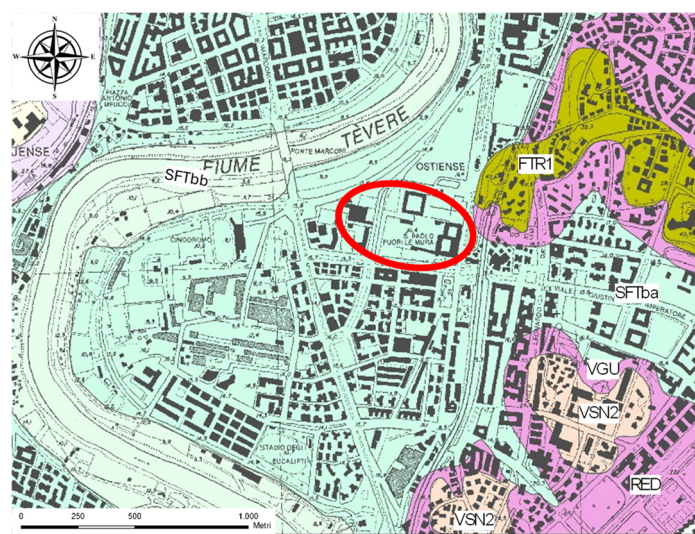


Figure 3: Excerpt of the geological map of the Rome municipal area – scale 1:10000 (Funiciello & Giordano, 2008) with location of the Basilica of Saint Paul Outside the Walls (red circle)

HISTORICAL SEISMICITY AND SELECTION OF INPUT MOTION

As already mentioned, throughout history Roman monumental heritage has undoubtedly sustained earthquakes-induced damage. [Galli & Molin \(2013\)](#) reported that the macroseismic intensity in Rome has reached level VII on the MCS scale during at least six different events in the past. In particular, the city of Rome is affected by earthquakes originating from three different seismogenic districts:

- 1) the central Apennine, situated approximately 90-130 km east of Rome, has produced events with magnitude around $M=6.7-7.0$;
- 2) the *Colli Albani* volcanic area, located 20 km south of Rome and associated with moderately-strong events ($M \approx 5.5$);
- 3) the Rome area itself characterized by rare, shallow and low-magnitude events ($M < 5.0$).

The spatial distribution of seismic damage in Rome appears to be primarily governed by ground motion amplification effects associated with local soil conditions. [Ambrosini et al. \(1986\)](#) and [Bozzano et al. \(2011\)](#), which analyzed the damage patterns resulting from 1915 Avezzano and 2009 L'Aquila earthquakes, respectively, highlighted a deep correlation between observed damage and Holocene alluvial deposits. Local amplification phenomena, related to these specific Tiber river's sediments and to the buried morphological features, were numerically investigated by [Pagliaroli et al. \(2014\)](#) referred to Central Archaeological Area, including the Palatin Hill, Colosseum and Roman Forum.

According to the national Code ([NTC, 2018](#)), the seismic hazard for the site has been defined in terms of elastic horizontal acceleration spectrum (target) referred to free-field conditions on a reference rock site with horizontal ground surface (Site Class A and Topographic Category T1). This reference action has been established for the Life Safety Limit State (SLV) characterized by predefined probability of exceedance ($P_{VR}=10\%$) and return period ($T_R=949$ years). The architectural structure under investigation is characterized by a nominal design working life of $V_N=50$ years and it is classified as importance class equal to IV (importance factor $C_u=2$). The reference life ($V_R=V_N \cdot C_u$) is therefore equal to 100 years. For the site of interest (Lat. 41.85889 and Long. 12.47525) the SLV target spectrum is characterized by $PGA = 0.162g$.

The target spectrum was used to select spectrum-compatible natural accelerograms for SLV. No information is available for the predominant period of the Quadriportico and also literature data on similar structures are rather limited. Therefore, the input motions have been selected to ensure spectrum compatibility within a fairly wide period range $T=0.1-0.5$ s.

Based on the historical seismicity studies, it is reasonable to consider that the seismicity of the city of Rome is associated with near moderate-magnitude earthquakes ($M_{max}=5.5-6.0$ and $D < 20$ km) and higher-magnitude events ($M_{max}=6.5-7.5$) occurring at higher distances ($D \approx 100$ km). On the basis of these considerations, the following magnitude-distance pairs were adopted for the selection of accelerometric records: i) $M_w=5.0-5.6$ $D=0-20$ km; ii) $M_w=6.0-6.6$ $D=65-100$ km, corresponding to near-field and far-field earthquakes respectively.

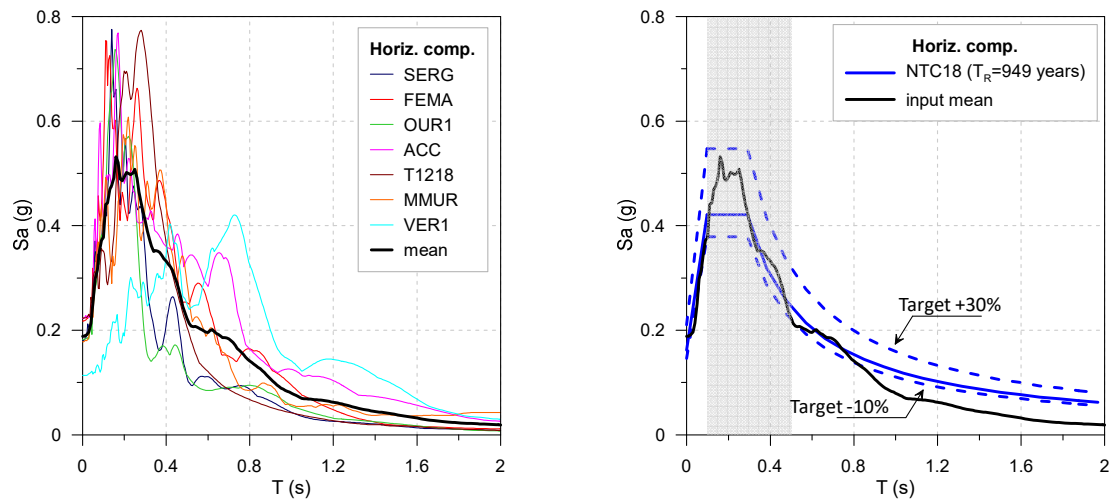
Seven natural accelerograms have been chosen from on-line databases in order to take into account uncertainties associated with the input motion. To this aim, the Engineering Strong Motion (ESM) ([Luzi et al., 2020](#)) and the Italian Accelerometric Archive (ItAcA) ([D'Amico et al., 2020](#)) repositories have been used.

The selection of the accelerometric records primarily targeted events recorded on rock or very stiff soils ($V_s \geq 680$ m/s) site categories according to NTC. These records were chosen to ensure a scaling factor (SF) ≤ 4 , based on the following criteria: (i) avoiding the use of both horizontal components from the same record, and (ii) excluding multiple records from the same seismic station. The selection procedure is considered complete when the mean response spectrum of the 7 selected signals falls within 90-130% of the target horizontal spectrum. Otherwise, the scaling factors of individual signals are adjusted, or one or more records are replaced, until the spectrum-compatibility requirement is fully satisfied.

The main features of the selected accelerograms are reported in [Table 1](#). [Figure 4a](#) shows the acceleration spectra of the selected accelerograms together with the related mean spectrum whereas [Figure 4b](#) compares this mean spectrum with the target horizontal acceleration spectrum (structural damping $\xi=5\%$) from NTC.

Table 1. Main characteristics of accelerograms selected for SLV (M_W : moment magnitude, PGA: peak ground acceleration, SF: Scale Factor).

Event Date	Hour	M_W	Station Code	R_{epi} (km)	NTC18 soil class	Comp.	PGA (g)	SF
12/01/2021	22:09:56	5.2	SERG	3.5	A	N/S	0.180	1.00
26/10/2016	17:10:37	5.5	FEMA	11.0	A	E/O	0.198	1.10
06/08/1983	15:43:56	6.8	OUR1	72.9	B (680 m/s)	HN2	0.083	2.20
18/01/2017	09:25:41	5.1	ACC	15.2	A	N/S	0.104	2.15
18/01/2017	13:33:37	5.0	T1218	23.6	A	N/S	0.072	3.10
30/10/2016	06:40:18	6.6	MMUR	67.9	A	E/O	0.049	3.60
13/05/1995	08:47:14	6.6	VER1	65.8	B (794 m/s)	HN2	0.030	3.80

**Figure 4:** Life Safety Limit State (SLV): horizontal acceleration spectra of the selected natural accelerograms and related mean spectrum (left); comparison between the mean spectrum and the NTC target spectrum (right)

SUBSOIL CONDITIONS AND GEOTECHNICAL MODEL

The definition of the geotechnical model was based on the results of three investigation campaigns carried out over the years. A plan view of these investigations, all located along the western side of the *Quadriportico*, is shown in Figure 5. The first campaign, executed in 1979, mainly aimed to identify and characterize the foundation walls of the portico and to obtain information on the stratigraphic conditions and the physical-mechanical properties of the soil deposit. It consisted of 6 vertical boreholes (S1-S6) up to a maximum depth of 33 m (S2) including the installation of an open standpipe piezometer. The 2018 geotechnical campaign was related to the underpinning works carried out by the Directorate for Infrastructure and Services of the Governorate of the Vatican City State between 2018 and 2022. Two inclined holes were drilled (Si1 and Si2) for a maximum investigation depth of 15 m. These tests were also supplemented by one SCPTu and two CPTu tests, and two 3D electrical tomography (ERT) surveys (P1 and P2), this latter with the aim of further investigating the foundation structures of the *Quadriportico*. The more recent 2024 campaign, carried out within the research project *GIANO*, was essentially devoted to determine the dynamic properties of all geotechnical units down to the geologic bedrock. One borehole was drilled (SL) to maximum depth of 66 m including down-hole (DH) and ambient noise (HVSr) measurements; about twenty undisturbed samples were also recovered for laboratory testing.

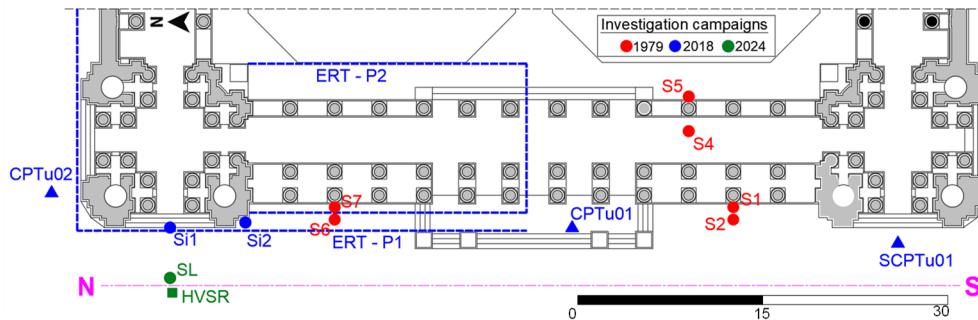


Figure 5: Plan view of the investigations carried out over the years (1979, 2018 and 2024 campaigns) along the western side of the Quadriportico

Results of geotechnical investigations

Figure 6 shows the stratigraphic profile along the section (N-S), as reconstructed based on boreholes data and CPT vertical profiles. Seven sub-horizontal geotechnical units can be identified: i) anthropogenic layer (A); ii) silty clay (SC) iii) clayey silt (CS); iv) silty sand (SS) with intercalated silty clayey layers; v) clayey silt with peat levels (CS); sandy gravels (SG); overconsolidated marine clays (MVA). The foundation masonry walls are of good quality and well-preserved.

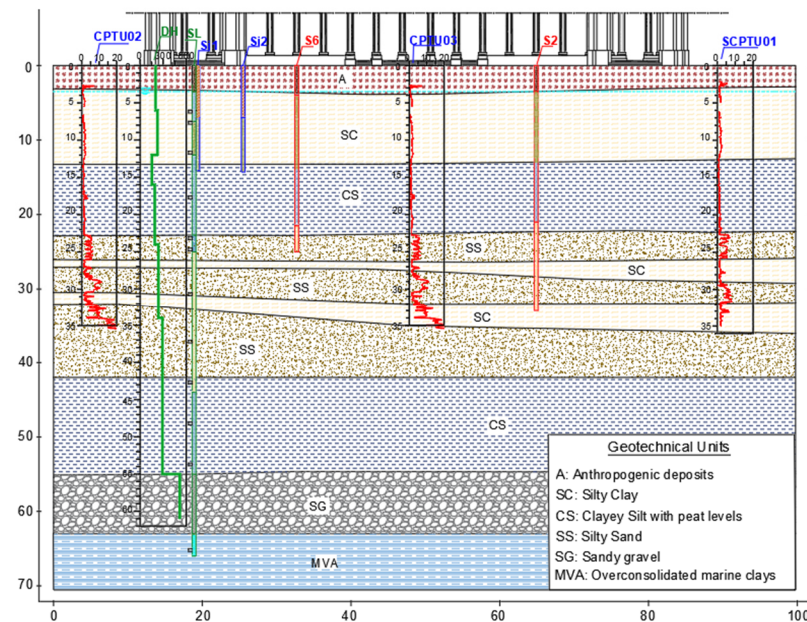


Figure 6: Stratigraphic section along the N-S alignment (1979, 2018 and 2024 campaigns)

Dynamic properties from in situ-and laboratory testing

Shear wave velocity (V_s) measurements were obtained from a down-hole test that reached 66 m depth (2024 campaign). The resulting velocity profile is consistent with the V_s trend obtained from the SCPTu test performed in 2018 (Figure 7). The equivalent shear-wave velocity $V_{s,eq}$, as defined according to NTC18, is 200 m/s, which corresponds to a soil category C. The single-station passive seismic measurement (HVSr), carried out near borehole SL (2024 campaign), returned a peak frequency $f_0=1$ Hz, which reasonably represents the fundamental resonance frequency of the soil deposit. This indicates a deep impedance contrast, likely to be located within the basal formation of the MVA unit. Laboratory testing was performed to evaluate index properties as well as modulus reduction and damping behavior. Figure 8 shows the results in terms of grain size distribution, unit weight (γ), water content (w), consistency index (I_c) and plasticity index (I_p). Where available, in the same figure physical properties of samples collected from the 2018 campaign are also reported. Several resonant column (RC) tests were carried out to obtain the modulus reduction ($G/G_0-\gamma_c$) and damping ratio ($D-\gamma_c$) curves. The corresponding curves for the different soil types are illustrated in Figure 9. The geotechnical model relevant for 1D local seismic response analyses, derived from available geotechnical and geophysical investigations, is summarized in Table 2. In particular, for the $G/G_0-\gamma_c$ and

$D-\gamma_c$ curves, where several experimental results were available for the same geotechnical unit, an average curve was defined to obtain a representative curve. All the curves used for the numerical modeling are shown in Figure 10.

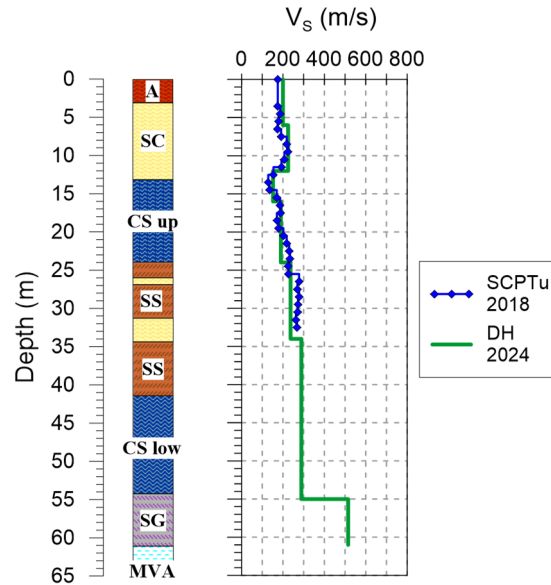


Figure 7: Shear wave velocity (V_s) profiles obtained from the DH (2024) and the SCPTu (2018) measurements

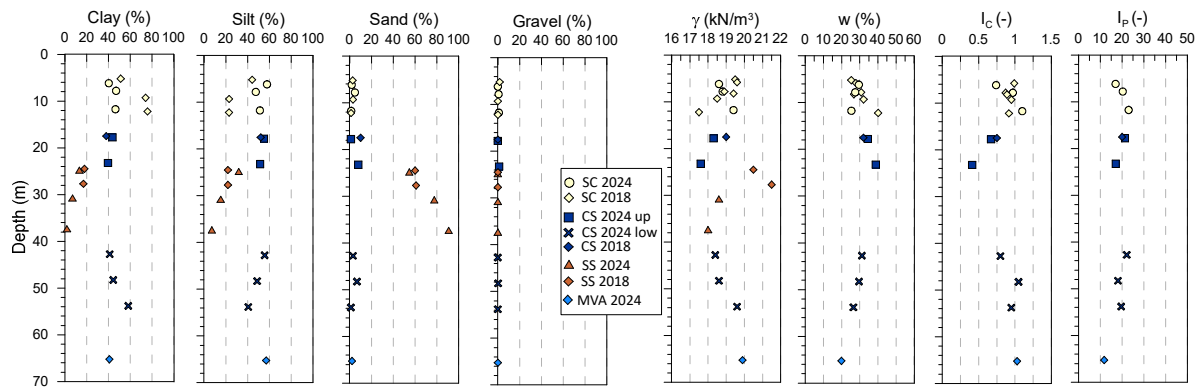


Figure 8: Results of laboratory tests (2018 and 2024 campaigns): grain size analyses (left) and main physical properties (right)

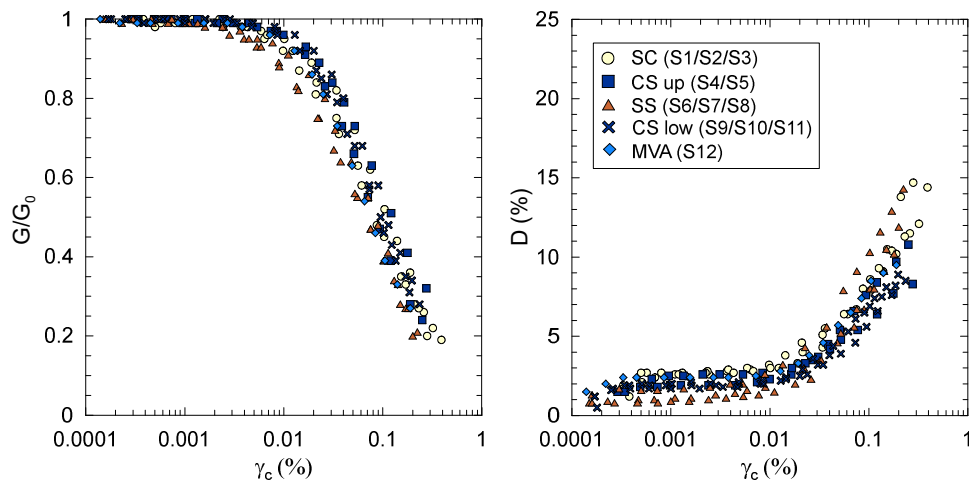
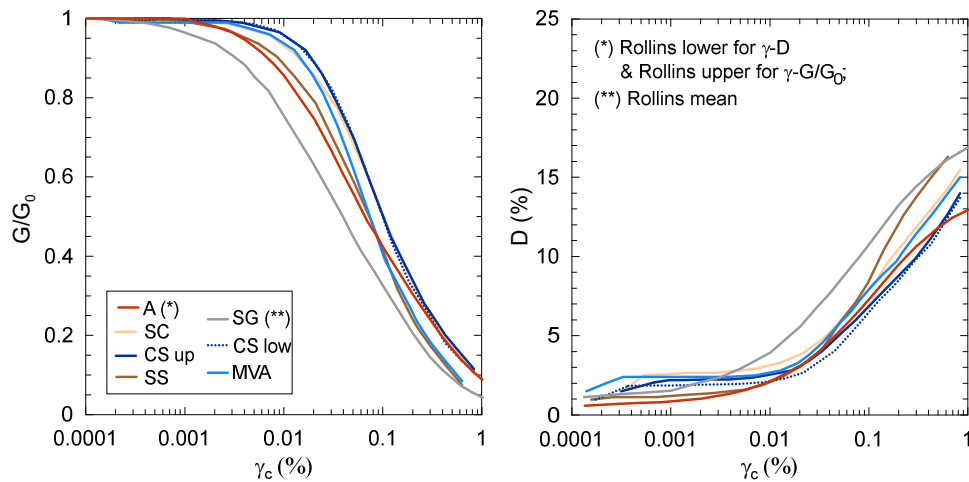


Figure 9: $G/G_0-\gamma_c$ and $D-\gamma_c$ curves obtained from RC tests (2024 campaign)

Table 2. Geotechnical model for 1D local seismic response modeling

Geotechnical Unit	γ (kN/m ³)	Depth (m)	V_s (m/s)	G/G_0 - γ_c and D - γ_c curves
A	17.5	0-3	180	Rollins et al., 1998
SC	18.0	3-13	200	Average RC curve
CS up	18.7	13-24	200	Average RC curve
SS	19.5	24-26	250	Average RC curve
SC	18.0	26-27	200	Average RC curve
SS	19.5	27-32	250	Average RC curve
SC	18.0	32-35	200	Average RC curve
SS	19.5	35-42	250	Average RC curve
CS low	19.0	42-55	290	Average RC curve
SG	20.0	55-63	500	Rollins et al., 1998
MVA (1)	20.0	63-93	550	RC curve
MVA (2)	20.5	93-130	650	RC curve
MVA (3)	21.0	> 130	800	Linear-Elastic D=1%

**Figure 10:** Linear G/G_0 - γ_c and D - γ_c curves used in numerical modeling for each geotechnical unit

LOCAL SEISMIC RESPONSE ANALYSES

One-dimensional (1D) site response analyses were performed using the STRATA code (Kottke *et al.*, 2013), which models a soil column as a layered continuum with linear visco-elastic behavior. The equations of motion are solved in the frequency domain and non-linear behavior is accounted for through an equivalent-linear approach. While alluvial deposits frequently exhibit complex geometries that require 2D/3D analyses, site investigations in the studied area confirm a nearly horizontal stratigraphy with laterally continuous layers and no significant heterogeneities (e.g., isolated lenses). Consequently, the fundamental assumptions of 1D wave propagation are strictly met. The seven acceleration time histories selected for SLV condition have been applied as outcropping motions for the site response analyses.

Linear calibration of the model

As mentioned, shear wave velocity measurements are available to the maximum investigated depth of 62 m where $V_s \approx 520$ m/s (Figure 7). However, to identify the position of the seismic bedrock ($V_s \approx 800$ m/s), a parametric analysis was conducted by applying a V_s gradient in the geotechnical unit MVA, where no experimental measurements are available. The V_s profile was validated by comparing resonance frequency derived from numerically computed linear amplification function with the experimental value obtained from HVSr technique. This comparison, illustrated in Figure 11, yielded a fundamental site frequency of approximately $f_0 \approx 1.0$ Hz, in full agreement with the HVSr measurement

($f_0 \approx 1$ Hz). Therefore, the seismic bedrock was located at 130 m below the ground surface and the V_s gradient in MVA was assumed as reported in Table 2.

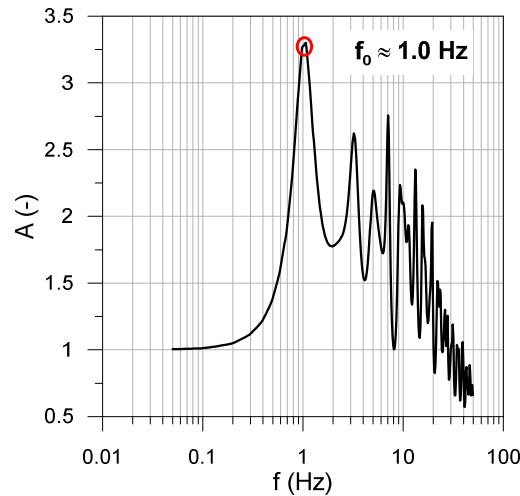


Figure 11: Computed amplification function from 1D linear site response analysis and identification of fundamental frequency

Results for SLV condition

Figure 12 presents the numerical results in terms of maximum horizontal acceleration and strain profiles, for each input motion and for the average value (in bold). Amplification of motion is observed in the alluvium soils, especially close to the ground surface where mean peak ground acceleration attains a value of 0.28 g. Peak shear strain levels for each input motion do not exceed 0.2%, with an average value lower than 0.1%. The computed strain levels are low enough that equivalent linear method can be considered applicable. In the same figure, the profiles of mobilized shear stiffness and damping ratio are also plotted.

Figure 13 compares response spectra obtained from numerical analyses with code NTC18 spectra. Specifically, Figure 13a shows the mean calculated spectrum at the ground surface exhibiting large amplification in comparison with mean input spectrum in the period range $T=0.1-0.4$ s where the structural period of the portico is supposed to fall (grey area in the plot); maximum spectral acceleration is around 0.75g. However, the smoothed calculated spectrum at the ground surface (Figure 13b), defined adopting the procedure by ICMS Working Group (2008), is just slightly higher ($\approx 0.65g$) than the code spectrum for soil category C ($\approx 0.6g$).

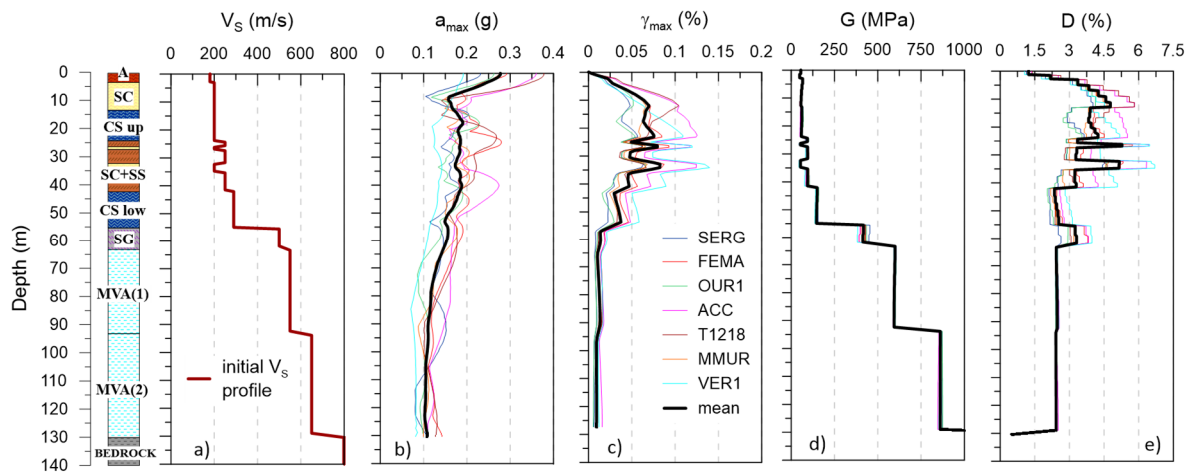


Figure 12: Numerical results in terms of profile of: a) initial shear wave velocity; b) maximum horizontal acceleration; c) shear strain; d) mobilized shear stiffness and e) damping ratio

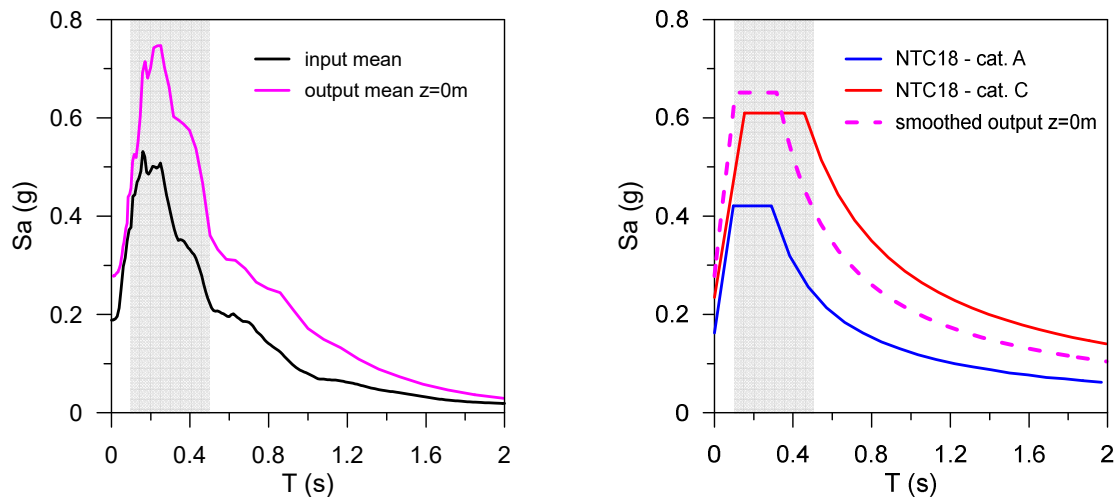


Figure 13: Calculated spectrum from site response analyses at the ground surface vs mean input spectrum (left); comparison between the smoothed spectrum from site response analyses and the spectra for soil class A and C according to NTC18 code (right)

CONCLUSIONS

A one-dimensional numerical site response study conducted in the *Quadriportico* area of the Basilica of Saint Paul Outside the Walls in the city of Rome is presented. A detailed geotechnical model has been set up based on extensive *ad-hoc* in-situ and laboratory site exploration program, further supplemented with data from prior investigations. The model developed has been calibrated in the linear range using experimental HVSR measurements and then it has been used to predict the seismic response under a scenario earthquake corresponding to Life Safety Limit State (SLV).

The experimental validation and the high density of site-specific data provide a minimization of the epistemic uncertainty typically associated with soil profiling. This level of confidence precludes the need for a parametric sensitivity analysis on the subsoil properties, as the model's reliability is inherently guaranteed by the robust empirical dataset. The natural aleatory uncertainty of the seismic demand was comprehensively captured by applying a suite of seven input motions.

As expected, results revealed amplification phenomena at the site, with maximum horizontal accelerations attaining mean peak value at the ground surface of about 0.25g and moderate peak shear strains, anyway lower than 0.1%. Amplification phenomena are also evidenced by the computed average response spectrum at the ground surface showing larger accelerations in correspondence of the range where the structural period of the *Quadriportico* is supposed to fall ($T=0.1-0.5$ s). Unfortunately, establishing a more robust correlation between the numerical site amplification and the structural implications for the *Quadriportico* is a challenging task, due to the lack of structural dynamic data (such as its fundamental period of vibration) even in the scientific literature for this type of structure. The smoothed horizontal spectrum computed at the ground surface compares satisfactory with the site-specific (site class C) code spectrum, with the former being characterized by a slightly higher plateau. The numerical results obtained in this study highlight the relevance of local conditions on the seismic response at the site and corroborate the occurrence of damages in the area over time and offer valuable insights to inform future restoration strategies and preservation efforts

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