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THE ROLE OF UNDERGROUND ARCHAELOGICAL REMAINS ON THE SEISMIC RESPONSE OF A HISTORIC SITE

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Abstract

Italy has an exceptional monumental and cultural heritage that, unfortunately, is often damaged by catastrophic seismic events. The reconnaissance surveys following strong earthquakes have highlighted the high vulnerability of monuments, typically masonry buildings dating back to several centuries ago. Nowadays the seismic safety of historic buildings can be assessed more reliably through a multi-step analysis procedure, where the dynamic identification of the structure is obtained first and then the seismic analysis is performed. In both stages, the geotechnical model of the subsoil should be as accurate as possible, by taking into account the geological and geotechnical setting of the site and any other discontinuity embedded below the ground level. The paper tries to shed light on the role that underground archaeological remains play on the foundation input motion of a masonry bell tower. For such an aim, a parametric study was carried out considering different configurations of the historical ruins embedded in the soil deposit. It was found that in some cases the buried masonry walls could alter both the frequency content and the maximum acceleration of the input signal at the base of the monument. Worst the case of embedded ruins with a grid spacing comparable to the characteristic dimension of the tower foundation.

Keywords: Soil-Structure Interaction, Underground Archaeological Remains, Masonry Bell-Tower, Seismic Response, Cultural Heritage.

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1 INTRODUCTION

Italy, like many other ancient countries in the world, is rich in historic buildings, built over the centuries to express the identity of the native populations but also the power of various foreign dominations. A borderland and easily accessible by sea, Italy has always been a place of conquests, wars, commercial exchanges, but also interweaving of different cultures, which have created one of the most appreciated artistic and archaeological heritage in the world**.** Among monuments, the masonry towers are distinctive elements of the cultural heritage of many towns, such as the iconic case of San Giminiano town in Tuscany.

Civic, clocks, bell or watch towers are often quite tall because in the past they had a defensive function as well as a symbol of power. Many cases are reported in the literature of towers that have suffered extensive damage or collapsed, mostly under seismic actions [1-4].

To assess the seismic safety of ancient towers, reliable numerical models should be developed, accounting also for soil-structure interaction [5-[7]. The interaction with the underlying soil should be taken into account especially when the masonry towers are very slender and placed on soft soils; in this case, the assumption of a fixed constraint at the base of the structure should be avoided. Although complex and time-consuming, continuum approaches or direct methods should be preferred since both the structure and soil response may be simulated at once [8].

In seismic-prone areas, heritage structures have often been raised on soils that already had their own history. It is not uncommon to find a variety of waste materials or reworked soils in the shallower layers of the subsoil, which incorporate remains of demolitions, renovations or excavations of ancient buildings or structures. It is not easy to reconstruct the precise geometry of these archeological remains since in many historic centers both excavations and boreholes may be prohibited by ministerial institutions (e.g., the Superintendence for Cultural Heritage in Italy). Therefore, different types of non-invasive techniques, common both in the engineering and archaeology field, are used to map the location and geometry of the buried remains [13]. In the past 60 years, survey methods such as geophysical prospecting, HVSR, tomography, electrical resistivity technique, ground-penetrating radar (GPR), and electromagnetic method have become widespread to investigate the subsoil due to their speed of execution and instrumentation technological advancement [14].

The shallow soil layers and anthropogenic cover generate a huge degree of uncertainty from the geotechnical viewpoint in what concerns, for instance, the shear wave velocity profile provided by surface dynamic tests as MASW or SASW, or characterization of soil properties [18]. Moreover, the archeological ruins represent a solid discontinuity, characterized by a certain stiffness contrast with respect to the free-field soil. This contrast, more or less accentuated depending on the ruin quality and geometry, is expected to affect the seismic motion transferred to the superstructure [14].

The paper refers to the case-history of Santa Sofia bell tower in Benevento (Italy). The bell tower is part of a monumental complex recognized as a UNESCO site. The dynamic identification of the tower has already been conducted and detailed in [19] while in [20] the role of soil-structure interaction on the dynamic behavior of the structure has been investigated through numerical approaches of different complexity.

The focus of the present study is to ascertain if the underground ruins, placed below and around the bell tower foundation, may affect the foundation input motion (FIM) and consequently the seismic response of the monument. To this aim, a parametric study was carried out by assuming different configurations of the underground remains.

2 CASE STUDY

The monumental complex of Santa Sofia in Benevento (IT) was recognized as a UNESCO site in 2011 because expression of the power of Longobards in Southern Italy. The Longobards migrated from northern Europe and developed their own specific culture in Italy where they ruled over vast territories from the VI to the VIII centuries.

The Santa Sofia complex comprises the bell tower, the church (A.D. 758-768), the monastery (XII century), and the fountain (A.D. 1810). The tower has approximately a total height of 26 m. It was built in 1703 after the severe earthquake of 1688 caused the collapse of the original bell tower coeval with the church. The construction (Figure 1-a) consists of a main body, a belfry and a pinnacle. It has a square base with a side of approximately 5.2 m. A stone staircase runs from the base to the top. There are two masonry vaults about 12.70 m above the ground level and several little openings at different levels. The tower foundation has a plan of 6.5 m x 6.5 m and a height of 2 m (Figure 1-b). The masonry texture is quite variable as the tower is made up of cladding masonry composed of regular or prism-shaped stones of different thickness, while internally it is made of heterogeneous masonry with red clay bricks, natural stone conglomerate and medium-sized pebbles while solid bricks were used for the vaults. By carrying out in situ inspections and photographic surveys with a drone, a detailed and accurate identification of the structure geometry at different elevations was achieved. All geometrical and material details may be found in [19].

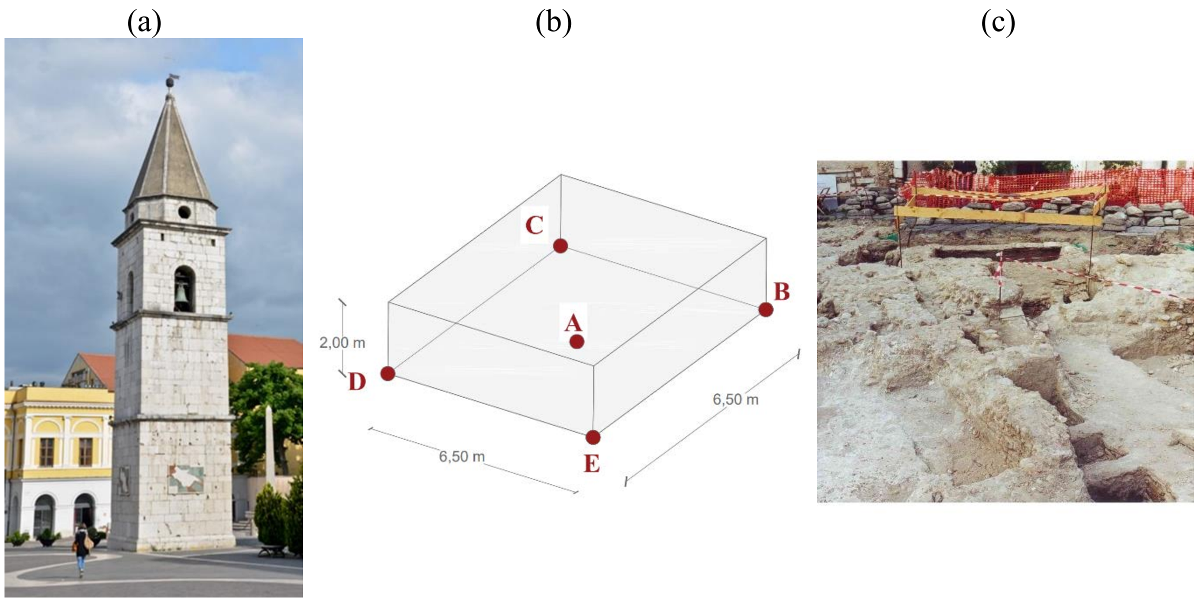


Figure 1. A view of the bell-tower (a); the foundation geometry (b); embedded archaeological remains (c).

Thanks to previous surveys performed at the site of interest [21] and data acquired from more recent geotechnical and geophysical investigations [19], a quite reliable subsoil characterization was achieved. Starting from the current ground level, the following soil layers were identified: an artificial fill up to a depth of about 3 m, comprising reworked soils resulting from excavations, demolitions and/or restructuring of buildings of the ancient city of Benevento; yellow sands between 3 m and 13 m depth (containing reworked anthropogenic remains of the ancient city up to a depth of 5 m); and well-cemented conglomerate between 13 m and 47 m of depth.

The existence of underground masonry ruins is not only corroborated by boreholes and tomography carried out at the site [19], but also documented by photos of the archeological surveys carried out during the pavement restoration about two decades ago (Figure 1-c). Nevertheless, there is no exhaustive information on the geometry and spatial arrangement of these ancient remains. For this reason, in this research work a parametric study was carried out by varying the configuration of the underground walls.

3 NUMERICAL MODEL

A complete 3D model of the tower with the soil and the embedded ruins was generated through the finite element (f.e.) software MIDAS FEA NX [19]. The structural model (Figure 2-a) was made of tetrahedral solid elements with a size of approximately 0.2 m. A linear-elastic constitutive model was assigned to all construction materials, with the values of the masonry Young modulus and specific weight listed in Table 1.

Element	Elastic Modulus E [MPa]	Specific weight γ[kN/m^3]
External leaf	12146	23
Shaft	6073	21
Belfry	2267	18
Vaults	2915	17
Foundation	4763	19

Table 1 Elastic modulus and specific weight assigned to the different types of masonry.

The soil domain has plan dimensions of 50m x 50m and a height of 47m. This volume was properly calibrated to avoid boundary effects and minimize wave reflection during the seismic analysis. The size of the soil elements was also optimized to assure a reliable propagation of the selected seismic signals in relation to the wavelengths involved. The adopted soil parameters are listed in Table 2. To represent soil non-linearity by means of the equivalent linear procedure, the G/G_0-γ and D-γ curves adopted for the seismic microzonation of Benevento and L'Aquila (characterized by similar soils) were adopted [19].

Layer	Depth [m]	V_s [m/s]	G_0 [MPa]	γ [kN/m^3]
AF	0 - 3	270	120	17
YS	3 - 13	640	820	20
CC	13 - 47	1340	4100	23

Table 2 Soil parameters adopted

In the parametric analysis carried out to assess the role of the archeological findings, two different configurations of the masonry walls embedded below the Santa Sofia square were figured out basing on the available documentation. The two configurations were assumed to be centered with respect to the tower foundation and characterized by a grid spacing of 4m or 6m as sketched in Figure 3. At this stage of the work, the buried walls were characterized with the same physical and mechanical parameters assigned to the material of the tower foundation (Table 1). In addition, the wall height and thickness were assumed to be equal to 2m and 0.70m, respectively.

For the coupled system shown in Fig. 2, during the dynamic analysis suitable free-field conditions were imposed along the vertical boundaries while the input motion was applied at the base of the model by removing the corresponding displacement constraint (see Figure 2-b). The selection of the input signals was consistent with the requirements on spectrum compatibility imposed by the current Italian technical code (NTC2018) [19].

Seven groups (x and y components) of spectrum-compatible accelerometric signals recorded on rock outcrop (a_g = 0.257g, $T_{R,SLV}$=475 years, Use class II) were selected through the tool REXEL [19]. The fourteen input signals (Figure 4) were transported to the model base by 1D deconvolution analyses and then re-propagated upward in the 3D soil domain of Figure 2.

4 RESULTS

This section illustrates the results of the dynamic analyses aimed to evaluate how the buried masonry ruins influence the input motion at the bell tower foundation (FIM). To this end, the time history and the Fourier spectrum of the acceleration at the central point (Point A) and edge (Point B) of the foundation have been shown (Figure 1b).

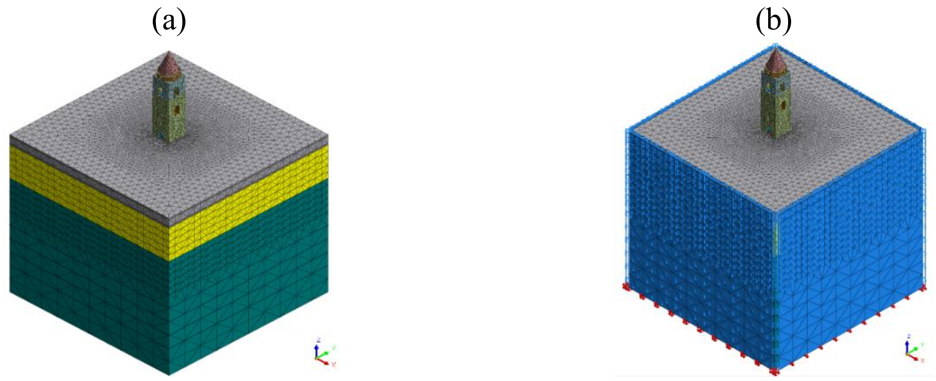


Figure 2 Full model with soil layering (a) and boundary conditions adopted in the seismic analysis (b).

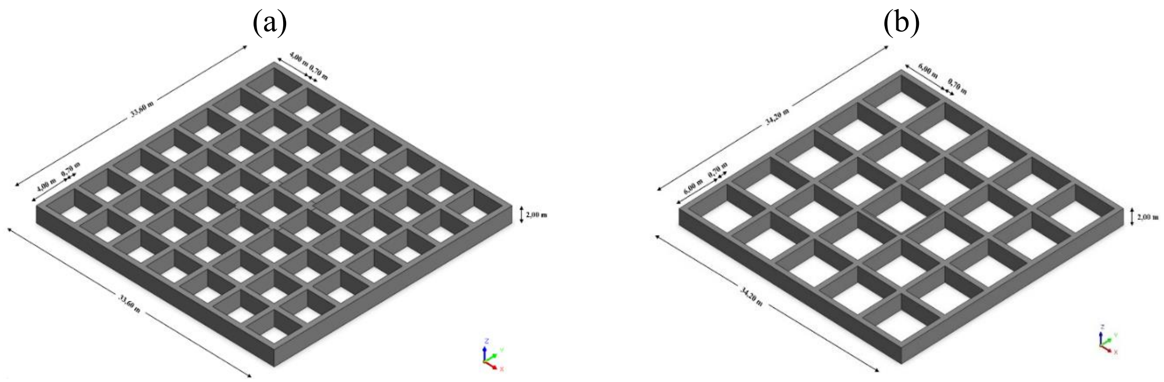


Figure 3. Reference schemes adopted for the underground remains with grid spacing i=4 (a) and i=6 (b).

For the sake of shortness, two representative signals (000242 and 006332) among all the natural accelerograms shown in Figure 4 were selected to comment on the seismic response of the historic site of Santa Sofia. The choice fell on these two signals because they differ significantly in both frequency content and waveform. Figures 5 and 6 show the time history and Fourier spectrum of the acceleration computed along x in the two reference points for signal 000242 and 006332, respectively. In addition to the predictions obtained with considering or disregarding the buried masonry remains, the input signal deconvoluted at the base of the f.e. model was also added for comparison.

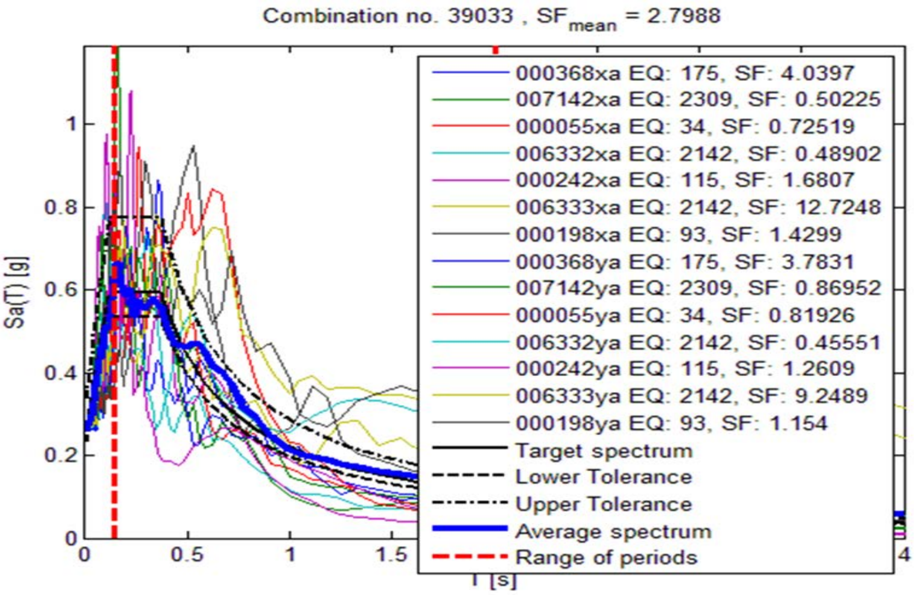


Figure 4. Selected spectrum-compatible input signals

With reference to Figure 5a, it may be observed that in Point A the maximum amplification in acceleration is obtained for the buried ruins having a spacing of 6 m, with an increase of PGA of approximately 30% with respect to the free-field condition (i.e., subsoil without archeological remains). The same effect occurred at the edge of the foundation (point B), with an increase of the maximum acceleration of approximately 15%. As the Fourier spectra concern (Figure 5b), in all cases the signal was amplified at frequencies close to the higher-order eigenfrequencies of the tower, which were estimated around 12 Hz [19].

For signal 006332, characterized by a more impulsive nature as typical of near-source conditions, the maximum acceleration is obtained again for a spacing among the embedded ruins equal to 6m. In this case, a percentage difference of about 20% with respect to the free-field soil was obtained. The Fourier spectrum highlights that the buried masonry amplifies the FIM in the medium-high frequency range.

Finally, Figure 7 shows the average acceleration response spectra (continuous line) along the x and y direction. The corresponding standard deviation curves are represented with dashed lines. It is evident a significant increase in the spectral accelerations for the larger spacing of the embedded ruins. This response is worthy of being considered in the assessment of the seismic safety of the superstructure.

The main outcome of this study is the modification of the FIM for the Santa Sofia bell tower due to the presence of the underground remains in the subsoil. This response may be explained considering that the embedded masonry walls, which represent discontinuities in the shallower layers of the soil deposit, could generate complex interference phenomena among the incoming, reflected and refracted seismic waves before the structure itself starts oscillating. In historic sites, this interference depends on the underground wall/soil stiffness contrast, the clear spacing of the ancient ruins and the wavelengths involved, with all the important implications from the design viewpoint.

The performed study deserves further investigation by performing additional parametric analyses to account for different heights and configurations of the underground walls together with different physical and mechanical properties of the buried archeological ruins.

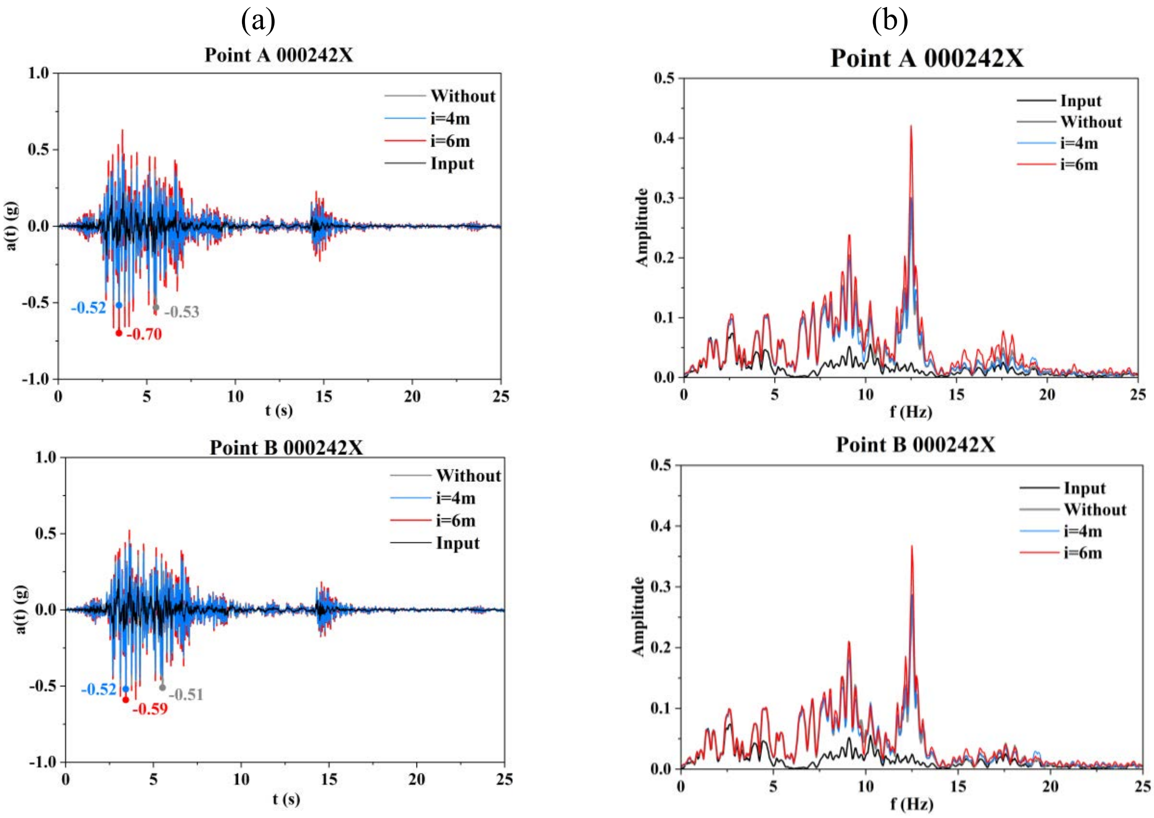


Figure 5. Time histories (a) and Fourier amplitude spectra (b) of the x acceleration in points A e B of the tower foundation. Input signal 000242

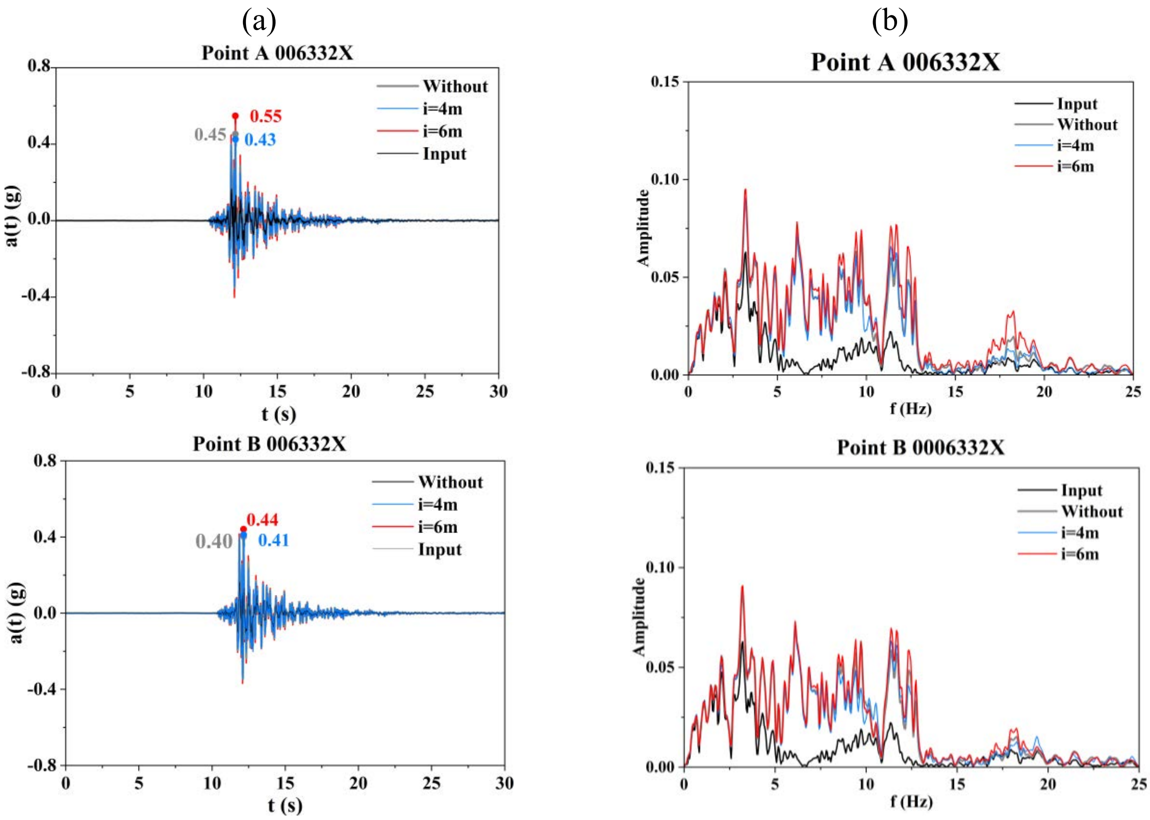
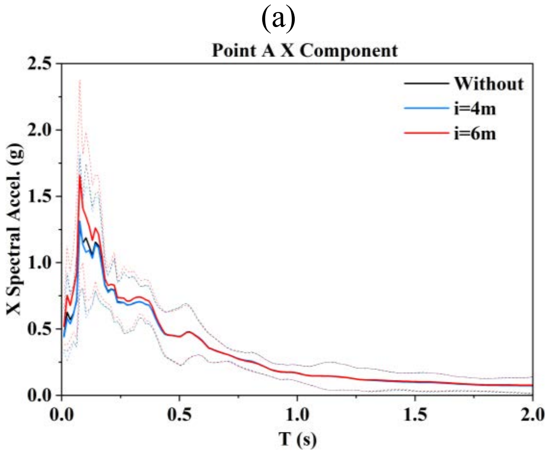


Figure 6. Time histories (a) and Fourier amplitude spectra (b) of the x acceleration in points A e B of the tower foundation. Input signal 006332



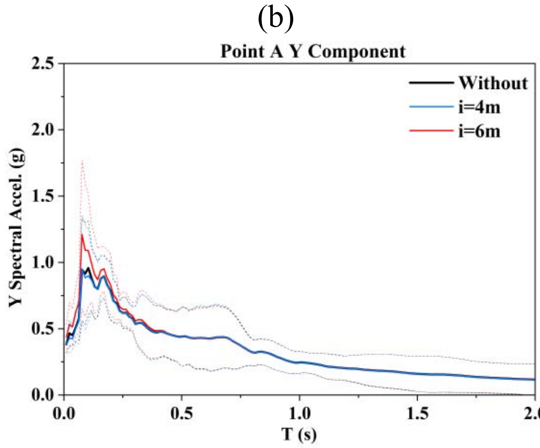


Figure 7. Acceleration response spectra (average ± stand. dev.) in point A of the tower foundation along direction x (a) and y (b)

5 CONCLUSIONS

Historic buildings are often built on historic soils, rich of underground archaeological remains that could affect foundation and structure response. The paper tried to shed light on this issue by referring to the iconic case-history of Santa Sofia bell tower in Benevento (Italy). A comprehensive 3D finite element model containing the subsoil, the bell tower and the underground ruins interacting with the monument was developed. By changing the configuration of the embedded walls, an amplification of the input motion at the base of the tower was ascertained, especially in the case of embedded ruins with a grid spacing comparable to the size of the tower foundation. It was found that for some input signals the buried masonry walls modified the foundation input motion (FIM), with an amplification in the frequency range corresponding to the higher vibration modes of the bell tower. As a future perspective of the work, additional parametric analyses will be carried out by implementing different geometrical configurations and mechanical properties of the underground buried masonry walls.

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