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Archaeoseismological project in Ostia: Tracking evidence on seismic damage by nonlinear numerical simulations

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ABSTRACT

Within the framework of an archaeoseismological project in Ostia (Italy), this paper discusses archaeological evidence of historic seismic damage of one of the arcade pillars in a building originally used as a warehouse for goods - "Piccolo Mercato" - located in the North-West part of the archaeological site. This interdisciplinary study is aimed at providing an interpretation of the detected damage by performing some numerical simulations. One of the pillars was represented by a finite element (FE) model, considering natural ground motion records. FE model allowed to conduct complete nonlinear time-history analyses. The results cross-validate the already provided interpretation of the historic damage, and suggest a possible dateline.

1. Introduction

Ancient buildings represent potential records of long-term seismicity since their construction. Traces of past earthquake effects have however to be decrypted below the heavy mantle of restorations (like anastylosis, integration and reinforcements) that through the decades have modified their original structures (Marino, 2009; Pecchioli, 2003). Damage identified as seismically induced, and general information on earthquake characteristics, can be analyzed based on the observed failure modes. In this respect, the classification of Earthquake Archaeological Effects (EAE) based on the seismic deformation of buildings and monuments within ancient urban areas proposed in Rodríguez-Pascua et al. (Rodríguez-Pascua et al., 2011) can be a significant guideline. EAE used with an interdisciplinary approach and combined with ad hoc structural analyses has been proven to be an efficient method (Kázmér, 2014).

Quantitative methods along with a multidisciplinary approach are considered relevant to many researchers in this field (Galadini et al., 2006; Hinzen et al., 2011). In this regard, current methodologies capable of supporting the outcomes of archaeological and historical studies are using innovative photogrammetry processes for data acquisition, 3D reconstructions and Digital Elevation Models (Forlin et al., 2018), mechanical methods of analysis and structural engineering knowledge, discrete elements (DE) models (Hinzen et al., 2013), analysis of failure mechanisms and damage scenarios (Pecchioli et al., 2018; Stiros, 2020), and also finite element (FE) models to perform advanced numerical simulations (Caputo et al., 2011).

The ancient Roman harbor of Ostia is one of the archaeological sites that can provide a wide range of damage on structures and partial collapses possibly related to earthquakes. The ancient city port was built on a sandy soil, and was regularly damaged by natural calamities and subsequently repaired. Diffuse collapses that have affected both civil and monumental buildings can be ascribed to a number of causative agents, including: natural degradation, prolonged abandonment, lack of maintenance and spoliation, natural disasters such as flooding, fluctuations by low depth of groundwater, and - not least - also earthquakes.

In 2017 and 2020, seismic surveys were carried out by placing sensors in some areas of the ancient city and in Portus. Overall, it was hypothesized the occurrence of a W-SW/E-NE fault located on the northern boundary of the city, which was probably active in the past. It suggested that this activity was accompanied by seismogenic phenomena which may be responsible for the damage of the buildings, causing local earthquakes as alternative hypothesis of their Appeninic origin (Pecchioli et al., 2018).

In the archaeological site of Ostia, the colonnade in the "Piccolo Mercato" is particularly interesting to detect historic seismic effects. R. Lanciani (Lanciani, 1918) already documented and interpreted the significant damage of a pillar of this colonnade as the effect of its torsional behavior under earthquakes. More recently, a mechanical analysis on

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some case studies was conducted with the aim to cross-validate the results of the archaeological-historical interpretation of the dynamic collapses (Pecchioli et al., 2018).

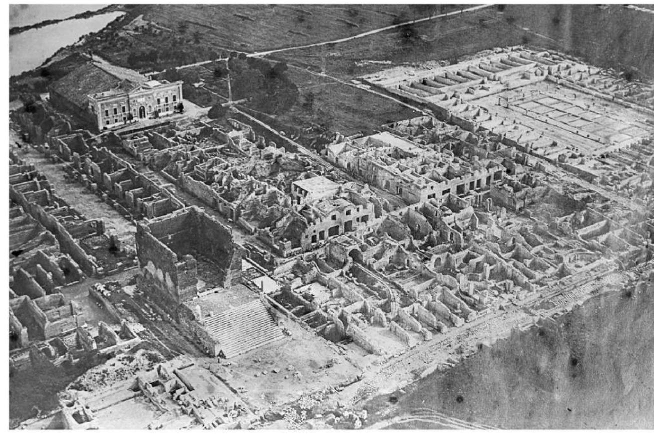
In this paper, simple numerical simulations which encompass nonlinear time-history analyses under natural ground motions are performed to evidence the damaging earthquake effects. The analyses aim to provide an interpretation of the damage observed on one of the pillars of the "Piccolo Mercato". In particular, they are performed to investigate if the damage can be attributed to a seismic action that affected the arcade when its vaulted roof was still in place or when it had already been lost.

2. The ancient roman city of Ostia

Ancient Roman colony named Ostia is one of the most important archaeological sites dating back to ancient Rome. Being 19 miles from Rome, its current geographical location is around 2 miles away from the sea. However, in antiquity, its position was different, and the relationship between the river and the sea certainly influenced the catastrophic events that affected it.

Ancient traditions date its foundation to 620 BC by the hand of the fourth king of Rome, Anco Marzio, for reasons related to exploiting the salt marshes placed at the mouth of the Tiber River (hence the name Ostia, from *ostium* = mouth). As a port city, the ancient Ostia was of fundamental importance for Rome (DeLaine, 2002): it was the representative façade of the capital towards the sea. Hence, it had to function as a commercial centre and transhipment point for goods. It lay on the alluvial coastal plain of the Tiber River, above sandy and clayey fluvial to coastal sediments saturated with water and rich in peat layers. After the progressive westward shifting of the coastline due to the progradation of the river's delta, the city is presently located within the coastal plain, in a sector characterized by a 20–40 m thick package of alluvial sediments (Marra et al., 2020).

Two aerial views of the archaeological site in 1919 and today are provided in Fig. 1.



(a)

(b)

Fig. 1. Aerial views of Ostia;

Fig. 1. Aerial views of Ostia; (a) from the Zeppelin (B-2430, photo archive, 1919, PAOA) and (b) nowadays.

2.1. Natural disasters in Ostia

By the Ancients, many descriptions about the natural disasters in the Mediterranean area are available. Each society tried to explain the events according to its culturally specific way of understanding reality. Since ancient times an empirical and intuitive approach has regulated the way of building and strengthening masonry structures. However, within the framework of a stubborn fatalism, there is a repetition of the construction systems seemingly devoid of seismic measures until almost a century ago, when the first seismic regulations began to be imposed.

A strong seismicity hazard has traditionally characterised the Mediterranean area. Ancient buildings preserve traces of seismic events, and it is often possible to identify the signs of both the earthquake and measures taken by man to repair or counteract its effects.

The city of Ostia was built on sandy ground and was regularly affected by natural disasters. Changes in the balance of the land-river-sea system have impacted urban development as probably the construction system.

Diffuse collapses, which affected civil and monumental buildings, can be attributed to several different causes, including earthquakes. A large number of buildings were erected on unfavourable ground conditions, repeatedly damaged and subsequently repaired. These buildings nowadays show the attempts to counteract the adversities of the ground conditions, even if the damage is often difficult to classify with regard to its causes.

About possible notes describing the collapsed buildings, the archive in Ostia shows several historical photos of archaeological excavations. On the basis of the photo documentation, diaries, inscriptions, archaeological investigations, historical sources etc. it can be reconstructed the probable cause of the dislocation of some monuments from their original position. The archaeologist Rodolfo Lanciani was a pioneer from an archaeoseismological point of view. His notes on evidence of seismic effects of some monuments in Ostia (Fig. 2) nowadays represent a reference for interpreting their collapse and supporting the hypothesis of earthquakes (Lanciani, 1918).

2.2. Historic seismic activity

Ancient earthquakes are often mentioned without a precise geographical location or fortuitously recorded in a single location that has suffered its effects, even if far away from the earthquake's origin, but where the epicentre is mistakenly placed. Often these *ante litteram* seismic observatories were important political or commercial centres, such as Rome, Ravenna or other cities/places that, depending on the period, held or somehow catalysed the regional presence of the sources.

The Romans were able to use preventive measures to achieve a targeted static adaptation of the structures. These measures as a holistic approach had a positive effect also on preventive earthquake protection. During the Roman Republic and Imperial period, significant progress was made in building technology and construction. Many basic elements of the applied construction techniques already demonstrated a high seismic load capacity (Giuliani, 2012). Since the Republican period, there was a development in the construction technique of multi-storey buildings, especially for the quality of mortar (under Hadrian) and the use of pozzolanic earth. When opportunely recognized, seismic damage affecting ancient buildings is a major source of information about the parameters of past earthquakes (intensity, directivity, etc.). Of course, besides the seismic parameters, the response to an earthquake depends

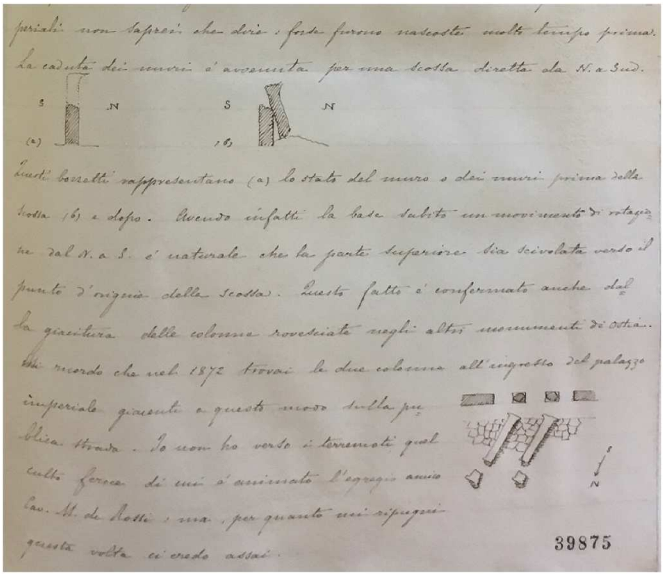

periali non saprei che dire: forse furono nascoste molto tempo prima.
La caduta dei muri è avvenuta per una scossa diretta da N. a Sud.
S N S N
(a) (b)
Questi bozzetti rappresentano (a) lo stato del muro o dei muri prima della
scossa (b) e dopo. Avendo infatti la base subito un movimento di rotazio-
ne dal N. a S. è naturale che la parte superiore sia scivolata verso il
punto d'origine della scossa. Questo fatto è confermato anche dal-
la giacitura delle colonne rovesciate negli altri monumenti di Ostia.
Mi ricordo che nel 1872 trovai le due colonne all'ingresso del palazzo
imperiale giacenti a questo modo sulla pu-
blica strada. Io non ho verso i terremoti quel
culto feroce di cui è animato l'egregio amico
Cav. M. de Rossi; ma, per quanto mi ripugni
questa volta ci credo assai.
S
N
39875

Fig. 2. Notes and drawings by Rodolfo Lanciani (Lanciani, 1918), illustrating two cases that the Author interpreted as earthquake-induced failure affecting the columns and a wall in the Palazzo Imperiale. Photo: Istituto Nazionale di Archeologia e Storia dell'Arte, Fondo Lanciani, colloc. Roma XI, 31 (http://digi.ub.uni-heidelberg.de/diglit/bcom1917/0007).

on the structural characteristics of the building, including a defect in design, employed material, craftsmanship, etc. (Cangi, 2005).

Earthquake dynamic response also depends on the site geology, enhancing ground shaking (e.g., site effects). In this regard, in 2017 and recently in 2020, two investigations of seismic effects were carried out, placing sensors in some areas of the ancient city with relevant seismic traces.

According to the first investigation, the foundations are built in alluvial soils and normally the sand is the main component probably interacting with the seismic waves and contributing to minimize the seismic shock (Pecchioli, 2020). From identifying several morphological structural elements, it has been hypothesized the presence of a W-SW/E-NE fault located on the northern boundary of the city, which was active in ancient times (Fig. 3). Therefore, it may suggest the occurrence of seismogenic phenomena that have originated local earthquakes damaging buildings in Ostia (Pecchioli et al., 2018).

Conversely, by the last results from the 2020 campaign, the seismologist has hypothesized another interpretation, which supports an Appeninic seismogenic origin with high intensity. Two interpretations that open up new, as yet unexplored horizons.

3. "Piccolo Mercato"

The name "Piccolo Mercato" (I, VIII, 1) refers to a building originally used as a warehouse for goods, located to the North-West of the Forum, near the river bank and next to one of the best preserved sections of the walls of the Republican castrum (Fig. 4).

This complex was built around 120 AD (*Opus mixtum*) with the

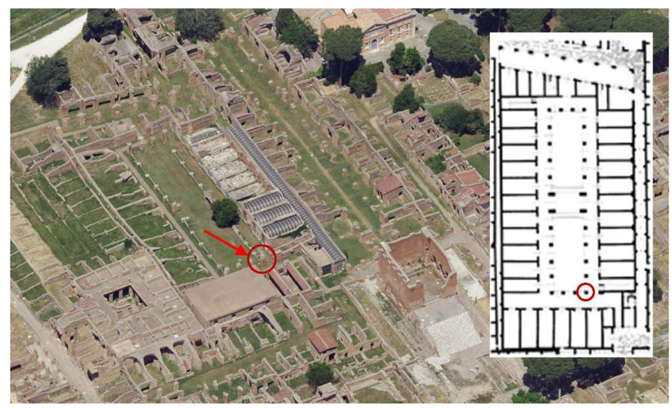


Fig. 4. Aerial view of the "Piccolo Mercato" in the archaeological site and plan with the location of the case study (the red circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

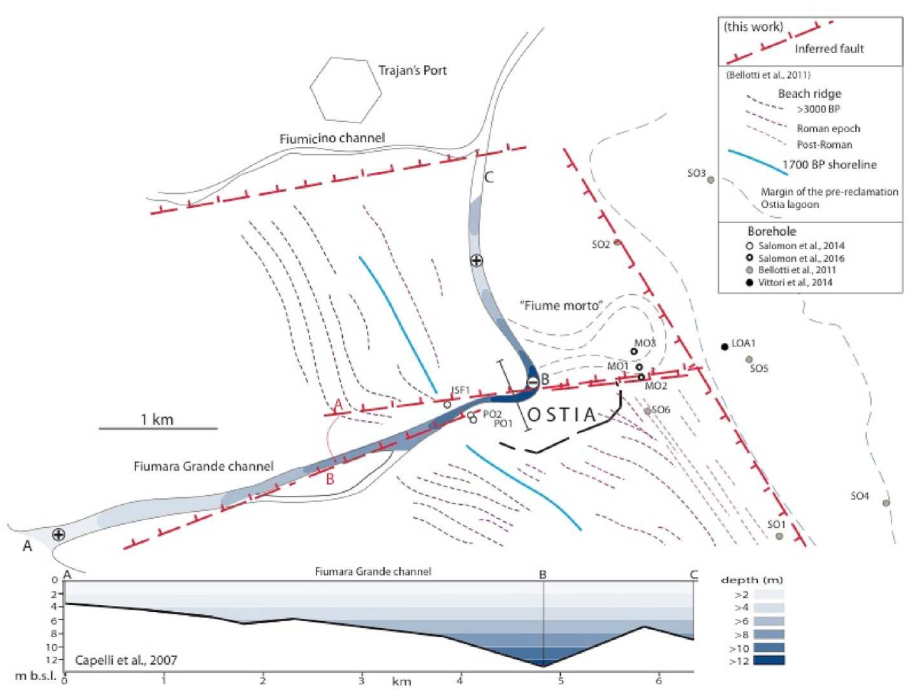


Fig. 3. Structural-geomorphological map of the investigated area (from (Marra et al., 2020)).

construction of Claudius and Trajan's ports. Pietro Rosa excavated the building in the early 1870s. It was an horreas of considerable size which occupied an area of over 46,000 square metres (about 1/7 of the city) made up of a series of rooms arranged around a backyard. The North-Eastern part presents some Severic interventions (*Opus latericium*), and part of the Castrum wall is preserved in the South side.

The "Piccolo Mercato" together with the neighbours Horrea (I, VIII, 2), the Caseggiato dei Misuratori del Grano (I, VII, 1) and the Horrea Epagathiana were planted according to a predetermined master plan. It was designed in Hadrian's time to form the district of the docks on the Tiber. The main entrance is in the northern part, with 28 rooms about 7 m high and covered by barrel vaults in the West, South, and East of the courtyards. They have been locked with two doors. Above the doors were square windows and slit windows in the rear walls for light and ventilation. In the South-East corner, there was a second entrance.

As the proximity of the river, docks could not be different from the activities of loading and unloading goods. In fact, the port of Ostia was configured as a kind of port-channel, with a long quay along the entire left bank and a wider entrance from semicircular shape to the mouth. The gate and the main front were turned to the North, directly connected with the river. This solution also offered the not inconsiderable advantage of increased ventilation, which is useful to lower humidity and keep wheat or other products dry.

The pillar investigated in this paper is shown in Fig. 5. It belonged in ancient times, with other three pillars, to an arcade: it was a corner element where two internal corridors, with a width of 4.70 m and 4.40 m, intersected. The cross-section of the pillar is about 1.1 $\times$ 1.1 m, and the today height is about 6 m. The typology of the vaulted corridors can be deduced from similar cases, such as the Insula degli Aurighi. It is possible to speculate the original presence of a barrel vault with lateral lunettes, pointing to the cross, compatible with rectangular structural modules (corridor wider than the front module).

Focusing on the construction technique of the pillars, it is noticeable that bonding (o leveling) courses of bipedales layers (large bricks ca. 58 cm square) are present that give an aesthetic interval and provide better load distribution. Courses of bipedales are common features in the brick-faced walls of many second-century buildings on Opus Testaceum in Rome. Bipedales were used to carry out the detailed design layout directly on site, with the dimensions measured in situ forming the basis. The pattern of the bonding courses suggests that they were used as organizational tools by setting certain key heights and in at least one case by providing a "benchmark" level to which all walls were brought before proceeding. In addition, normally bonding courses of bipedales and brick linings were used as formwork for vaulting.

All the pillars of the arcade mentioned above show similar damage, which is more evident on the one here analyzed (Fig. 6). This pillar exhibited rotation around its vertical axis at the level of the bipedals. In 1918, R. Lanciani (Lanciani, 1918), attributed this damage to a seismic event, later confirmed in recent literature. Among the other, a kinematic analysis was applied in (Pecchioli et al., 2018) to analyse the crack patterns and to hypothesize the dynamic and direction of the seismic event.

From documentary sources, it seems that around the 3rd century, the complex of the "Piccolo Mercato" was already abandoned due to the growing importance of Portus and consequently it had less use and interest. It is possible that a seismic event around this date could also have affected the town.

The numerical analyses reported in the following are aimed to evaluate the effects of the configuration of the pillar at the time of damage, i.e. with or without the arcade when the damage occurred, in order to allow a possible dateline of the damage.

4. Seismic scenarios and FE analysis

To perform the numerical analyses, a relatively simple FE model of the reference pillar which exhibits possible historic seismic damage (Fig. 6) was built using the FE code ANSYS (Betti et al., 2016; Bartoli et al., 2017). The model was employed to conduct some preliminary dynamic analyses aimed at assessing the possible configuration of this pillar when the damage occurred.

The numerical model is shown in Fig. 7: a block-like model representing the pillar through a series of layered rigid blocks, each connected to the adjacent ones with mono-lateral interface elements. For the rigid blocks an elastic modulus of 2000 MPa and an own weight of 1.800 kN/m^3 was selected. Element SOLID45 were used to model the blocks, while the interface elements between the blocks were modeled with CONTACT178 elements. These elements do not have tensile strength but transfer normal compressive loads; they also ensure a transfer of shear actions between blocks according to an attritive Coulomb model. A friction coefficient equal to 0.4 was assumed. As shown in Fig. 7, the model is made up of ten rigid blocks ($i_b = 10$) and, consequently, nine mono-lateral interface elements ($i = 9$).

To investigate the possible configuration of the pillar at the time of the occurred damage two limit structural schemes were considered. The first one (here named "*cantilever*") intends to investigate the situation in which the seismic event that produced the damage occurred when the vaults of the portico had already been lost. The second scheme (here named "*hinged*") aims to investigate the configuration in which the seismic event that produced the damage occurred when the portico was still present, and the piers were sustaining the vaults.

In the first case, the block-like numerical model has been assumed fixed at the ground but free at the top as a cantilever beam.

(a) (b)

Fig. 5. Pillars of the arcade: a) view from the corridor b) view from the courtyard.

Fig. 6. Historic damage in one of the pillars of the "Piccolo Mercato". The fracture zone due to the twisting of the pillar is clearly visible.

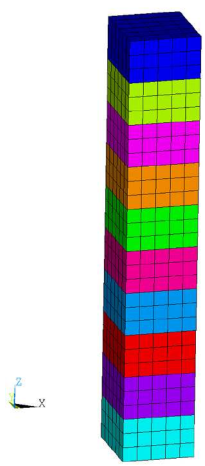


Fig. 7. Block-like numerical model of the reference pillar.

In the second case, appropriate boundary conditions were also introduced at the top to represent the restrained effects induced by the vaulted covering structures of the portico. In particular, ANSYS Constraint Equations (CE) where employed to set-up relations between the DOF's of the top joints of the numerical model. Master and slave nodes were defined, and the master node was allowed to rotate but not to translate. This allowed to create a hinge at the topside of the pillar. For the "*hinged*" case the axial load resulting from the weight of the vaults was considered. This load, estimated based on the archaeological hypotheses about its geometry, was assumed as 19.5 kN and was applied on the top of the pillar.

These two schematic limit cases are quite simple and are solely aimed to have an initial assessment. To compare the two cases a modal analysis was performed, and the first three main mode shapes and frequencies are reported in Fig. 8.

The block-like numerical models of the pillar were employed to perform time-history analyses. As input ground motion, two bi-components natural accelerograms were used. The first one was recorded in 1997 at Colfiorito (Umbria, Italy), and has a magnitude of 4.54, a value that falls within the range of events given in (Marra et al., 2020) that can be referred to as the Appeninic seismogenetic origin. The second accelerogram, recorded in 2016 in Roma, with a magnitude of 3.6, can represent a local event. Both Colfiorito-1997 and Roma-2016 were recorded in ground type B.

The seismic records were scaled (with the same scale factor equal to 0.5 for all the components) to obtain a x-PGA of 1.05 m/s^2 and a y-PGA of 1.24 m/s^2 for Colfiorito, and a x-PGA of 1.2 m/s^2 and a y-PGA of 0.99 m/s^2 for Roma. The accelerograms of the x- and y-components of the two scaled natural earthquakes are reported in Fig. 9, while their response spectrums in terms of acceleration, velocity and displacement are shown in Fig. 10.

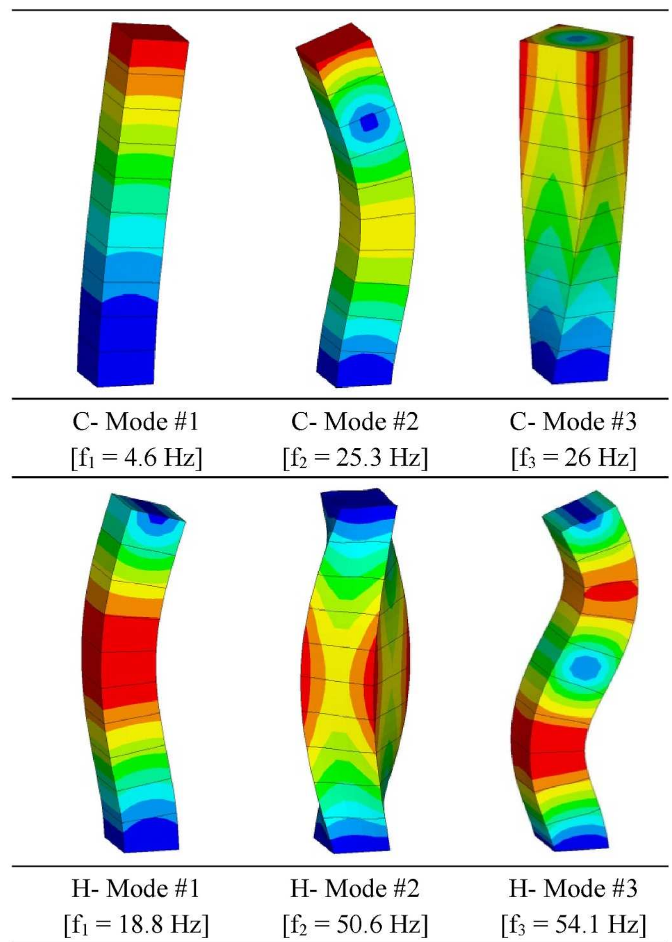


Fig. 8. Mode shapes and main frequencies: C = "*cantilever*" case, "H" = "*hinged*" case.

The time-history analyses were performed applying the two selected accelerograms for 15 s; thereafter, the model can vibrate freely.

To compare the results of the analyses, the relative rotation $\Delta\varphi_i$ and displacement Δu_i at the center G of each block with respect to the previous one during the time-histories were computed. These parame-

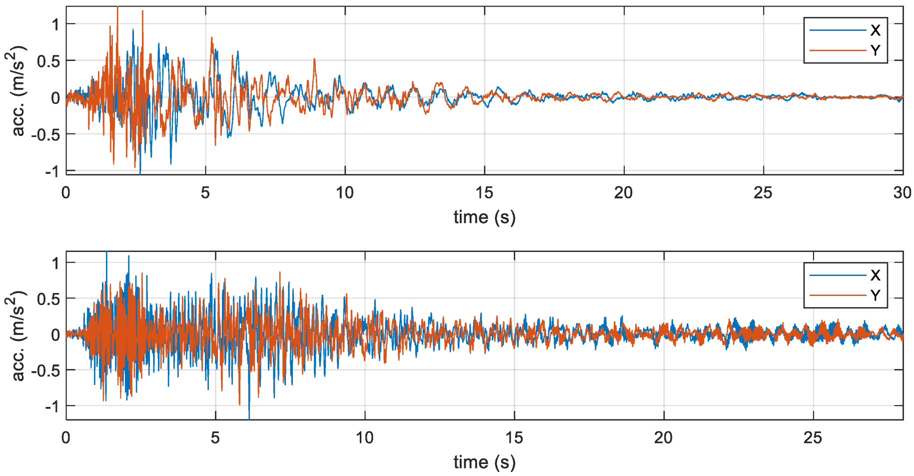


Fig. 9. Accelerograms of the *x* and *y* components of the (scaled) natural earthquakes used: Colfiorito-1997 (up) and Roma-2016 (down).

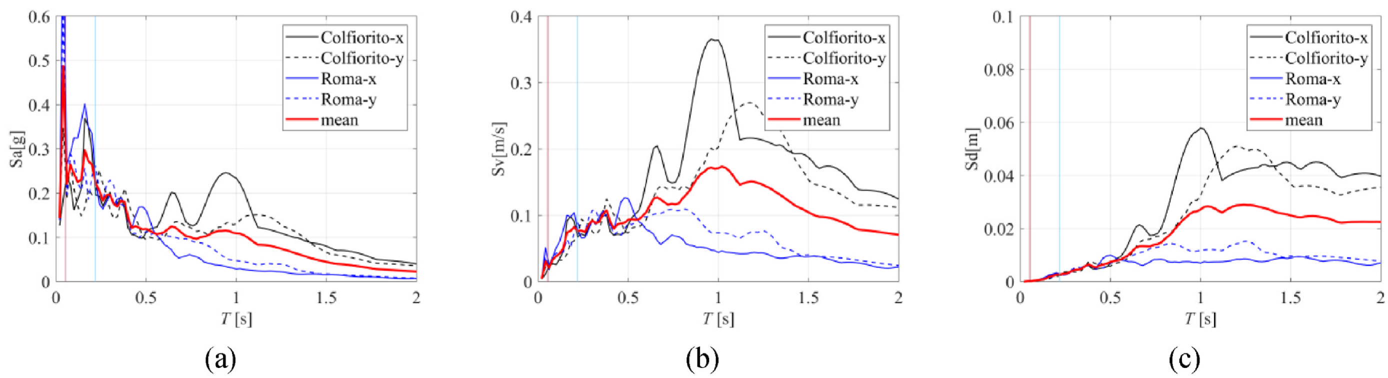


Fig. 10. Response spectrums of Colfiorito-1997 and Roma-2016 ground motions: (a) acceleration, (b) velocity and displacement (c).

ters have then been non-dimensionalized to the corresponding maximum values attained during the whole time-history, and are reported in Eqs. (1) and (2):

$$\Delta\varphi_i = \frac{\varphi_{G,ti+1} - \varphi_{G,bi}}{\max\limits_i \left(\max\limits_t \left| \varphi_{G,ti+1} - \varphi_{G,bi} \right| \right)} \quad (1)$$

$$\Delta u_i = \frac{u_{G,ti+1} - u_{G,bi}}{\max\limits_i \left(\max\limits_t \left| u_{G,ti+1} - u_{G,bi} \right| \right)} \quad (2)$$

For the "*cantilever*" model, Fig. 11 and Fig. 12 show the time-histories of the displacements Δu and rotations Δφ as obtained at the interfaces, numbered from 1 to 9 from the bottom to the top of the pillar and denoted as "*i#*". The analogous results for the "*hinged*" model are reported in Fig. 13 and Fig. 14.

From both Figs. 11 and 12 it is possible to observe a residual displacement and a residual rotation localized at the first interface *i1*, i.e. the one near the pillar foundation. On the contrary, the results for the "*hinged*" case depicted in Figs. 13 and 14 show that the maximum relative rotations and the maximum relative displacements are located in the highest part of the pillar, mainly affecting the three interfaces closest to the top.

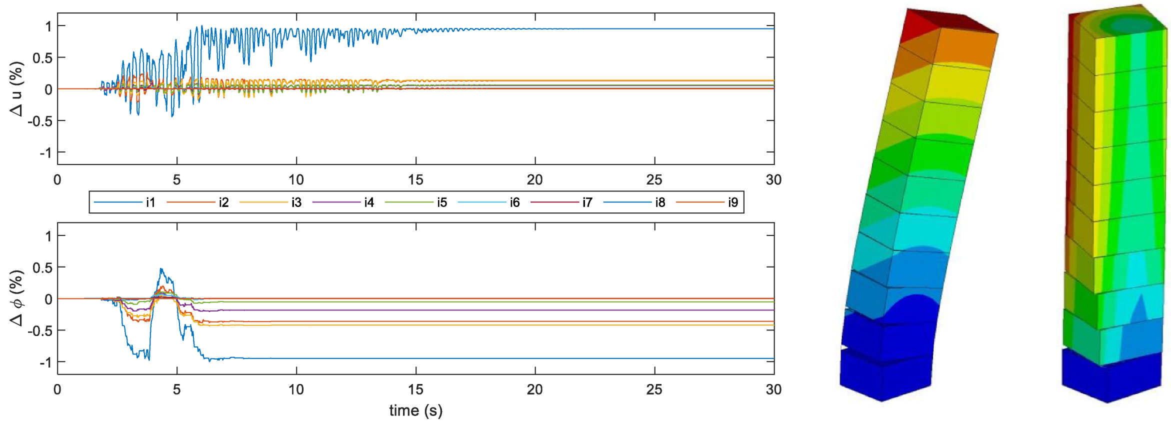
Even if preliminary and quite simple, these analyses confirm that the observed damage can be ascribed to a seismic action and suggest that the damage occurred in the pillar when the portico had already been lost. Further analyses will be performed by considering additional seismic records and more refined numerical models and modeling approaches.

5. Conclusive remarks and future research

The Roman town of Ostia provides a unique opportunity to study a wide spectrum of structural damages affecting different typologies of ancient buildings. The geologic feature of the soil represents an important aspect in the response of a building to seismic shaking. The campaign of seismic noise measures and a review of available stratigraphic logs performed in the investigated area for civil engineering purposes have provided first information on the subsurface geology and two interesting hypotheses of possible earthquakes.

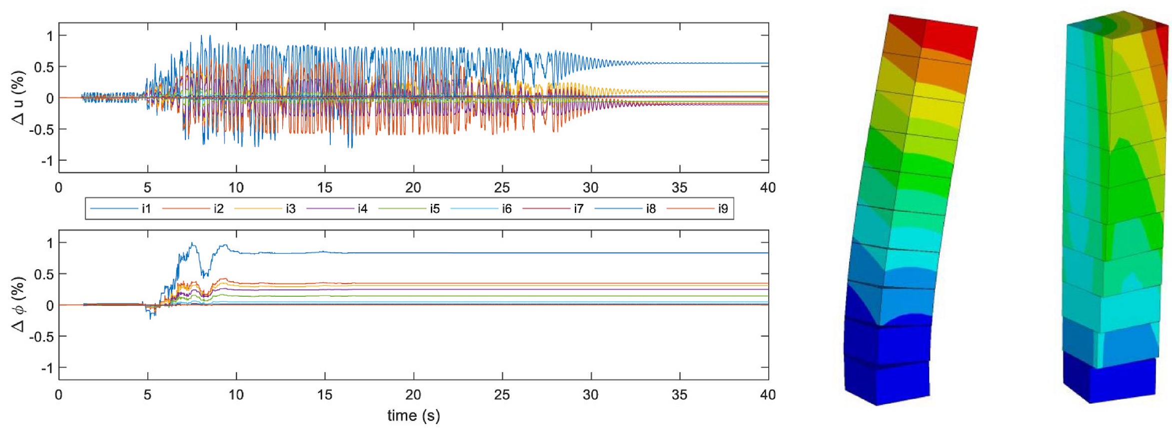
Through the nonlinear time-history FE analyses, performed under natural earthquake records, a possible dateline of the damage was obtained. Two limit cases were considered: a first aimed to investigate the configuration in which the seismic event that produced the damage occurred when the portico had already been lost; a second aimed to investigate the configuration in which the seismic event that produced the damage occurred when the portico was still present. According to the comparison between the numerical results and the observed historic damage it is possible to hypothesize that today's seismic damage is attributable to an earthquake of medium to a strong intensity that occurred when the complex was already in a state of abandonment.

At this early stage of study, only some limited numerical investigations have been conducted, despite suggesting a quite clear indication. Next step of this study will require an experimental campaign (possibly no-contact) to assess the dynamic signature of the pillar in its current configuration. Meantime, the investigation of the foundation typology and the soil stratigraphy would be useful to perform soil-structure-interaction analysis. This would allow to remove the fixed base hypothesis here assumed. With respect to the numerical



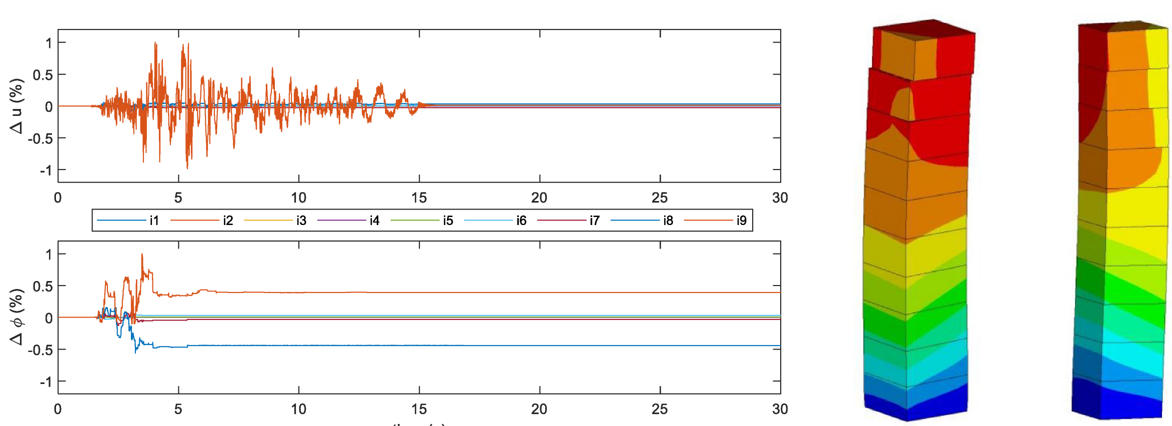
(a) (b) (c)

Fig. 11. "*cantilever*" case (Colfiorito-1997): time histories of the relative displacement Δu and rotation Δφ between blocks at the interfaces *i* (a); deformed configuration at the maximum Δu_i (b), and at the end of the analysis (c).



(a) (b) (c)

Fig. 12. "*cantilever*" case (Roma-2016): time histories of the relative displacement Δu and rotation Δφ between blocks at the interfaces *i* (a); deformed configuration at the maximum Δu_i (b), and at the end of the analysis (c).



(a) (b) (c)

Fig. 13. "*hinged*" case (Colfiorito-1997): time histories of the relative displacement Δu and rotation Δφ between blocks at the interfaces *i* (a); deformed configuration at the maximum Δu_i (b), and at the end of the analysis (c).

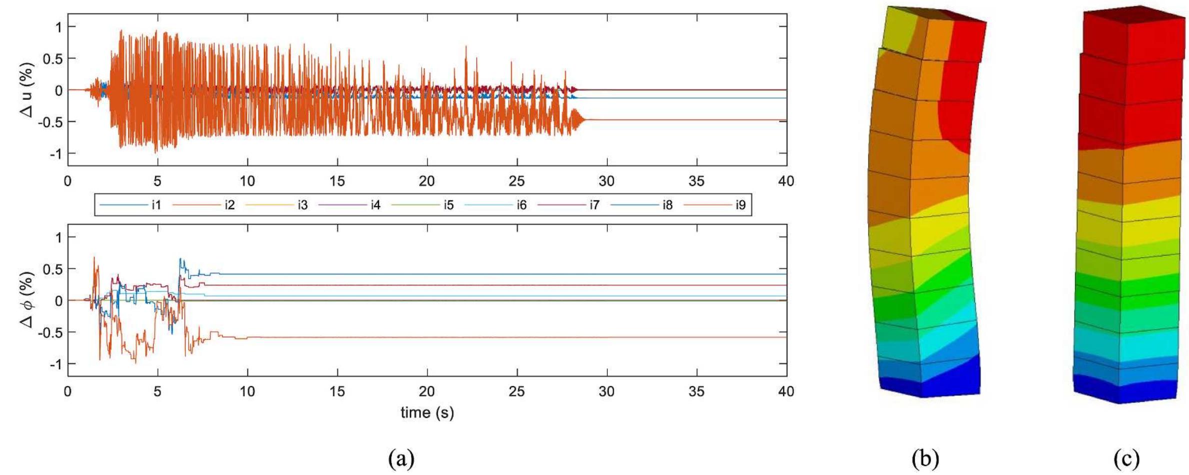


Fig. 14. "*hinged*" case (Roma-2016): time histories of the relative displacement Δu and rotation Δφ between blocks at the interfaces *i* (a); deformed configuration at the maximum Δu_i (b), and at the end of the analysis (c).

modelling, additional analyses through a micro-modelling or a discrete element approach will be useful to properly account for the leveling courses of bipedales that have been hypothesized to be responsible for the location of the damage. After that, the effect of more natural ground record spectra-compliant selected according, f.i., the current code can be considered.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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