Journal of Archaeological Science: Reports 21 (2018) 117–127

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Evidence of seismic damages on ancient Roman buildings at Ostia: An arch mechanics approach

Laura Pecchioli[a,b,*], Giovanni Cangi[c], Fabrizio Marra[d]

[a] Technical University of Berlin, Department Building Archaeology and Built Heritage Conservation, Germany
[b] Humboldt University, Winckelmann-Institut/Klassische Archäologie, Ostia Forum Project, Germany
[c] Research Associated ITABC-CNR, Rome, Italy
[d] INGV, Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

ARTICLE INFO

Keywords:
Structural analysis
Archaeoseismology
Ostia
Virtual arches model
Roman masonry structure

ABSTRACT

In this paper, we present archaeological evidence of seismic damage in the ancient Roman town of Ostia and we perform structural analysis on damaged buildings based on the application of the principles of arch mechanics, in order to provide an objective means to identify the seismogenic origin of the observed ruptures and collapses. We combine a review of literature reports on possible earthquake damages affecting the ancient structures with field investigations, aimed at selecting representative cases in which collapse modalities can be traced back and the seismic origin evidenced. Nine cases of failure affecting masonry structures are analysed, illustrating the collapse dynamics through the virtual arches model. Using this method we also reconstruct tentative collapse vectors for the analysed cases, highlighting iso-oriented, prevalent horizontal components, indicative of earthquake-induced ruptures.

1. Introduction

Analysis of archaeological data to study historical earthquakes was introduced since the 19th and early 20th centuries (Hinzen, 2011, and references therein). However, distinguishing between seismogenic and other causes such as static failure due to natural (weathering, fire, floods, differential soil compaction) or anthropic (spoliation, destruction, etc.) factors may be a challenging task (e.g., Guidoboni and Santoro Bianchi, 1995; Galadini, 2009). Recognizing a seismic origin for the damage affecting ancient buildings is indeed a crucial issue in archaeoseismology.

High vulnerability of ancient buildings, due to abandonment and lack of maintenance, influences the archaeoseismological interpretation, so that the cause for collapses can be wrongly interpreted as coseismic or the earthquake intensity might be overestimated (Galadini et al., 2006). On the other hand, the lack of historical sources reporting the occurrence of an earthquake cannot be considered always as a diriment factor. Even in the case of a long and rich historical record, such as that characterizing the city of Rome, it may be difficult to distinguish between local and far-field events. Moreover, the report of seismic events may be incomplete due to the lack of historical records during the long time span since the fall of the Empire and throughout the Middle Ages (Molin and Guidoboni, 1989; Guidoboni and Ferrari, 2000); as a matter of facts, no strong earthquake with epicentre in Rome is reported after the year 847 CE in the catalogue of strong earthquakes in Italy from 461 BCE to 1980 CE (Table 1; Boschi et al., 1995a).

The goal of this paper is to study archaeological evidence of seismic damage in the ancient Roman town of Ostia. Aimed at this scope, we report results of the structural analysis on damaged buildings based on the application of the principles of arch mechanics, in order to provide an objective means to identify the seismogenic origin of the observed ruptures and collapses. Through the virtual arches model, we analyse the kinematic behaviour of the architectural structures and we reconstruct the collapse vectors showing a prevalent horizontal component, indicative of earthquake-induced ruptures.

2. Historical and architectural overview of ancient Ostia

According to an ancient tradition testified by historical texts and epigraphy, the origin of Ostia dates back to the 7th century BCE during the reign of Ancus Martius, while archaeological data constrain its origin to the 4th–3rd century BCE (Zevi, 2002). Since this period and through the early Imperial age, Ostia was the harbour district of Rome. It was originally located on the ancient shoreline at the mouth of the Tiber River (Fig. 1), where the earliest fluvial port was built. The first

* Corresponding author.
E-mail address: l.pecchioli@campus.tu-berlin.de (L. Pecchioli).

https://doi.org/10.1016/j.jasrep.2018.07.006
Received 30 March 2018; Received in revised form 15 June 2018; Accepted 7 July 2018

Table 1
Earthquakes reported in the historical sources with epicentre located in Rome after the "Catalogue of Strong Earthquakes in Italy from 461 BCE to 1980 CE" (Boschi et al., 1995a).

Date	I_{max}	M_e
461 BCE	V–VI	4.6
436 BCE	VII–VIII	5.3
192 BCE	V	4.5
179 BCE	V	4.5
118 BCE	–	–
83 BCE	VII–VIII	5.3
72 BCE	VII–VIII	5.3
49 BCE	–	–
47 BCE	V	4.5
43 BCE	V	4.5
5 CE	V	4.5
15 CE	VII–VIII	5.3
51 CE	VIII	5.5
191 CE	IV	4.3
217 CE	V	4.5
223 CE	V	4.5
262 CE	IV–V	4.4
275 CE	V–VI	4.6
408 CE	–	–
484 CE	VII–VIII	4.5
618 CE	V	4.3
801 CE	VII–VIII	5.3
847 CE	V–VI	4.6

maritime harbour (Portus) was built by emperor Claudius in 42 CE and it was successively enlarged by Trajan during the early 2nd century, before progressive progradation of the delta caused the retreat of the sea coast and silting up of the port (Giraudi et al., 2009; Bellotti et al., 2011).

During the Imperial Age Ostia was the principal commercial hub for the City of Rome, and grew up larger and richer. From the Augustan period onwards, the gain of importance of Ostia is testified by the construction of several public monuments as well as stores and warehouses. Mostly under Trajan and Hadrian large civil and commercial quarters constituted by several multy-storey insulae were built through the consolidated employment of distinctive building techniques, mainly brick-faced concrete for outer walls and opus mixtum for inner walls (brick-faced concrete with panels of opus reticulatum) (for the building techniques see DeLaine, 2002; for the residential districts DeLaine, 2012; for commercial buildings DeLaine, 2005; more in general see the archaeological guide of Ostia by Pavolini, 2018).

Following the decline and fall of the Empire, despite a brief "renaissance" (Pecchioli, 2018), the town was progressively abandoned since the 5th century. The large buildings suffered ruin and spoliation, and were buried under a thick cover of natural and anthropic fills (Pavolini, 2016; Gering, 2012). A relative rejuvenation occurred only in the 9th century with the development of Gregoriopoli (nowadays the *Borgo di Ostia*), promoted by Pope Gregorio IV in the area adjacent the ancient town, to contrast the Saracenes invasions. Since the beginning of the 19th century, archaeological excavations promoted by Pope Pio VII began to bring back into light the remains of the ancient city. Thanks to the prolonged excavation and restoration interventions, including re-composition, re-collocation, integration, today much of the remains of ancient Ostia stands in relatively good conditions and represents a unique opportunity to study Roman construction techniques on an extensive and city-wide scale.

3. Site geology

The ancient Roman city of Ostia developed on the alluvial coastal plain of the Tiber River, above sandy and clayey fluvial to coastal sediments that are saturated with water and rich in peat layers, resting with erosional contact above a more consolidated, Lower Pleistocene marine clay substrate. After the progressive westward shifting of the coastline due to the progradation of the Tiber delta (Belluomini et al., 1986; Giraudi, 2004; Bellotti et al., 2007), the city is presently located within the coastal plain, in a sector characterized by a 20 to 40 m thick package of alluvial sediments. Although far from the deepest portion of the fluvial channel of the Tiber, which during the last glacial maximum was excavated to a depth > 60 m below the sea level, as reconstructed through borehole data in Ciotoli et al. (2015) (Fig. 1), the occurrence of a relatively thick soft sedimentary package upon a more rigid bedrock in Ostia can be a factor of amplification of seismic shaking during an earthquake. As shown in the case of the City of Rome, such geologic conditions play a key role in characterizing the soil column deformation profile and on the local seismic response (Bozzano et al., 2008; Caserta et al., 2013). Following pioneer studies by Ambrosini et al. (1986), it has been demonstrated that the subsurface geology in Rome is capable of producing important spatial variations in the amplification of seismic waves (Salvi et al., 1991), and that historical monuments built on the alluvial deposits of the Tiber River and its tributaries are expected to suffer higher seismic shaking (Boschi et al., 1995b; Moczo et al., 1995). Strong-motion recordings (Caserta et al., 2013) have confirmed previous theoretical studies aimed at quantifying the effects of local geology (Fäh et al., 1993; Rovelli et al., 1994, 1995; Panza et al., 2004; Olsen et al., 2006; Bozzano et al., 2008), showing a pronounced amplification near the theoretically predicted frequency of 1 Hz in the alluvial valley of the Tiber River in Rome.

Another important geologic factor to be considered is the natural subsidence to which the alluvial terrains are subjected, due to water expulsion and sediment compaction. This behaviour is a direct consequence of the lithostatic load, enhanced by anthropic factors like urban construction and groundwater exploitation (e.g., Stramondo et al., 2008).

In particular, if compressible layers of the sedimentary package are characterized by variation in lateral thickness, differential subsidence may be induced causing structural damages and the weakening of the building, enhancing potential seismic effects.

Finally, Ostia Antica is situated in correspondence of a structural lineament (Fig. 1), which has been hypothesized to represent an active principal fault of the Tiber delta half-graben (Ciotoli et al., 2015).

All these particular morpho-structural features are capable of producing peculiar effects in the amplification of the ground shaking, which need to be assessed through dedicated surveys at the site. Such investigations are ongoing and will be the subject of future work.

4. Historical seismicity of Rome

The record of felt earthquakes in Rome spans almost 2500 years, with the earliest event dated to 461 BCE followed by a large number of reports of significant effects affecting the City until the 20th century with estimated intensities from VI to VIII degree of the Mercalli-Cancani-Seiberg scale (Molin and Guidoboni, 1989). However, most of these events have been considered the effect of far-field earthquakes, for which the attribution to the most important urban centre of the region is a well-known process in macroseismics (Molin and Guidoboni, 1989). Nevertheless, 24 events with estimated $5.5 \geq M \geq 4.3$ and epicentre in the Rome zone are reported in the catalogue of strong earthquakes for Italy for the time span 461 BCE–847 CE (Boschi et al., 1995a) (Table 1). Epicentres of these earthquakes are conventionally located in the historical centre, lacking any criterion to establish a precise location within the larger Rome's area. Since the 18th century, instrumental seismicity affecting the area of Rome has been recorded, allowing for more precise location of the epicentres of the local events. Among these local events, a few earthquakes occurred in the southern area of Rome, close to the Tiber delta (Riguzzi and Tertulliani, 1993; Basili et al., 1996). In particular, isoseismal map of the 1 November 1895 earthquake reported by Tacchini (1895) individuated a maximum intensity area corresponding to the terminal reach of the Tiber and its