Archaeoseismological study of the Segesta site (western Sicily): first results from geophysical investigations

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Introduction

The archaeological site of Segesta is one of the most important Elimian settlements of western Sicily, well-known also for its thermal springs, as documented by historical sources. It is located on the north-western slope of Monte Barbaro (429 m. a.s.l.), a calcareous hill near the confluence of two river valleys named Fiume Freddo and Fiume Caldo, respectively, and characterized by fortified and naturally sheltered steep slopes. The site was developed over time in three different areas (Fig. 1a): 1) the Aphrodite Temple on top of a rural hillside (270 m a.s.l.) located outside the city walls and built around 430 BCE; 2) the Acropolis on top of Monte Barbaro identified as the public area with the main Greek-Roman buildings like the Agora and the Theatre; and 3) the Mango Sanctuary at the south-eastern foothills of Monte Barbaro, probably used for religious purposes. Since its foundation in the 9th century BCE, the ancient site of Segesta (known as *Aegesta*) underwent four periods of occupation at least.

We focused on the Greek-Roman one that ended with an abandonment probably related to a collapse phase. Since 2000, archaeological excavations carried out by the Scuola Normale di Pisa have revealed the occurrence of oriented collapse of buildings, large-scale destruction and temporary abandonment in the Acropolis area (Ampolo and Parra, 2018). This phase, dated around the mid- 3rd. century CE (220-240 CE), could be possibly related to an earthquake not documented by historical sources. This study focuses on the origin of the site destruction - dynamic (earthquake), static (ageing) or anthropic (war) – by performing a multidisciplinary study based on the analysis of historical, archaeological, geological, and geophysical data. Here, to better characterize the different behaviour of the three historical buildings mentioned above, we show results of HVSR and MASW surveys, supplemented by a drone survey to map in detail the Segesta site.

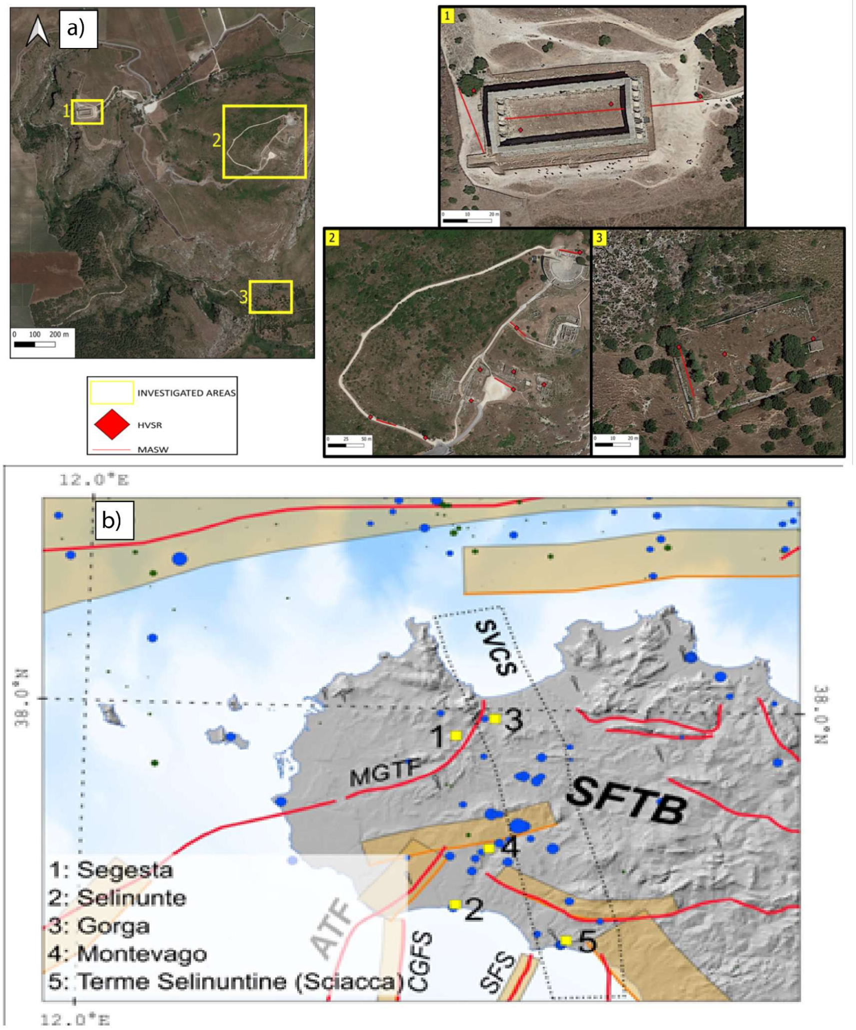

Figure 1 a) Map of the archeological site of Segesta. The geophysical acquisitions were carried out in three different areas of the site: 1) the Aphrodite Temple, 2) the Acropolis, 3) the Mango Sanctuary; b) Seismotectonic map of western Sicily showing seismicity from the CPTI catalogue (Rovida et al., 2021), active faults shown as red lines and seismogenic sources from the DISS database (DISS Working Group, 2021). ATF Adventure Thrust Front; CGFS: Capo Granitola Fault System; MGTF: Montagna Grande Thrust Front; SFS Sciacca Fault System; SFTB: Sicilian Fold and Thrust Belt; SVCS: San Vito lo Capo - Sciacca System.

Seismotectonics of western Sicily

According to the Italian seismic catalogues, western Sicily is a low seismic moment release region, characterized by an intermediate seismic hazard (Stucchi et al., 2004). Before the 1968 Belice seismic sequence, western Sicily was considered a seismically quiescent region, due to the lack of historical recordings of past earthquakes (CPTI15, Rovida et al., 2021; CFTI 5 Med, Guidoboni et al., 2019). After the 1968 events, instrumental records revealed that the seismicity of south-western Sicily was characterized by sparse low-moderate magnitude earthquakes (ISIDe Working group, 2007; http://terremoti.ingv.it/search).

In 1968, from January 14th to 25th, a seismic sequence was recorded with more than 300 events affecting the Belice valley area (De Panfilis and Marcelli, 1968; Bottari, 1973), six of which with a Mw ranging from 5.1 to 6.4 (Fig.1b) (CPTI15, Rovida et al., 2021; Azzaro et al. 2020). The sequence highlighted the activity of compressive structures of the SFTB and caused severe damage to fourteen villages, some of which were later completely rebuilt in different sites (Gibellina, Poggioreale, Salaparuta and Montevago), whereas others were rebuilt in the same place with different urban layout. The 1968 seismic sequence is the only significant one that occurred in the instrumental period in western Sicily. After the 1968 events, the seismicity localized onland is characterized only by sparse low magnitude earthquakes.

Other potential sources located offshore produced damaging earthquakes along an E-W contractional belt running about 50 km off the northern Sicily coast (Cuffaro et al., 2011; Barreca et al., 2014), such as the several historical events that hit Palermo (Guidoboni et al., 2003). Excluding the offshore sources, the Italian historical catalogue does not list any other moderate or large earthquake that occurred in the region. Possible events that caused the collapse of historical buildings occurred before 1000 CE, indications of which are still preserved in the site of Selinunte (Guidoboni et al., 2002; Bottari et al., 2009). These occurred in 370-300 BCE and 330-500 CE, causing collapses in Selinunte and probably in other sites, as well as the Selinunte thermal bath located in the Sciacca territory.

Archaeological evidence of seismic destruction

The most frequent damage observed in the northern area of the Agora of the Acropolis refers to oriented collapses of the central portion of the northern stoa (Erdas, 2004; Parra, 2006; Ampolo and Parra, 2018; Olvito and Serra, 2016), more precisely the back wall and the arch located in front of it, which collapsed one above the other (Fig. 2a, b). During the collapse, the back wall suffered a rotation of about 45° (Olvito and Serra, 2016). The stratigraphy was perfectly preserved until the archaeological dig, when the two structures fell down on the paved floor of the stoa square, causing cracks in the paved floor of the square. Also dipping broken corners in the column drums observed in the eastern wing of the stoa (Fig. 2c) probably due to seismic oscillation, as well the offset in steps, have been observed in the whole of the agora. In addition, basal drums of octagonal columns built to support the first floor of the stoa were found rotated in situ (Fig.2e). As a consequence of the collapse, we noted a shock breakout in flagstone in the northern stoa of the Acropolia.

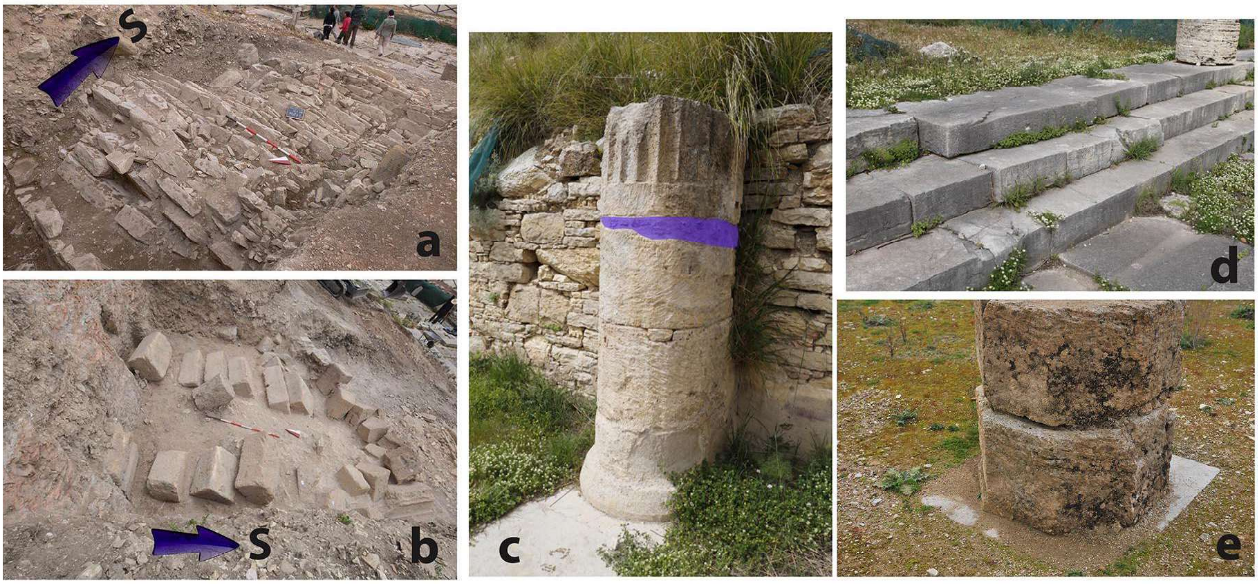

Figure 2 a) Oriented collapse toward the south of the back wall of the northern stoa at Segesta; (b) an arch fell down in the same direction of the back wall; c) Column of the stoa in the eastern wing, the portion highlighted in blue represents a broken corner in the column drums; d) offset in steps; e) rotated basal drums.

Seismostratigraphic model and Local Seismic Response

The destructive seismic events that affected the studied area in the past have caused several damage of different intensities to the buildings. A heterogeneous distribution of the damage caused by each event was observed. These effects, in addition to the intrinsic differences in the seismic vulnerability of the buildings, can be mainly attributed to different seismic motion amplification effects induced by local geological and geomorphological conditions. In fact, when a seismic motion propagates from the bedrock to the surface, it can change in amplitude, duration and frequency spectrum, due to the local geological characteristics of the site (Lanzo, 1999).

At the scale of the single structure or geotechnical system, the Local Seismic Response (LSR) allows to define the changes of a seismic signal, due to the aforementioned factors, with respect to that of a rigid reference site with a horizontal topographic surface.

To this purpose, a seismostratigraphic model has been reconstructed using a combined method of multichannel analysis of surface waves (MASW) and ambient noise array measurements to determine horizontal to vertical component spectral ratios (HVSR). The aim of MASW surveys was to reconstruct S-waves velocity profiles by surface waves dispersion spectrum analysis, while HVSR method allowed to obtain information about frequencies for which site effects of resonance and seismic amplification can occur (e.g. Mucciarelli and Gallipoli, 2001; Lunedei and Malischewsky, 2015). 16 HVSR registrations and 10 MASW surveys have been carried out, in the three studied areas of the site (see fig. 1a). The combined use of these two seismic methods allowed the inversion of the HVSR curves, constrained by MASW results, producing a robust and detailed subsoil velocity model.

To calculate the LSR, the input earthquakes search was carried out by the software REXEL (Iervolino et al., 2010) using the following research parameters: Magnitude ranges between 5,5 - 6,5; distance range 0-30 km. The soil classification corresponds to A type (Vs >800 m/s). The obtained 7 accelerograms, shown in figure 3a, were used as accelerograms input in the LSR code. A preliminary LSR has been calculated by the finite element method, using the software LSR2D and considering the simplified 1D seismostatigraphic models obtained. The Local Seismic Response obtained for sites 1 and 2 differs for periods between about 0.2 and 0.6 s (Fig. 3b); indeed, an amplification for site 2 (Stoa) is shown which may be related to the several collapses and damages observed in this area.

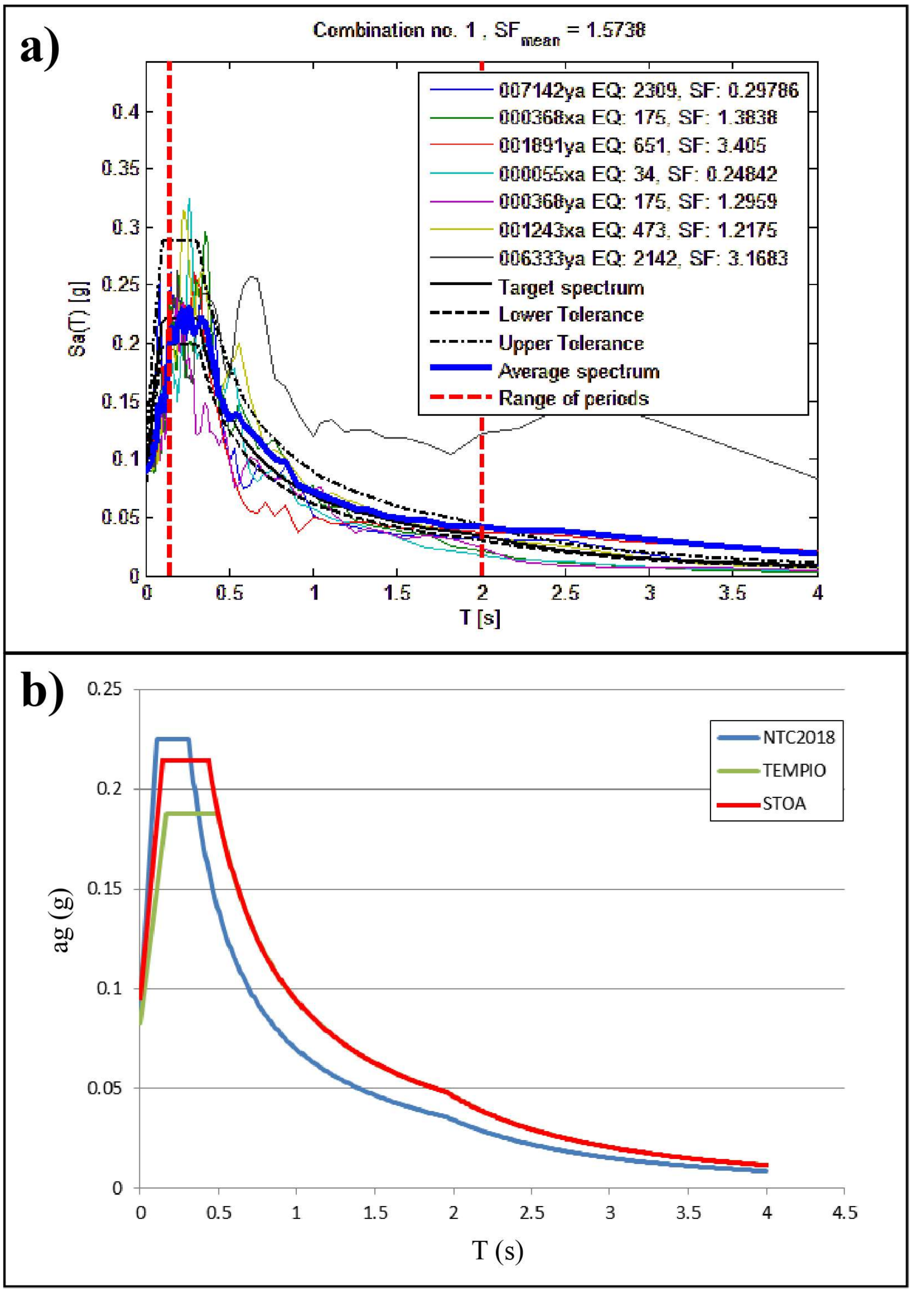

Figure 3 a) The seven accelerogram of the reference earthquakes; b) Local Seismic Response spectrum computed.

References

Ampolo C., Parra M.C.; 2018: *Lavori pubblici e urbanistica tra storia, epigrafia e archeologia: l'agorà ellenistico-romana di Segesta*. In O. Belvedere and J. Bergemann (ed.) Roman Sicily: cities and territories between monumentalization and economy, crisis and development, Palermo University Press.

Azzaro R., Barbano M.S., Tertulliani A., Pirrotta C.; 2020: *A reappraisal of the 1968 Valle del Belìce seismic sequence (western Sicily): a case study of intensity assessment with cumulated damage effects*. Annals of Geophysics 63, 1, SE105, 2020. doi:10.4401/AG-8308.

Barreca G., Bruno V., Cultrera F., Mattia M., Monaco C., Scarfì L.; 2014: *New insights in the geodynamics of the Lipari–Vulcano area (Aeolian Archipelago, southern Italy) from geological, geodetic and seismological data*. Journal of Geodynamic 82, 150-167. doi:10.1016/j.jog.2014.07.003.

Bottari A.; 1973: *Attività sismica e neotettonica della Valle del Belice*. Ann. Geof., XXVI (1), pp. 55-84, doi:https://doi.org/10.4401/ag-5008.

Bottari C., Stiros S.C., Teramo A.; 2009: *Archaeological evidence for destructive earthquakes in Sicily between 400 B.C. and A.D. 600*. Geoarchaeology 24, no. 2, 147–175. doi: 10.1002/ gea.20260.

Cuffaro M., Riguzzi F., Scrocca D., Doglioni C.; 2011: *Coexisting tectonic settings: the example of the southern Tyrrhenian Sea*. International Journal of Earth Sciences 100 (8), 1915-1924.

De Panfilis M., Marcelli L.; 1968: *Il periodo sismico della Sicilia occidentale iniziato il 14 gennaio 1968*. Ann. Geof. XXI (4), 343–421, doi:https://doi.org/10.4401/ag-5072.

DISS Working Group (2021). Database of Individual Seismogenic Sources (DISS), Version 3.3.0: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/diss3.3.0

Di Stefano P., Favara R., Luzio D., Renda P., Cacciatore M.S., Calò M., Napoli G., Parisi L., Todaro S., Zarcone G.; 2015: *A regional-scale discontinuity in western Sicily revealed by a multidisciplinary approach: A new piece for understanding the geodynamic puzzle of the southern Mediterranean*. Tectonics 34, 20672085. doi:10.1002/2014TC003759.

Erdas D.; 2004: *Segesta settore settentrionale dell'Agorà (SAS 4 Nord; 2005-2006)*. Annali della Scuola Normale di Pisa, 462-470.

Faccenna C., Becker T.W., Lucente F.P., Jolivet L., Rossetti F.; 2001: *History of subduction and back-arc extension in the Central Mediterranean*. Geophysical Journal International 145, 809-820. doi:10.1046/j.0956-540x.2001.01435.x.

Facella A.; 2009: *Segesta tardoantica: topografia, cronologia e tipologia dell'insediamento.* In Ampolo C. (ed.), Atti delle VI Giornate Internazionali di Studi sull'area Elima e la Sicilia occidentale nel contesto mediterraneo, Pisa, 589-607.

Guidoboni E., Muggia A., Marconi C., Boschi E.; 2002: *A case study in archaeoseismology. The collapses of the Selinunte temples (Southwestern Sicily): two earthquakes identified*. Bulletin of Seismological Society of America 92 (8):2961–2982. https://doi. org/10.1785/0120010286.

Guidoboni E., Mariotti D., Giammarinaro M.S., Rovelli A.; 2003: *Identification of amplified damage zones in Palermo, Sicily (Italy), during the earthquakes of the last three centuries*. Bulletin of Seismological Society of America 93 (4), 1649-1669.

Guidoboni E., Ferrari G., Tarabusi G., Sgattoni G., Comastri A., Mariotti D., Ciuccarelli C., Bianchi M.G., Valensise G.; 2019: *CFTI5Med, the new release of the catalogue of strong earthquakes in Italy and in the Mediterranean area.* Scientific Data 6, Article number: 80 (2019). doi: https://doi.org/10.1038/s41597-019-0091-9.

Iervolino I., Galasso C., Cosenza E.; 2010: *REXEL: computer aided record selection for code-based seismic structural analysis.* Bulletin of Earthquake Engineering, 8(2), 339-362.

Lanzo G., Silvestri F.; 1999: *Risposta sismica locale: teoria ed esperienze*. Hevelius.

Lunedei E., Malischewsky P.; 2015: *A review and some new issues on the theory of the H/V technique for ambient vibrations.* Perspectives on European earthquake engineering and seismology, 371-394.

Mucciarelli M., Gallipoli M.R.; 2001: *A critical review of 10 years of microtremor HVSR technique*. Boll. Geof. Teor. Appl, 42(3-4), 255-266.

Olvito R., Serra A.; 2016: *Segesta. Agora. Stoa Nord. Settore centrale (SAS 4; 2014-15).* In Notizie degli Scavi d’Antichità, Annali della Scuola Normale di Pisa, 9-16.

Parra M.C.; 2006: *Note di architettura ellenistica a Segesta, intorno all’agorà*. In Sicilia ellenistica, consuetudo Italica: alle origini dell’architettura ellenistica d’Occidente, eds Osanna M., Torelli M., 107-122, Roma Ateneo.

Rovida A., Locati M., Camassi R., Lolli B., Gasperini P., Antonucci A.; 2021: *Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 3.0.* Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/CPTI/CPTI15.3.

Stucchi M., Meletti C., Montaldo V., Akinci A., Faccioli E., Gasperini P., Malagnini L., Valensise G.; 2004: *Pericolosità sismica di riferimento per il territorio nazionale MPS04*. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/sh/mps04/ag.

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