Profiling of the recent deposits of Nafplio coastal plain (Greece) from engineering geological modelling and geophysical surveys

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ABSTRACT: In the current paper, some preliminary results from the research performed in the EU funded project “STABLE: Structural Stability risk assessment”, which aims to develop a methodology and tools to determine the seismic vulnerability of buildings in historical centres, are presented. The area of the historical centre of Nafplio was selected as case-study since it is one of the most important historical centers in Greece and a not negligible local seismic response may be expected based on the geological and geomorphological setting. The geological - geotechnical conditions in the study area were collected and evaluated and a geological model was identified. For this study, seismic noise measurements have been performed in the coastal plain where the town is built and processed with output resonance varying from 1 Hz up to 5 Hz, moving from the coastline towards the Acronafplia ridge. The results will be used to perform a structural stability analysis of the historical buildings using a simplified approach for specific earthquake scenarios in the future.

Keywords: engineering-geological model, geophysical investigation, local seismic response, Nafplio.

1. Introduction

The paper presents results from research performed in the EU funded project “Stable: Structural Stability risk assessment”, which aims to develop a methodology and tools to determine the seismic vulnerability of buildings in historical centres. In this context, the engineering geological conditions and seismic response of the ground in the historical centre of Nafplio is studied. For this purpose, relevant geological and geotechnical data have been collected, the seismotectonic conditions and the local seismicity has been studied and geophysical investigations have been performed in the field. The preliminary results of the study and a discussion on the main findings are presented.

2. Engineering geological model

From a geomorphological point of view, the study area is characterized by the mountainous landscape prevailing in the south and the flat landscape dominating to the north. The prominent topographic features are the Palamidi hill on the southeast (223 m), the Acronafplia peninsula (85 m) on the south and the Bourtzi island 600m NW from the harbour (Figure 1). The north slopes of Acronafplia present a relatively low angle. On the contrary, the northwestern and the southern slopes of Acronafplia are very steep. The altitude in the area where the old and the new city extend, varies from 0.50 m in the plain area to 60 m on Palamidi slopes.

To better understand the geological and engineering-geological features, geological and geophysical field surveys were integrated with previously available data.

A seismic reflection campaign was carried out by the Hellenic Survey of Geology & Mineral Exploration (HSGME) in 2006. HSGME also conducted a series of seismic reflection surveys, electrical resistivity tomography (ERT), boreholes with associated crosshole analysis in the coastal area and in the mainland with the aim of detecting the depth of the bedrock and the possible presence of tectonic elements (Apostolidis & Koutsouveli, 2010). Furthermore, 21 boreholes were drilled from various contractors (Triton SA, 2003, 2017) both in the sea and in the mainland to determine the thickness of recent soft-soil deposits and the depth of the bedrock. The stratigraphy obtained is consistent in the geotechnical investigations.

Figure 1. Satellite view of the Nafplio historical centre, harbour and modern town

Geological and engineering-geological surveys were directly conducted in the field during 2020 to provide a detailed geological model that is functional to reconstruct the local seismic response model of the study area. The results revealed that Acronafplia peninsula composes of limestone bedrock (Cretaceous), except for the SW side in which conglomerates (of Pleistocene age) outcrop. The latter are heavily eroded by the marine action on the coast, with the consequent retreat of the coastline. In this area, metric to decimetric limestone blocks are evident, which have fallen from the slope above and testify the high susceptibility of the southern slope to evolve due to rock fall phenomena. Palamidi hill is composed of limestone (Cretaceous), affected by the presence of a NW-verging thrust and an inverted stratigraphic series. In the thrust footwall, corresponding to the connection area between Palamidi and Acronafplia reliefs, the bedrock is composed from intensely fractured limestone (Cretaceous) and clayey-marly flysch (Upper Cretaceous-Eocene). It is also evident that, from west to east, there is a repetition of the outcropping formations with the identification of calcite steps that suggest the presence of a fold in the footwall and of a normal fault that lowers the western sector (Acronafplia peninsula). The northern slope of the Palamidi hill is also characterized by the presence of Pleistocene gravels and breccias, that surround its base, in erosional unconformity with the underlying Eocene flysch. The base of the slope is also characterized by the presence of limestone blocks placed above the breccias, testifying active rock fall phenomena. The flat landscape of the Nafplio historical and modern city is characterized by recent soft soil materials and man-made ground (Sabatakakis & Koukis, 2010).

The combination of information deriving from previous data and field surveys has allowed to reconstruct nine detailed engineering-geological sections and an engineering-geological chart that highlighted the presence of three main geological units: bedrock, recent soft soil materials, man-made ground (Figure 2). Furthermore, to perform future numerical modelling for local seismic response analysis, the characteristic geotechnical parameters were attributed to each geological unit defined in terms of natural weight per unit volume, shear stiffness and damping properties (G/G0 and D% curves) and seismic wave velocity.

3. Seismotectonic context and local seismicity

The area of Nafplio demonstrates a vertical diversity consisting of the slab of the Hellenic subduction zone and the Aegean plate on top of it. The subduction of the African plate lies several tenths of kilometres under the study area producing earthquakes of intermediate, mostly, depth. Like seismological and geodetic data suggest, the overriding Aegean plate is stretched in a N-S direction in the Gulf of Corinth, and changes in a E-W direction while moving southwards to the South Peloponnesus.

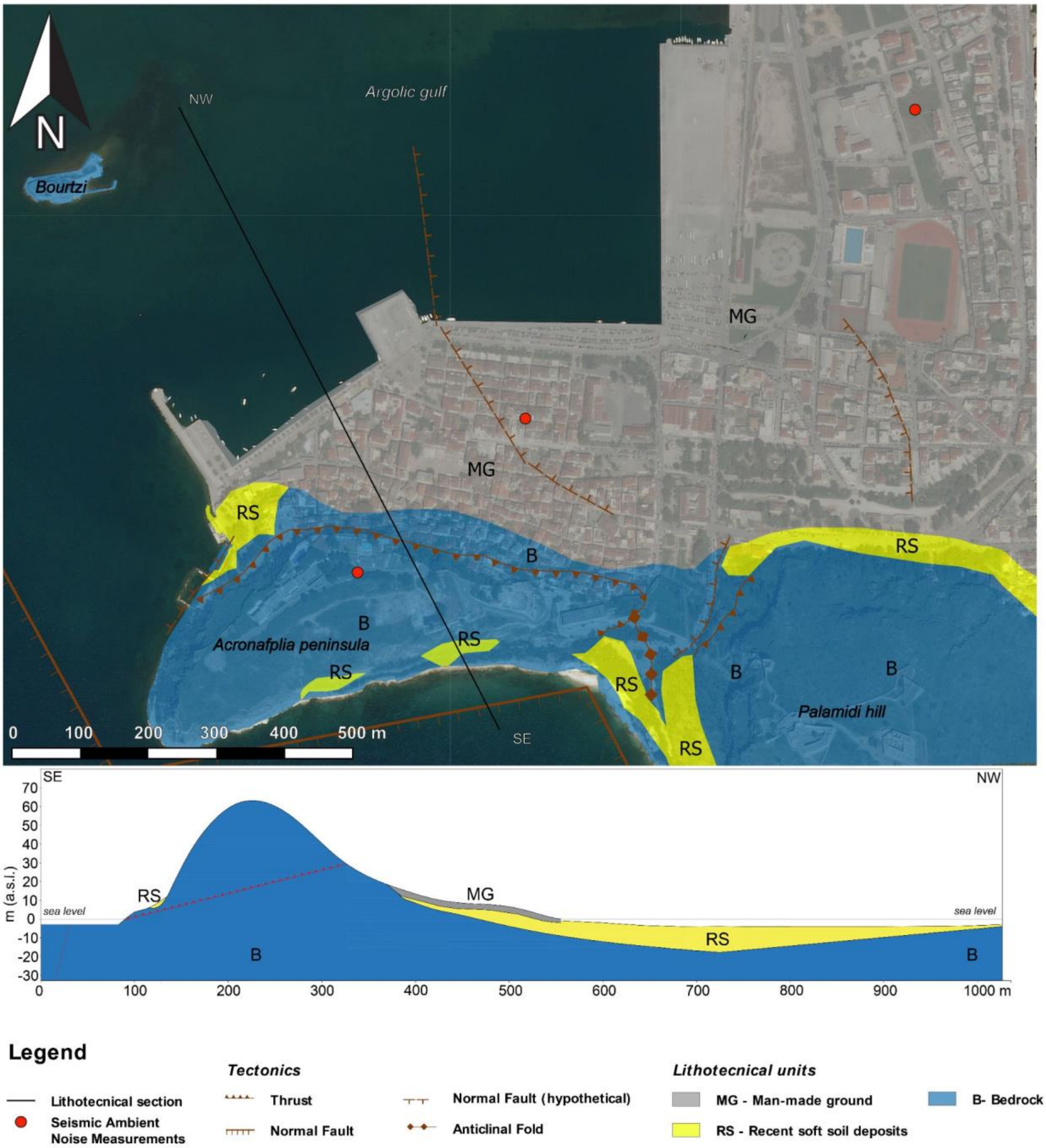
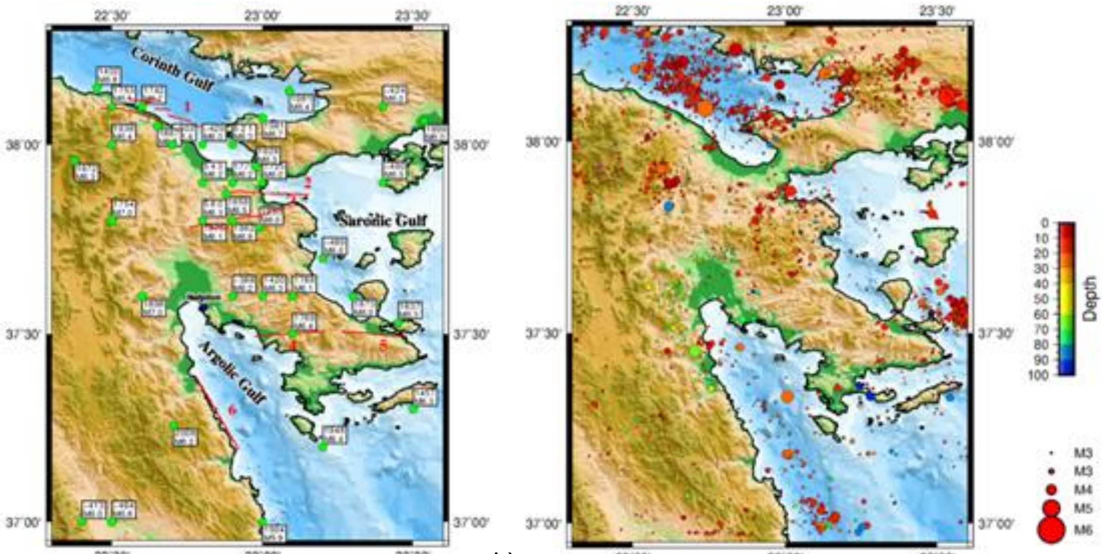


Figure 2. Engineering-geological map and simplified geological section of Nafplio study area.

Seismic activity in the broader region in historical times is characterized by several events with proposed magnitudes >M6 (Figure 3a), according to the earthquake catalogue of Papazachos & Papazachou (2003). The occurrence of many of these events, as well as their possible location and magnitudes are highly debated, since they are based on historical observations, rather than actual recorded data (Ambraseys, 2009). Despite this fact, most of these events have been associated with known regional fault zones. The most notable of them are:

- The Xylokastro fault zone (e.g., Ferentinos et al., 1988; Armijo et al., 1996), located in the southeastern coast of the Gulf of Corinth and associated with a M6.7 event that occurred in 1742, as well as several other events with magnitudes of M6.0.

- The Athikia and Kechriae fault zones, south of the Corinth canal (e.g., Goldsworthy & Jackson, 2001; Roberts et al., 2011), possibly related to the M6.5 event of 1858.
- The Iria and Epidaurus fault zones to the east of the city of Nafplio (e.g., Papazachos & Papazachou, 2003; Karakaisis et al., 2010) which are the most probable candidates for the strong M6.4 event of 1769, as well as several others in their region, shown in Figure 3a. Both these faults are provided by Papazachos & Papazachou (2003) as linear sources, since they are based only on proposed focal mechanisms in combination with scaling laws relating their length with the proposed magnitudes.
- The Tyros fault to the south of the study area (e.g. Papanikolaou et al., 1988), with a highly debatable activity however. Also presented as alinear source in Figure 3a, since no detailed information about its characteristics is available.



a) b)

Figure 3. a) historical seismicity according to Papazachos & Papazachou (2003) and most notable faults in the broader area of Nafplio (1: Xylokastro fault zone, 2: Kechriai fault, 3: Athikia fault zone, 4: Iria fault, 5: Epidaurus fault and 6: Tyros fault) and b) modern seismicity in the as recorded by NOA for the period of 2000-2021 (showing events with magnitude M>3).

Recent seismicity in the region around the city of Nafplio is characterized mostly by low magnitude events (< M5.0 Figure 3b). Most of these events have a depth >40km, indicating that they are associated with the Greek subduction zone and not with shallow local faults. Some events with larger magnitudes appear further to the NNE, in the Athikia fault zone and towards the North, within the Gulf of Corinth, which shows a significant seismic activity (Figure 3b).

4. Seismic ambient noise measurements

Single-station seismic ambient noise measurements were performed in several sites distributed between the historical centre of Nafplio, the modern town and the Acronafplia ridge (Figure 2). Seismic ambient noise was recorded for 1 hour in each site using LE-3D/5s 3-component seismometers by Lennartz Electronic GmbH coupled with REFTEK 130-01 dataloggers set to a sampling frequency of 250 Hz.

The seismic ambient noise measurement was analyzed by the Horizontal-to-Vertical Spectral Ratio (HVSR) technique (Nakamura, 1989) that is commonly used to derive the fundamental frequency (f0) of sites characterised by a stratigraphy with a marked impedance contrast, traditionally a soft soil on a stiff bedrock (Bour et al. 1998; Haghshenas et al. 2008). Using Geopsy software (Wathelet et al., 2020), each 1-h record was divided in non-overlapping windows of 40 s with 5% cosine taper; the Fast Fourier Transform (FFT) was computed for the three components (North-South, East-West and Up-Down) in each window and the obtained FFT spectra were smoothed by the Konno and Ohmachi (1998) function; the single-window spectra and HVSR ratio were averaged to obtain mean FFT spectra for each component and the HVSR function.

It is possible to observe that the HVSR functions obtained by analyzing the seismic ambient noise measurements on the Acronafplia ridge do not show any significant peak (Figure 4, right panel), indicating that this limestone acts as seismic bedrock. On the contrary, the HVSR functions are characterized by marked peaks for the measurements carried out on the recent deposits of the Nafplio coastal plain, with frequency values that vary between 1 and 2 Hz in the modern town area (Figure 4, middle panel) and 2 and 5 Hz in the historical centre (Figure 4, left panel). These resonance values can testify to a lower thickness of the recent deposits in the historical centre area.

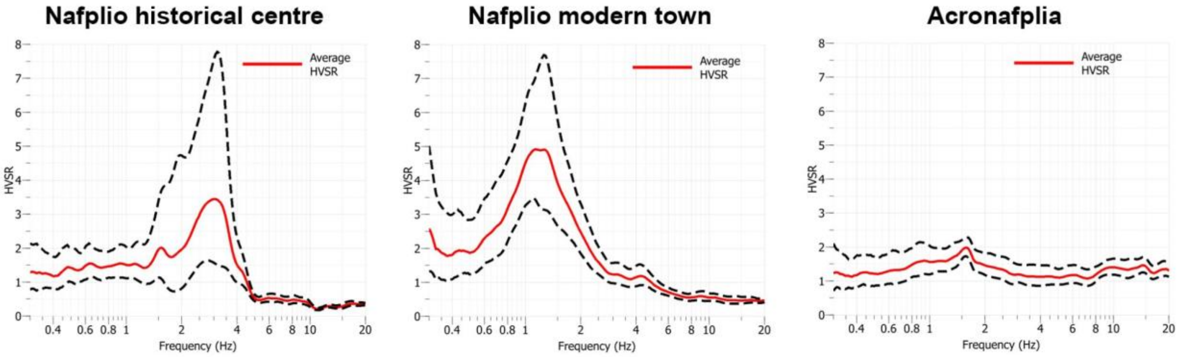


Figure 4. Examples of HVSR function (the dashed black lines show the standard deviation of the curve) obtained for Nafplio historical centre, Nafplio modern town and Acronafplia.

5. Conclusions and future activities

In future perspective, two-dimensional numerical modelling (for seismic input at different return periods) will be carried out to obtain the amplification functions along different engineering geological sections that will allow to analyze the distribution of site amplification effects due to both morphological and stratigraphic characteristics in Nafplio's municipality. Furthermore, it will be possible to obtain:

- elastic response spectra for the characterization of the site response in the design of seismic vulnerability mitigation interventions.
- specific amplification factors that will allow to perform a zonation of the seismic local response as a useful tool for urban planning and seismic risk mitigation.

The generation of a three-dimensional multi-source model is one of the most challenging aspects among the future developments of the project. The data modelling activities proceed through the construction of a geodatabase, a sort of data storage model used for geospatial analysis in a GIS environment and editing. The processing activities on point data, employing appropriate interpolation algorithms, may aspire to build a 3D mesh capable of storing and representing site-specific geological-geophysical aspects. The overlapping of geological, engineering, and geophysical knowledge within a solid geo-referenced model can potentially lead to both the manipulation of spatial information and the extraction of useful elements for the decision-making process.

Based on preliminary results from the STABLE project research which is carried on at Nafplio town area (Greece), a not negligible local seismic response was observed from HVSR computed after seismic noise measurement. In particular, the town area closest to the coastline reveals a resonance due to recent deposits (marine and continental) at almost 1Hz. On the contrary, the portion of the plain closest to the Acronafplia ridge shows a resonance up to 5Hz. It is not possible to exclude 2D amplification effects due to the lateral contact between the seismic bedrock outcropping along the ridge and the soft soil which fills the plain. In view of structural stability analysis, a quantitative evaluation of the local seismic amplification will be performed through numerical modelling. A 3D geological model of the subsoil will be derived to support the conceptual model for local seismic response, allowing the extrapolation of effects where only indirect data are available.

Acknowledgements

This work was prepared in the framework of the STructural stABiLity risk assEssment project (STABLE), H2020-MSCA-RISE-2018 with Grant Agreement number: 823966. The Authors wish to thank Luigi Marino for his technical co-operation in the geophysical field surveying. The first author thanks Dr. C. Georgiou from HSGME and Mr. A. Kokoromytis for providing previous geological and geotechnical data for Nafplio.

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