Seismic behaviour and 3D reconstruction of Cultural Heritage: the Column of the Hera Lacinia Temple in Capo Colonna (Calabria, Southern Italy)

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Seismic behaviour and 3D reconstruction of Cultural Heritage: the Column of the Hera Lacinia Temple in Capo Colonna (Calabria, Southern Italy)

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Abstract. The study aims to characterize the seismic behaviour of the Doric Column, last remaining of the Hera Lacinia Temple, located on the promontory of Capo Colonna near Crotone (Calabria, Southern Italy). Recordings of ambient vibration has been acquired both at the base and on the top of the column, simultaneously, in order to detect the predominant frequencies of the element. In addition, a high-resolution 3D model of the column has been reconstructed through laser scanning to support the analysis of the current state of the heritage element. The fundamental frequencies of the column and those associated to the site have been compared to verify potential resonance phenomena at the occurrence of an earthquake. In addition, a significant inclination of the column was detected by analysing the 3D model.

1. Introduction and Historical Setting

The site of Capo Colonna in ancient times hosted the main polyadic sanctuary of Kroton. In this site, the Greeks since the foundation of the colony had established the most important place of worship for the community with a cult dedicated to Hera, the most revered divinity in the Peloponnese. As for the sanctuary, archaeology has shown the presence of a classical temple in Doric order associated with the only surviving column. In addition, a series of buildings have been identified and brought to light over the years. The monumentality of the temple was accentuated by the pediments and the roof internally composed of marble tiles, that had to shine on the extreme tip of the promontory and constitute, together with the decorations and statues depicting horses and divinities, an important reference point also for the purposes of navigation.

The huge classical temple rested on a platform in limestone blocks extending over an area of about 59 meters by 22. This platform was made by removing part of the rocky bank which was subsequently filled with blocks in order to obtain a structure solidly anchored to the ground. The *crepidoma* emerged from the platform, consisting of a staircase with three levels above which the *peristasis* developed with 6 columns on the facades and probably 14 on the long sides. The entablature in Doric order, together with the pediments and the roof, surmounted the structure that must had to contain an internal cell (*naos*), preceded by a *pronaos*, where the statue of the goddess must be imagined.

Today, the column of the facade is what remains after a series of damage that are often attributed to earthquakes. However, the CFTI5-MED catalogue [1] of the strong earthquakes in Italy allows evaluating that related-earthquake effects in the Crotone area are mainly due to events with epicentre at least 50 km away and maximum macroseismic intensity VIII-IX at the site. Moreover, there are no specific effects in the area of Capo Colonna. Nevertheless, Galli et al. [2] have hypothesised another destructive local earthquake based on archaeoseismological studies, in particular this could justify the contemporary, extensive and simultaneous collapses datable in the area around the third century A.D..

Moreover, we have information that up to the first half of the 17th century two columns stood on the promontory, as reported in cartographic maps by Piri Reis [3] and Ligorio [4]. One of these two columns collapsed few years before 1649 [5], probably due to the earthquake that occurred in the area in 1638 [2].

The entire external perimeter of the promontory has always been characterized also by detachments and landslides due to the particularly fragile conformation of the cliff [6] (Figure 1). This fragility was probably also perceived by the ancient Greeks as a typical peculiarity of the place. In fact, the attribute with which the goddess was venerated, namely *Lacinia / Lakinia*, preserves memory of this phenomenon, deriving from the term *lakis* (or *lakisma*) which means fragment, shred, in reference to the jagged appearance of the coast and the landslides that conferred (and confer still) an irregular shape to the profile of the cliff.

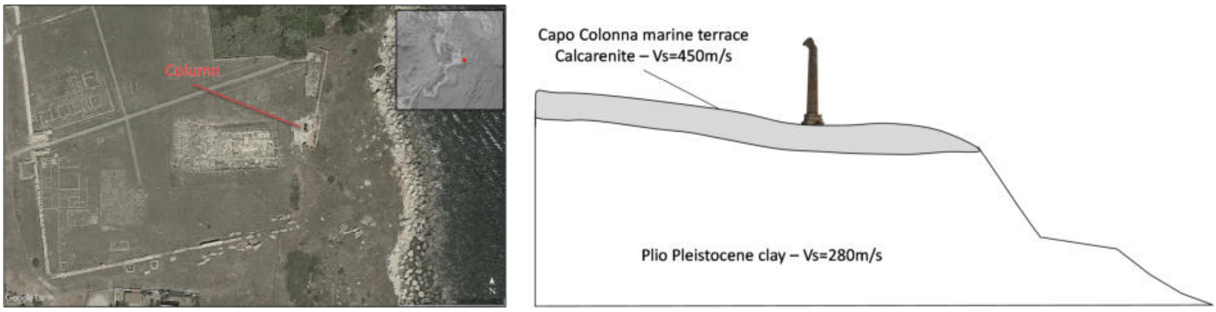

Figure 1. Satellite image of the Capo Colonna archaeological site (by Google Earth®) with indication of the column and sketch of the geological setting (modified by [2]).

As part of an educational project aimed at increasing the knowledge of local places in high school students, a specific survey campaign was conducted to characterize the dynamic behaviour of the column and the current geometric state.

2. Material and Methods

The campaign consists: (1) in the measurement of ambient vibrations at the base and on the top of the column, in order to analyse the predominant frequency of the heritage element and verify the potential resonance phenomena (cf. [7]) - as mentioned by [2] on the base of previous measures on the column; (2) the survey by means of terrestrial laser scanning, in order to evaluate the current state of the column and measure its inclination (cf. [8]). The survey campaign involved the "G.V. Gravina" high school of Crotone, the National Institute of Geophysics and Volcanology, the National Archaelogical Museum of Crotone, the Department of firefighters and the National Association of the "Carabinieri di Brugherio" as nucleus of the Civil Protection.

Figure 2 represents the measurement chain from the field surveys to the data-processing, in order to define the current geometrical state and the potential amplification phenomena during an earthquake. Both these information can support the risk analysis related to the earthquakes due to the local conditions.

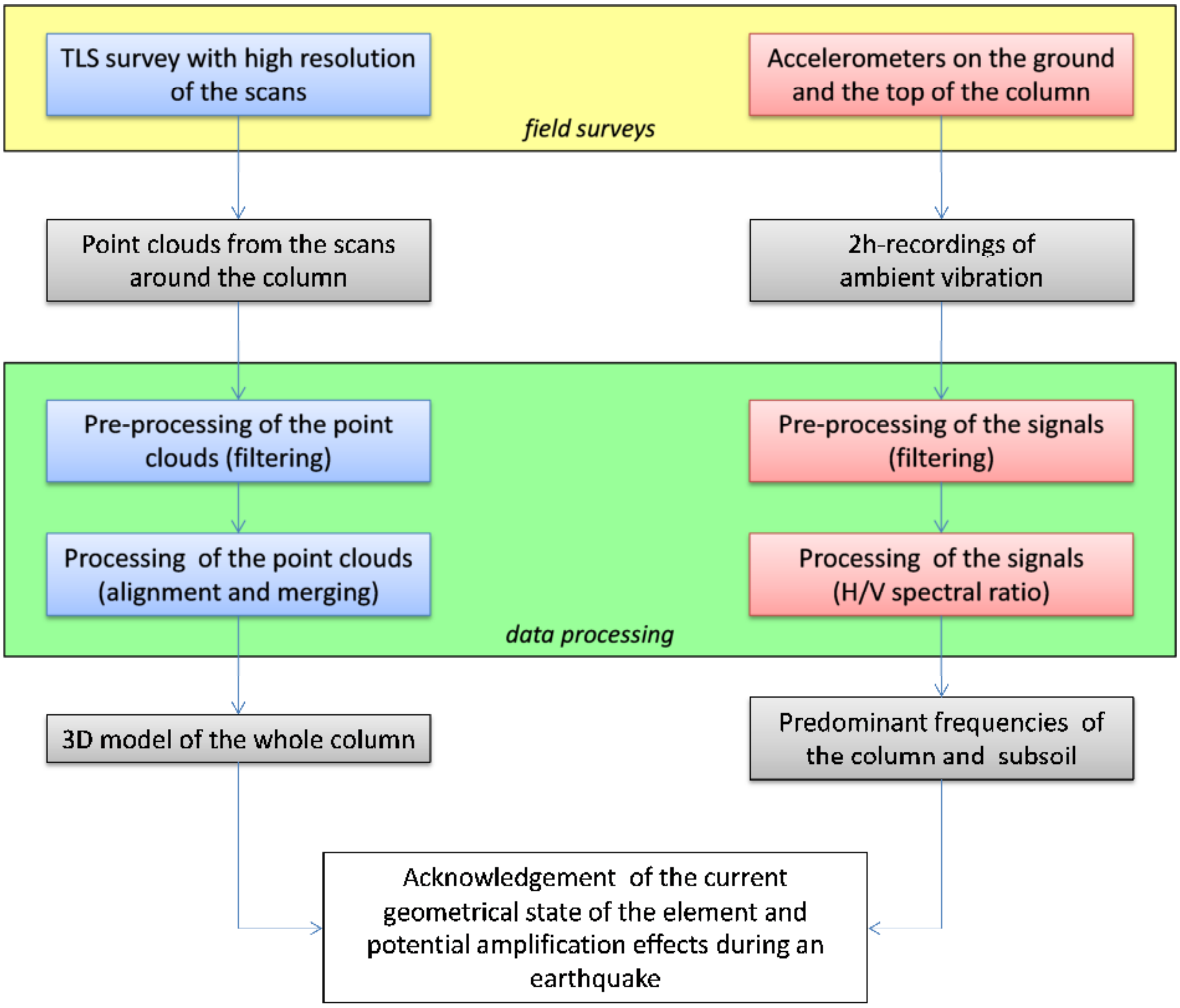

Figure 2. Sketch of the measurement chain.

2.1. *Measures of ambient vibration*

Accelerometric sensors were placed at the base and on top of the column, for the latter position particular attention was paid to avoiding any contact with the column. In particular, the firefighters have adopted the technique called "*Italian staircase*" to deploy the sensor (cf. Figure 3).

The 100Hz-sampled recordings were acquired by means of CENTAUR Nanometrics seismic digitizers, using 24-bit analog-to-digital converter, which were equipped with triaxial TITAN Nanometrics accelerometric transducers. Time synchronism was provided by the embedded GPS system and the recordings lasted about 2 hours.

2.2. *Terrestrial laser scanning*

The terrestrial laser scanning survey was performed using a Z+F Imager® 5010c laser scanner, using a measurement resolution of 3.2 mm to the distance of 10 m between receiver and target (cf. [9]). In addition, the embedded high dynamic range (HDR) camera was used to generate panoramic pictures characterized by high resolution for the colorization of the point clouds. This survey was aimed to freeze the state of the column and at measuring its current inclination.

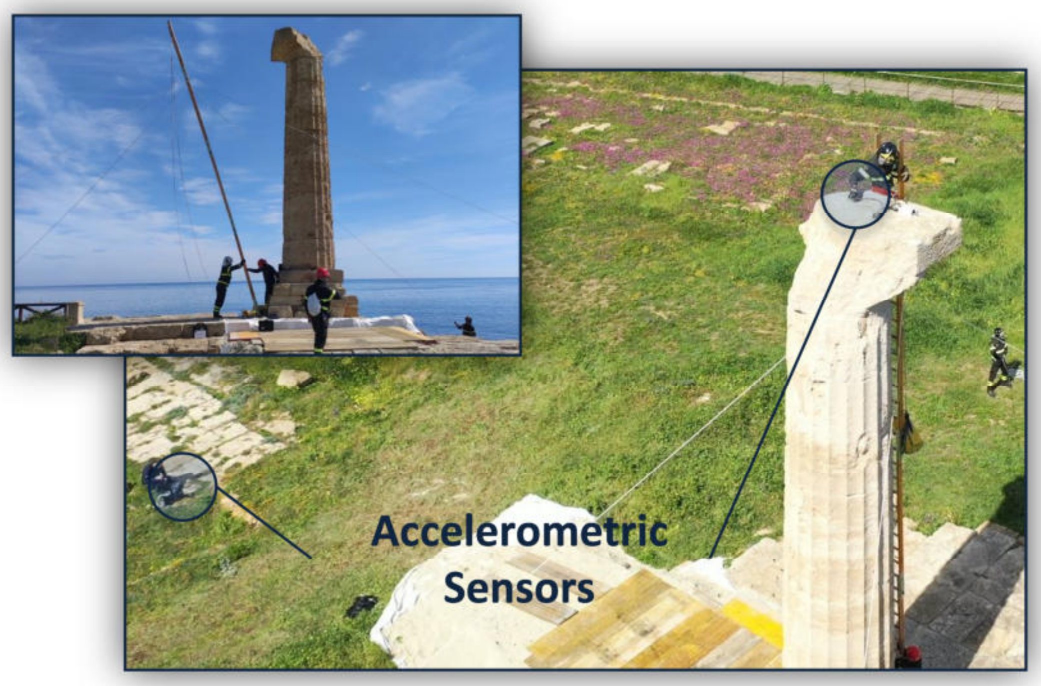

Figure 3. Deployment of the accelerometric sensors: at the base (circle in the lower-left) and on the top of the column (circle in the upper-right). Technique adopted by firefighters to reach the top avoiding contacts with the heritage element (upper-left box).

3. Results and Discussion

3.1. Vibration characteristics of the column

The processing of the recordings was performed by GEOPSY software [10]. The offset and mean removal and the application of a causal 4-pole Butterworth band-pass filter in the range of 0.1–40 Hz were applied to the signals. Afterwards, the recordings were analysed in the frequency domain using 50s windows, in order to obtain the Horizontal-to-Vertical Noise Spectral Ratios (HVNSR) at the base and on the top of the column (Figure 4). The spectra were smoothed using the method proposed by [11].

The Figure 4a shows a peak around the frequency of 0.5Hz at the base of the column, although the amplitude of the ratio is less than 2 (value generally indicated to detect a resonance peak). This peak is probably related to the wave motion of the sea. The shape of the spectral ratio shows a flat trend, without apparent local amplifications at least with low energies involved. Instead, the Figure 4b shows two peaks at about 3.2Hz and 4.1Hz, these are the predominant vibration frequencies of the column in the two orthogonal directions. Rotational maps of the HVSR were calculated as a function of azimuth and frequency (cf. [12]) to provide more information about directional effects, they confirm quasi orthogonal directions between frequency related to two peaks on the top of the column. In addition, the high dispersion of the values up to about 2Hz is due to the wind action.

The co-registration of the point clouds permitted to reconstruct the entire model of the column (Figure 5a). A preliminary analysis of the model showed an inclination of the element greater than 2% in south-east direction (Figure 5b). By taking into account that the column was erected with an inclination towards the inner part of the temple, the accumulated shift was probably also greater than that measured.

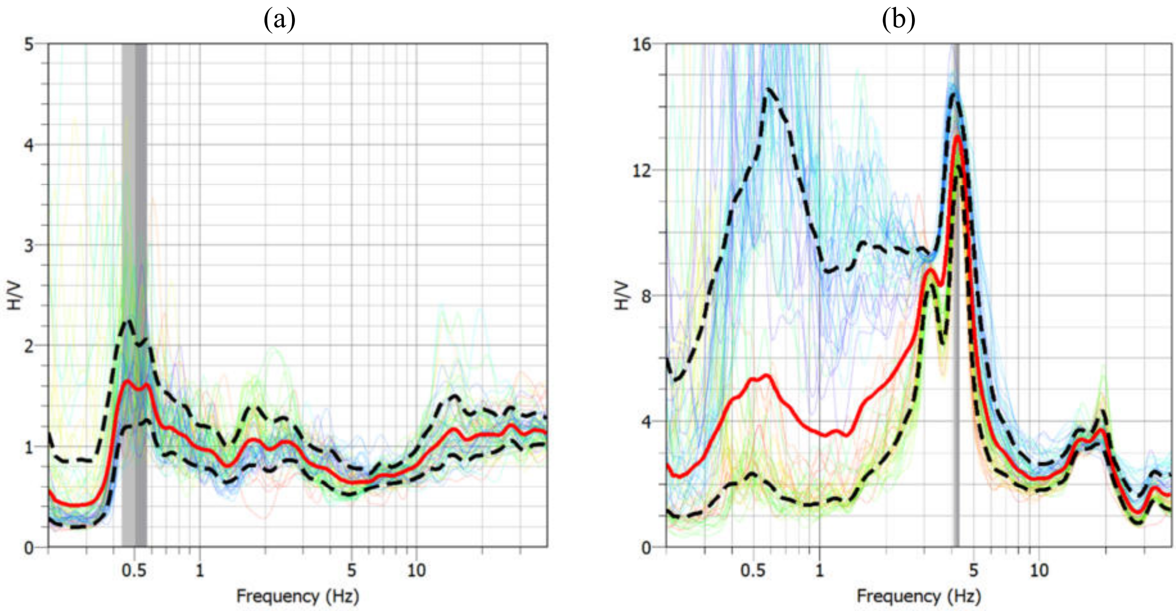

Figure 4. Horizontal-to-Vertical Spectral Ratio (H/V) at the base (a) and on the top of the column (b). In the charts the mean values (thick red curves) are reported, also considering the standard deviations (dashed black curves); instead, the thin coloured curves represent the ratio obtained from each window of the signals.

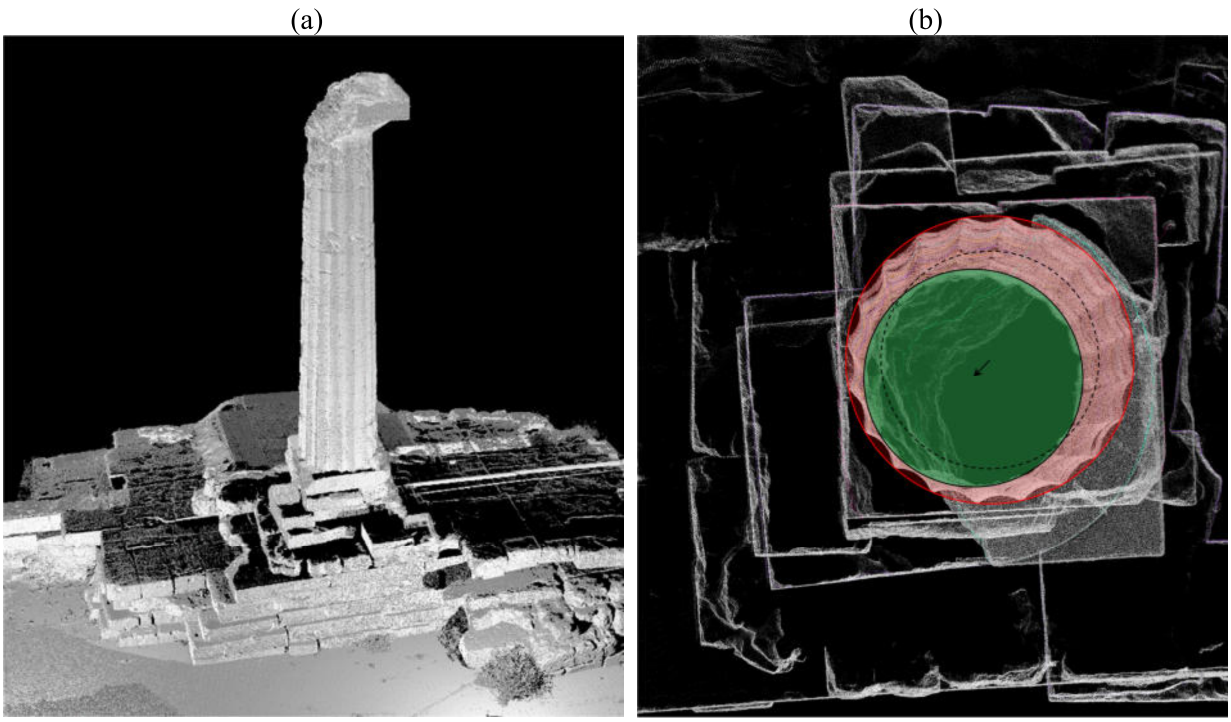

Figure 5. 3D model of the column obtained by laser scanning survey (a) and inclination respect to the vertical direction (b). The dashed circle represents the hypothetic position of the upper part of the column for the verticality.

4. Conclusions

The HVNSR made it possible to obtain information on the fundamental frequencies (about 3.2 and 4.1 Hz) related to the column of the Capo Colonna archaeological park. Instead, the same ratio does not seem to show particular amplification at the base of the element, only a slight peak is observed around 0.5Hz. It therefore seems reasonable to say that local conditions do not seem to produce significant amplifications of the ground motion in correspondence of the fundamental frequencies of the heritage element. In addition, a significant inclination of the column was estimated by analysing the geometrical model reconstructed through the terrestrial laser scanning survey. This high-resolution model will be used in a next study to analyse the degradation of the stone material. The combination of proximal remote sensing and geophysical surveys provided information to better understand the potential damage of the column due to past earthquakes and to support analyses of future damage scenario.

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