MONITORING AND SIMULATING THE SEISMIC RESPONSE OF THE HILL AND THE CIRCUIT WALL OF ACROPOLIS OF ATHENS

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ABSTRACT

The Acropolis of Athens is regarded as one of the most important ancient archaeological sites in the world. Apart from the Parthenon which is the exceptional monument on the Acropolis, the Circuit Wall around the hill is a masonry structure retaining backfill materials. Since Athens is characterized by moderate to high seismicity, during the last decade an accelerographic array has been installed to record the seismic response of the hill and the dynamic structural response of some of the monuments. In parallel, a new array of strain, temperature and acceleration optical fibre sensors has recently been installed on specific locations on the Wall, transmitting real-time data. The current study, after a short description of the prevailing local site conditions and a presentation of the geometrical and mechanical characteristics of the Circuit Wall and its backfill, focuses initially on the available records coming from the existing accelerographic array and the optical fibre sensors. Then, the study includes (a) a set of ground response analyses that investigate the impact of local site conditions on the seismic motion at the ground surface of the hill, and (b) preliminary two-dimensional dynamic numerical simulations of the Circuit Wall that have been developed utilizing a finite-element code in order to make comparisons and verifications with the available records. It becomes evident that the combination of (a) strain measurements via optical fibre sensors, (b) recordings via accelerographs, and (c) realistic numerical simulations can provide useful information about the dynamic response of the hill and the seismic behavior of the Circuit Wall.

Keywords: Acropolis of Athens; retaining wall; real-time monitoring; local site conditions; seismic response

1. INTRODUCTION

The Acropolis of Athens is regarded as one of the most outstanding ancient Greek monumental complex still existing in our time. Apart from Parthenon which is the exceptional monument on the Acropolis hill, the masonry Circuit Wall serves a pure geotechnical purpose since it functions as a typical gravity wall retaining the backfill that forms the plateau of the Acropolis. Since Greece, including Athens, is characterized by moderate to high seismicity, during the last decade a seismic array of ten accelerographs has been installed by the Institute of Geodynamics of National Observatory of Athens (IG-NOA) and the Acropolis Restoration Service (YSMA) in order to record in real time the seismic response of the hill, along with the dynamic structural response of the monuments. It is worth mentioning that the dynamic response of the hill dominates the seismic distress of any structure or monument founded on the hill. In parallel, a new array of strain and acceleration optical fibre sensors has recently been installed on specific locations of the masonry Circuit Wall in order to record the wall distress in terms of strain and acceleration.

The current study, after a short description of the local site conditions (i.e. topographical, geological, geotechnical) prevailing on the Acropolis' hill and a presentation of the geometrical and mechanical characteristics of the masonry Circuit Wall and its backfill, focuses initially on the available records coming from the existing accelerographic array and of the optical fibre sensors. Then, the study includes (a) a set of ground response analyses that investigate the impact of local site conditions on the seismic motion at the ground surface of the Acropolis' hill, and (b) preliminary two-dimensional numerical models of the south wall that have been developed utilizing a commercial finite-element

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2. LOCAL SITE CONDITIONS AND THE CIRCUIT WALL

The dynamic response of any structure is directly related to the local site conditions since the seismic motion at the ground surface may be altered by (a) the topography, (b) the geomorphology of the seismic bedrock, and (c) the soil stratigraphy. Although instrumental evidence of topographic amplification is abundant in weak seismic motions and rather limited during strong and destructive seismic events, the impact of the “unusual” topography has been repeatedly shown to be detrimental to structures and infrastructures (Psarropoulos, 2009).

2.1 Geology and seismicity of the hill

The Acropolis hill is geologically composed mainly by limestone overlying the Athenian schist which is visible on the main entrance of the Archeological Site and less in other positions. The limestone is visible on the hill, when is not covered by artificial soil materials (i.e. backfill), which have been used in the past in order to create the surface level of the hill (Andronopolous & Koukis, 1976; Koukis et al., 2015). The soil materials are thicker on the south side and held around the Wall and the limestone karstification has led to cavities which facilitate the water flow, further erosion and rock fall phenomena. Figure 1 shows a geological section and a geological plan view of the Acropolis’ hill (Higgins & Higgins, 1996).

![Figure 1. Geological section and plan view of the Acropolis' hill.](image-url)
The seismic history of the region is described relatively well over the last centuries by the available historical data and during the last years by instrumental recordings. The damages of the monuments due to seismic events are relatively small and originate mainly from earthquakes of greater epicentral distance (Galanopoulos, 1967; Ambraseys, 1994; Ambraseys & Jackson, 1997). In particular, damages are attributed to the earthquakes of 1705 in Athens (M ≈ 6.2), 1805 in Athens (M < 6), 1837 in Trozen (M ≈ 5.5), 1981 at Halcyon (M ≈ 6.7), and 1999 in Parnitha (M ≈ 5.9) (Zampas et al., 2011; Ambraseys, 2010). However, the greater damages to the Acropolis monuments are a result of human interventions in the past, such as military operations, environmental pollution, theft, inefficient rehabilitation interventions, and others.

2.2 The Circuit Wall

During the Mycenaean period (1200 BC), the first fortified Wall was built, called the 'Cyclopean' Wall, surrounding the top of the hill. This Wall with minor modifications was preserved until 480 BC, when it was severely damaged during the invasion of the Persians. The Acropolis was fortified again by Themistocles on the north side (Themistoclean Wall) followed by Kimon on the south side (Kimonion Wall). The Wall of Acropolis has suffered the actions of extreme weather conditions, various types of loading, e.g. earth pressures due to the backfill (under static and seismic conditions), as well as the human interference, leading to structural damages such as cracks, block falls and displacements (Egglezos et al., 2013).

The importance of the Circuit Wall is very high since it provides foundation of other structures of the hill and the passing of time has seen it undergo numerous damages increasing the risk of local and/or extensive structural failures. In Figure 2 a view of the South Wall is presented which comprises mainly of irregular mixed courses made up of marble and small stones, added in later repairs. It has a height of approximately 20 meters and retains a poorly compacted backfill material which overlies the inclined bedrock (i.e. the limestone) (Eleftheriou, 2015).

![Figure 2: View of the Acropolis of Athens, where the Parthenon and the masonry Circuit Wall are shown.](image)

3. OPTICAL FIBRE SENSORS ARRAY & RECORDS

Fibre Bragg Grating (FBG) sensors are integral special treated fibre portions, with the ability to act as an optical filter to incoming radiation, reflecting a minimal amount of wideband light signal. This modified area is sensitive to tensile stress, compression and changes due to temperature alterations so that the wavelengths reflected change accordingly. Sensors can be placed on critical positions of the structural material and by using the appropriate equipment (data loggers) the change in the reflected wavelength can be recorded regularly.

In the period 2015 - 2016 a new optical fibre array was developed on the South Wall, near pre-existing accelerographs, consisting of eight active strain sensors attached every two (one on the inside and one outside of four Smart Rods, noted as IN and OUT respectively), two temperature (attached on one Smart Rod) and one acceleration sensor (attached directly on the South Wall), continuously transmitting real-time data since June 2016 to date (Kapogianni et al., 2016; Kapogianni et al., 2017). Connection in series was achieved via in situ splicing, while measurements were made possible with
use of an optical sensing interrogator. In Figure 3 the Smart Rod Sensors are noted in vertical and horizontal direction, including the anchoring steel used for the attachment on the South Wall. As various physical phenomena affect the Acropolis Hill and the Circuit Wall, such as very high and low temperatures, excessive rainfalls, earthquakes, etc, the optical fibre monitoring array aims to quantify their influence on the monument. In Figure 4(a) the maximum strain measured with and without the influence of temperature is presented for a time frame of one (1) day, underlining the importance of the temperature sensors on the South Wall, which act complementary to the strain sensors, resulting to optimum strain recordings. Furthermore, indicative continuous recordings for a time period of ten (10) days are presented in Figure 4(b), and as can be noted similar maximum values occur during the morning until noon, for each day. This phenomenon is reversed during the afternoon and the night.

Figure 3. Smart Rod optical fibre sensors on the South Wall in vertical and horizontal direction.

Figure 4. (a) Maximum strain measured with and without the influence of temperature during one (1) day, and (b) indicative continuous recordings for a time period of ten (10) days

4. ACCELEROGRAPHIC ARRAY & RECORDS

Over the last years, ten (10) high-quality broadband accelerometers (Guralp CMG-5TD) were installed on specific locations of the hill, recording in continuous mode on 24-bit digitizers and transmitting data in real-time to the Institute of Geodynamics of National Observatory of Athens (IG-NOA) facilities in Thissio and the Acropolis Restoration Service (YSMA) facilities in Plaka, using governmental telecommunication infrastructures (Kalogeras et al., 2012). The accelerographs were installed, considering the various geotechnical conditions on the hill as well as the specific interest of YSMA for individual sites (Parthenon, South Wall etc.). In Figure 5(a) the locations of the accelerometers are noted and in Figure 5(b) the equipment used on specific locations on the hill.
Figure 5(a). Location of accelerometers on the Acropolis hill.

Figure 5(b). Equipment used on specific locations on the Acropolis hill.
Even though no strong earthquake occurred to date in the near field, more than 70 earthquakes created the relevant database and the following useful conclusions were drawn:

- There are no high values of seismic vibration (ground acceleration, speed, displacement) due to the fact that no strong earthquake has occurred in the near field. The maximum accelerometer values range from 15 cm/s/s to less than 1 cm/s/s. However, the technical specifications of the instruments make it possible to record small earthquakes in the near field (<50km) or stronger from longer epicentral distances of 100–400 km.

- In the near-field earthquakes the recordings are quite different, as a result of the influence of local site conditions. Generally, the smallest values are observed at the ACRJ site, the highest at the ACRD position, while intermediate values in the remaining positions (ACRA, ACRB, ACRE, ACRF, ACRG, ACRH and ACRI) (Figure 5(a)).

- For earthquakes from longer epicentral distances (> 150km), records show uniformity with the exception of the corresponding recordings of the horizontal components of the Parthenon epistyle, where even 10 times higher values of ground acceleration has been recorded in comparison to other positions.

- The Parthenon epistyle shows an eigen-period of 0.5s resulting from the processing of site ambient noise.

4. ACCELEROGRAPHIC RECORDS

Since the installation of the first accelerograph in 2006 and of the deployment of the array in two periods (2008 and 2013), many near-field and far-field seismic events have been recorded (Kalogeras & Egglezos, 2013). In the current study only two earthquakes have been considered. The first seismic event (on 05/12/2014) was a small earthquake close to Athens with local magnitude $M_L = 2.4$ and focal depth of 18.4 km from a distance of 17 km, while the second seismic event (on 24/05/2014) was a strong earthquake almost 300 km away from Athens, close to the island of Samothraki, Northern Aegean, with local magnitude $M_L = 6.3$ and focal depth 28.3 km. Figure 6(a) shows the acceleration time-histories of the instrument ARCB (N-S component) recorded during the two fore-mentioned seismic events. It is evident that the recorded ground motion of the small near-field seismic event is characterized by very low peak ground acceleration (PGA) levels, short duration and high frequency content, while on the contrary, the recorded ground motion of the strong far-field seismic event is characterized by higher PGA levels, longer duration and lower frequency content.

![Figure 6(a)](image)

Figure 6(a). The acceleration time histories recorded by ACRB instrument during the small near-field seismic event (left) and the strong far-field seismic event (right).

Figure 6(b) shows the elastic response spectra of four recorded ground motions (ACRB, ACRF, ACRG and ACRI) during the two examined seismic events. Judging from the shape of the spectra, it becomes evident that, apart from the obvious great differences between the two seismic events, the discrepancies between the four records during the far-field earthquake are relatively small, while on the contrary, during the near-field event there is a substantial variability referencing to the installation site characteristics: the instruments located at the north side of the hill (i.e. ACRF and ACRG) exhibit higher PGA levels and higher spectral accelerations.
5. GROUND RESPONSE ANALYSES

Before the simulation of the seismic response of the retaining structure (i.e. the South Wall), two-dimensional (2D) ground response analyses were performed in order to investigate the impact of local site conditions on the seismic motion at the ground surface of the Acropolis Hill. In geotechnical earthquake engineering the term "local site conditions" is used to describe apart from the soil stratigraphy, the shape of the seismic bedrock and/or the topographic conditions (i.e. the geomorphology of the site). Records and analyses in the literature (Psarropoulos et al., 2007) have shown that local site conditions may lead to substantial amplification of the ground shaking. Nevertheless, the Acropolis hill actually consists of limestone resting on the marls and sandstones of the Athens schist rock series. Therefore, the amplification levels on the Acropolis hill were a-priori expected to be low (as it had been indicated by the available records).

In order to verify the available records and comprehend the amplification pattern, the numerical model shown in Figure 7 was developed, without the existence of the Parthenon, the Walls and the backfill materials. The ground response analyses were performed with the finite-element code QUAD4M (Hudson et al., 1994). Note that, although QUAD4M is capable to take into consideration the radiation damping and the potential nonlinear behavior of the ground, the behavior of the ground was expected to be linear in this case due to low levels of acceleration and the high stiffness of the geomaterials. The model was initially excited by two simple Ricker pulses that are characterized by smooth Fourier spectra covering a certain range of frequencies, and then with real acceleration time histories. The first pulse is a low-frequency excitation (representative of the far-field seismic event) and the second pulse is a high-frequency excitation (representative of the near-field event). As it is shown in Figures 8 and 9, in the case of the low-frequency acceleration the seismic response is almost uniform along the ground surface, while in the case of high-frequency excitations discrepancies exist, a phenomenon that had been evident in the available recordings as well.

Judging from the available records in the vicinity of the South Wall (ACRJ and ACRD), it becomes evident that in the case of the far-field event there is no amplification at the backfill, while in the case of the near-field event the amplification is substantial. As it is shown in Figure 10 (Trikkalinos, 1972; Trikkalinos, 1977), the South Wall is a masonry retaining wall that retains a poorly-compacted backfill overlying an inclined bedrock (i.e. the limestone). Since in the literature there are analytical and numerical solutions that do not refer to a retained layer with inclined bedrock, preliminary numerical models were initially developed with the finite-element code PLAXIS (Brinkgreve et al., 2010) in order to be verified with the available results in the case of a horizontal bedrock (Psarropoulos et al., 2005; Psarropoulos et al., 2011). After this verification and given the shape and the dimensions of the Wall at the location of the installed accelerographs, the realistic 2D model shown in Figure 11 was developed. It should be noted that, since no geotechnical survey had been conducted, a certain degree of uncertainty exists for the mechanical properties of the geomaterials.
Figure 7. The 2D finite-element model developed for the ground response analyses with QUAD4M.

Figure 8. The low-frequency pulse excitation and the seismic response at the ground surface.

Figure 9. The high-frequency pulse excitation and the seismic response at the ground surface.
Figure 10. Cross section sketch of the South Wall.

Figure 11. The 2D numerical model developed for the evaluation of the seismic response of the South Wall.

Figure 12 shows the recorded and estimated ratio of the Fourier spectra of ACRD and ACRJ in the case of the near-field excitation. This ratio defines actually the amplification factor AF. The numerical results are quite satisfactory, since the observed discrepancies are mainly attributed to the various uncertainties of the model (i.e. mechanical and geometrical properties).

Figure 12. Comparisons between the recorded and the estimated amplification factor AF (i.e. the ratio of the Fourier spectra of ACRD and ACRJ).
6. CONCLUSIONS

Based on the aforementioned records and analyses, the following conclusions are drawn:

a) Real-time monitoring is a very useful tool to assess the dynamic structural response of any structure subjected to an earthquake, including retaining walls, such as the examined Circuit Wall of Acropolis. In particular, the acceleration levels can be recorded during regional and near-filed seismic events, showing the characteristics of the input seismic excitations and the corresponding dynamic structural response, either in the time domain, or in the frequency domain. Furthermore, strain and temperature variation can be recorded via optical fibre sensors.

b) The fact that on the Acropolis hill a stiff material (i.e. limestone) overlies a relatively "soft" formation (i.e. schist) leads actually to no amplification of seismic ground motion and to uniform response in the case of low-frequency far-field seismic events. On the contrary, in the case of high-frequency excitations, the response may vary from position to location depending on the "very local" conditions (e.g. weathered rock on the ground surface and / or karst phenomena). The aforementioned resulted from the analyses and are consistent with the available records.

c) The numerical simulations of the dynamic response of a structure may be realistic, provided that the geometrical and mechanical properties of the structure and the geomaterials are known. In the case of the hill and the Circuit wall of Acropolis, the numerical results of the current study are in a good agreement with the available records despite the various uncertainties of the numerical modelling.

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