

Seismic Response of the Acropolis of Athens (Greece) through Recorded Earthquake Data and Numerical Simulations.

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ABSTRACT

We present in this contribution preliminary results obtained through seismic data analyses and numerical simulations of the response of the Acropolis of Athens, Greece. We use earthquake and ambient vibration data recorded by the high-quality accelerometer array operated by the Institute of Geodynamics, National Observatory of Athens (NOA-IG), in collaboration with the Acropolis Restoration Service (YSMA). The array consists of 10 strong-motion sensors (Guralp CMG-5TD) recording in continuous mode on 24-bit digitisers, sampling the main geological units constituting the Acropolis and including two sites devoted to monitoring monumental elements of the Parthenon. We compare the experimental amplification functions (SSRs, HVSRs, 5%-damped SRs) with those obtained from numerical simulations of the seismic response of the hill. The 3D computational mesh is designed in CUBIT while the simulations are carried out using the discontinuous Galerkin spectral element (SEM) computer program SPEED, naturally oriented to the evaluation of multi-scale wave propagation problems.

Introduction and motivation

Spurred by the establishment of the Acropolis Restoration Service (YSMA, <http://www.ysma.gr/en/>, last accessed 12.07.2015) in 1999, extensive restoration and conservation works have been carried out within the last two decades in the Acropolis of Athens, a worldwide renowned symbol of the cultural and historical heritage of Greece within the context of western civilization. The Acropolis of Athens hosts the Parthenon, one the most important surviving buildings of Classical Greece, generally considered the apotheosis of the Doric order. The restoration framework includes a permanent seismic monitoring network deployed and maintained starting from 2008 by the Institute of Geodynamics, National Observatory of Athens (NOA-IG, <http://www.gein.noa.gr/en/>, last accessed 12.07.2015) in collaboration with YSMA. Similar to other topographic irregularities in the Athens basin, the Acropolis is a block of late Cretaceous limestone ($V_S \sim 1500 \text{ ms}^{-1}$, Eurocode 8 ground type A; CEN, 2004) resting on the Athenian Schist ($V_S \sim 700 \text{ ms}^{-1}$), a slightly metamorphosed series of Cretaceous marls and shales with lenses of sandstone and limestone. Large portions of the Acropolis are covered by anthropic infill with $V_S \sim 350 \text{ ms}^{-1}$ and thickness exceeding 5 m (Eurocode 8 ground type E), overlaying the limestone unit (Figure 1). The foundation of the Parthenon is made of porous-stone blocks

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with dry masonry structure with average $V_S \sim 600 \text{ ms}^{-1}$ (Kalogeras and Egglezos, 2013).

The Acropolis ridge is well approximated by an ellipse elongated in the EW direction (Figure 1) with major axis length $\sim 250 \text{ m}$ and minor axis length $\sim 150 \text{ m}$. The hill is characterised by very steep topography on the northern, eastern and southern edges, where the geomorphology is dominated by a 30-35 m thick limestone outcrop and the average slope of the hill flanks exceeds 30 degrees. The Acropolis is therefore a complex 2D irregularity that falls within topography class T4 of the Eurocode 8 (*i.e.* ridges with crest width significantly less than the base width and slope $> 30^\circ$). For this class, the code prescribes amplifying the design seismic actions by means of a frequency-independent amplification factor = 1.4. However the same code recommends carrying out refined *ad-hoc* analyses for these complex geometries, due to the uncertainties typically associated with the quantification of topographic amplification. Indeed, from an observational perspective, amplification phenomena due to topography are often difficult to segregate from the effects of structural layering and near-surface geology, unless refined tomography models are available. The most recent investigations in this direction have been recently carried out in Europe within the framework of the EC-funded project NERA (Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation; www.nera-eu.org, last accessed 12.07.2015; contract no. 262330), where a research group (JRA1) focused on “establishing scientifically solid and practically acceptable propositions to incorporate basin and surface topography effects in seismic design (building codes, microzonation studies, critical facilities)”. The key results of this effort, summarized in Burjanek et al. (2014a and b), indicate that systematic large amplifications at topographic sites cannot be explained by surface geometry only and amplification – correlated with ground motion polarization and directionality - is controlled in first place by the sub-surface velocity structure. Burjanek et al. (2014b) identify detailed numerical simulations as a tool that can reveal the joint effect of surface geometry and subsurface velocity structures. With this background, the main goal of the present study is a refined 3D seismic response evaluation of the Acropolis. Our study is to our knowledge the first to address the issue of the 3D site response of the Acropolis using seismic data and numerical simulations. The numerical tool used in this study will allow the inclusion of the monumental components of the Acropolis in the computational domain.

Overview of the Acropolis strong-motion array

The Acropolis strong-motion array presently consists of 10 high-quality broadband accelerometers (Guralp CMG-5TD) recording in continuous mode on 24-bit digitisers and transmitting data in real-time to NOA-IG and YSMA using governmental telecommunication infrastructures (Syzefxis). The geometry of the accelerometer array samples the main geological units constituting the hill of the Acropolis (*e.g.* Athens’ Schist, limestone and anthropic backfill) and includes two stations devoted to monitoring structural elements of the Parthenon. The geometry of the array is shown in Figure 1, while selected information on the installation sites are listed in Table 1. Noise monitoring tools and real-time seismic waveform plots are available at http://accelnet.gein.noa.gr/index.php?option=com_wrapper&view=wrapper&Itemid=209 (last accessed 12.07.2015). Comprehensive descriptions of the Acropolis network are also available in Kalogeras et al. (2010), Kalogeras et al. (2012), Kalogeras and Egglezos (2013) and Egglezos et al. (2013). High-quality real-time continuous accelerometer monitoring (*e.g.* Cauzzi and Clinton, 2013) means 100% recovery of earthquake data over a broad range of amplitudes and

frequencies, from local events to teleseismic signals. Notable amongst the teleseismic events well recorded by the Acropolis array is the Tohoku (Japan) $M9$ earthquake that occurred on March 11th, 2011, as documented by Kalogeras and Egglezos (2013).

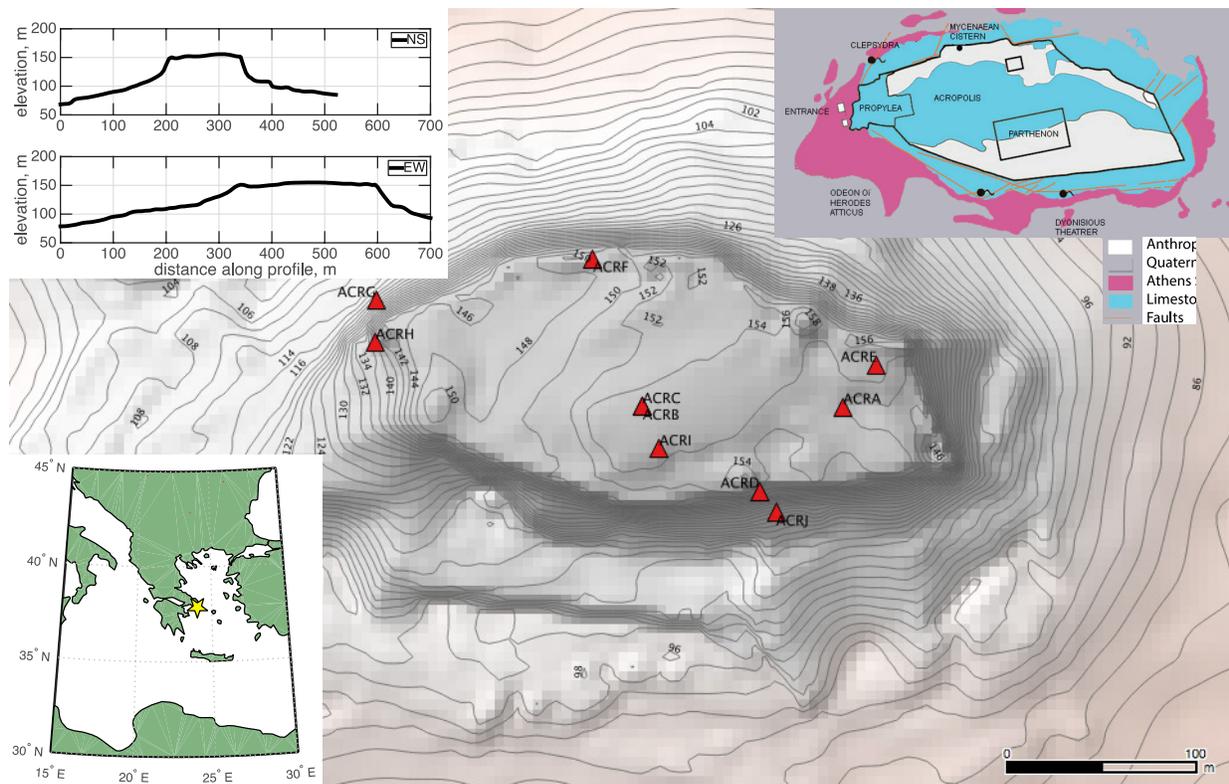


Figure 1. 5m-resolution Digital Elevation Model (DEM) of the Acropolis. Elevation ranges in the picture between ~ 80 m and ~ 160 m on top of the Acropolis ridge. Bottom-left inset: geographic location of Athens. Top-left: representative NS and EW cross-sections. Top-right: simplified geological map of the Acropolis modified after Higgins and Higgins (1996) and Andronopoulos and Koukis (1976).

Site response from earthquake and ambient vibration recordings

In this section we discuss possible amplification effects at the Acropolis strong-motion stations based on Standard Spectral Ratios (SSRs; Borchardt, 1970; Figure 2), H/V spectral ratios (originally by Nakamura, 1989) and ratios of 5%-damped elastic response spectra. The earthquake dataset used in this study is given in Table 2. It consists of 4 events that occurred at distances < 50 km and 11 at distance < 100 km recorded by the whole array. Magnitudes (M_L) do not exceed 5.2 for regional events, while the maximum magnitude for local events is 3.4. Candidate reference stations were ACRJ and ACRF, both located at the bottom of the Acropolis limestone flanks, none on flat topography though. ACRJ was preferred to ACRF as reference station in this study due to expected better mechanical properties (less weathered) of the southern limestone outcrop. ACRJ exhibits a flat H/V ratio over the frequency range of interest for the present study and ground motions at ACRJ are generally lower than those recorded at any other Acropolis site.

Table 1. List of stations presently contributing to the Acropolis strong-motion array.

Station code	Lat., deg.	Lon., deg.	Elevation, m	Location	Geology
ACRA	37.9716	23.7277	154	free-field	limestone
ACRB	37.9716	23.7265	156	Parthenon basement	porous stone blocks on limestone
ACRC	37.9716	23.7265	174	Parthenon N colonnade	(-)
ACRD	37.9712	23.7272	147	free-field	anthropic infill
ACRE	37.9718	23.7279	155	free-field	limestone
ACRF	37.9723	23.7262	126	free-field	limestone
ACRG	37.9721	23.7249	114	free-field	Athenian schist
ACRH	37.9719	23.7249	134	free-field	limestone
ACRI	37.9714	23.7266	156	Parthenon basement	porous stone blocks on limestone
ACRJ	37.9711	23.7273	130	free-field	limestone

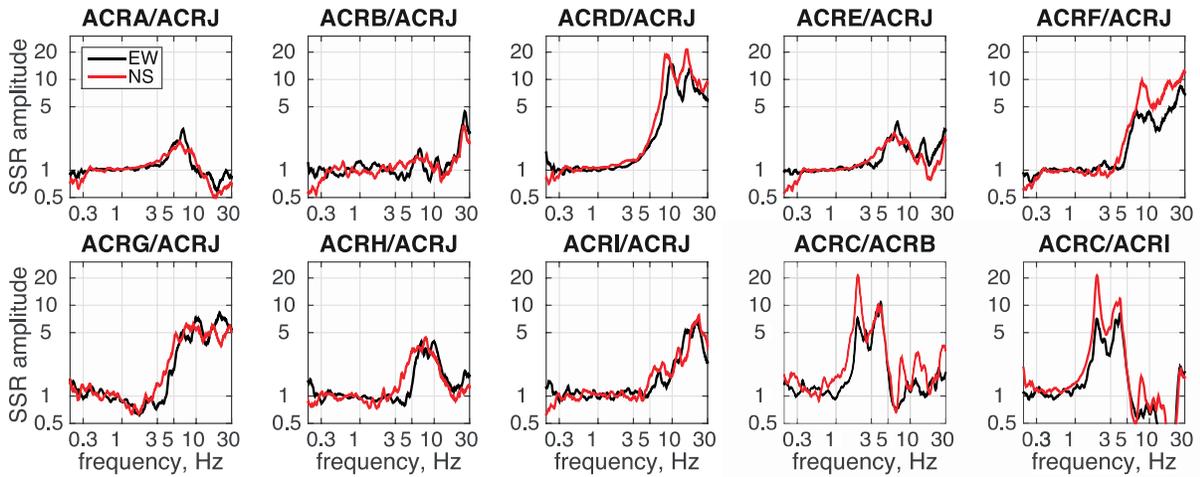


Figure 2. Standard spectral ratios (SSRs) for the events listed in Table 2. Note the high amplification values reached on anthropic infill (ACRD) and weathered limestone (ACRF) under low-strain seismic excitation, confirming that sub-surface velocity structure plays a significant role in the seismic response of the site, possibly dominating the geomorphological effects.

All the free-field stations installed on outcropping limestone (ACRA, ACRH, and ACRE) exhibit a clear amplification peak between 5 Hz and 10 Hz. Although not dominant, this peak is also apparent at other stations in the array. This can be explained either based on: a) Paolucci (2002), who applied the Rayleigh's method for estimating the fundamental vibration periods of homogeneous 2D reliefs as $\hat{T}_{0-SH} = W / (0.7\beta)$ and $\hat{T}_{0-SV} = W / \beta$ (based on the width W of the mountain cross-section and the shear wave velocity β), or b) Cauzzi et al. (2012), who represented the topographic irregularity as an idealized uniform fixed-free shear-beam with

vibration periods (*e.g.* Blevins, 1979) $T_i = \frac{4\Delta}{(2i-1)\beta K^{1/2}}$, $i = 1,2,3\dots$, where Δ is the span of

the beam – *i.e.* the height of the relief - and K the shear coefficient that they assumed equal to 1. At ACRF the aforementioned peak is dominated by a broad amplification bump at higher frequencies, most likely due to the degradation of the mechanical properties of the limestone on the northern flank. The SSRs at ACRF are very similar to those at ACRG installed on Athens' Schist nearby. ACRB and ACRI, installed on the porous stone blocks of the Parthenon foundation, show amplification phenomena between 10 Hz and 30 Hz. The SSRs at ACRD, located on anthropic infill, show a multiplicity of maxima at frequencies larger than 5 Hz. Similar results were obtained using 5%-damped response spectra (not shown here for brevity) instead of Fourier spectra. Single station H/V ratios performed on ambient vibrations recordings at the same stations did not capture any significant amplification phenomenon with the exception of stations ACRD and ACRF, where amplification is apparent in the same frequency bands of the SSRs ratios. The spectral ratios ACRC/ACRB and ACRC/ACRI show dominant peaks of amplification at ~ 2 Hz and ~ 4 Hz, the former being clearly associated through coda-wave analyses to the free vibrations of the monitored monumental element, *i.e.* a marble column pertaining to the northern colonnade of the Parthenon.

Table 2. List of local and regional events used in this study.

Date Time (UTC)	Lat., deg	Lon., deg	Depth, km	M _L	Distance from Acropolis, km
20131127 142116	37.34	23.01	25	4.4	93
20131222 180402	37.85	22.76	27	3.5	86
20140330 203103	37.58	23.45	20	3.4	46
20140404 200808	37.2	23.72	113	5.5	84
20140711 094605	38.45	23.71	26	4.4	55
20140711 104701	38.45	23.71	25	3.8	55
20140730 005504	38.04	24.12	19	3.6	35
20141117 230555	38.64	23.4	24	5.2	80
20141117 230903	38.64	23.41	23	5.2	80
20141205 020436	38.09	23.6	18	2.4	17
20150116 063251	38.03	23.76	12	3.2	7

Site response from numerical simulations

The computational mesh was designed using the commercial software CUBIT (<https://cubit.sandia.gov/>), a mesh generation toolkit developed by Sandia National Laboratory. CUBIT allows unstructured hexahedral meshing of complex 3D geometries and mechanically heterogeneous domains typical of the vast majority of engineering seismology and geotechnical earthquake engineering problems. Hexahedral meshing is required by the computer code SPEED (SPectral Elements in Elastodynamics with Discontinuous Galerkin; Mazzieri et al., 2013) used in this study. SPEED builds on consolidated experience in using spectral elements for solving viscoelasto- (and viscoplasto-) dynamic problems (Faccioli et al., 1997; Stupazzini et al., 2009) to approach seismic wave propagation analysis in heterogeneous 3D media at both local and

regional scale. Based on the discontinuous Galerkin spectral approximation and efficient and scalable algorithms, the code allows dealing with a non-uniform polynomial degree distribution as well as a locally varying mesh size. The open source code is optimised for parallel computing. We designed two meshes, namely: (i) a uniform mesh with $V_S = 1500 \text{ ms}^{-1}$ aimed at capturing the sole possible contribution of topography to the site response of the Acropolis (Figure 3) and (ii) a computation mesh sampling the main geological units shown in Figure 1. Including the monumental elements of the Acropolis (iii) in the computational domain is expected in the near future.

Based on the recorded earthquake and ambient vibration data (Figure 2), mesh (i) was designed to accurately propagate maximum frequency components up to $f_{max} = 10 \text{ Hz}$, while (ii) allows 30 Hz simulations. In all cases, excitation was a vertically propagating plane S-wave of the Ricker type with dominant frequency $f_{peak} = f_{max}/3$. We explored three options for polarization: EW, NS and simultaneous EW-NS. Viscoelastic properties of the materials were taken from Kalogeras and Egglezos (2013). While detailed results will be presented at the conference (scheduled 01-04.11.2015), we anticipate in this contribution (written 15.03.2015) that the topographic effect of the Acropolis ridge is satisfactorily captured by our numerical simulations (Figure 4) as to both amplitude and shape of the amplification observed at outcropping limestone sites on top of the Acropolis ridge.

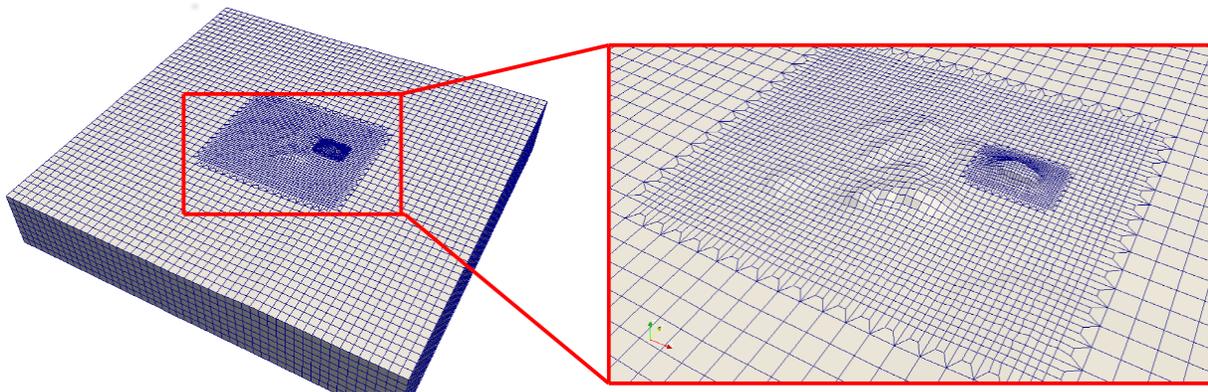


Figure 3. Computational grid for the homogeneous limestone model aimed at understanding the sole contribution of geomorphology to the site response. Note how the density of tetrahedral elements changes in the model, from a characteristic size of $\sim 16.5 \text{ m}$ (Acropolis ridge – based on the 5m-DEM shown in Figure 1) to 50 m (Athens downtown region, based on ASTER 30m-DEM data; LP DAAC, 2001) to 150 m (portions of the model with flat free surface included to accommodate potential spurious reflections from the absorbing boundaries).

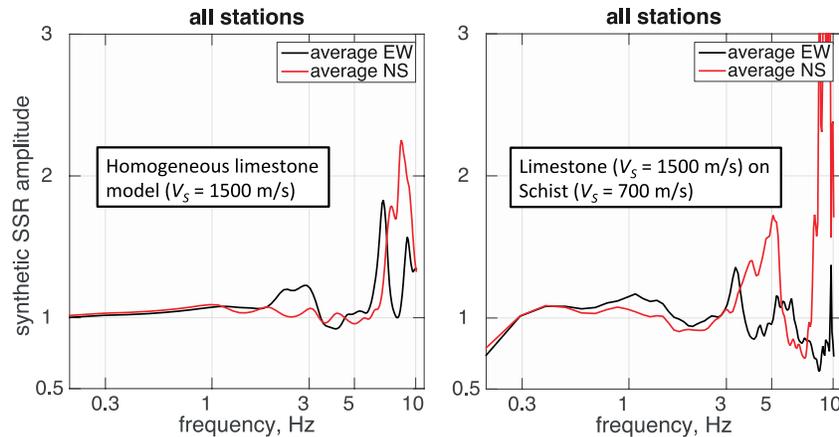


Figure 4. Average SSRs as obtained from alternative numerical models aimed at capturing the potential topographic amplification of the Acropolis ridge.

Conclusions and outlook

Based on seismic recordings of the high-quality strong-motion array of the Acropolis of Athens and dynamic properties of geo-materials published in the international literature, we attempted at investigating the seismic response of the Acropolis of Athens by means of both recorded and synthetically generated spectral ratios. Our preliminary results seem to indicate that the effect of topography (geomorphology) on the seismic response of the site can be appreciated in the frequency range 5-10 Hz as confirmed by 3D numerical simulations. The amplification peaks apparent in the recorded data at higher frequencies (10-30 Hz) are most likely governed by the sharp velocity contrast between the limestone and the anthropic infill of the Acropolis ridge, as well as by mechanical degradation and weathering of the outcropping bedrock. From a numerical modeling perspective, high-frequency amplification is presently (12.07.2015) being better investigated along with a joint analysis the seismic response of the natural site and its monumental buildings.

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