Seismic Actions on the Acropolis Monuments
Scientific and technical choices during the restoration interventions

December 2, 2013

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Seismic Actions on the Acropolis Monuments

Damages and transformations to the Acropolis Monuments

The Morosini bombardment - Fanelli 1687

The Parthenon transformed to a ruin
Christian Hansen 1836

Propylaia east side, 1838

Propylaia west side, 1819
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Structural damages to the Acropolis Monuments such as collapses, cracks and displacements of the marble blocks, rotations of the column drums, caused by

• **Physical actions** during the 2,500 years of their history as the destruction and displacements caused by earthquakes

• **Human interventions** : explosions, fires, bombardments and the rusting of the iron reinforcements of the previous restoration
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The restoration of Nikolaos Balanos 1898 -1940

Parthenon – The restoration of the north side

Parthenon – The restoration of the west side

Propylaia east side before and after the restoration of Balanos
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Current restoration of the Acropolis Monuments

1975 – Establishment of the ESMA – The Committee for the Conservation of the Acropolis Monuments - of interdisciplinary specialists,

2000 – Establishment of the YSMA – The Acropolis Restoration Service - an independent Service of the Ministry of Culture

Main features of the Acropolis Restoration

- the interdisciplinary approach to the work
- the scholarly research underlying the interventions in all their phases
- the high quality of execution
- the transparency which accompanies them
- the meticulous documentation and recording
- the advanced technological applications
- the transparency which accompanies them

The current restoration on the Acropolis forms the modern Greek approach (‘school’) to the restoration of classical monuments, which enriches and exercises a considerable impact on similar projects on Graeco-Roman monuments in the Mediterranean region.
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**The initial aim of the Acropolis’ interventions**

A rescue work in order to confront the problems of serious structural damage and surface erosion suffered by the monuments,

In the course of the works it is possible

- to find the authentic position of the marble pieces that had been restored in random places,
- to locate the positions of many of the marble pieces that lay scattered on the ground and had not been recognised or used in the Balanos restoration.

Thus, the character the interventions, was expanded a broader anastelosis, increasing the comprehensibility of the monuments.
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Seismic damages on the Acropolis monuments during their history

According to historical facts the powerful earthquakes that have stuck the Acropolis monuments caused small or medium damages to the Acropolis monuments.

In the future: The strong mechanical strains to the Acropolis monuments are expected to be seismic, since we certainly hope that there will no longer be damage inflicted by mankind.

Imperative to evaluate the efficiency of the monuments in seismic activity, taking into account the damage they have suffered through their long history.

The Question: What is the reason for the proven resistance of the monuments to the seismic events of the past? The good seismic behavior of the Acropolis hill or is it that the way in which the buildings were constructed enabled them to withstand successfully the seismic actions?

The way of construction of the monuments,

•the formation of the structural system,
•the choice of materials,
•the high quality of construction,
•the construction details

show that the builders had taken into consideration the likelihood of seismic loading.
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Structure of the Acropolis monuments

• simple and clearly defined structural function regularity of their plan, symmetrical arrangement of their bearing elements and mass

• great rigidity of the walls together with the diaphragm function of the ceilings and roofs by means of friction, add to the resistance of the building to horizontal stress

• founding of the monuments for the most part on solid rock and good quality of construction of the foundations favour their good anti-seismic behaviour.
Structure of the Acropolis monuments

- built of worked stones of marble in the form of rectangular blocks or drums, without mortar, joined to each other with metal elements.

- although constructed of separate architectural members, their «dry masonry» joining has been done so accurately that in some cases the joins are imperceptible, giving the impression that the construction is continuous.

The temple of Athena Nike
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Structure of the Acropolis monuments

• The joining elements (horizontal-clamps, or vertical to the layers of stones-dowels) are made of iron, placed in specially cut tenon-holes or sockets and sheathed with cast lead.

• The **clamps** connect members in the same horizontal series and **absorb chiefly the tensional forces**,  

• The **dowels** connect members of successive courses and **withstand shear forces**.

• The connecting elements assure the total resistance of the construction, especially against seismic load or deformation due to various other disturbances (violent shifting or displacements, foundation yielding, etc.).

• The basic purpose of the **lead sheathing**, however, is to protect the iron of the joining elements from rusting by shielding them from the atmosphere.

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Clamp

Dowel
The Acropolis hill

• is a block of Late Cretaceous grey limestone resting on the marls and sandstones of the Athens Schist rock series

• The grey limestone is well exposed on the top of the hill, while the Athens Schist at the west of the west entrance

• The top of the hill has been leveled with artificial fill up to 17 m thick in order to form the plateau where the monuments stand.

Geological section of the rockhill (N-S direction)
From Higgins and Higgins 1996
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Seismicity of Athens

1. The seismicity of the broader Aegean area is caused by the relative motions of the Africa, Arabia and Eurasia plates

2. From older and recent studies by various authors Attiki is considered as an area of low seismicity

3. A review of the long term seismicity of Athens is presented by Ambraseys in 2010. According to it, the active faults are more than 10 km away the center of Athens and are of short length

4. As a conclusion the seismic hazard in the center of Athens is rather low.

5. Various authors, however consider that seismic events are to be expected from possible movements of the Attiki mapped faults
# Seismic Actions on the Acropolis Monuments

## Earthquakes that Affected Acropolis (according to the literature search)

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Distance (Km)</th>
<th>M</th>
<th>PGA (cm/s² estimated)</th>
<th>Structural damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>426 BC</td>
<td>Atalanti</td>
<td>140</td>
<td>?</td>
<td>?</td>
<td>Parthenon, NE corner</td>
</tr>
<tr>
<td>1705</td>
<td>Oropos</td>
<td>35 - 40</td>
<td>&gt;=6.0</td>
<td>45</td>
<td>South and east Wall</td>
</tr>
<tr>
<td>1785</td>
<td>Oropos</td>
<td>40</td>
<td>&gt;=6.0</td>
<td>40</td>
<td>North Wall</td>
</tr>
<tr>
<td>1805</td>
<td>Oropos</td>
<td>40</td>
<td>?</td>
<td>40</td>
<td>Parthenon and North Wall</td>
</tr>
<tr>
<td>1874</td>
<td>Athens?</td>
<td>?</td>
<td>?</td>
<td>60 (?)</td>
<td>North Wall</td>
</tr>
<tr>
<td>1894</td>
<td>Atalanti</td>
<td>100</td>
<td>6.9</td>
<td>30</td>
<td>Parthenon' pediment</td>
</tr>
<tr>
<td>1938</td>
<td>Oropos</td>
<td>37</td>
<td>6.1</td>
<td>40</td>
<td>South Wall</td>
</tr>
<tr>
<td>1981</td>
<td>Korinthos</td>
<td>77</td>
<td>6.7</td>
<td>30</td>
<td>NE corner of the Parthenon</td>
</tr>
<tr>
<td>1999</td>
<td>Athens</td>
<td>20</td>
<td>5.9</td>
<td>65</td>
<td>Propylaia</td>
</tr>
</tbody>
</table>
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**Structural damages to the Acropolis Monuments**: Cracks, displacements, shifts, and failure of joining elements.

The recognition of the structural damages on the Acropolis Monuments due to seismic events from these caused by other reasons is a complex process with a compound content: historical, archaeological and technical.

**SW corner of the Parthenon**

The west end of the entablature of the Parthenon south colonnade, Balanos archive, 1933

The west end of the entablature of the Parthenon south colonnade showing the cracked, architrave block after the earthquakes of 1981 and 1999
**Structural damages of the West side of the Parthenon**: curvature of the façade on the horizontal level, cracking of the corner architrave blocks, opening of joints between the members, fracture of members, rotations and fractures of the edges of the column drums

**Reasons**: The fire of ancient times (276 AD), the explosion of 1687, the earthquakes that struck the monument and the rusting of the iron reinforcements of the previous restoration.
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Shifting of the South wall of the Propylaia: led to the fracturing of many architectural members and joining elements (clamps and dowels)

Reason: The explosion in 1640 of the dynamite that the Turks had stored in the monument.

The south wall of the Propylaia

Fractures of architectural members and joining elements
2008: Installation of a network of 7 accelerographs from the Geodynamic Institute of the National Observatory of Athens.

2013: Installation of 3 more accelerographs from the Geodynamic Institute of the National Observatory of Athens, elaboration of the seismic data and insertion them in the data base of YSMA.

Purpose: record seismic action and the response of the hill and the monuments to these.

Positions of the accelerographs

Mandoudi Earthquake
(14.10.2008)
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2008 – 2013: Joint research program in cooperation of YSMA with the NTUA and MIE University of Tokyo includes:

- Installation of a network of accelerographs on the Parthenon
- Microtremor monitoring at the Parthenon
- D.E.M. procedures for proper simulations of earthquake response of the Acropolis monuments

**Purpose:** selection and validation of the seismic data on the Acropolis Monuments

Earthquake Monitoring at Parthenon Athens
Analytical methods for proper simulation of the behavior of classical monuments under seismic loads

Problems

• The presence of joints between the wall blocks means that only compression and shear stresses are undertaken and not tensile, resulting in the non-linear behavior of the structure.

• From the quantitative aspect, controlling the composite movement of the hundreds of a classical monument under seismic load is an extremely difficult problem.

• The problem is further complicated by cracks, deformations, shifts and failure of joining elements.

• Special care must be taken in the formation of the simulation model of the monument as it is needed the evaluation of assumptions, difficult to be determined.
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A analytical investigation is in progress in collaboration of YSMA with the Laboratory of Earthquake Engineering of the NTUA

**Purpose:** the investigation of the structural restoration of the north and south cella walls of the Parthenon with ancients blocks whose their original position was recognized after research, limiting to the minimum possible, the additions in new marble.

2008: Investigation from NTUA of two reference scenarios for the restoration of south and north walls

2013: In progress the investigation in collaboration of YSMA with NTUA for the structural restoration of the north wall with 252 ancient blocks and 109 blocks of new marble

**1st proposal:** External surface of the north wall  Full supplementing of the burnt blocks of the interior surface of the north wall with new marble and partial reconstruction of the partition wall

**2nd proposal:** Internal surface of the north wall  Partial supplementing of the burnt blocks of the interior surface of the north wall with new marble, according to the structural assessment and partial reconstruction of the partition wall
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Principles of the structural restoration of the monuments

- Principles of the Charter of Venice
- Additional principles arising from the system of construction of classical monuments

**Basic principle**: Respect and preservation during the restoration of the initial structural system of the monument, which has ensured its sufficient seismic behavior.

*Consolidation of the cracked from fire columns of the Opisthonaos of the Parthenon with special injections, preserving the initial structural system.*
Preservation of the original structural system means:

• Respect for the authentic material of the monuments
• Retention of the structural autonomy of the architectural members
• Retention of the original structural function of the architectural members
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1. Restriction of the interventions to the absolutely necessary
   The Propylaia entablature, the temple of Athena Nike, the north side of the Parthenon areas with serious structural problems
2. Preservation of the original structural function of the architectural members during their restoration

Structural Restoration of the Propylaia beams with titanium rods and white cement
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Filling in with new marble

Joining a supplement with the ancient fragment

New marble filling with a pontadoros

New marble filling in a column capital

Carving a column capital from new marble
3. Assembling of the blocks with titanium clamps and dowels in the ancient cuttings
4. Restoration of parts of the monuments by resetting the ancient members in their original positions and members of new marble

The ceiling of the West Hall of the Propylaia
The restored ceiling of the Propylaia east portico
5. Maintenance of the high quality of the original construction during the restoration thus as:

• Maintenance of the exact geometry of the architectural members during the joining of fragments
• Carving of the supplements’ and new marble blocks’ surface with special care
• Correction of the deformations of the restored areas of the monuments, in the degree allowed from the deformation and displacements of the areas not dismantled.
• Careful working of the contact surfaces between the marble blocks insures the development of friction forces among them and the cohesion of the structure.

This concern is necessary not only for aesthetic reasons but also for structural reasons:

Respect for the ancient structural system, which thus insured the safe transfer of the loads to the ground.
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Parthenon North side – Resetting the marble blocks with two cranes
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