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Seismic Vulnerability of Classical Monuments

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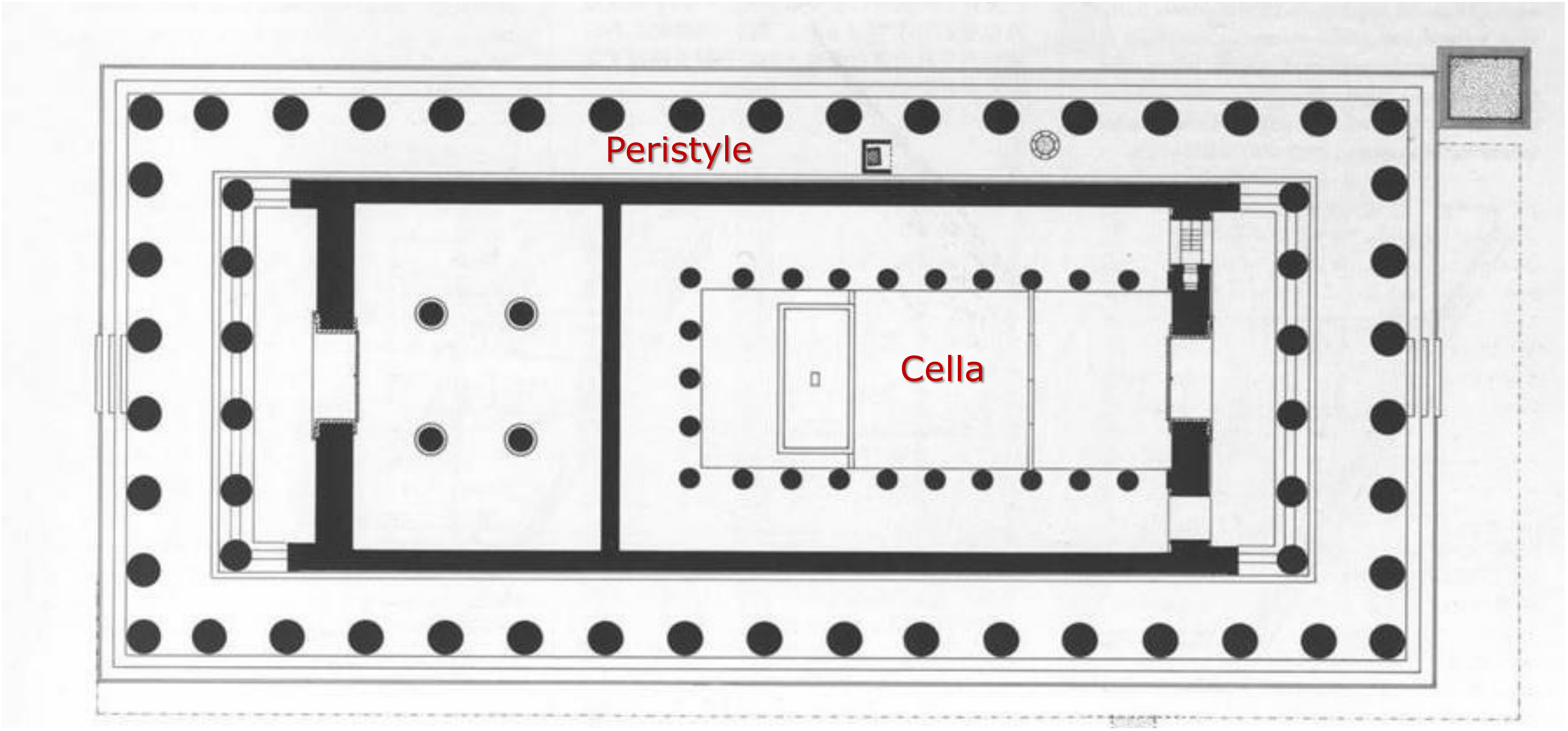
Classical monuments

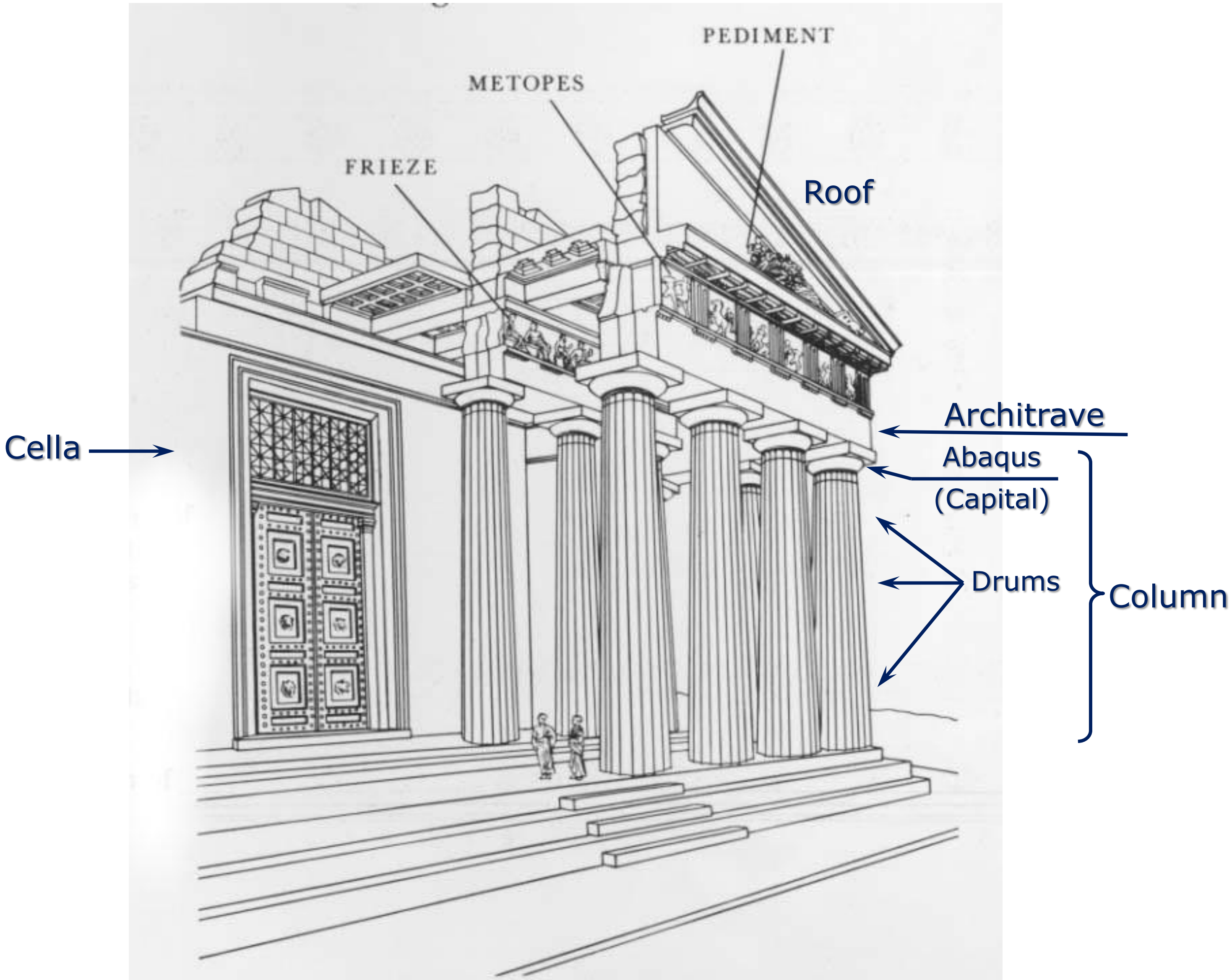
The Parthenon, Athens, Greece

Built: 5th century B.C.

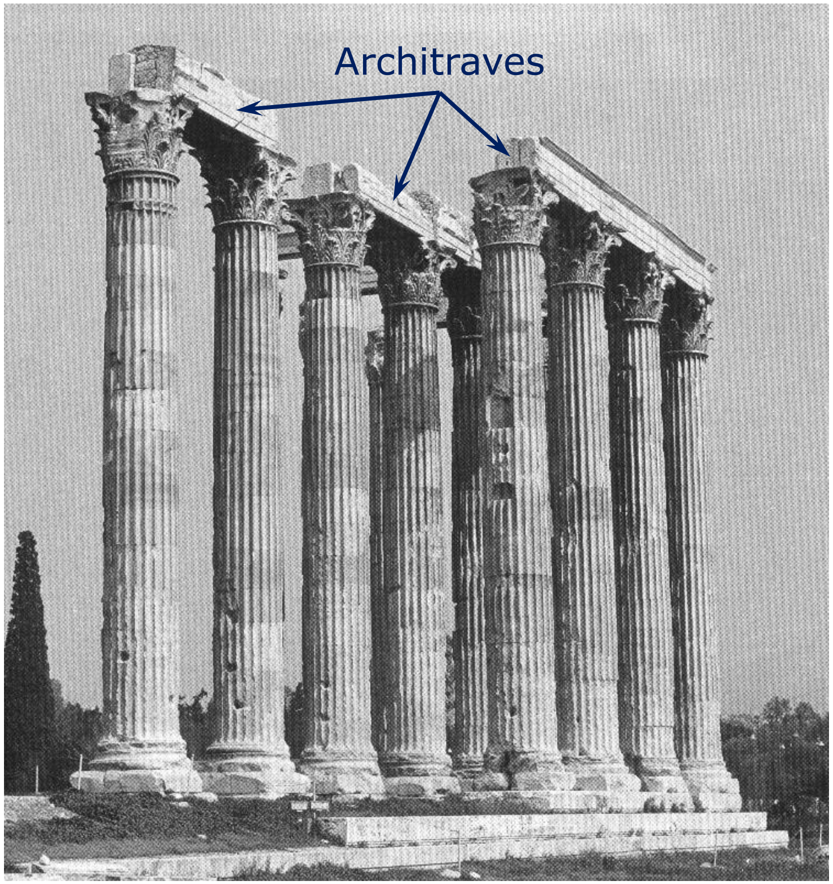
Plan view



Main parts of an ancient temple



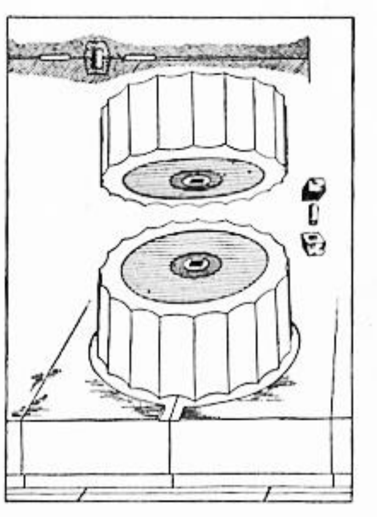
Construction of columns



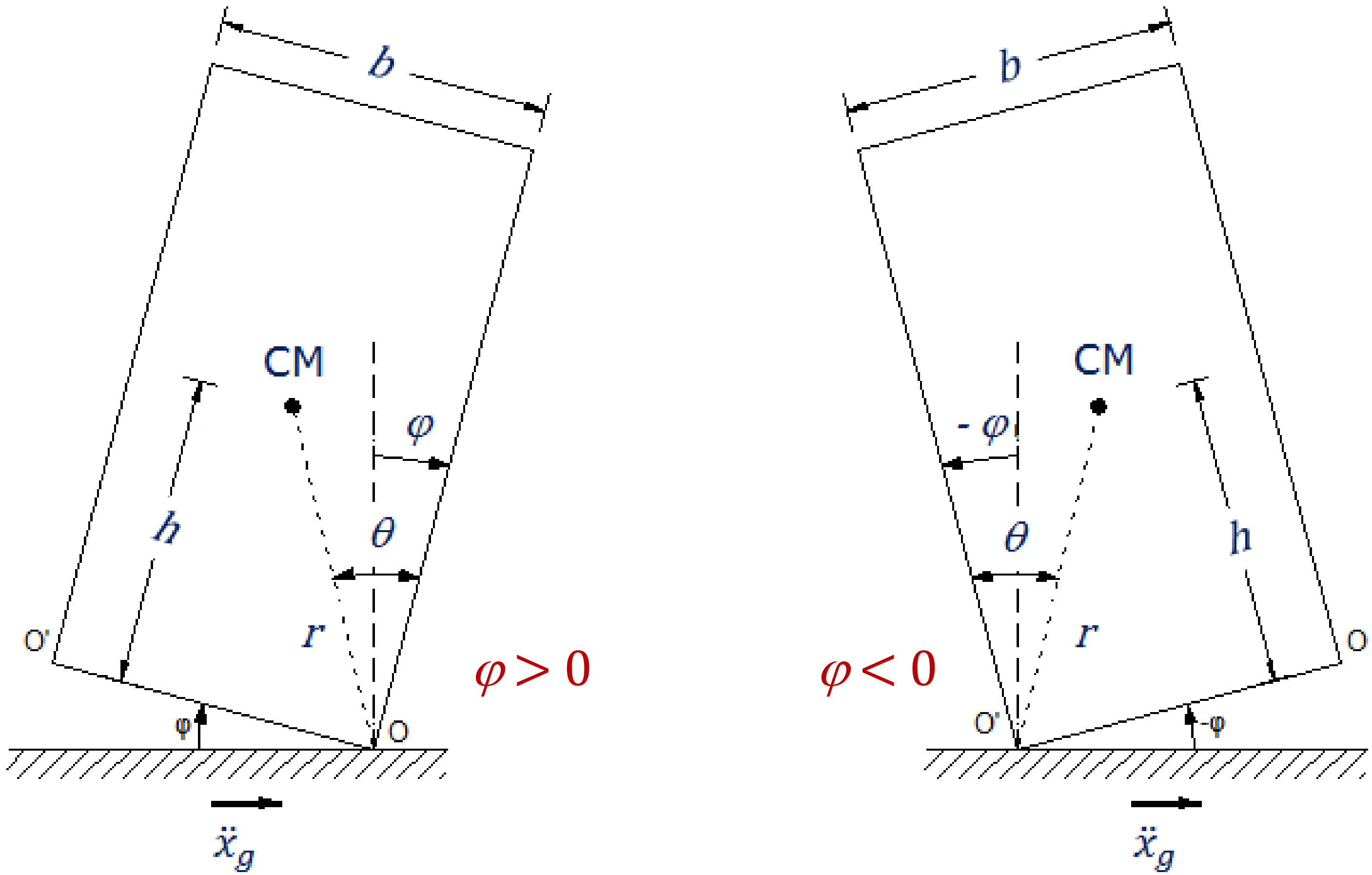
Olympieion of Athens

Columns: made of drums placed one on top of the other without mortar and, usually, nor any other type of connection:

→ spinal structures



Rocking rigid block



Linearized Equation of Motion

$$I_0\ddot{\varphi} - mgr\varphi = \mathrm{sgn}(\varphi)\, mgr\theta - m\ddot{x}_g r$$

Rocking rigid block

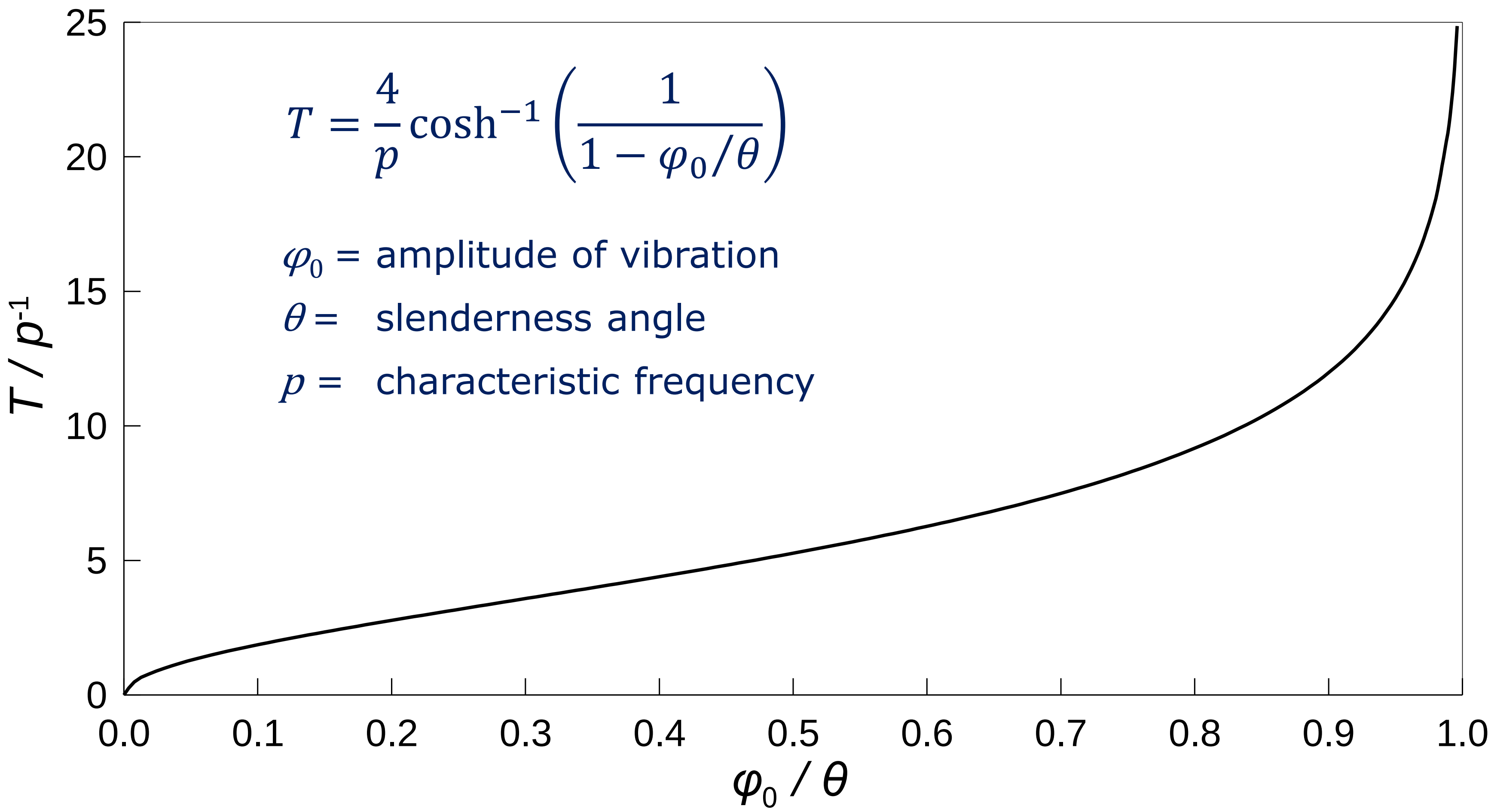
The period of free vibrations is amplitude dependent

$$T = \frac{4}{p}\cosh^{-1}\left(\frac{1}{1-\varphi_0/\theta}\right)$$

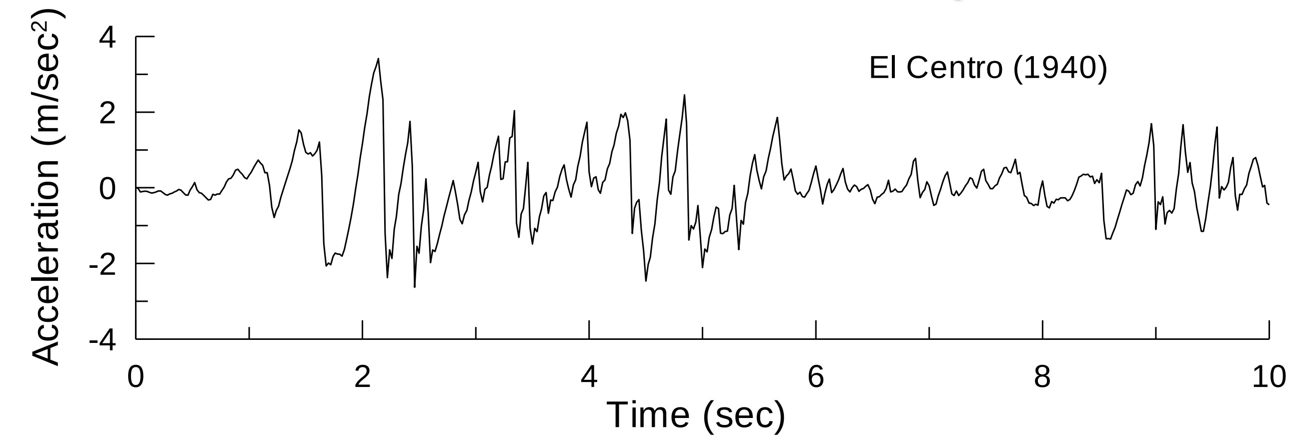
φ_0 = amplitude of vibration

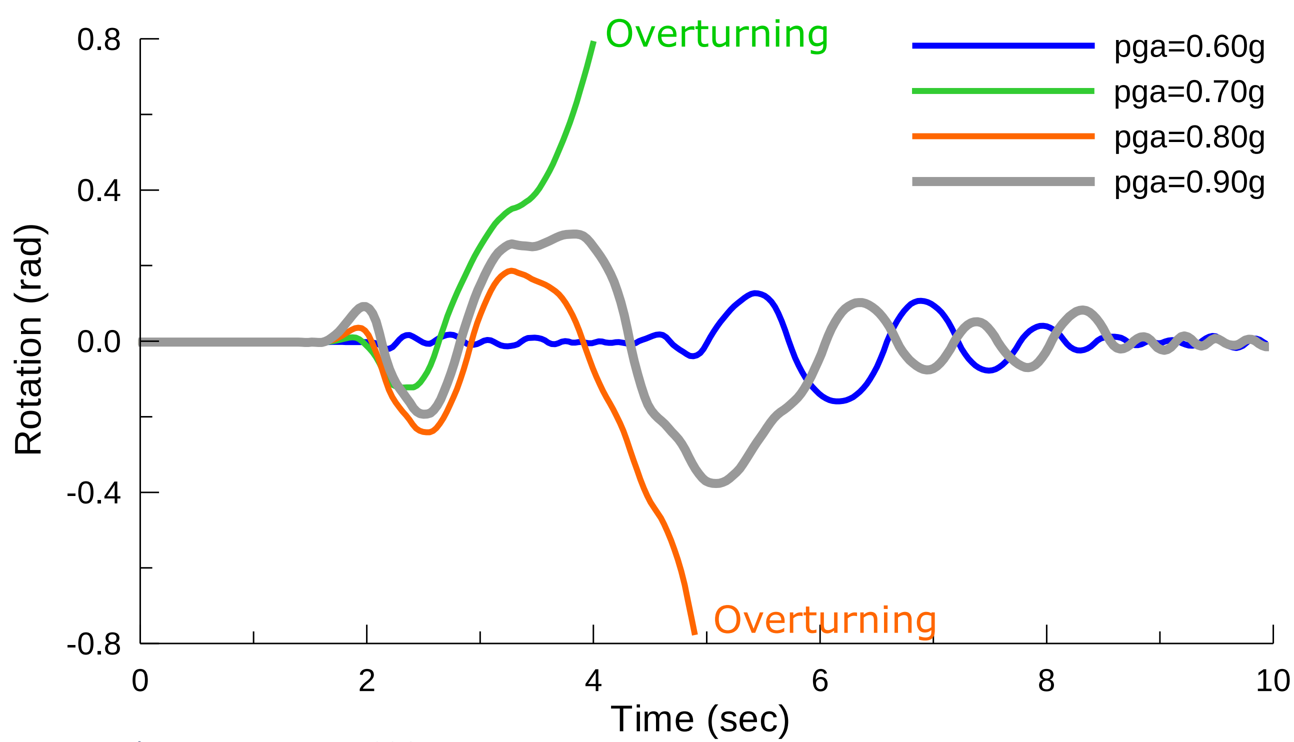
θ = slenderness angle

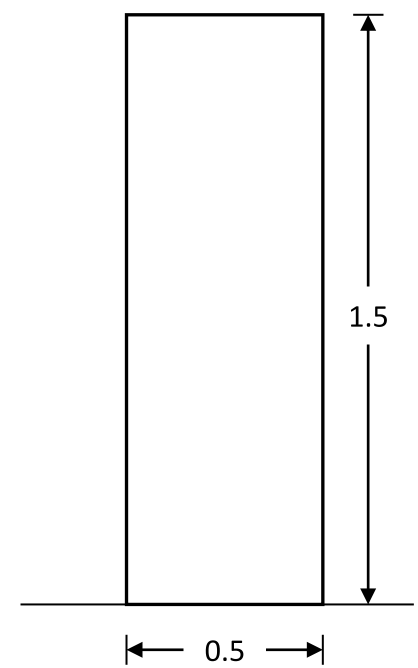
p = characteristic frequency



Nonlinearity







Impact with the base

The change of the pole of rotation from O to O′ or vice versa is accompanied by impact which causes dissipation of energy:

$$\dot{\varphi}_2 = \varepsilon \cdot \dot{\varphi}_1 \quad \text{where:} \quad \varepsilon = 1 - \frac{mb^2}{2I_0}$$

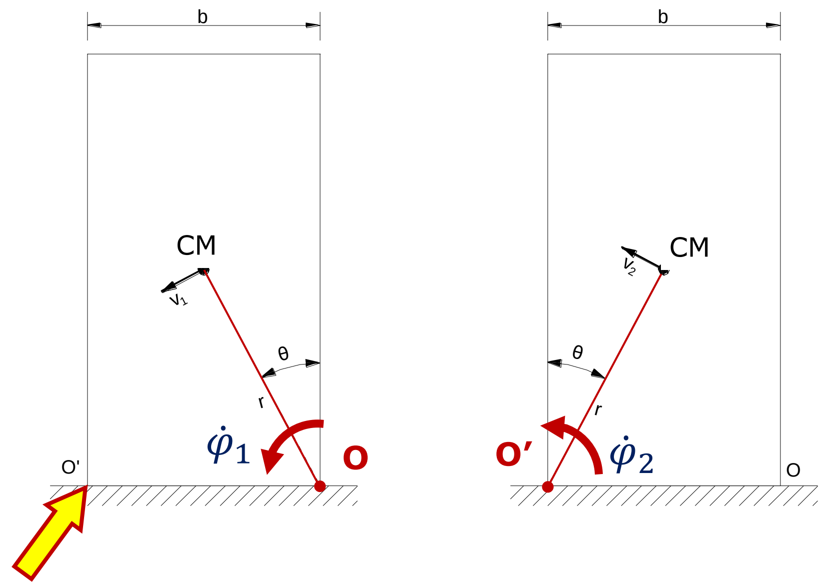
The amplitude of free vibrations reduces with the number of impacts:

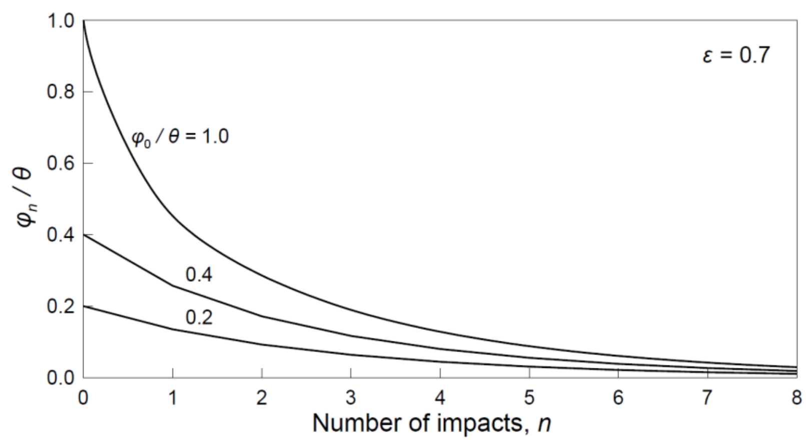
$$\frac{\varphi_n}{\theta} = 1 - \sqrt{1 - \varepsilon^n \left[1 - \left(1 - \frac{\varphi_0}{\theta}\right)^2\right]}$$

φ_0 = initial amplitude

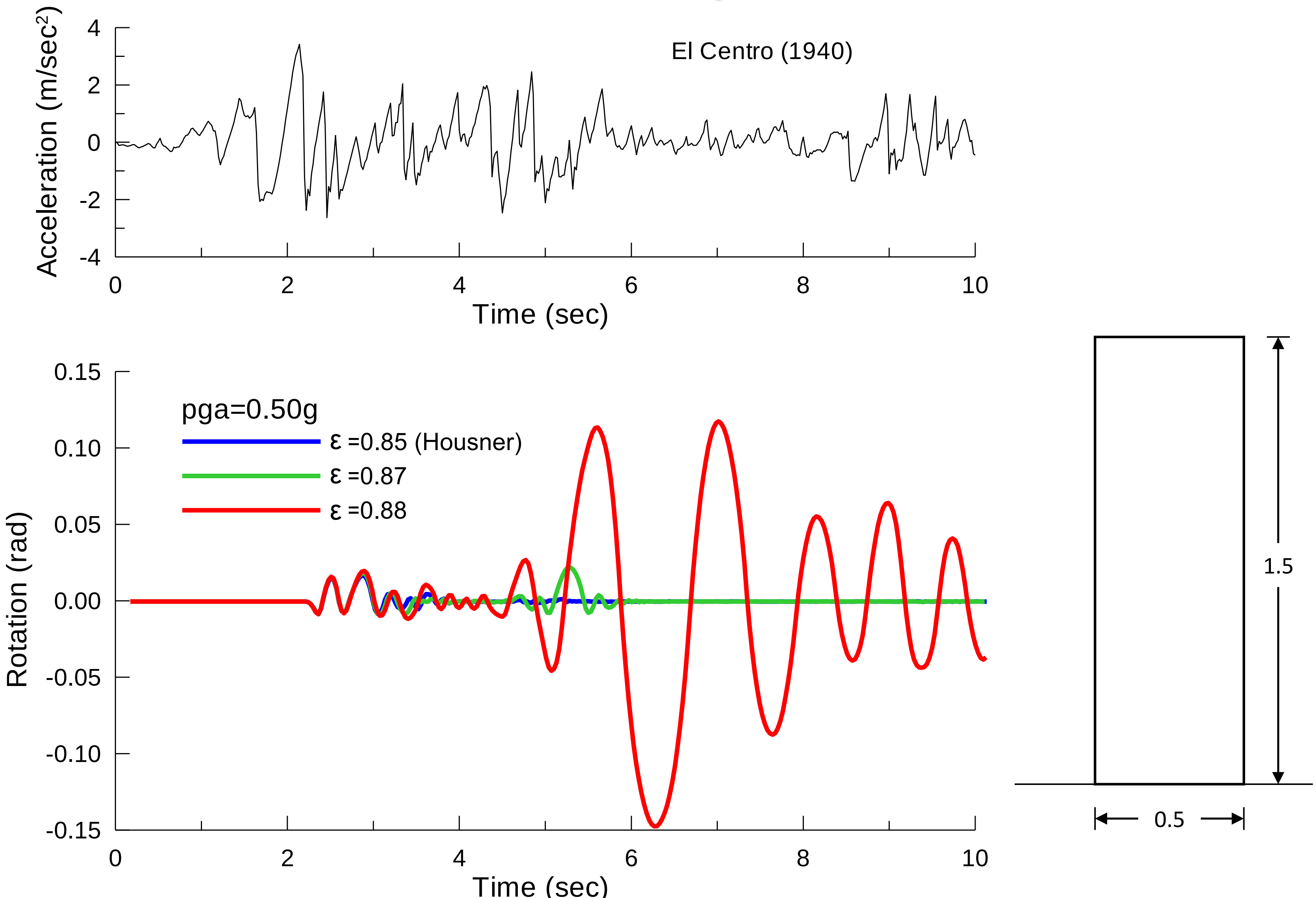
φ_n = amplitude after n^{th} impact

θ = slenderness angle





Sensitivity

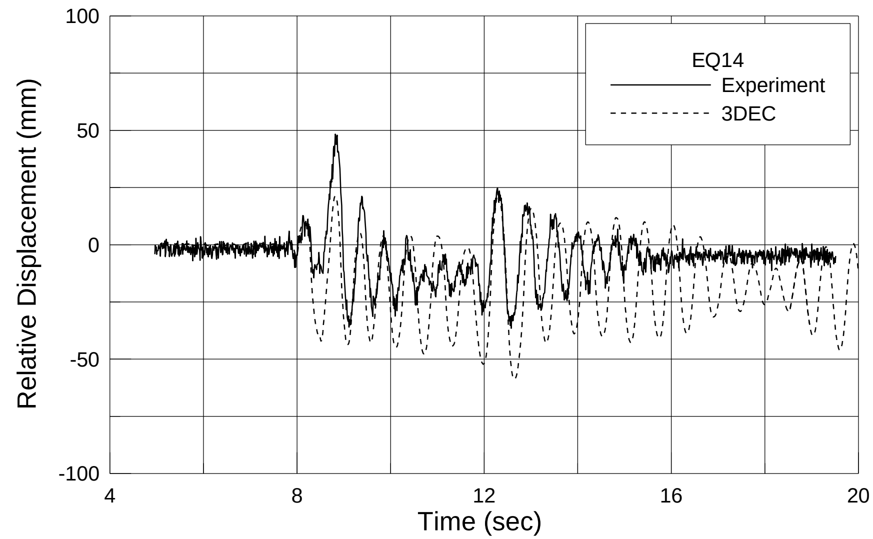


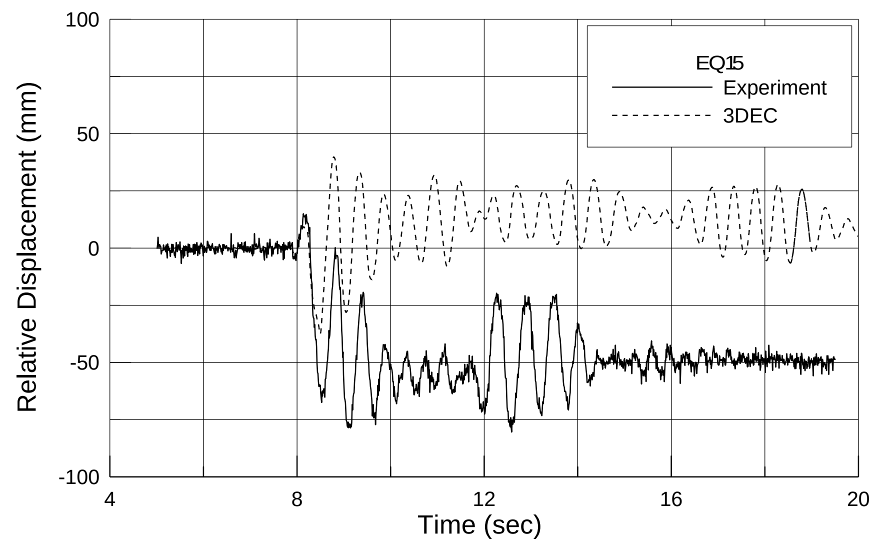
Sensitivity

Shake table experiments on a marble model of the Parthenon column (scale 1:3)

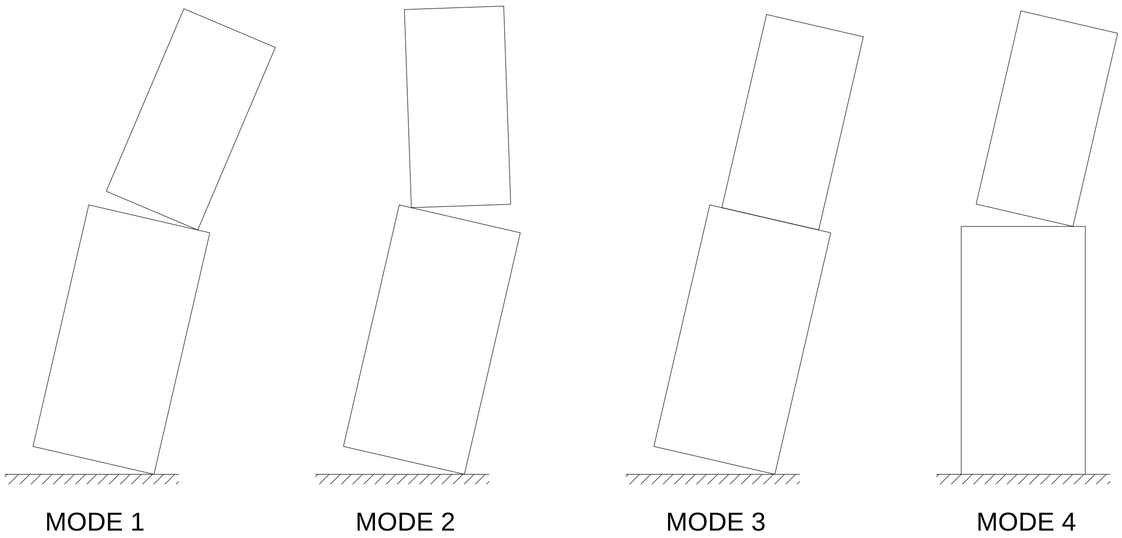
- Repetition of the same experiment (EQ15) showed an unexpected slip.

- Sensitivity was also apparent in numerical calculations in which the recorded acceleration on the shaking table was used $\Rightarrow$ different response due to the small difference in the excitation.





Assemblies of rocking blocks



(Psycharis, 1990)

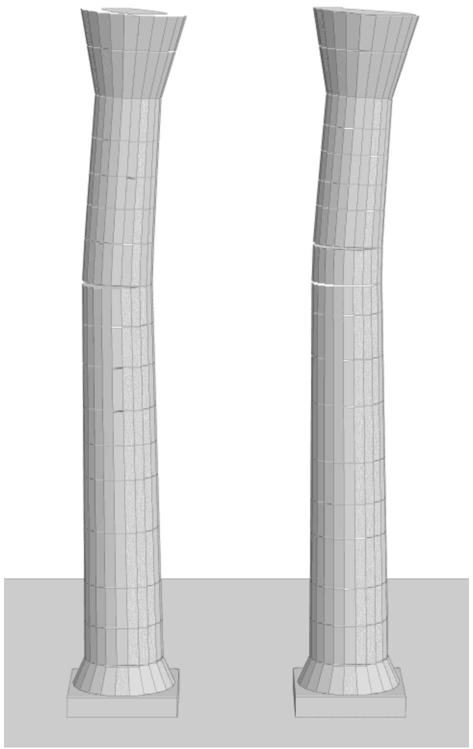
Many different "modes" of vibration, each one governed by a different set of equations of motion.

- Two-block assembly: 4 modes

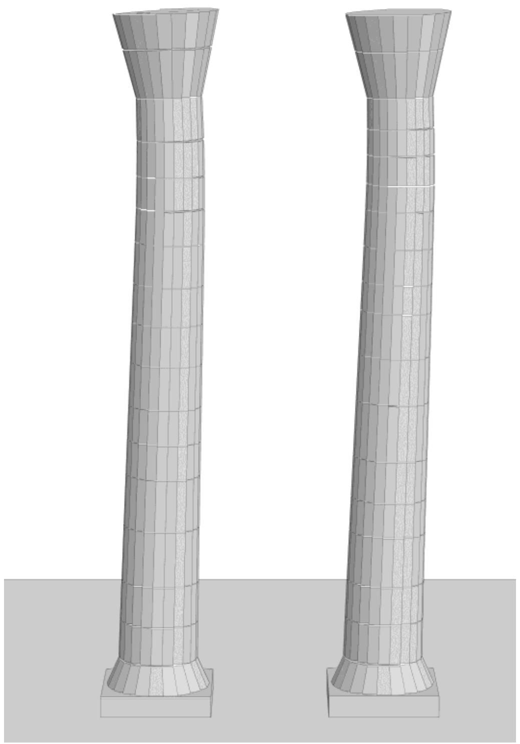
Multi-drum columns

Columns of Olympieion of Athens

(Numerical results)



$t = t_1$



$t = t_2$

- Column with 11 drums: 88573 modes (Zambas, 1994).
- During the seismic response, there is a continuous transition between modes.

Seismic response

Seismic response

Question:

Can such structures survive strong earthquakes ?

Answer:

Generally, YES

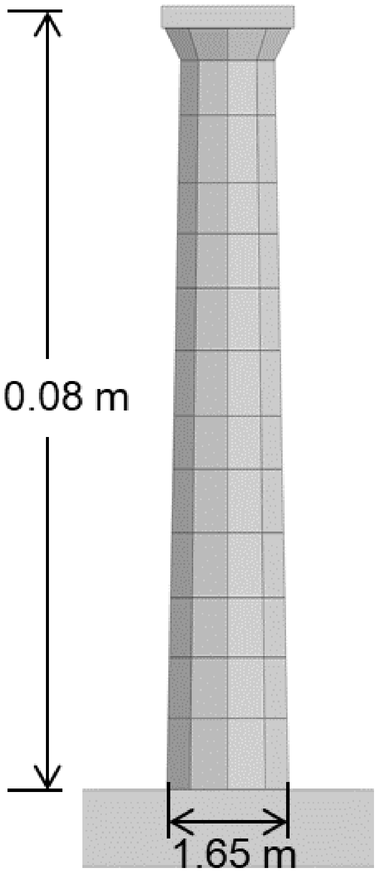
Proof:

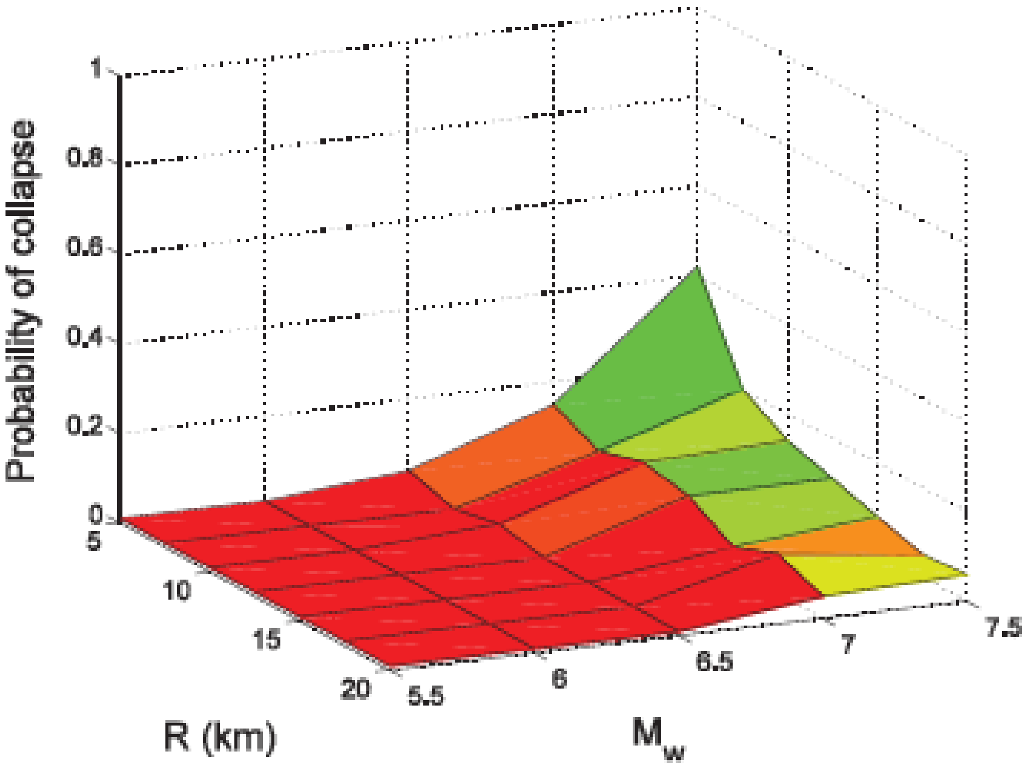
Many classical monuments are still standing in seismically prone areas (Greece, Italy, Turkey, etc.), after 2500 years from their construction, with evidently displaced drums, though, due to their response during earthquakes.

Columns of Thrasyllos, Athens, Greece, free-standing for more than 2000 years.

Vulnerability of the column of the Parthenon

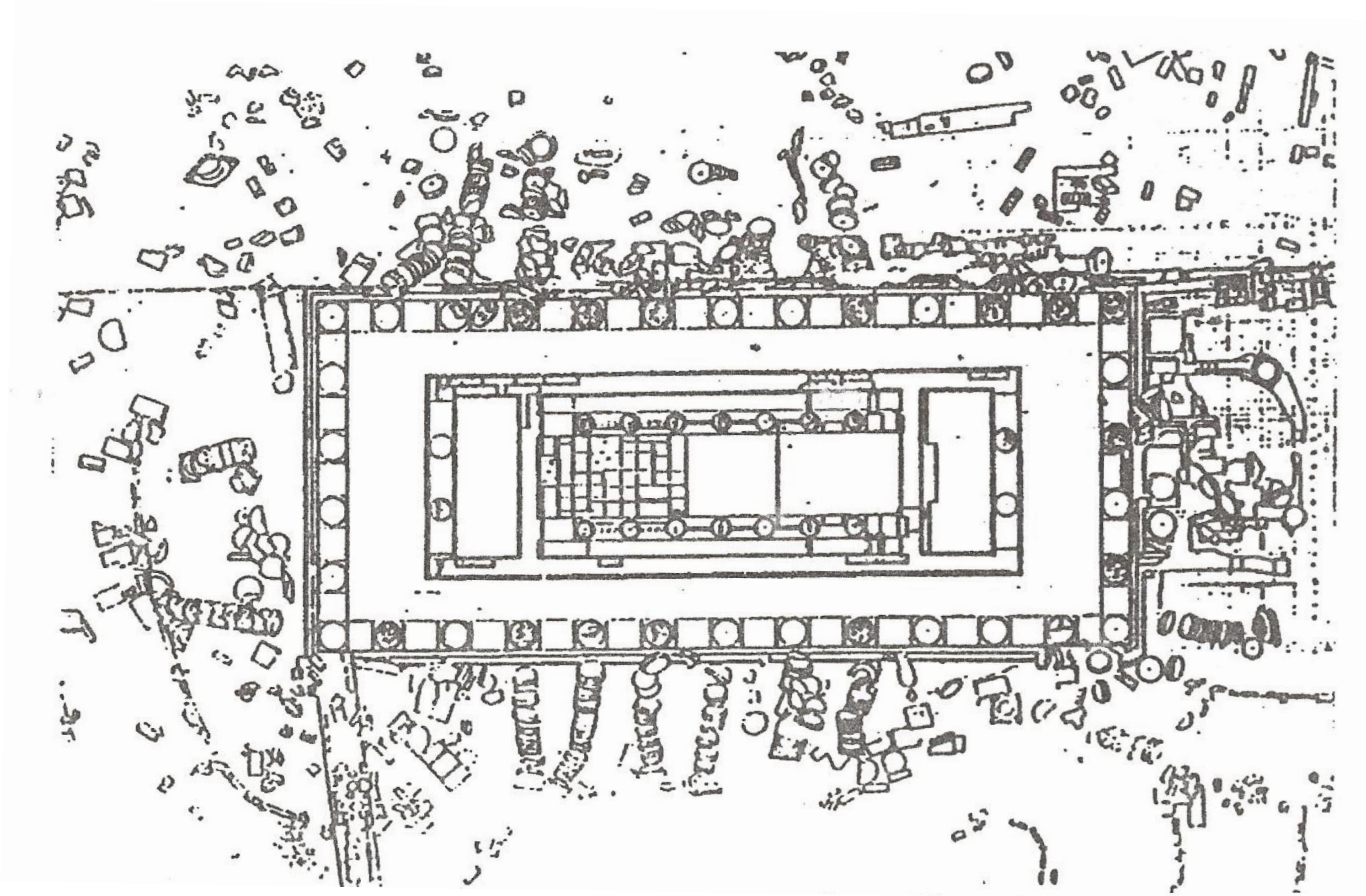
Collapse probability for 3500 artificial near-fault ground motions of magnitude M_w = 5.5 ÷ 7.5.





(Psycharis *et al.*, 2013)

However, many other monuments have collapsed!



The ruins of the Temple of Zeus at Olympia, Greece, as discovered during the excavations of the 19th century.

Factors affecting the vulnerability

- The size of the structure
- The predominant period of ground motion
- The existing damage
- The connections between the structural members (clamps and dowels).

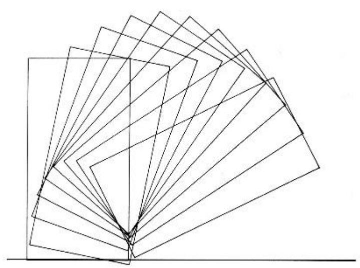
Size effect

Rocking block

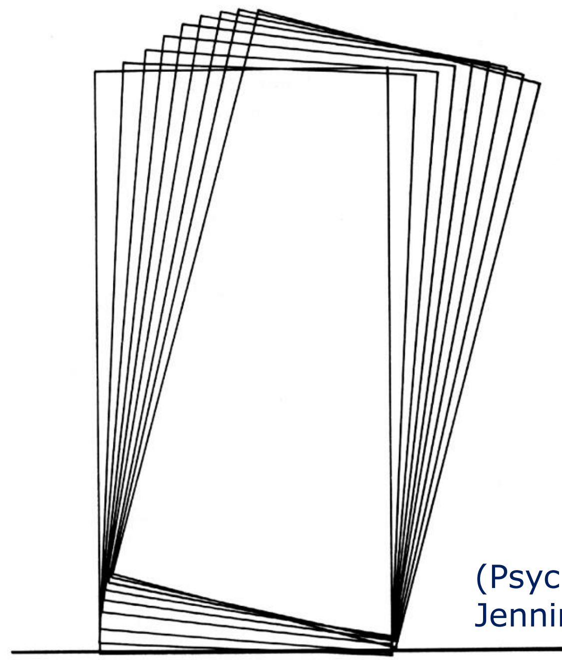
Smaller blocks overturn easier than larger ones with the same slenderness.

Example:

Response of blocks with $\tan\theta = 0.5$
to the same initial velocity of the C.M.



b = 0.50 m

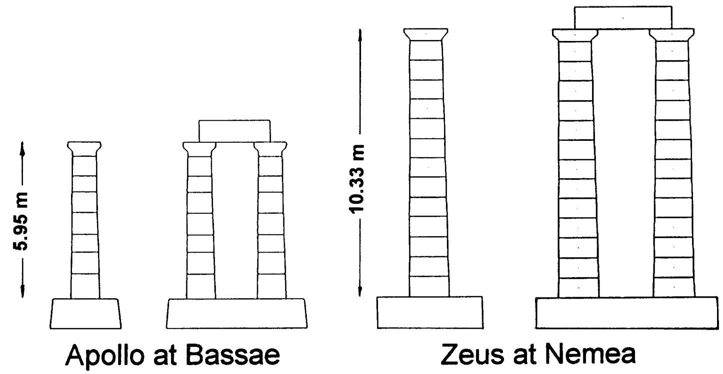


(Psycharis & Jennings, 1985)

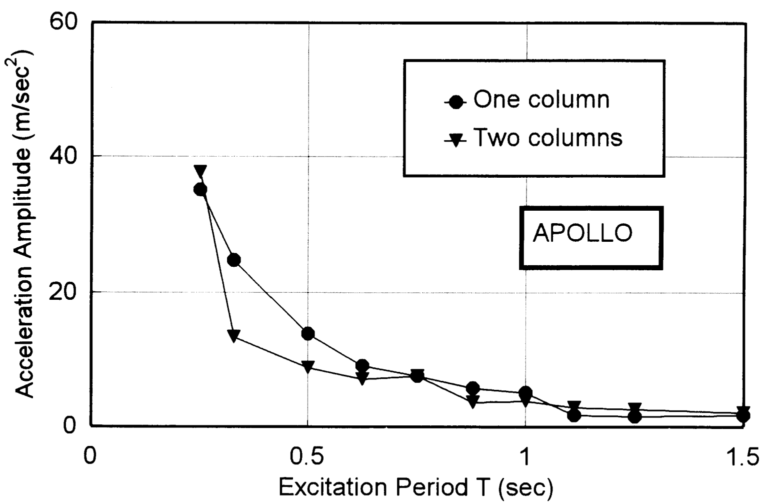
b = 1.50 m

Size effect – multi-drum columns

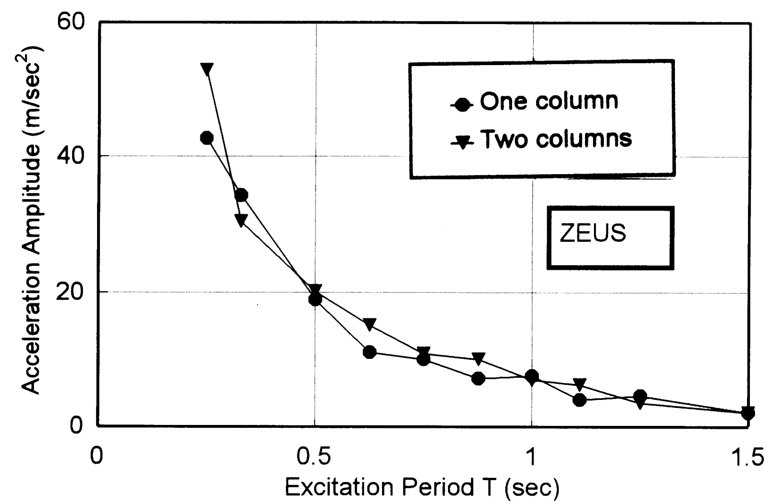
Required base acceleration for collapse under harmonic excitation



Apollo at Bassae



Zeus at Nemea

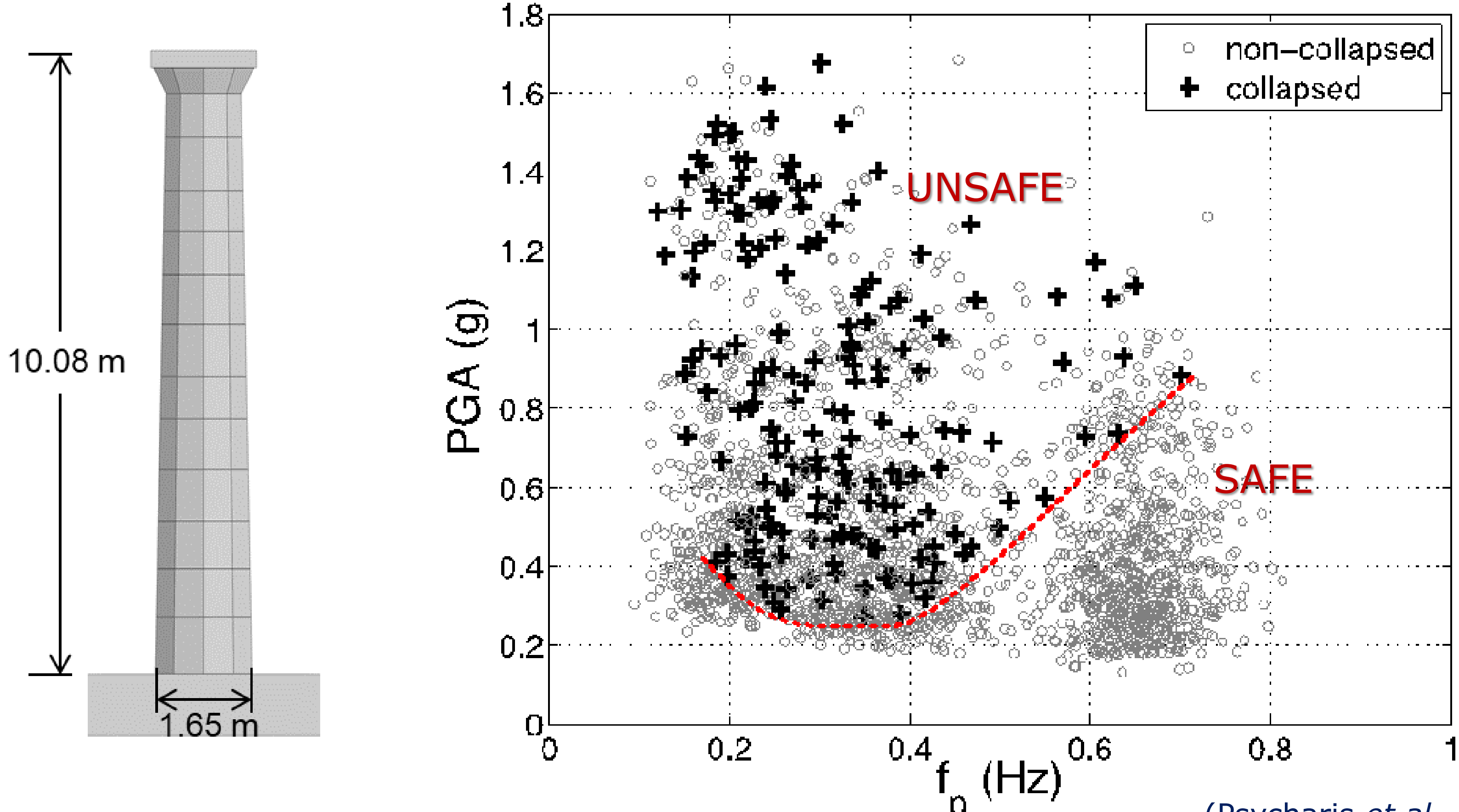


(Psycharis *et al.*, 2000)

Effect of predominant period of the ground motion

Overturning of the Parthenon column under pulse-like ground motions

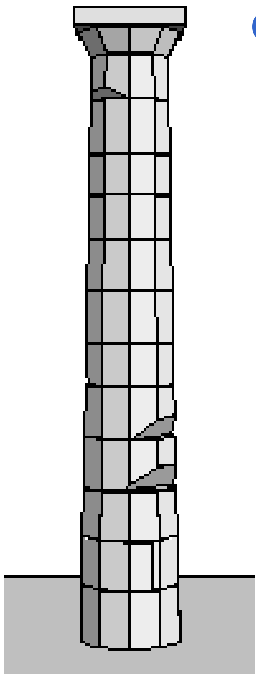
(3500 synthetic ground motions)



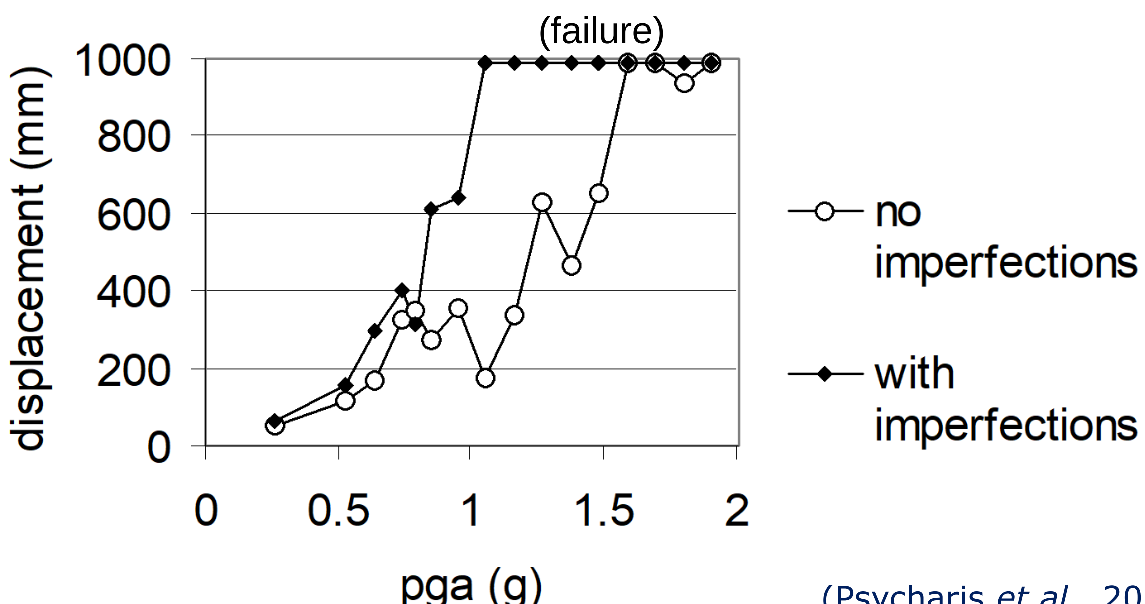
(Psycharis *et al.*, 2013)

Effect of existing damage

Existing damage increases significantly the possibility of collapse and should be included in the numerical model as accurately as possible.



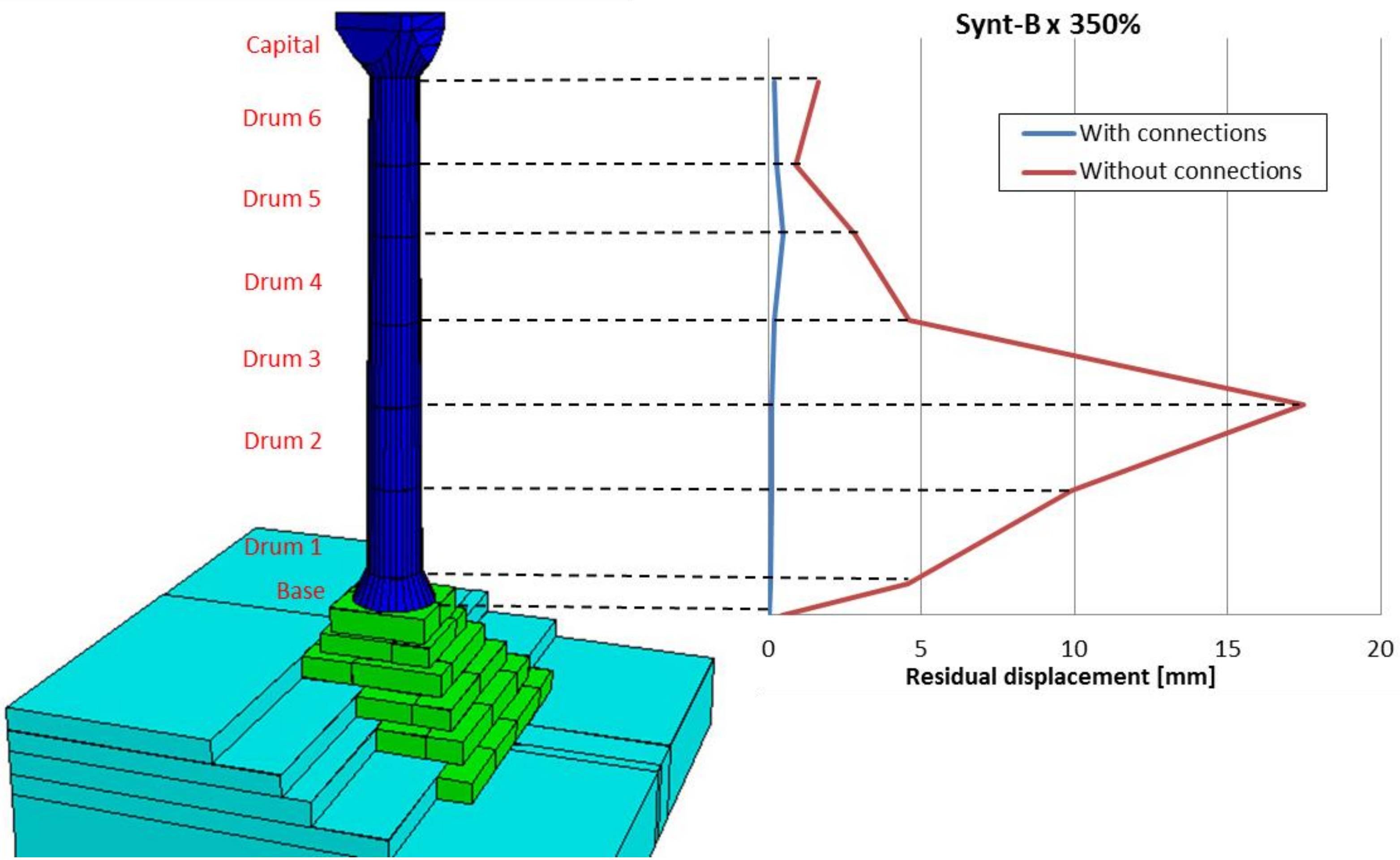
Column of Parthenon



(Psycharis *et al.*, 2003)

The effect of various types of damage (corner cut-offs, column inclination, cracks, etc.) is cumulative.

Effect of connections



Column of Thrasyllos

Vulnerability assessment

- Due to the nonlinear and sensitive response, case-specific analyses are required to assess the vulnerability of a monument.
- In such analyses, caution should be paid to:
  - Accuracy of the models
  - Model parameters
  - Selection of ground motions
- For the correct decision making during a restoration process, the *Performance-based design* concept can also be applied for the assessment of the seismic reliability of a monument.

Performance-based reliability assessment

The *seismic fragility* F_R is defined as the limit-state probability of exceeding certain values of predefined *Engineering Demand Parameters, EDP*, that characterize the system response, conditioned on the *seismic intensity, IM*, which can be expressed in terms of magnitude M_w and distance R :

$$F_R = P(EDP > edp | M_w, R)$$

For classical monuments, the vulnerability assessment can be expressed in terms of two *EDP*s:

1. The intensity of shaking during the earthquake
2. The magnitude of the expected residual displacements that affect the risk to future earthquakes

Engineering Demand Parameters, *EDP*s

1. Intensity of shaking

Measured by $u_{\mathrm{top}} = \max[u(\mathrm{top})]/D_{\mathrm{base}}$

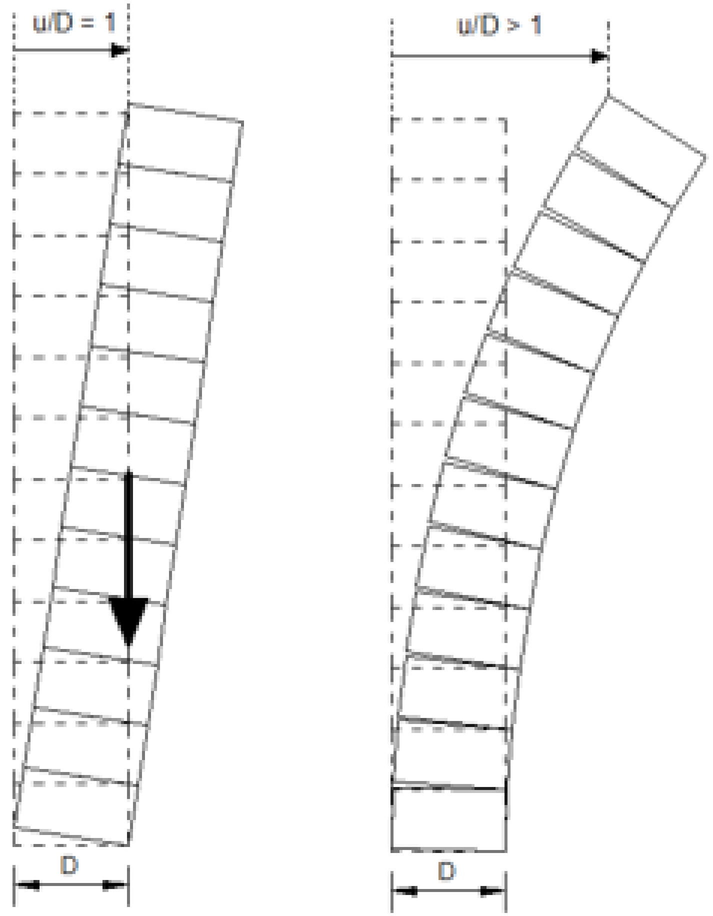
- It provides a measure of the column’s deformation
- It shows how close to collapse the column was brought

u_{top}	Performance level	Description
0.15	Damage limitation	No danger for the column. No permanent drum dislocations expected.
0.35	Significant damage	Large opening of the joints with probable damage due to impacts and considerable residual dislocation of the drums. No serious danger of collapse.
1.00	Near collapse	Very large opening of the joints, close to partial or total collapse.

Engineering Demand Parameters, *EDP*s

Example:

- $u_{\text{top}} = 0.3 \Rightarrow$ large joint openings but no danger of collapse.
- $u_{\text{top}} > 1 \Rightarrow$ intense shaking and large deformations of the column, which do not necessarily lead to collapse.
  - Response as a monolithic block: probable collapse.
  - Response with many joints opened: u_{top} can be larger than unity without threatening the stability of the column.



Engineering Demand Parameters, *EDP*s

2. Residual drum dislocations

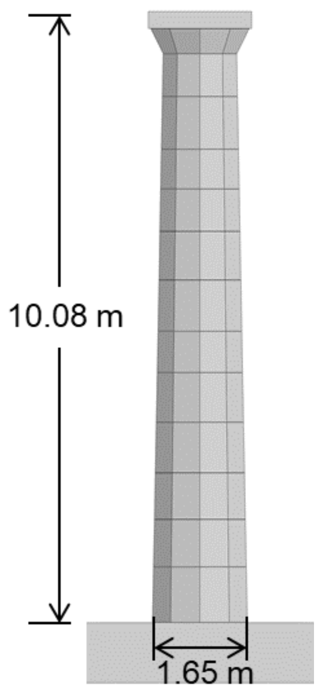
Measured by $u_d = \max(\text{res}\,u_i)/D_i$

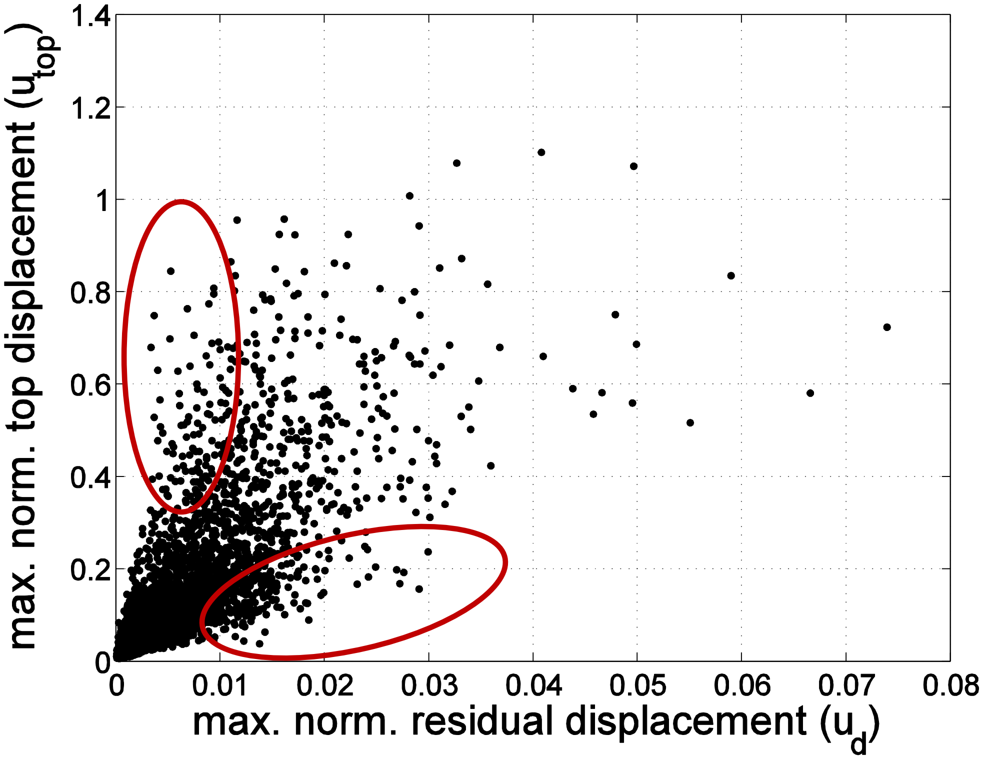
It provides a measure of how much the geometry of the column has been altered after the earthquake, increasing thus the vulnerability of the column to future events.

u_d	Performance level	Description
0.005	Limited deformation	Insignificant residual drum dislocations without serious effect to future earthquakes.
0.01	Light deformation	Small drum dislocations with probable unfavourable effect to future earthquakes.
0.02	Significant deformation	Large residual drum dislocations that increase significantly the danger of collapse during future earthquakes.

Correlation of proposed *EDP*s

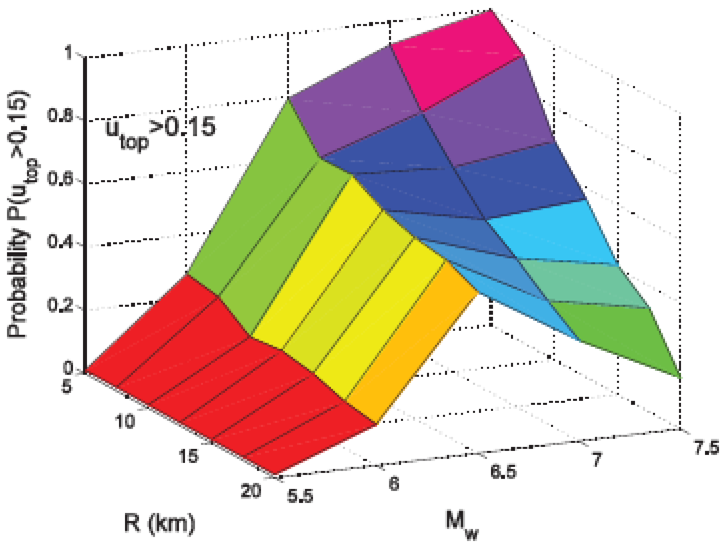
- Parthenon column
- 3500 synthetic near-fault ground motions of $M_w = 5.5 \div 7.5$ and $R = 5 \div 20$ km

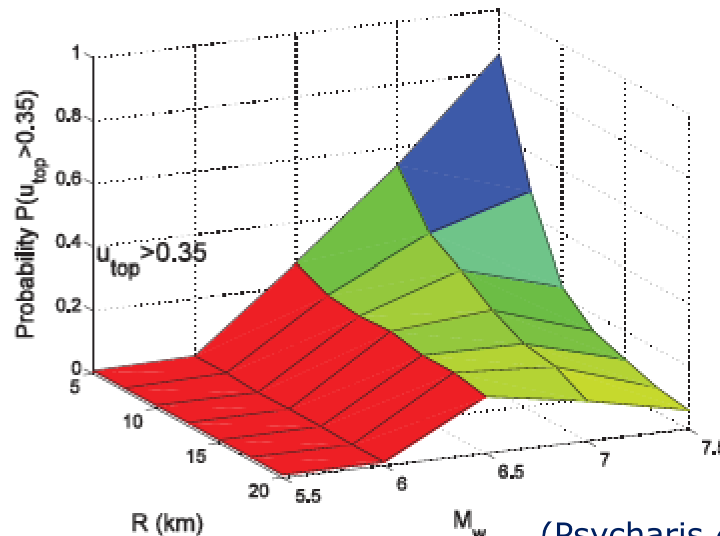




Fragility surfaces

Intensity of shaking, u_{top}





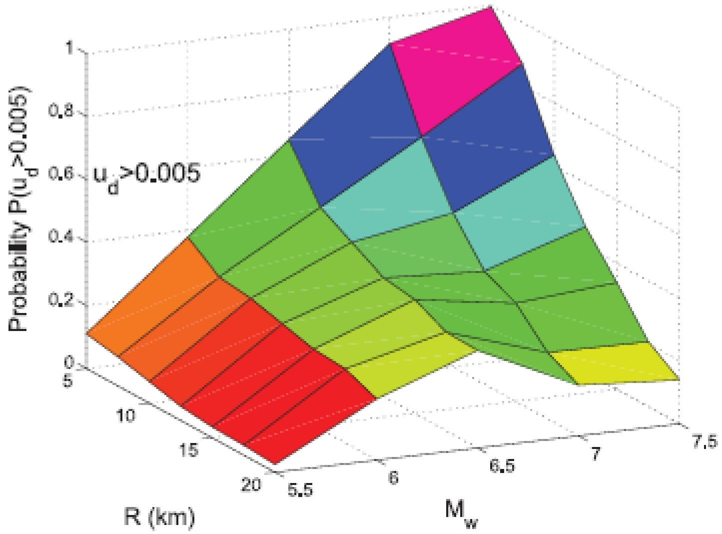
(Psycharis *et al.*, 2013)

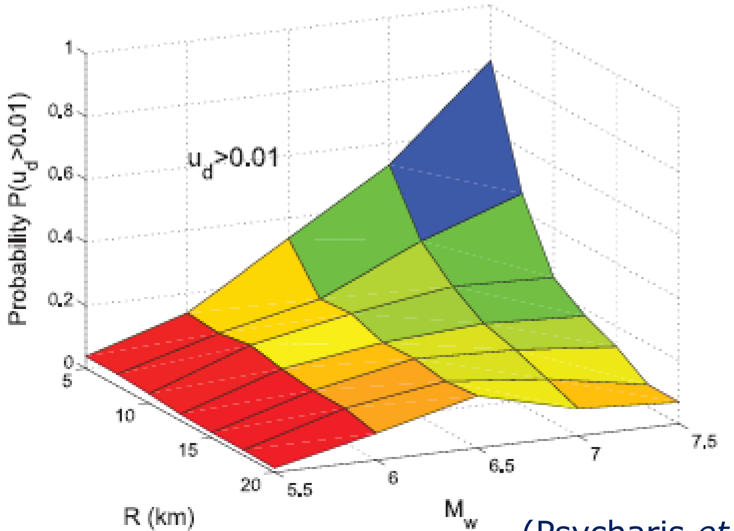
Probability of exceeding Damage Limitation ($u_{top} > 0.15$)

Probability of exceeding Significant Damage ($u_{top} > 0.35$)

Fragility surfaces

Permanent drum dislocations, u_d





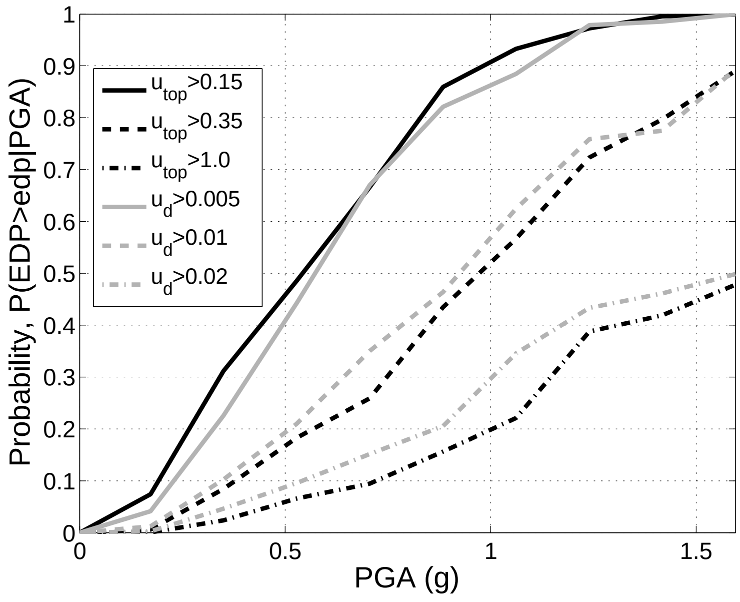
(Psycharis *et al.*, 2013)

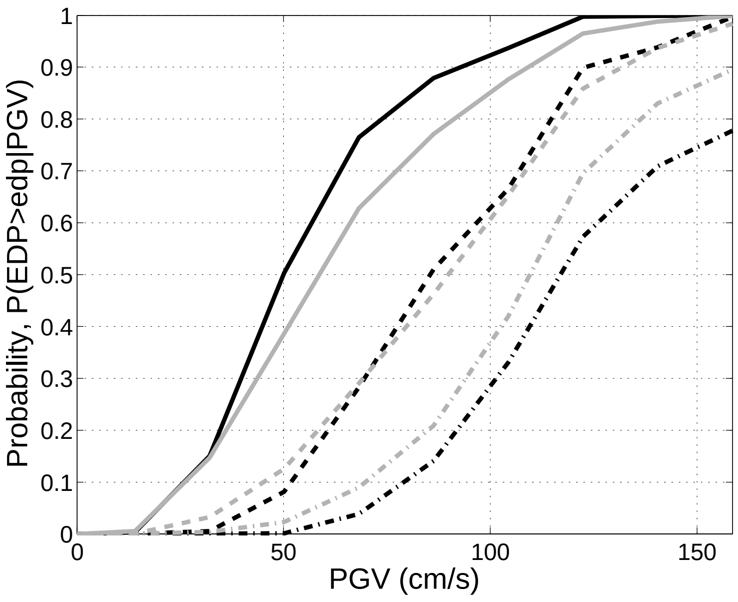
Probability of exceeding
Limited Deformation ($u_d > 0.005$)

Probability of exceeding
Light Deformation ($u_d > 0.01$)

Fragility curves

Using *pga* and *pgv* as Intensity Measures

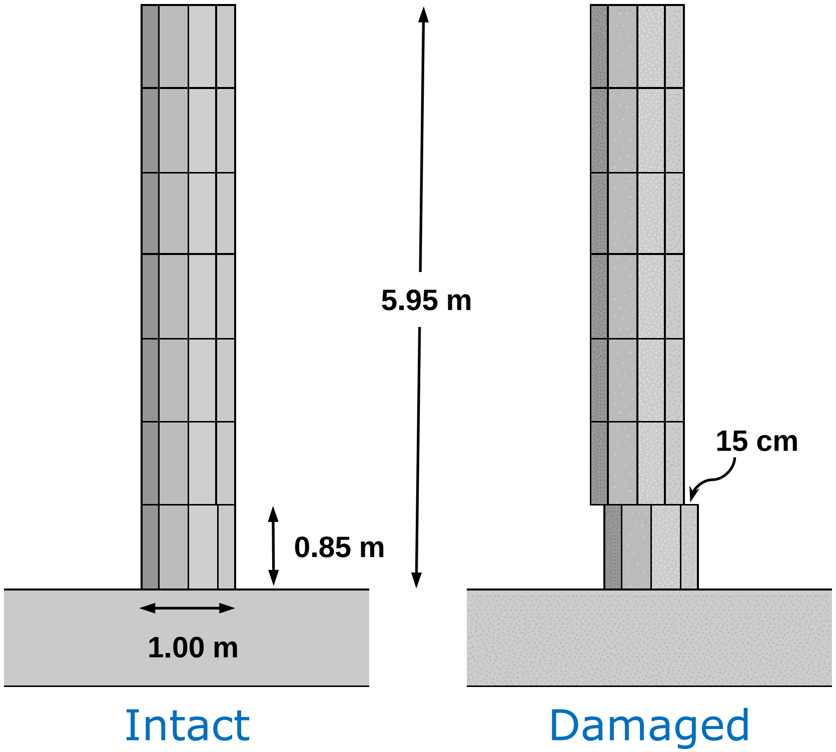




(Psycharis *et al.*, 2013)

Vulnerability of damaged columns

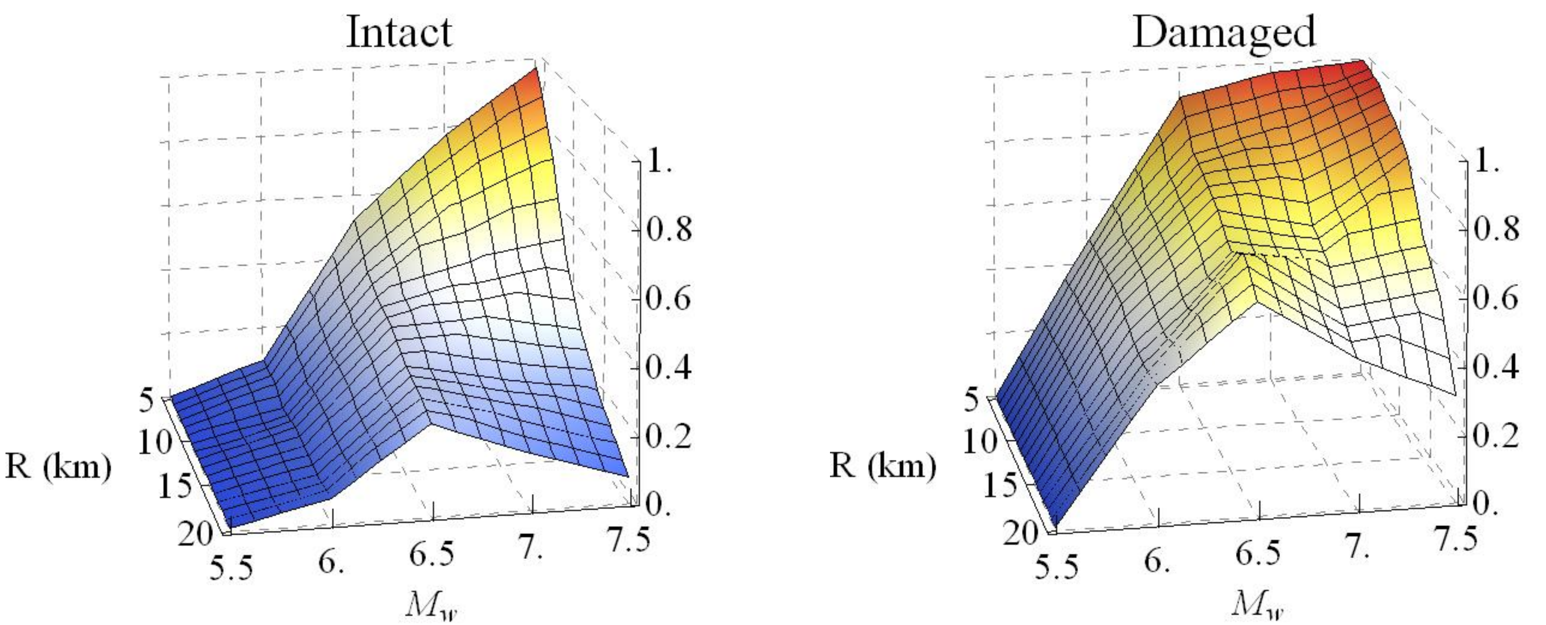
Case study: Column at the Propylaia on the Acropolis of Athens



Fragility surfaces

Maximum top displacement, u_{top}

Probability of exceeding **Significant Damage** ($u_{\text{top}} > 0.35$)

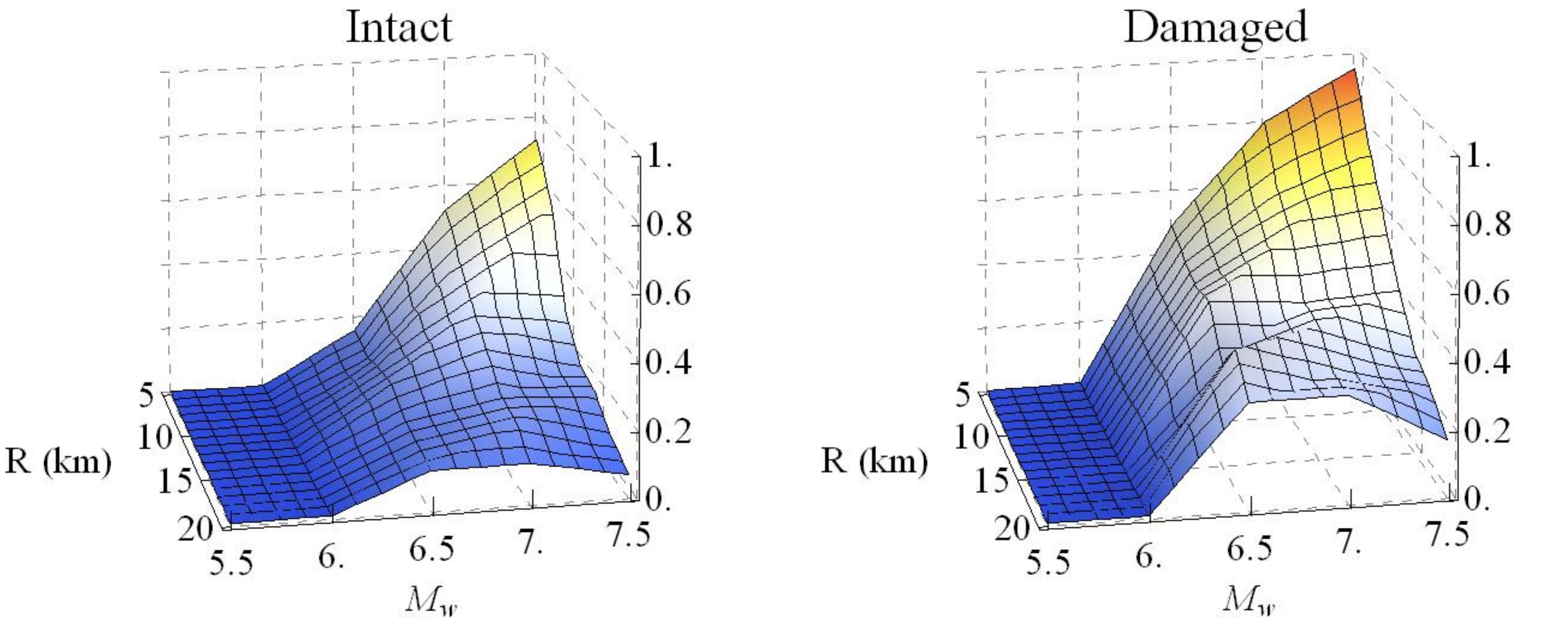


(Fragiadakis *et al.*, 2016)

Fragility surfaces

Maximum top displacement, u_{top}

Probability of exceeding **Near Collapse** ($u_{\text{top}} > 1.0$)

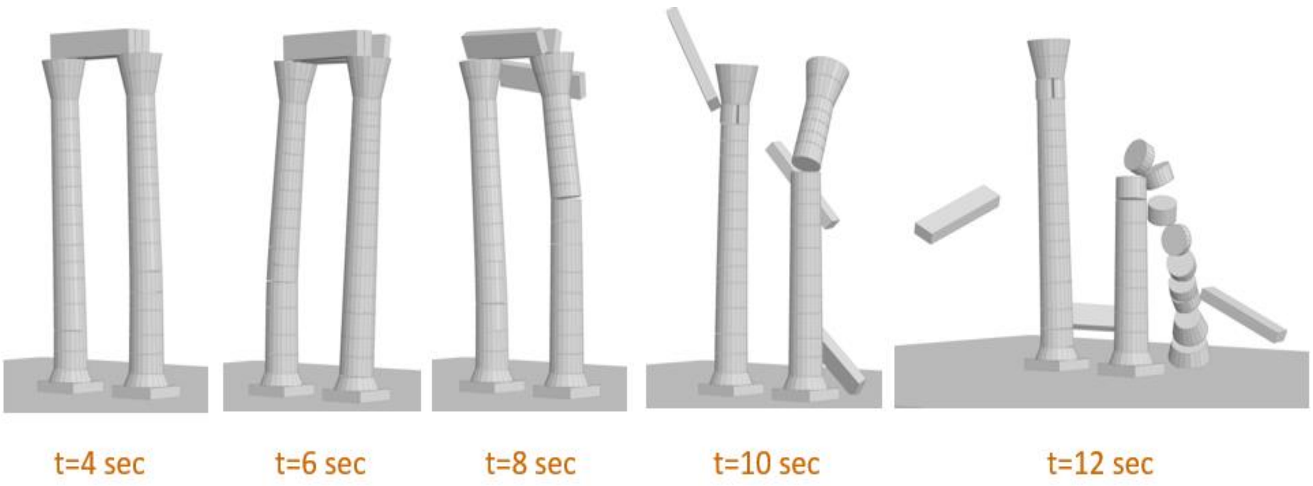


(Fragiadakis *et al.*, 2016)

Conclusions

- The vulnerability of classical monuments greatly depends on:
  - The size of the structure, with smaller columns being more vulnerable than larger ones.
  - The predominant period of ground motion, with long-period excitations being much more dangerous than high-frequency ones.
  - The existing damage
  - The connections between the structural members (clamps and dowels)
- The assessment of the seismic reliability of a monument can be expressed applying the concept of Performance-based design in terms of two *EDP*s:
  - The intensity of shaking during the earthquake
  - The magnitude of the expected residual displacements that affect the risk to future earthquakes

Thank you!



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