Aristotle University of Thessaloniki

School of Civil Engineering

Numerical investigation of the seismic response of classical multi-drum and monolithic columns

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SDGEE
Research Unit of Soil Dynamics and Geotechnical Earthquake Engineering

IAMON workshop
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Structural characteristics of classical Greek temples

- Greek classical temples constitute world class monuments of great historical, architectural and cultural value.
- Most of them are built from 6th century BC to 3rd century AC
- Few of them remain entirely intact. The majority remain nowadays as free-standing multi-drum or monolithic columns and portals

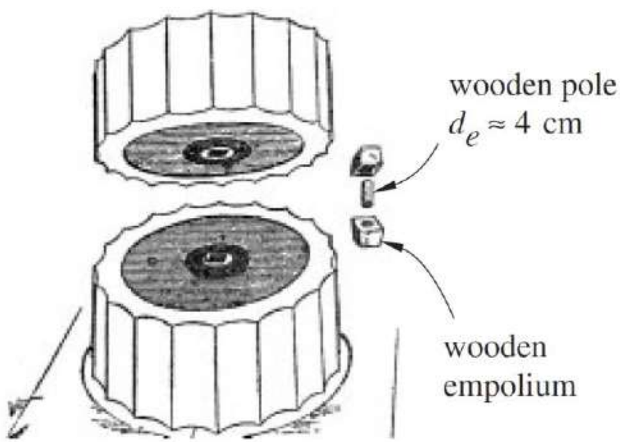
Parthenon, Acropolis Athens (5th BC)

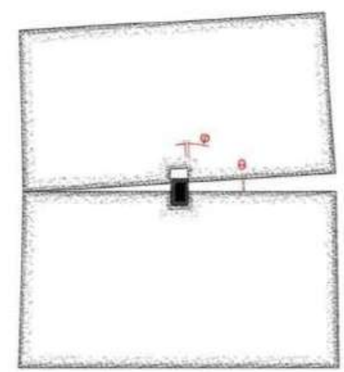
Temple of Athena Lindia, Acropolis of Lindos, Rhodes (6th BC)

Structural characteristics

- The technology applied for their construction is very advanced
- Each column is composed of several drums often of high-quality marble, which are placed one on top of the other, **without connecting mortar. It is a genius mechanical system having high capacity to efficiently absorb seismic motion**

- **Polos (pin) and empolio (plug)**



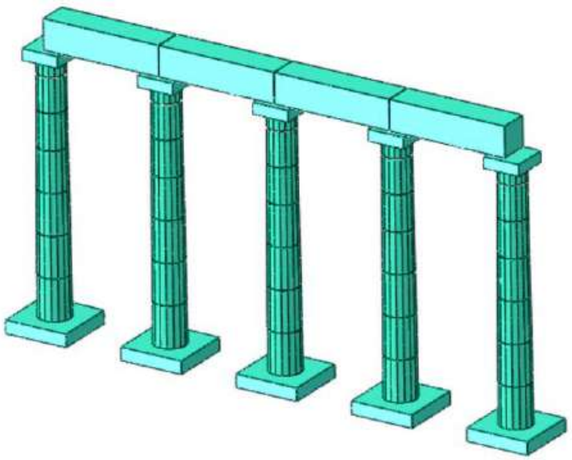


Seismic response

- **The response** to seismic ground shaking of multi-drum columns is **quite distinct compared to that of modern structures**
- A free standing multi drum column has **no eigenvalues**!
- **Rocking and/or sliding of the drums** along their interfaces **control the response**, with significant **energy dissipation** during shaking
- Monolithic columns vs multi-drum columns

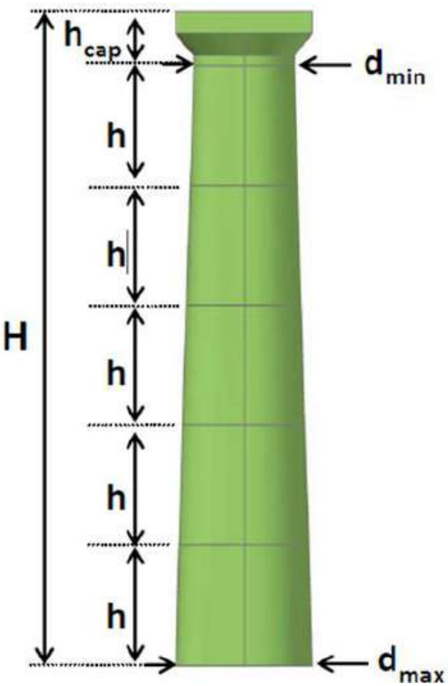
- **Controlling parameters**

✓ Slenderness
✓ Frequency of ground excitation
✓ Amplitude of ground excitation
✓ Epistyle (i.e., connecting beam)
✓ Friction coefficient among drums



Validation of the numerical modelling
Numerical versus experimental results

Shaking table model of multi-drum column



scale = 1 : 5

H = 6.0 m [1.2 m]

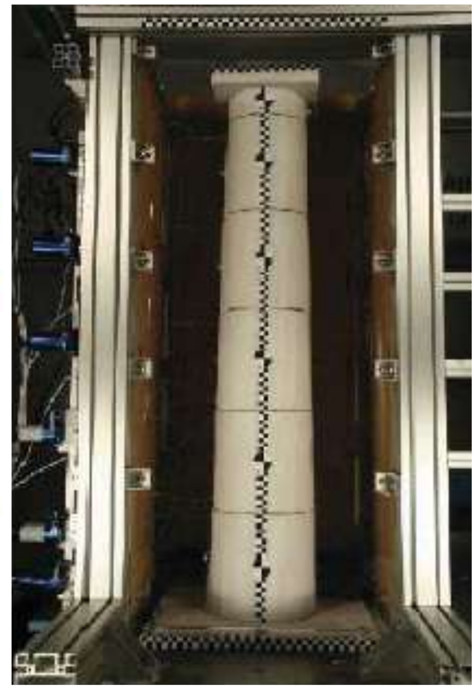
d_{max} = 1.2 m [0.24 m]

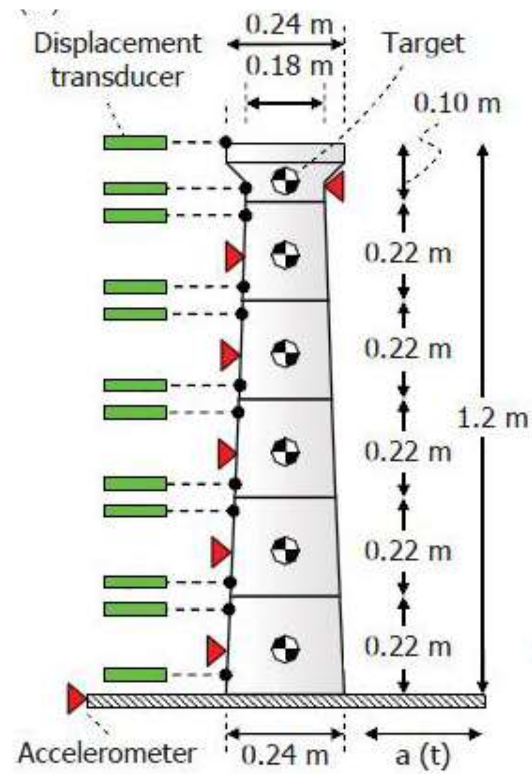
d_{min} = 0.9 m [0.18 m]

no. of drums = 5

h = 1.1 m [0.22 m]

h_{cap} = 0.5 m [0.10 m]



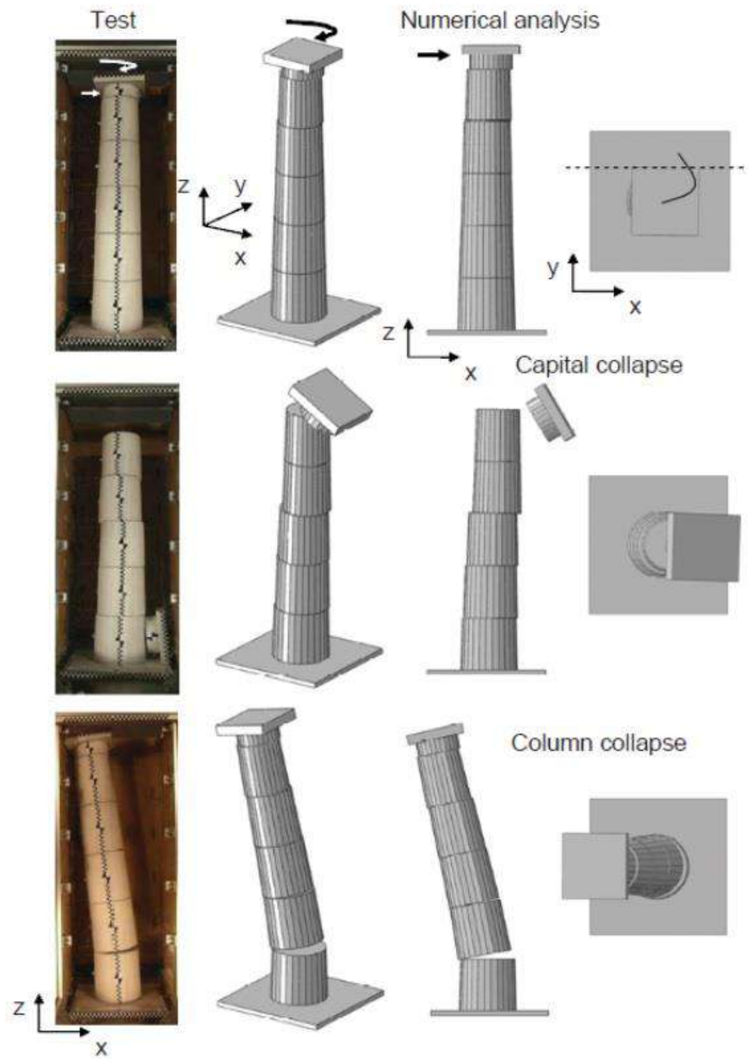


NTUA

Deformation patterns

Uniaxial loading with:

- Ricker wavelet with *PGA* = 0.60 g and frequency f_o = 3.30 Hz (1.8 Hz in prototype scale)
- Ricker wavelet with *PGA* = 0.80 g and frequency f_o = 2.20 Hz (1.2 Hz in prototype scale)
- Ricker wavelet with *PGA* = 1.0 g and frequency f_o = 2.75 Hz (1.4 Hz in prototype scale)



Collapse of the column for rather **long period Ricker** pulses

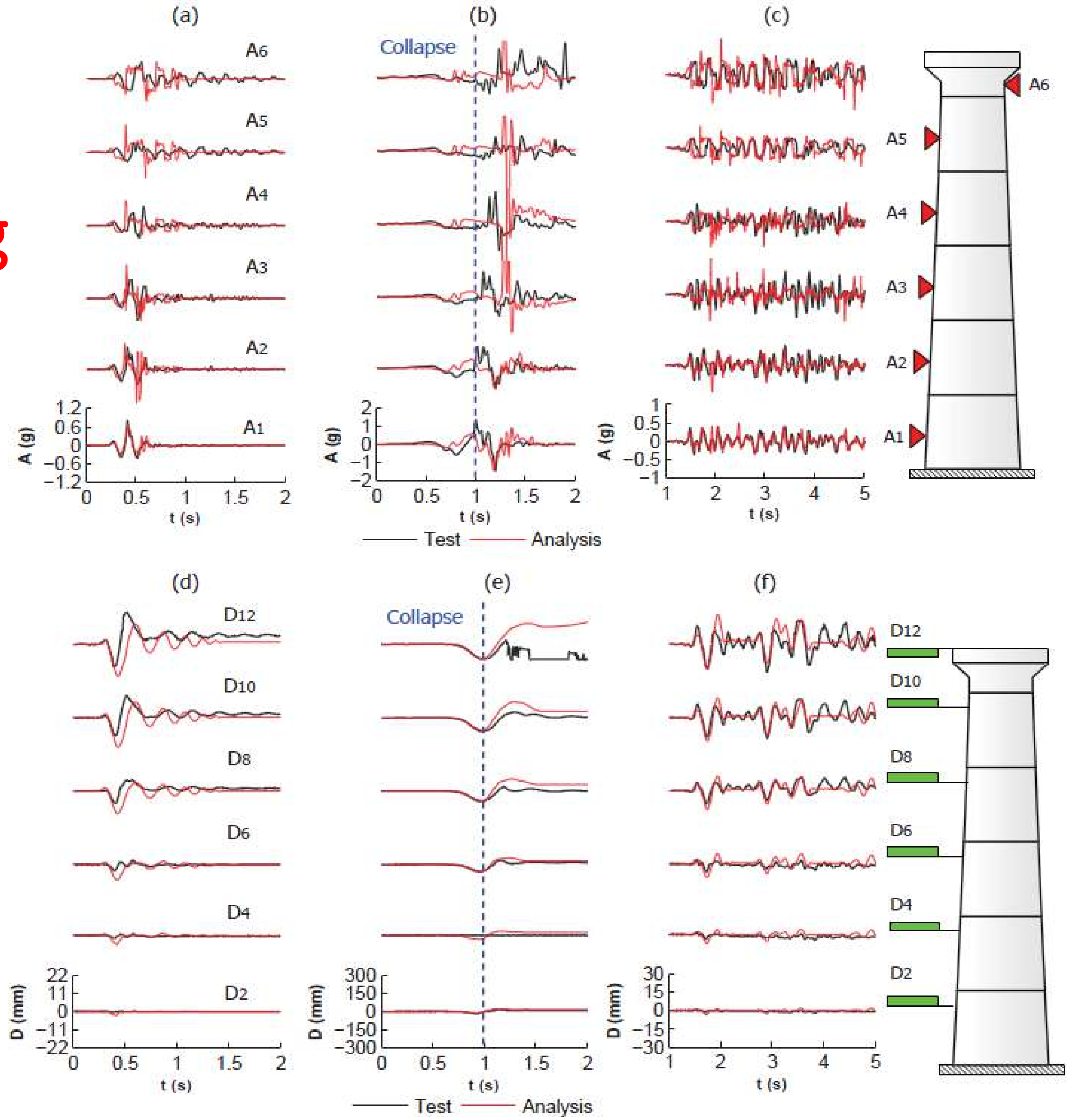
Validation of numerical modelling

Experimental results vs
Numerical Modelling

Input motions:

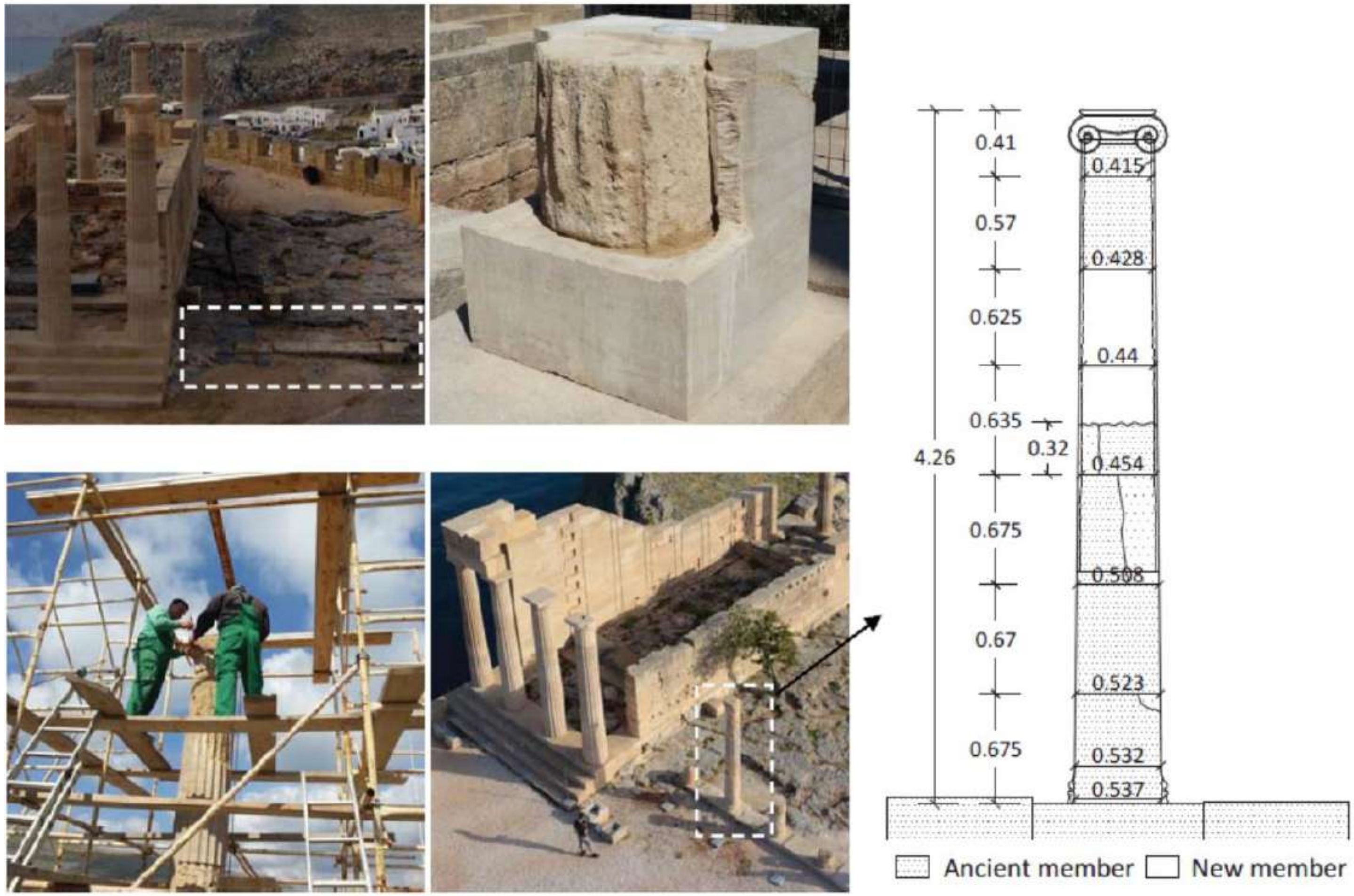
2 Ricker wavelets
0.6g, f_0=3.3Hz
1.0g, f_0=2.75Hz

1 real record:
Lefkada 2003 EQ, 0.41g

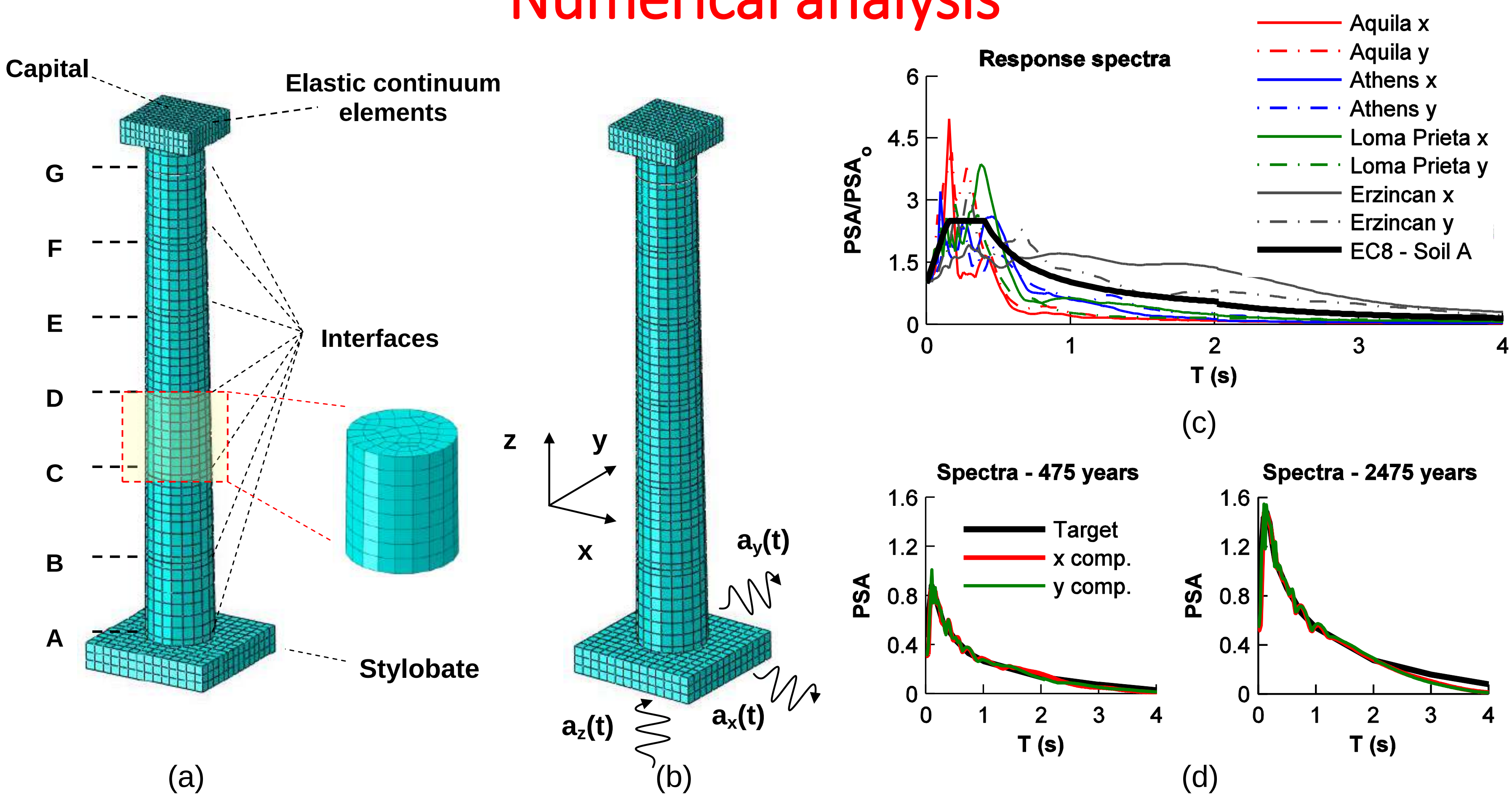


Investigating friction coefficient on the seismic response of Greek temple columns
and
multi-drum versus monolithic free-standing column

Acropolis of Lindos, island of Rhodes, Greece

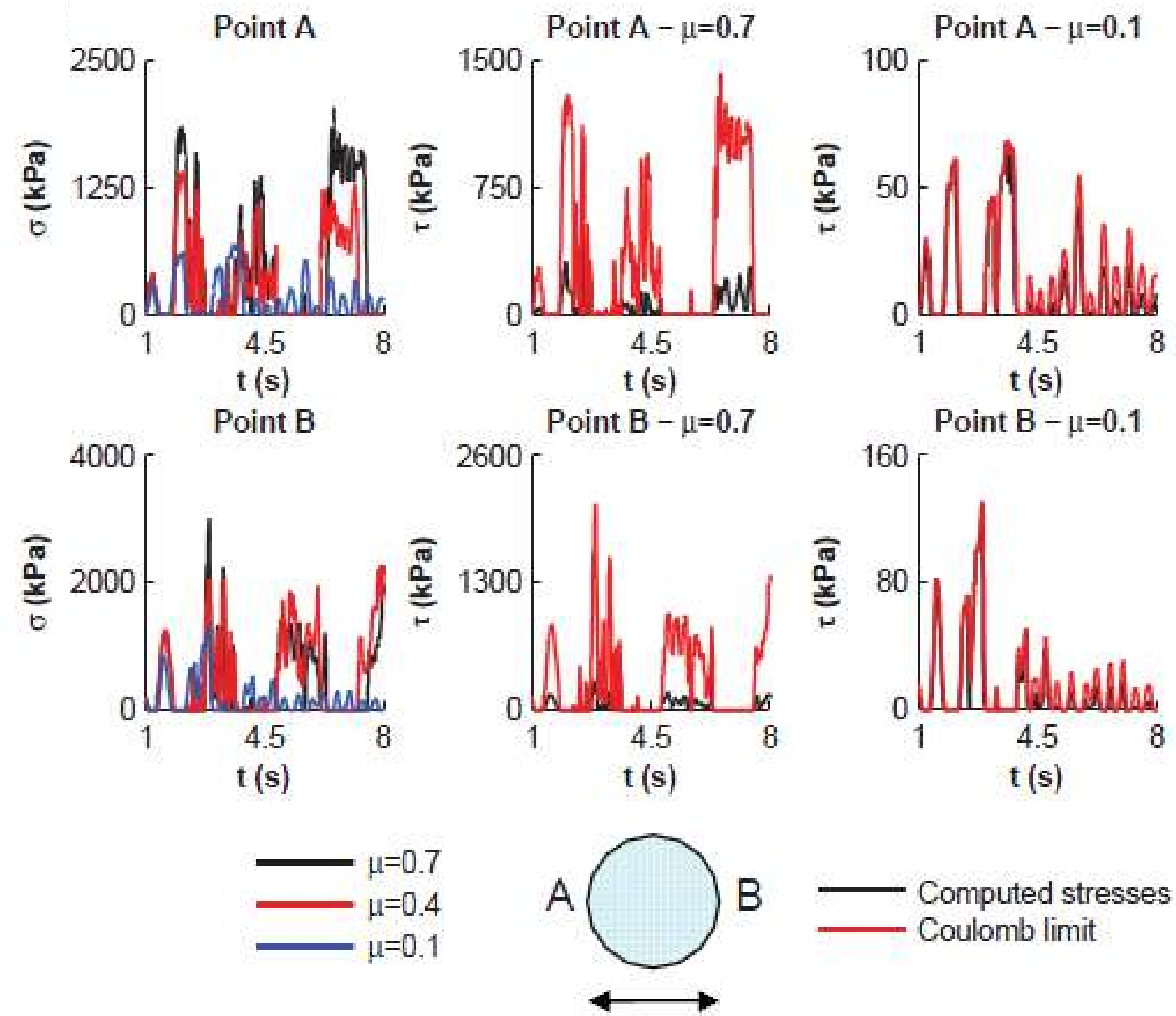


Numerical analysis



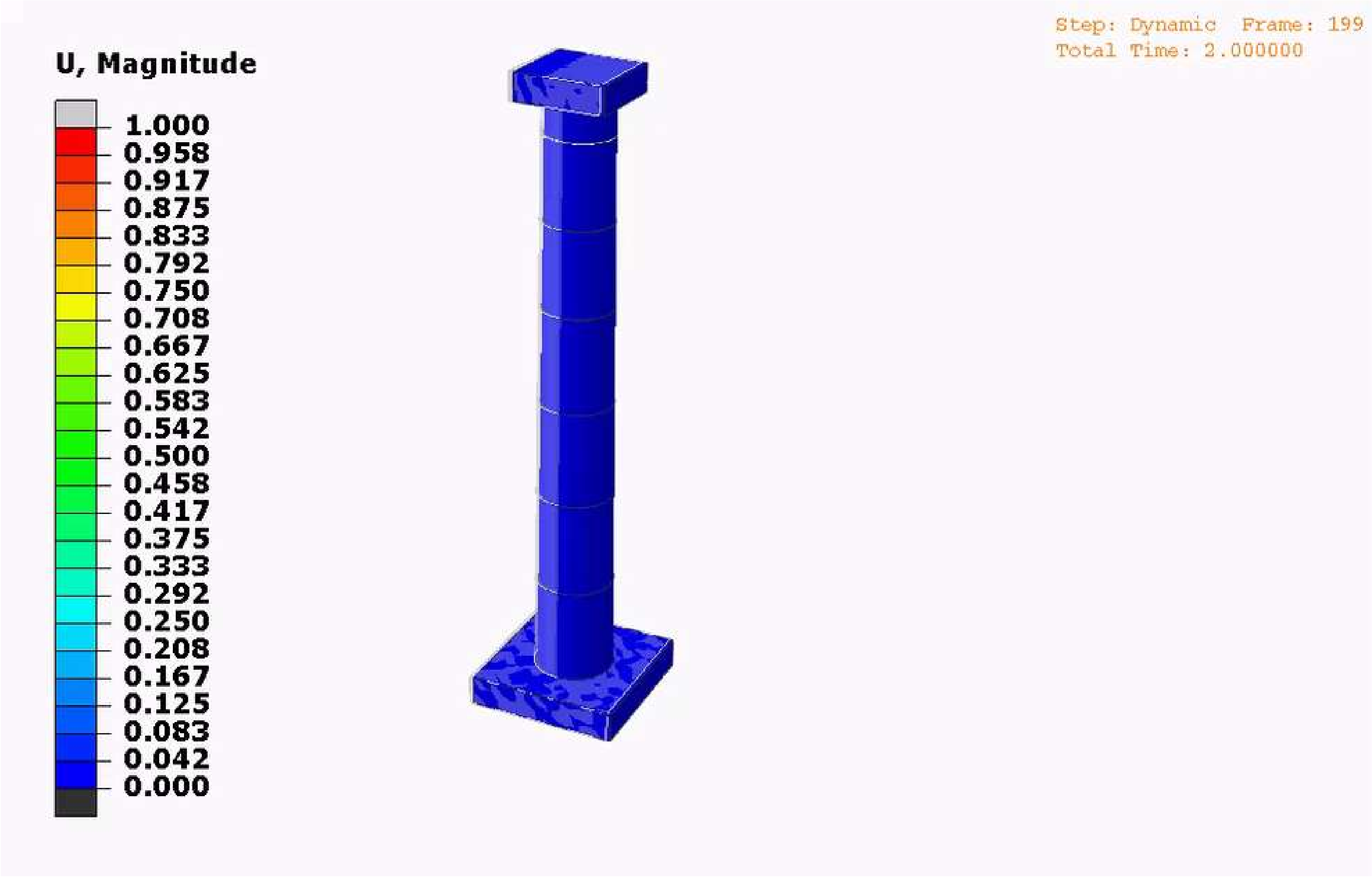
Three-dimensional full dynamic time history analyses in ABAQUS

Effect of the friction coefficient



Loma Prieta excitation, uniaxial (x) loading, scaled to PGA = 0.52 g

Effect of the friction coefficient μ = 0.7, PGA=0.6g



Erzincan excitation scaled to PGA = 0.6g and friction coefficient of **μ = 0.7**

Effect of the friction coefficient μ=0.1, PGA=0.6g

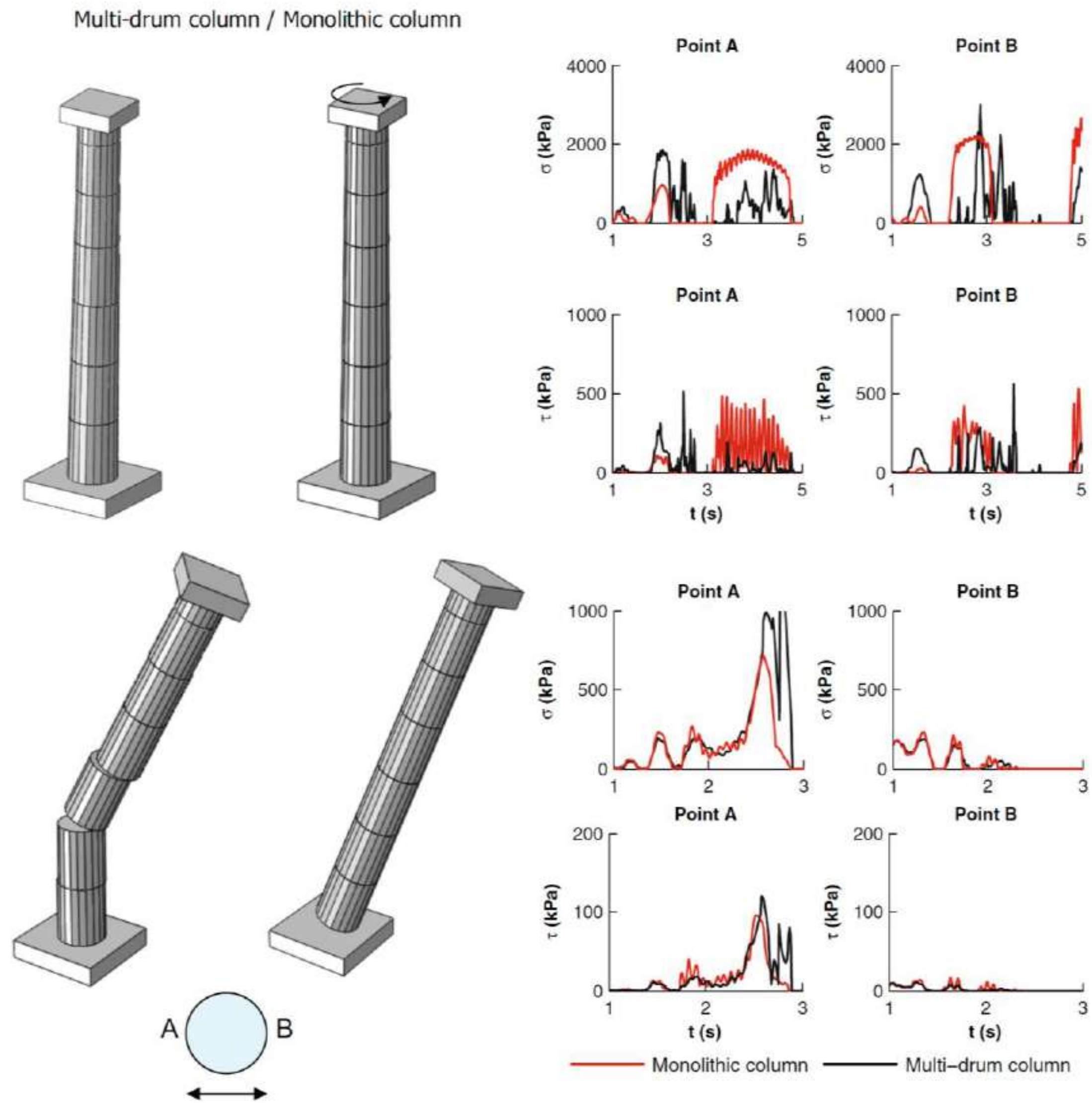
Erzincan excitation scaled to PGA = 0.6g and friction coefficient of **μ = 0.1**

Multi-drum versus monolithic free-standing column

Deformed shapes at the completion of the analysis

Time windows of the normal stresses σ and shear stresses τ on diametrically opposed points A and B of the base of the column during shaking

- Top: Loma Prieta, uniaxial (x) loading, PGA = 0.52 g
- Bottom: Erzincan, biaxial (x+y) loading, PGA = 0.40 g (long period seismic motion)



Multi-drum versus monolithic free-standing column

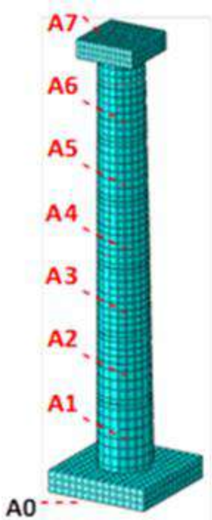
Uniaxial loading

Loma Prieta record

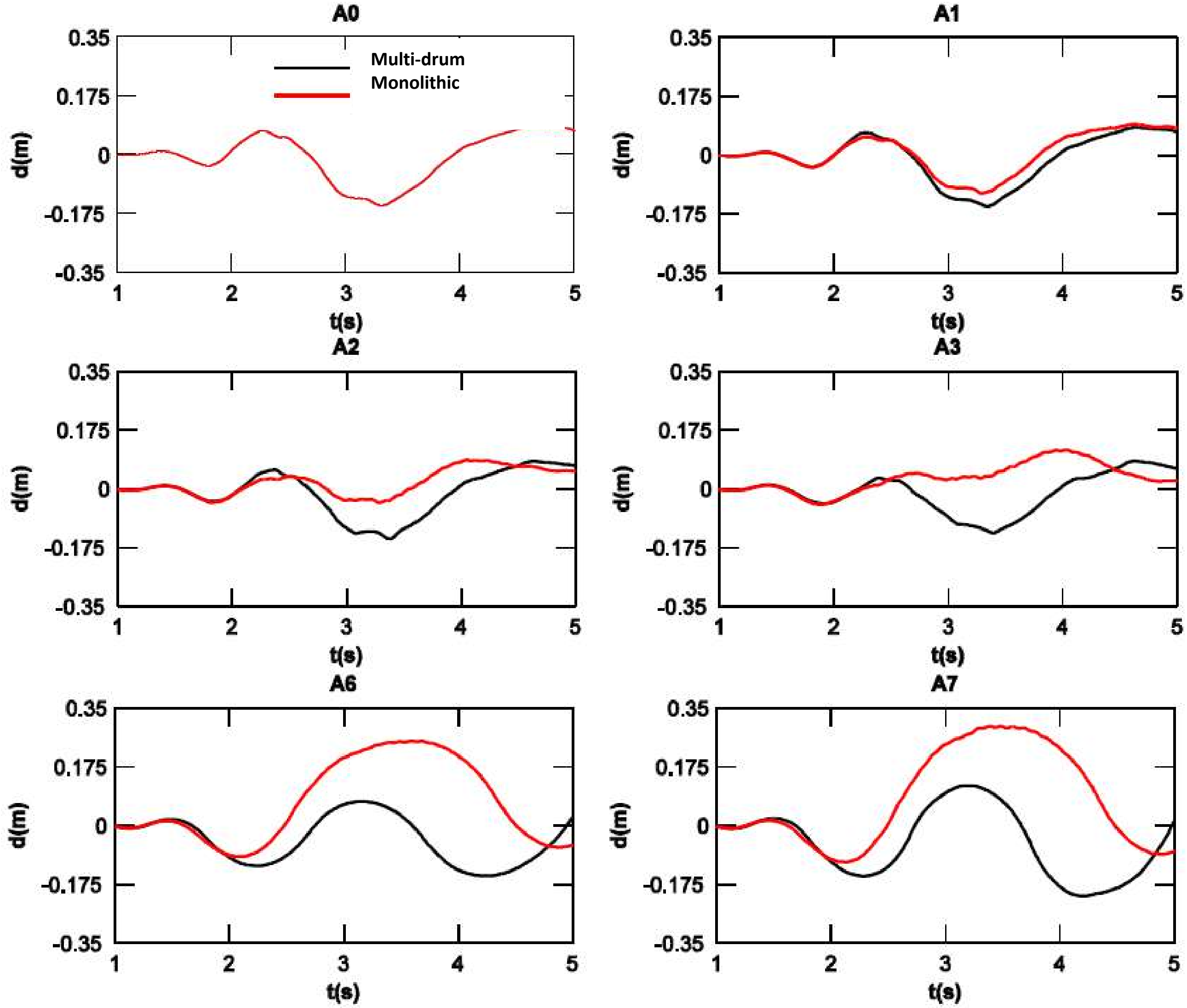
scaled to PGA = 0.52g

friction coefficient

μ = 0.7



Absolute displacement time histories

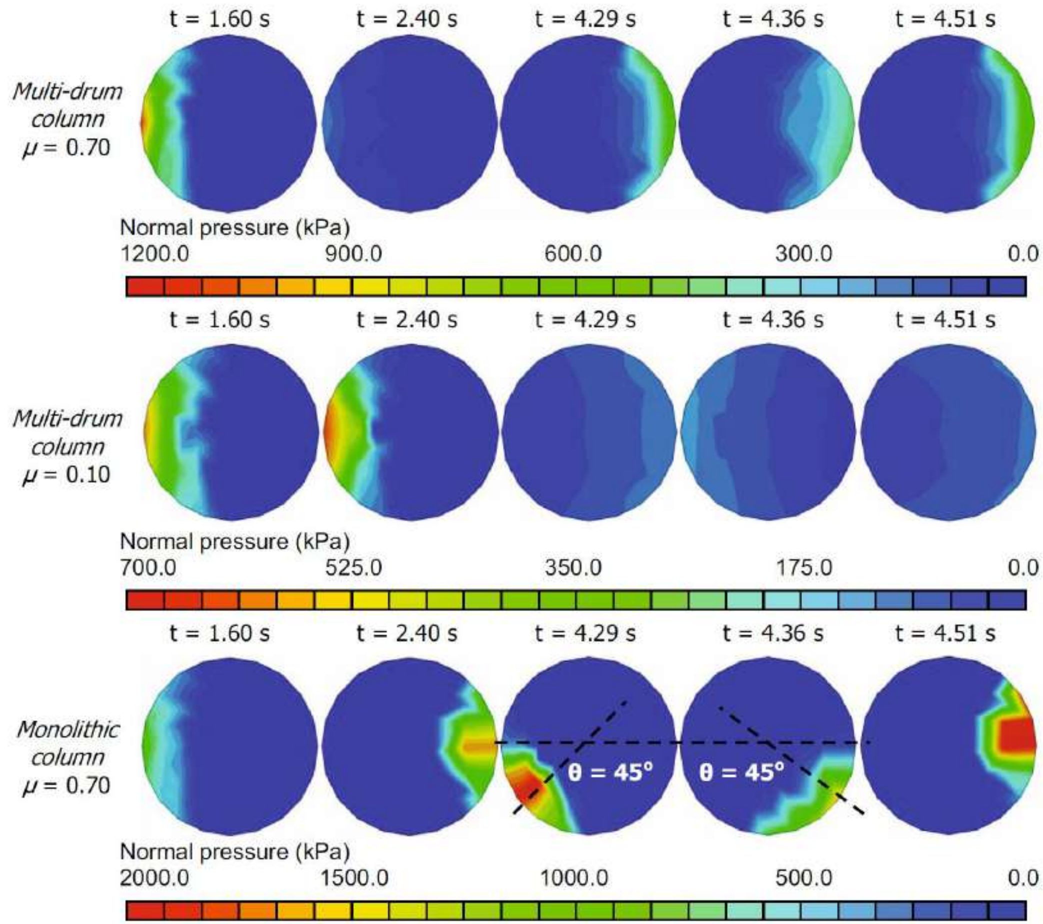


Multi-drum versus monolithic free-standing column

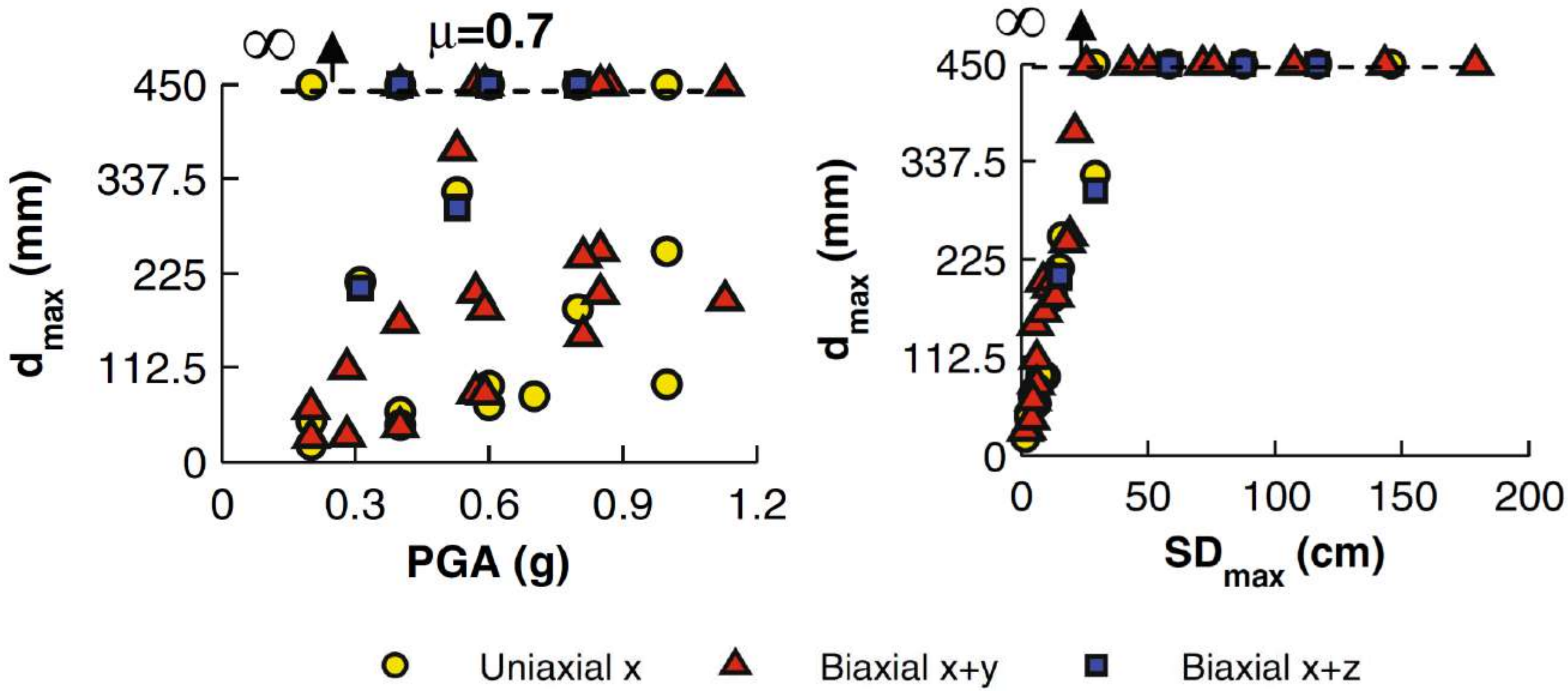
Effect of the friction coefficient

Contours of the dynamic part of the normal stresses σ computed at the base of the column (base drum–stylobate interface) during uniaxial (x) shaking.

Loma Prieta record (PGA = 0.52 g)



Structural performance of the multi-drum column



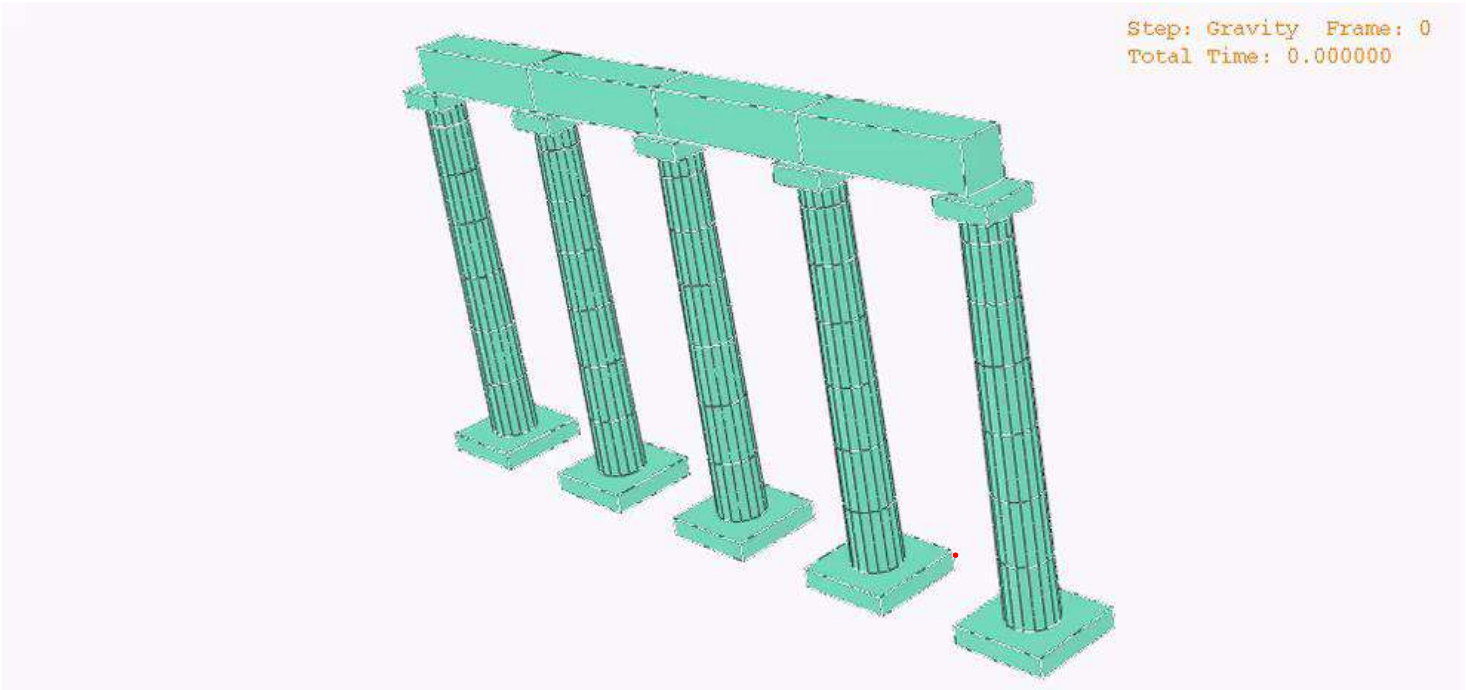
Fundamental remarks

- **Monolithic columns** are **more vulnerable than multi-drum ones**
- The **friction coefficient** and its dynamic evolution along the drum interfaces during the dynamic excitation is a **very important factor** controlling the seismic response
- The **monolithic column** exhibited a **higher rocking and rolling response** along its base **compared to the multi-drum** one. The difference was generally higher for high-frequency seismic excitations
- The **PGA** of the base excitation was found to be a **very poor intensity measure for this type of structures**
- The **SD_{max}** of the base excitation was found to **better describe the performance and stability** of the multi-drum column (generally stable for $SD_{max} < D/2$, where D the diameter of the base drum)

Publications

- Pitilakis K, Tsinidis G, Karafagka S (2017). Analysis of the seismic behavior of classical multi-drum and monolithic columns. Bulletin of Earthquake Engineering, 15(12):5281–5307, https://doi.org/10.1007/s10518-017-0160-4.
- Karafagka S, Tsinidis G, Ntinoudi O, Pitilakis K (2018). Efficient intensity measures for the seismic assessment of free-standing columns and colonnades. Proceedings of the 16th European Conference on Earthquake Engineering, 18-21 June, Thessaloniki, Greece.
- Pitilakis K, Karafagka S, Karatzetzou A, Riga E, Manakou M (2022). How safe is Acropolis of Athens and its monuments to low probability earthquakes? Lancellotta, Viggiani, Flora, de Silva & Mele (Eds), Geotechnical Engineering for the Preservation of Monuments and Historic Sites III, Proceedings of the Third international symposium on Geotechnical Engineering for the preservation of monuments and historic sites (TC301-IS 2022), 22-24 June, Napoli, Italy, DOI 10.1201/9781003308867-53.

Thank you



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