IAMON Workshop
Reinforced interfaces between structural members in ancient monuments

10th July, 2024

Can we use the seismic response of free standing monuments to verify Probabilistic Seismic Hazard estimates?

Anastasios Sextos

Kosmas Stylianidis

University of Bristol

Εθνικό Μετσόβιο Πολυτεχνείο National Technical University of Athens

Aristotle University of Thessaloniki

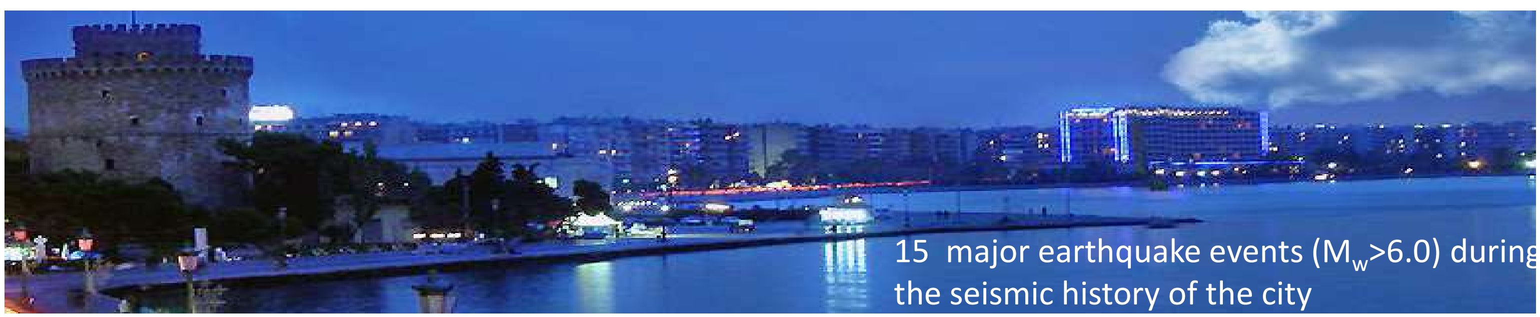
Design accelerations significantly increase every time the seismicity is revised

in fairness, this is also due to more data becoming available

Seismic History

Date	M_w	Epicenter	R	Intensity
597 A.D.	6.8	Serres	110 km	VI0
620 A.D.	6.6	Thessaloniki	40 km	
667 A.D.	6.6	Thessaloniki	20 km	
700 A.D.	6.6	Thessaloniki	12 km	
1395 A.D.	6.7	Edessa	70 km	VII
1430 A.D.	6.0	Thessaloniki	30 km	VII
1677 A.D.	6.2	Thessaloniki	20 km	VII-VIII
22/06/1759	6.5	Thessaloniki	15 km	IX
05/05/1829	7.3	Drama	120 km	V+ ~ VI
05/06/1902	6.6	Thessaloniki	20 km	VII+
04/04/1904	7.3	S. Bulgaria	130 km	VI
08/11/1905	7.5	Chalkidiki	120 km	VI
08/03/1931	6.7	S. Yugoslavia	85 km	VI
26/09/1932	7.0	Chalkidiki	75 km	VI
20/06/1978	6.5	Thessaloniki	28 km	VII

Source: G. A. Leventakis (2003) “Microzonation Study of the city of Thessaloniki”, PhD.Thesis, Aristotle University Thessaloniki.

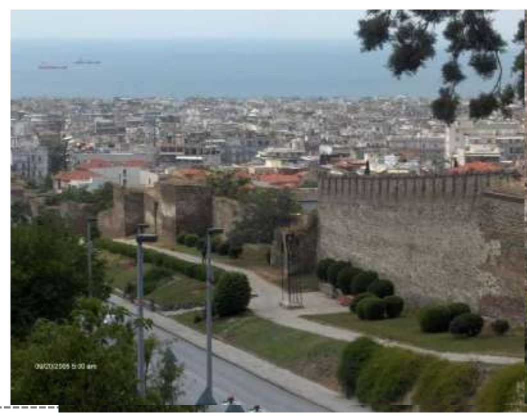


15 major earthquake events (M_w>6.0) during the seismic history of the city

Objectives

To take advantage of the long-term exposure of Byzantine and Roman monuments within the modern city grid to back-trace the seismic history of the city

1. Assess the seismic capacity of monuments to predict the minimum level of seismic intensity that is required to trigger collapse.
2. Given the extreme damage state of collapse has not yet been observed, their overturning threshold corresponds to the lower bound of ground motion intensity that has not yet occurred.
3. Compare the predicted probability of exceeding (or not exceeding) particular levels of ground motion intensity within a given time frame, with the seismic hazard assessment for the city of Thessaloniki.

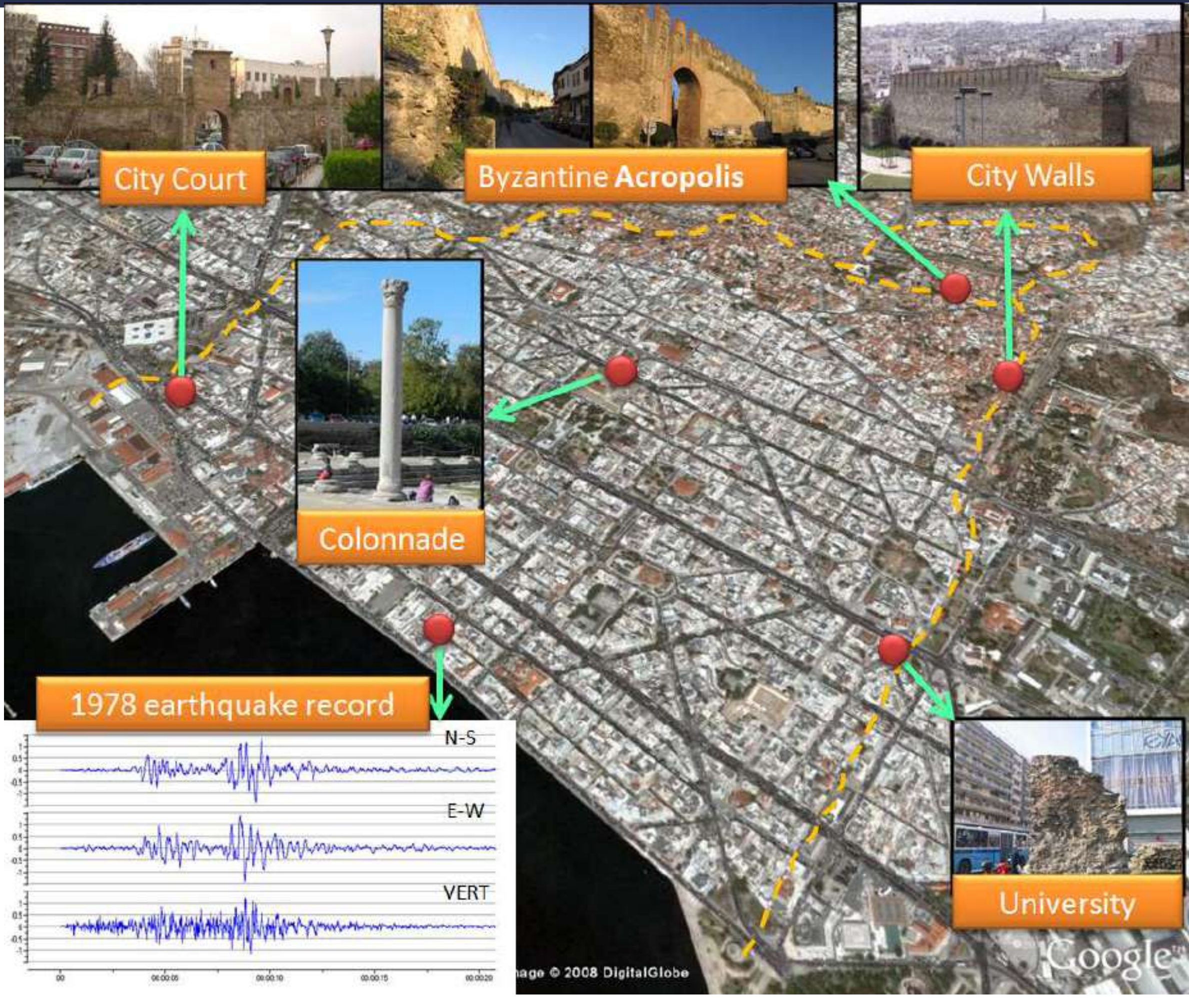


Monuments studied & uncertainties involved

Earthquake input uncertainty

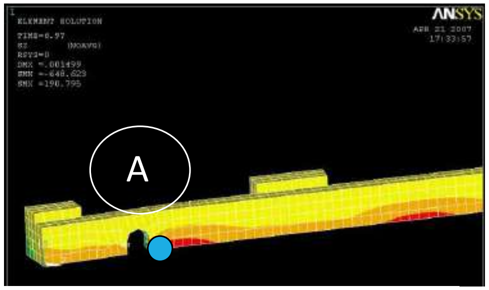
Material uncertainty

mechanical properties of materials and their distribution in space within the structures body

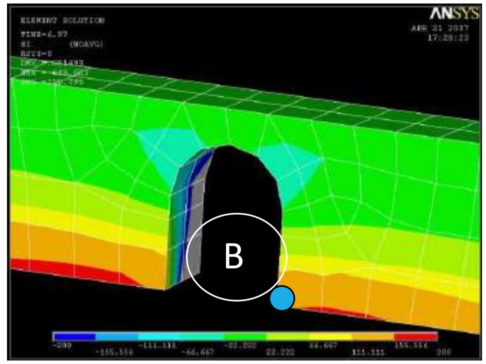


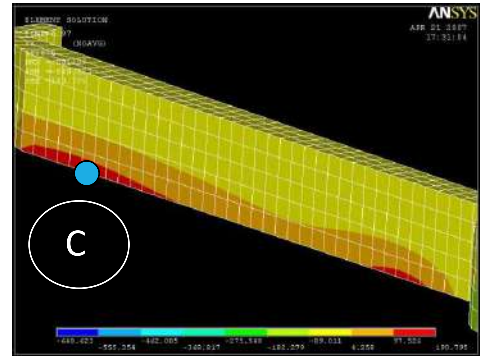
Stylianidis, K. and Sextos, A. (2009) "Back analysis of Thessaloniki Byzantine Land Walls as a means to assess its Seismic History", *International Journal of Architectural Heritage*, 3(4), 1-23.

Asynchronous ground motion for extended historical structures

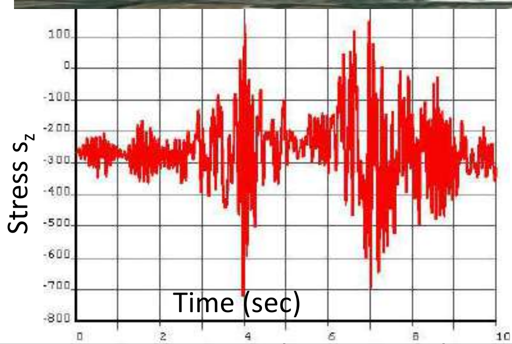


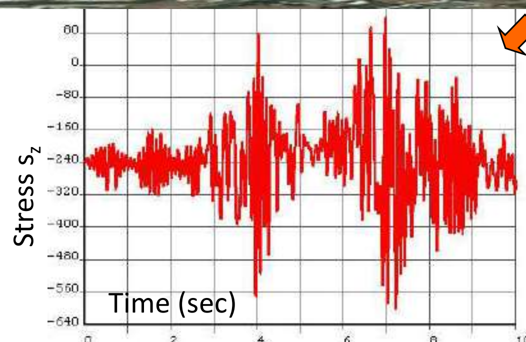
West gate stresses s_z at time t=6.97 sec



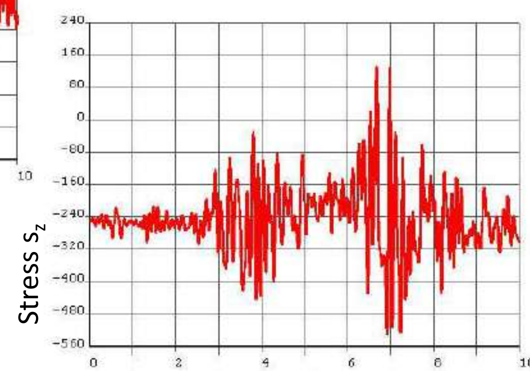


s s_z at time
ec



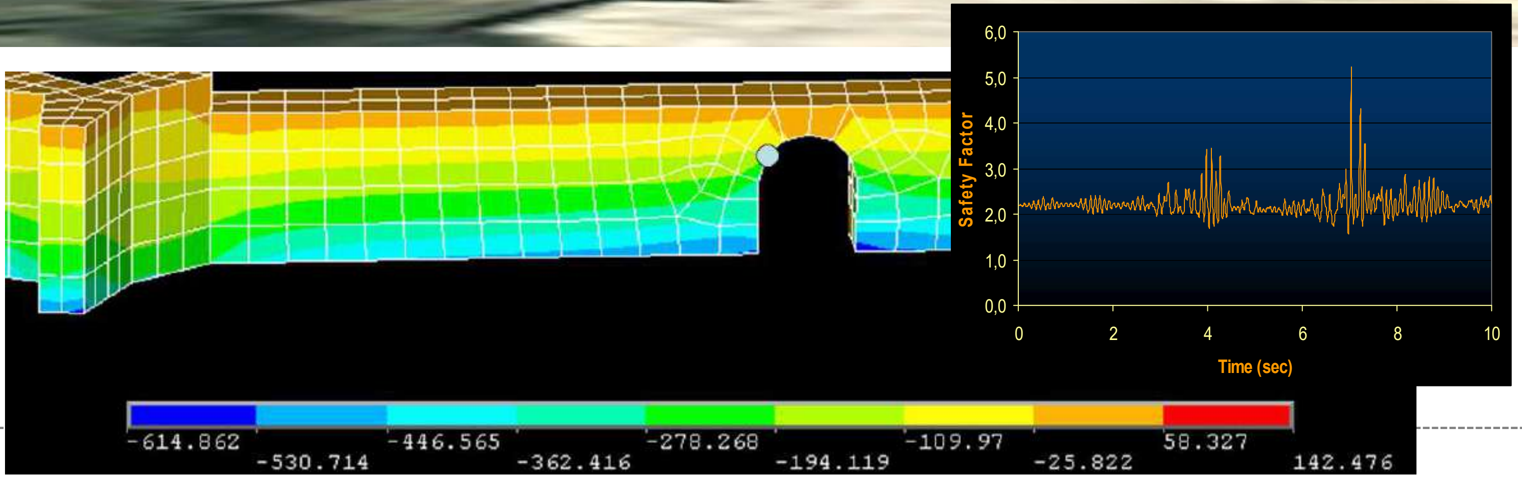


Location	A	B	C
Max tensile σz(t)	0.15 MPa	0.12 MPa	0.13 MPa
Tensile strength	**0.15MPa**		
Max compression σz(t)	0.71 MPa	0.60 MPa	0.53 MPa
Compression Strength	**2.0 MPa**		



Time (sec)

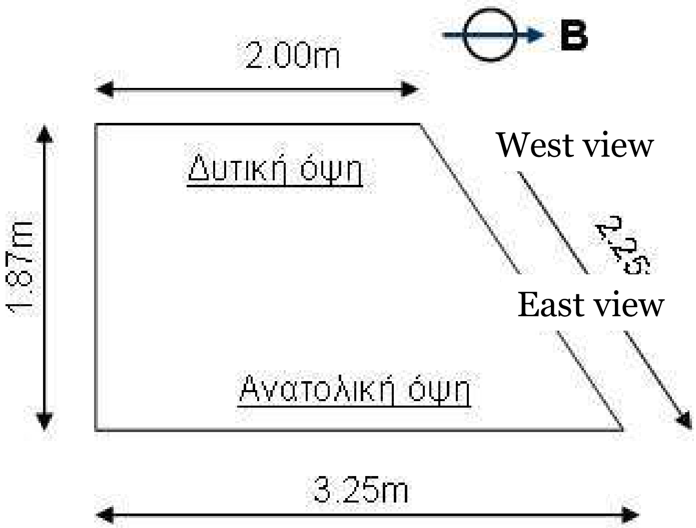
Shear strength is a function of axial load and varies with time & space

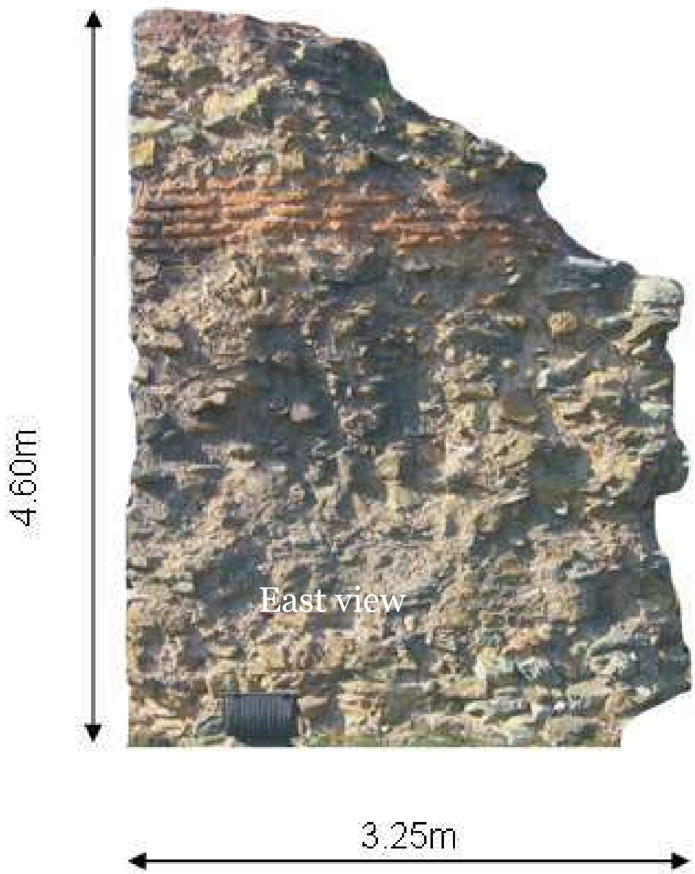


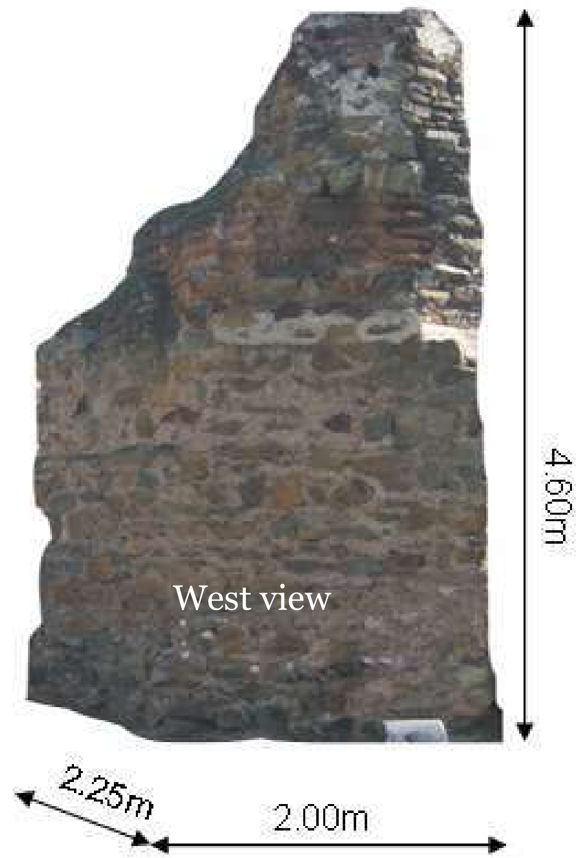
Simplest possible Byzantine wall residuum

Trace of Roman Tower over a pre-christianic masonry

Simplest possible Byzantine wall residuum







Simplest possible Byzantine wall residuum

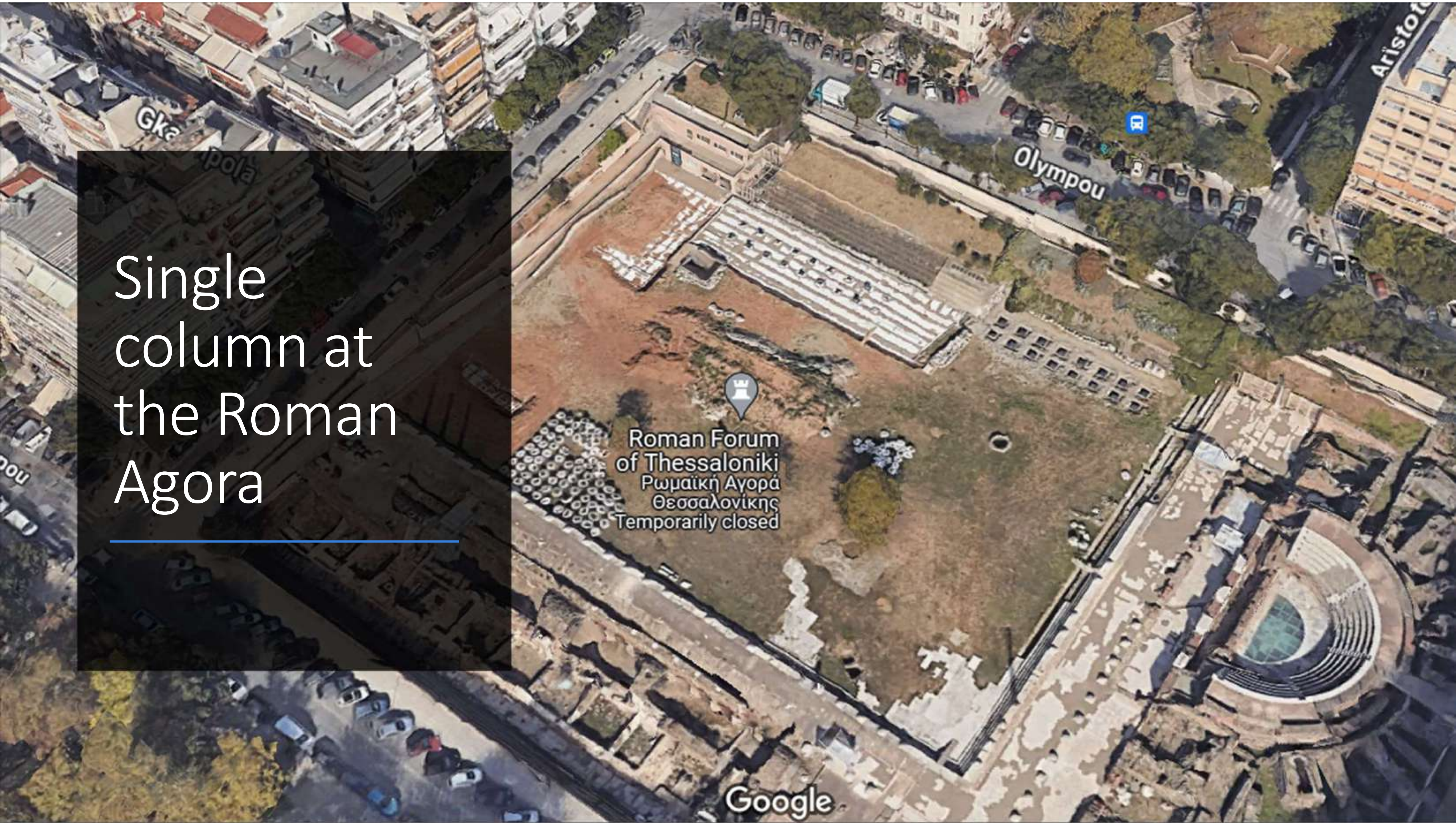
- Compression strength f_{mc}=2.0MP
- Tensile strength f_{mt}=0.15MPa
- Modulus of Elasticity E=3500MP
- Self weight γ=22KN/m^3
- Soil Class: B-C according to Eurc
- Shear wave velocity $Vs_{,30}$=250 m,
- Soil density ρ=1.8kg/m^3
- Poisson ratio ν=0.2

? Material properties distribution

? Rocking response

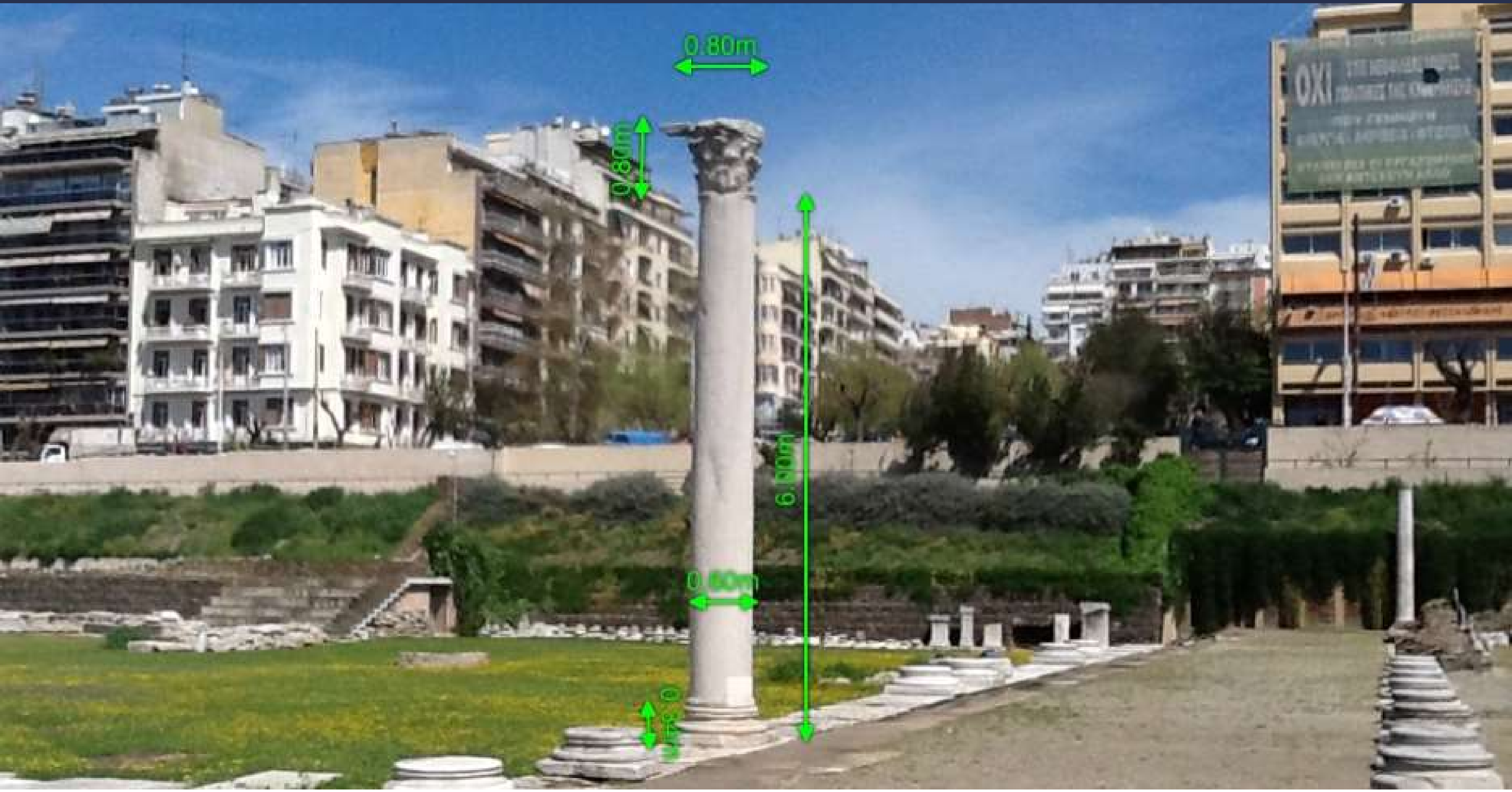
? Unknown when the structural system took its present shape

Single column at the Roman Agora



Overview of the Roman Colonnade

Overview of the Roman Colonnade



Overview of the Roman Colonnade

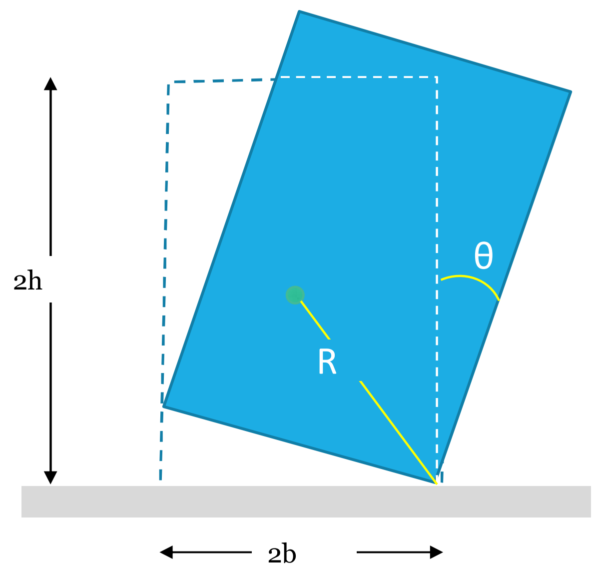
reestablished at its original state in 1969

Rocking dynamics

The equation of motion under zero vertical and positive horizontal base acceleration:

$$\begin{cases} I_o\ddot{\theta} + mgRsin(-\alpha - \theta) = -m\ddot{u}_g Rcos(-a - \theta), \theta < 0 \\ I_o\ddot{\theta} + mgRsin(\alpha - \theta) = -m\ddot{u}_g Rcos(a - \theta), \theta \geq 0 \end{cases}$$

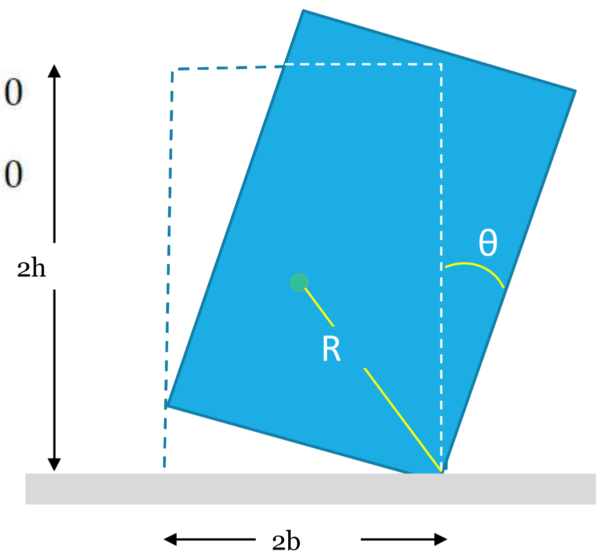
• R_o distance of center of gravity from a base corner
• Stockiness (slenderness) angle α of the block: $tan(\alpha)=b/h$ (the smallest its value, the more likely to uplift)
• θ = the rigid body rotation of the block from the vertical axis (positive when the rocking takes place around the right base corner)
• I_o = the moment of inertia of the rigid structure and m is its mass.



Rocking dynamics

$$\begin{cases} \ddot{\theta} = -p^2\left[sin(-a-\theta) + \frac{\ddot{u}_g}{g}cos(-a-\theta)\right], & \theta < 0 \\ \ddot{\theta} = -p^2\left[sin(+a-\theta) + \frac{\ddot{u}_g}{g}cos(+a-\theta)\right], & \theta \geq 0 \end{cases}$$

Sliding, rocking & overturn depends on:
- geometrical characteristics (R, a and p),
- coefficient of friction μ,
- restitution coefficient e,
- mass distribution,
- foundation compliance
- properties of ground motion (amplitude a_p and the persistence of the pulse $L_p = a_p T_p^2$, T_p)



- Konstantinidis, D. and Makris, N. (2009) Experimental and analytical studies on the response of freestanding laboratory equipment to earthquake shaking. Earthquake Engineering & Structural Dynamics 38:December 2008, 827–848.
- Makris, N. and Vassiliou, M.F. (2013) Planar rocking response and stability analysis of an array of free-standing columns capped with a freely supported rigid beam. Earthquake Engineering & Structural Dymamics 42:3, 431–449.
- Voyagaki, E., Psycharis, I.N., and Mylonakis, G. (2013) Rocking response and overturning criteria for free standing rigid blocks to single—lobe pulses. Soil Dynamics and Earthquake Engineering 46, 85–95.
- Papaloizou, L. and Komodromos, P. (2011) Investigating the seismic response of ancient multi-drum colonnades with two rows of columns using an object-oriented designed software. Advances in Engineering Software 44:1, 136–149.

Dynamic characteristics of the two systems studied

System studied	Dimensions [m]	Stockiness (Slenderness) α	Size parameter R_0 [m]	Frequency parameter [rad/sec]	Fixed-base deformable system T_s [sec]
	W=1.87÷2.30 B = 2.05÷3.60 H=3.30÷5.25	α_W = 0.342÷0.608 α_B = 0.372÷0.829	R_w = 1.89÷2.86 R_B = 1.94÷3.18	p_w = 1.60÷1.96 p_b = 1.52÷1.94	E_s=3.5GPa T_s =0.09s
	D=0.66 H=6.0	α_D = 0.109	R_d = 3.01	p_d = 1.56	E_s=40GPa T_s =0.15sec

Sextos A.G., Nalmpantis S., Faraonis P., Skiada, D., Stylianidis, K. (2013) "Probabilistic seismic hazard assessment through geometrically non-linear back-analysis of Byzantine and Roman Monuments". 10th HSTAM International Congress on Mechanics, Chania, Crete, Greece.

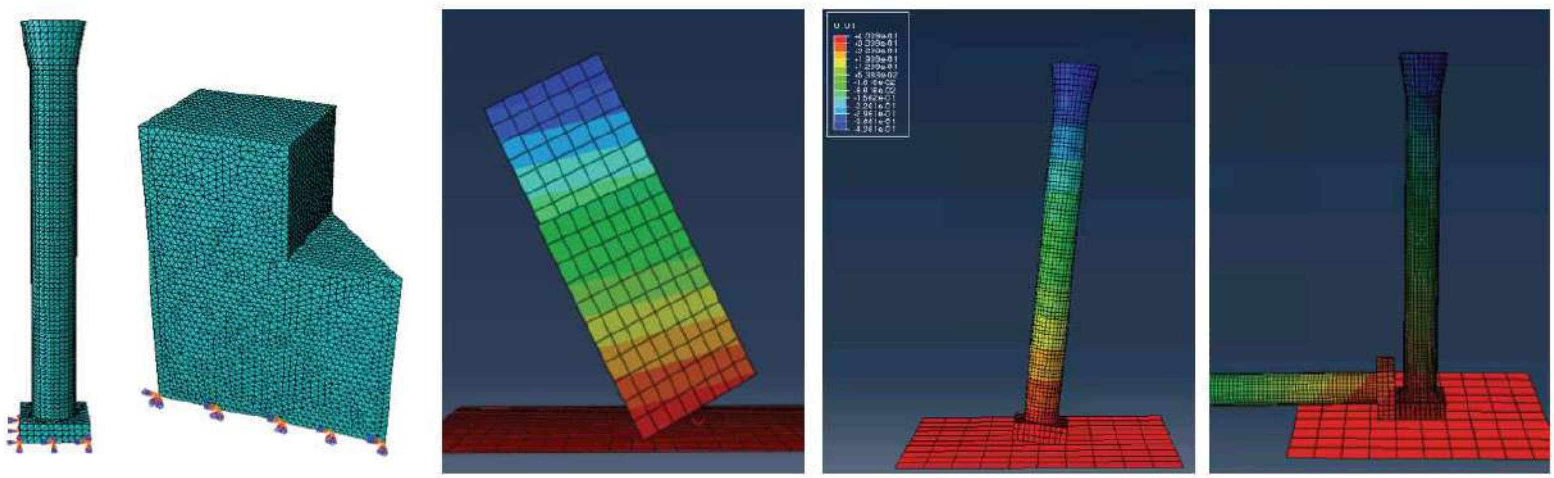
FE analysis

Both structures were deemed as rigid resting on a rigid base with a coefficient of friction exponentially decaying from a static value μ_s at the initiation of sliding, to a lower value, μ_k:

$$\mu = \mu_k + (\mu_s - \mu_k)e^{-d_c \gamma'_{eq}}$$

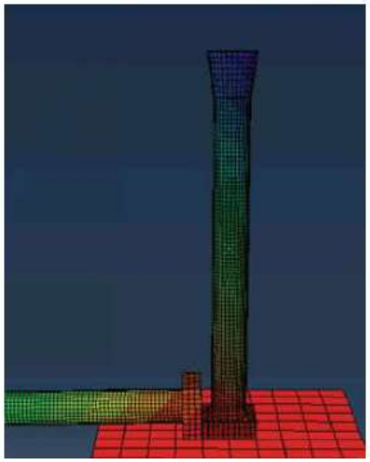
where γ'_{eq} is the equivalent slip rate and d is the decay coefficient from static state to kinetic state.

Two (equally probable) cases were examined: μ_s=μ_κ=0.7 and μ_s=0.7, μ_k=0.3 with d=0.05

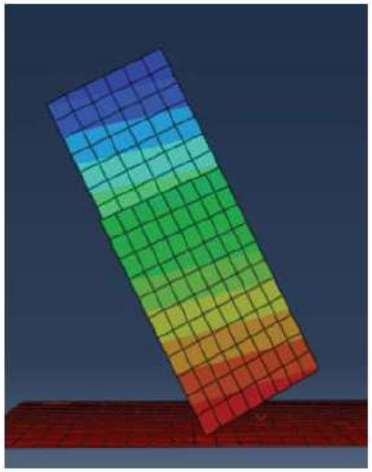


Distinct oscillation mechanisms

Distinct vibration mechanisms



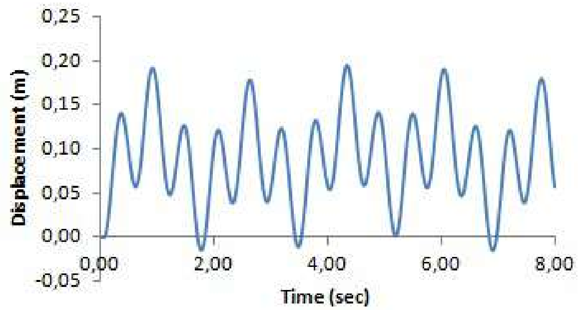
- Pure rocking
- Pure sliding
- Rocking with sliding
- Overturn after multiple impacts
- Overturn after a single impact
- Direct overturn

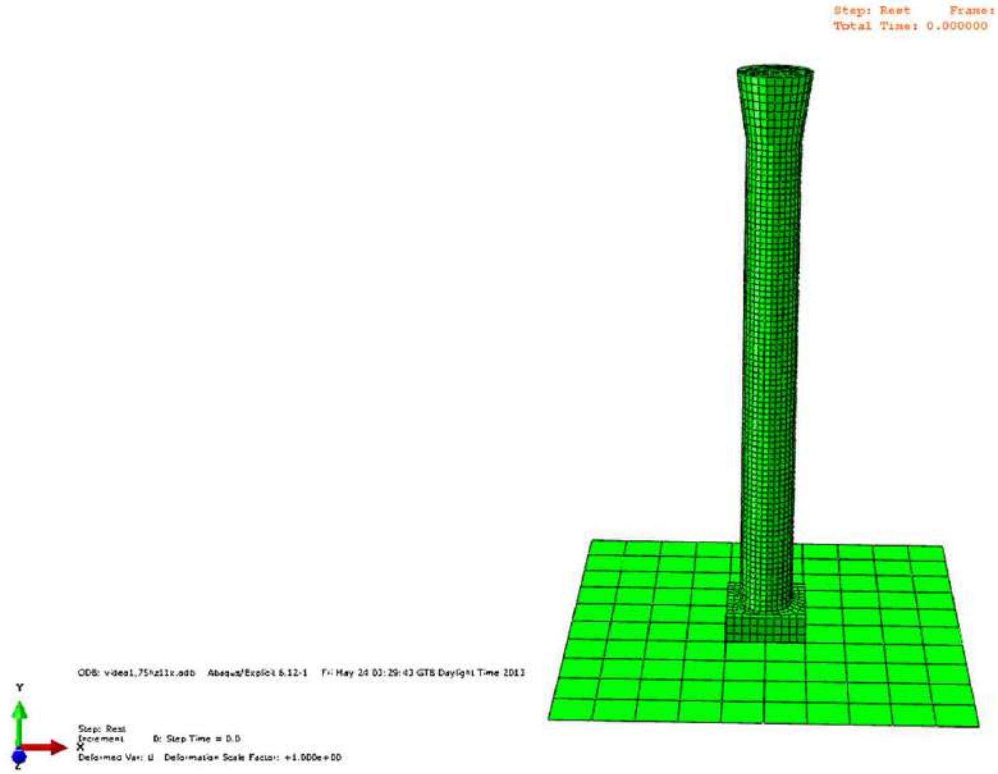


- Pure rocking
- ~~Pure sliding~~
- ~~Rocking with sliding~~
- Overturn after multiple impacts
- Overturn after a single impact
- Direct overturn

Distinct oscillation mechanisms

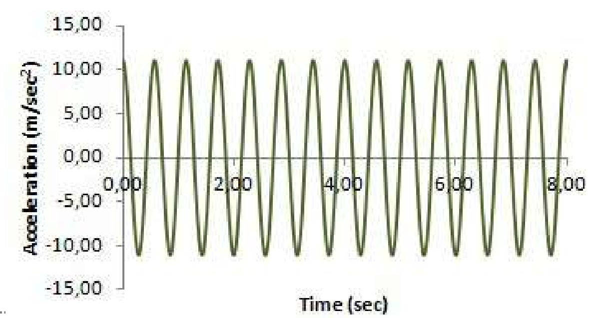
Pure rocking





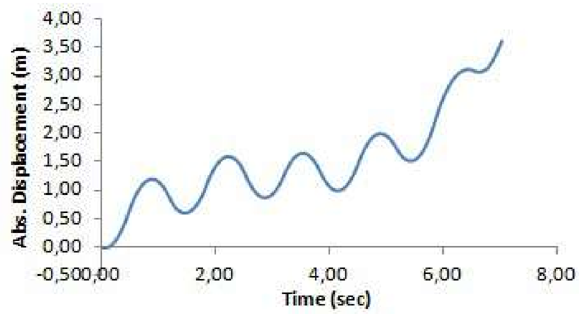
1D lateral Excitation

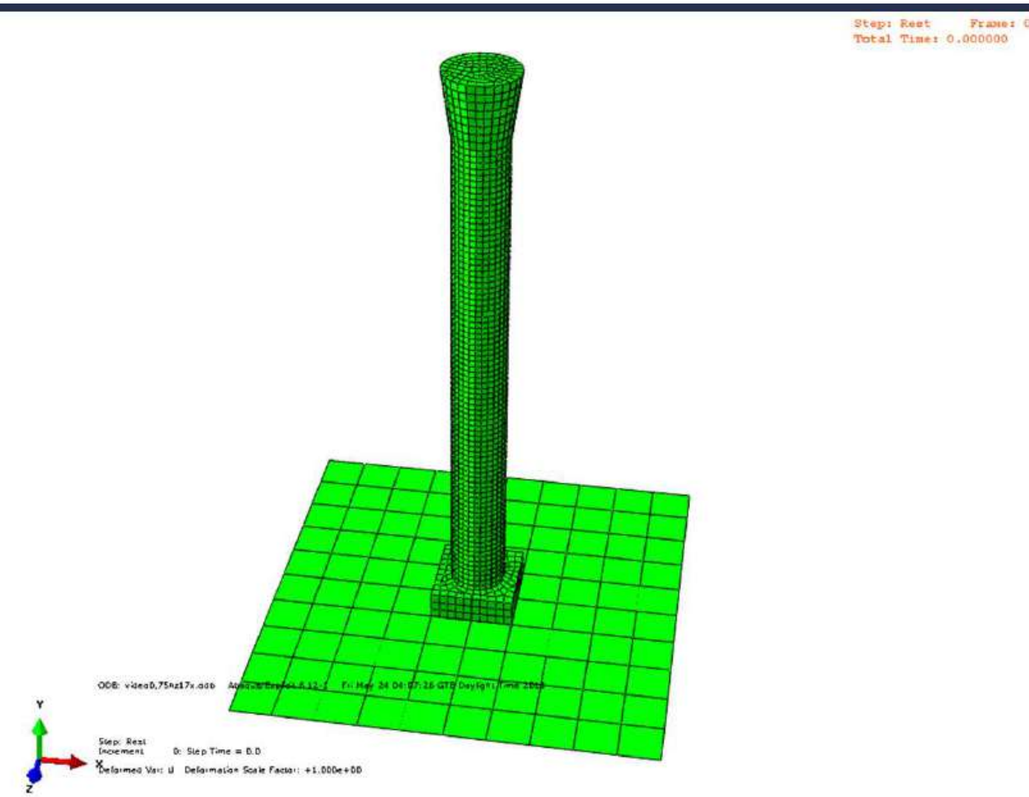
f= 1,75Hz, PGA=1.1g



Distinct oscillation mechanisms

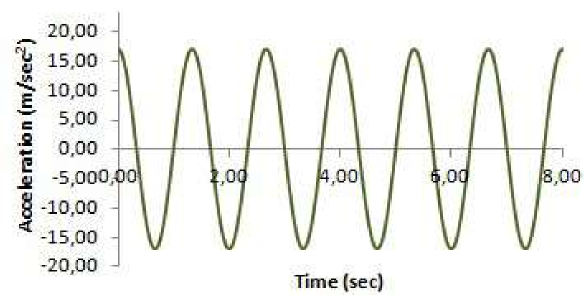
Overturn after multiple impacts





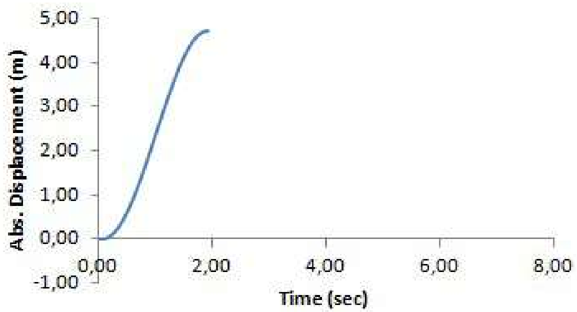
1D lateral Excitation

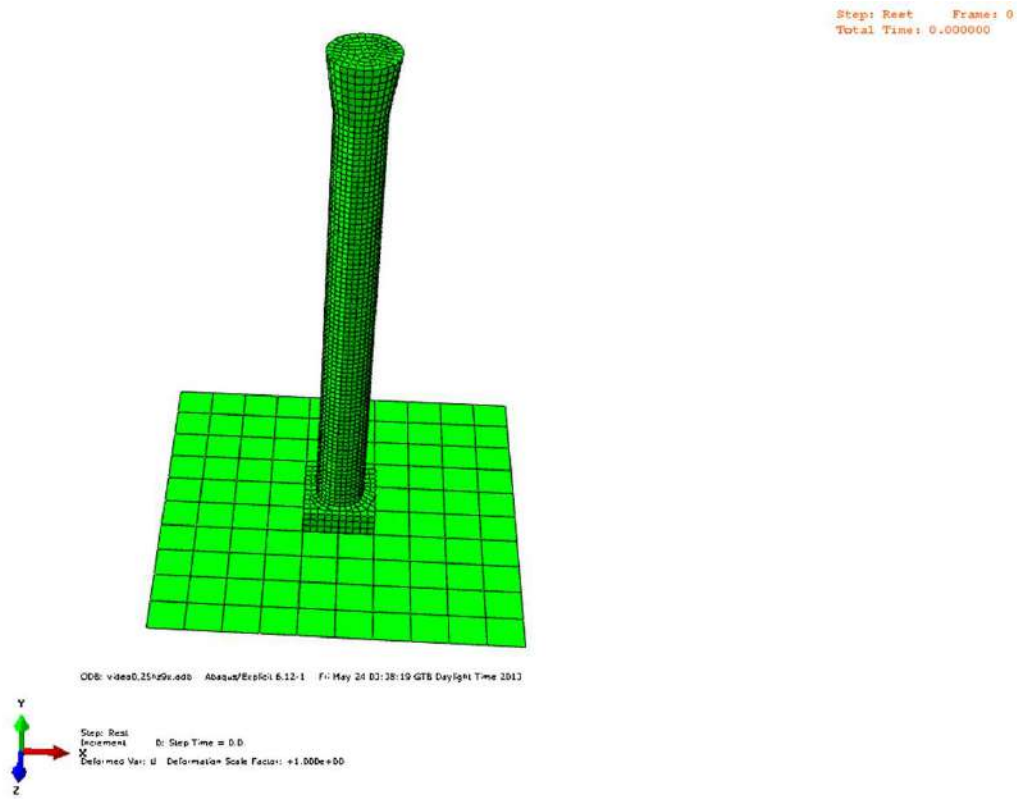
f= 0,75Hz, PGA=1.7g



Distinct oscillation mechanisms

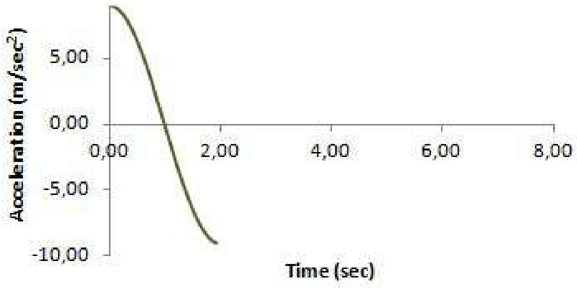
Direct Overturn





1D lateral Excitation

f= 0,25Hz, PGA=0.9g

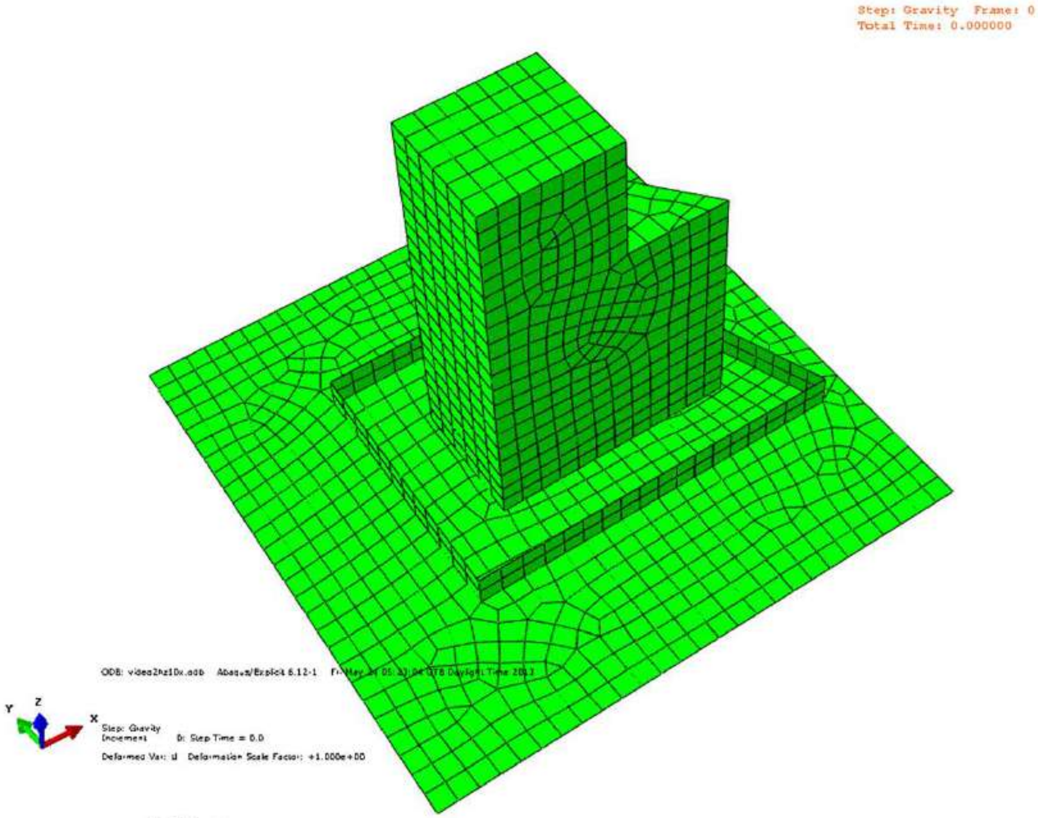


Distinct oscillation mechanisms

Pure rocking

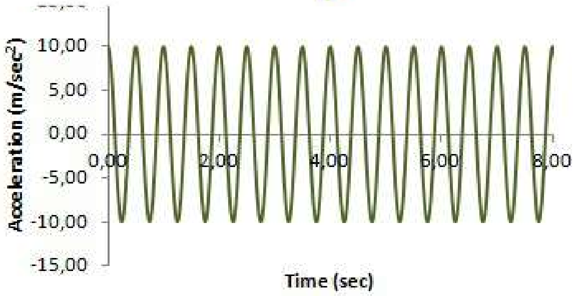
More complex behavior due to:

• 0.5m depth embedment
(modeled with lateral spring supports)
• lack of axisymmetry
• bi-lateral excitation



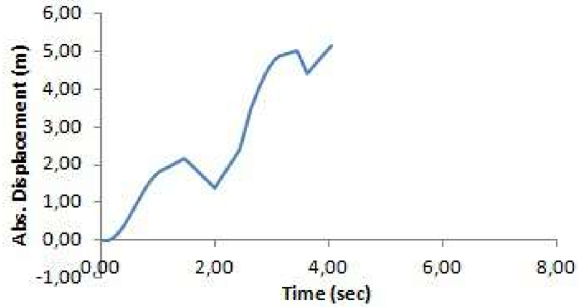
Bi-lateral
Excitation

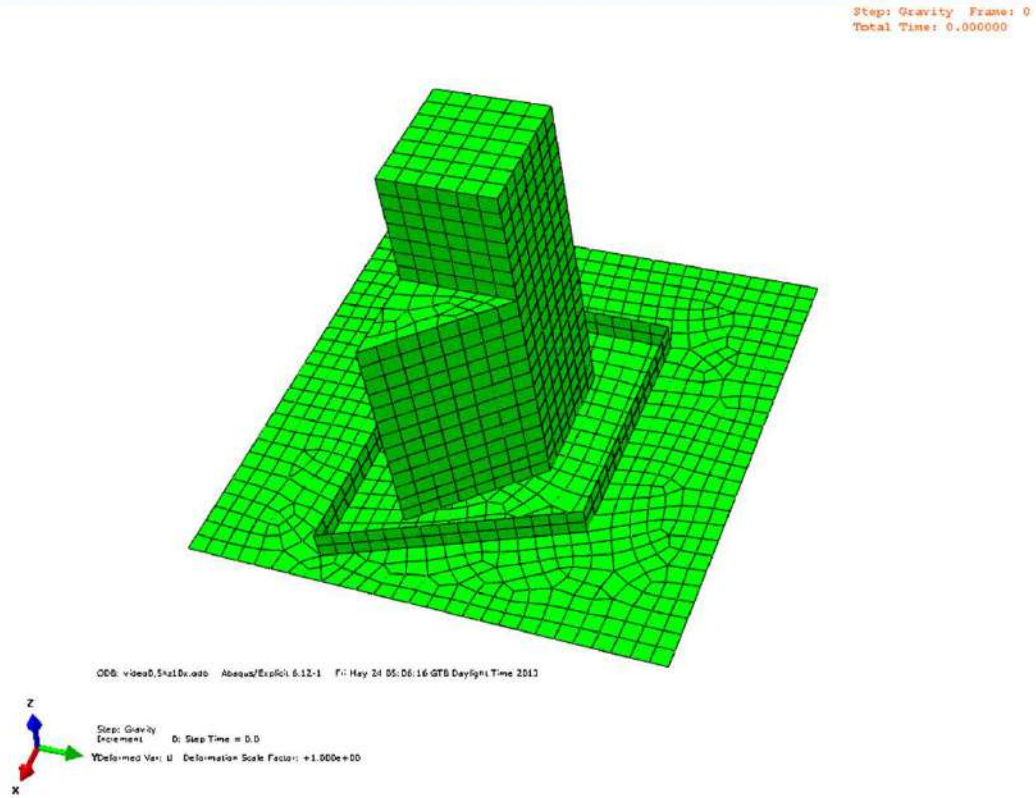
f= 2,00Hz,
PGA=1.0g



Distinct oscillation mechanisms

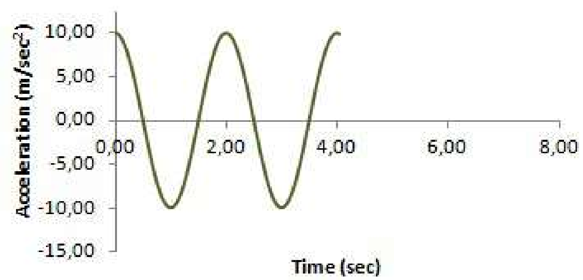
Overturn after multiple impacts





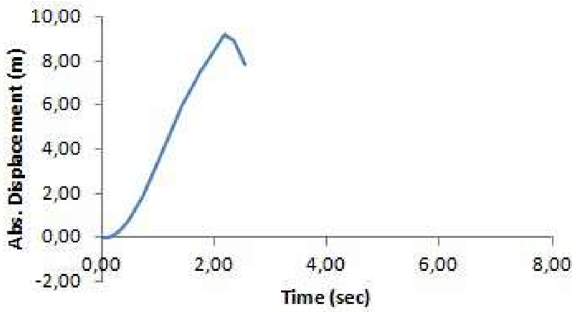
Bi-lateral Excitation

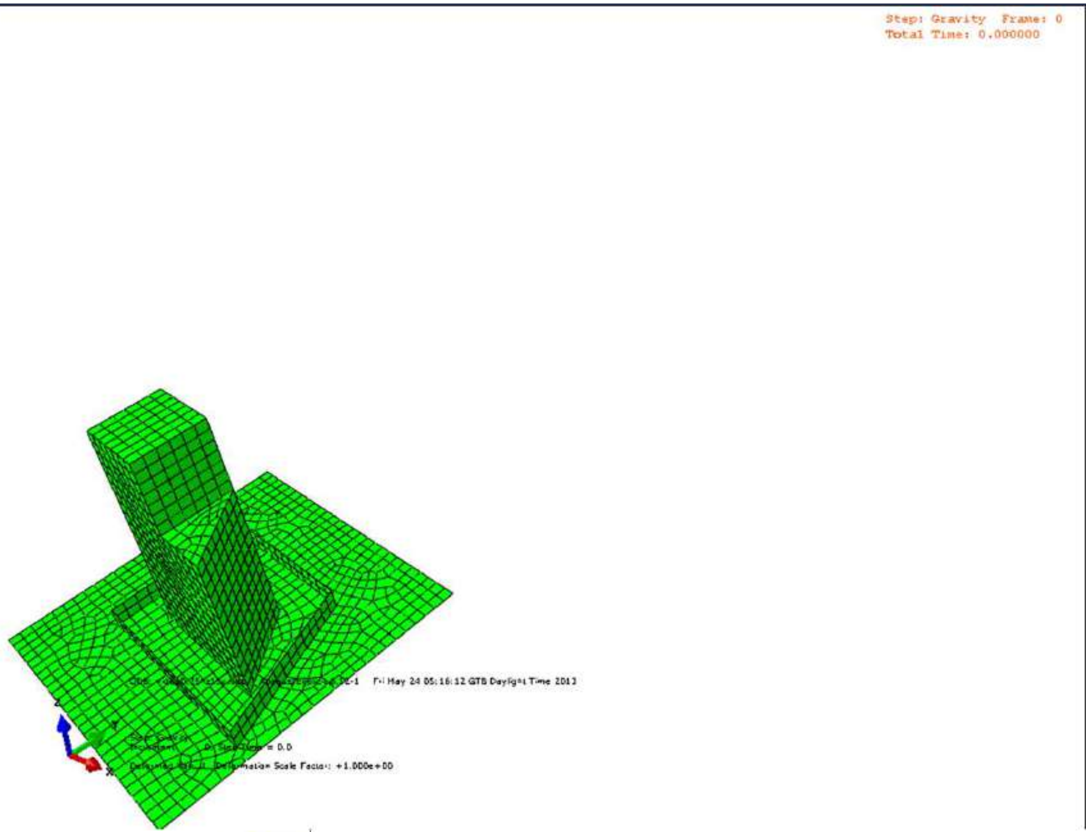
f= 0, 50Hz, PGA=1.0g



Distinct oscillation mechanisms

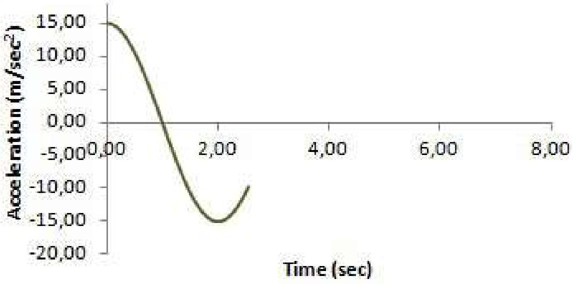
Direct overturn



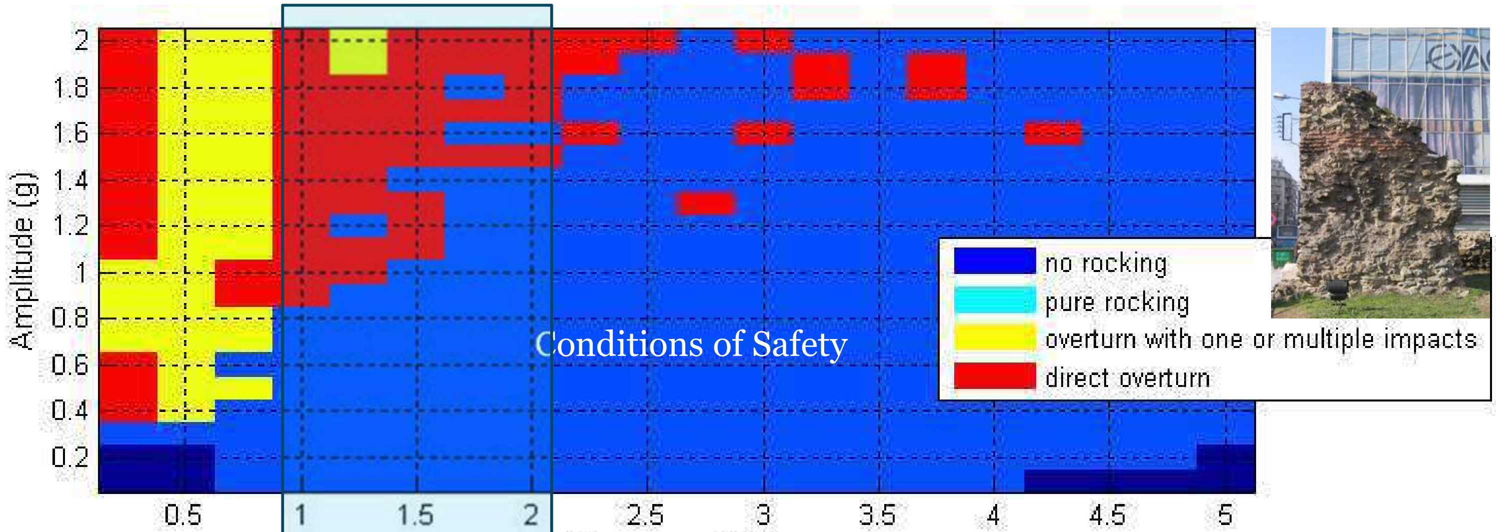


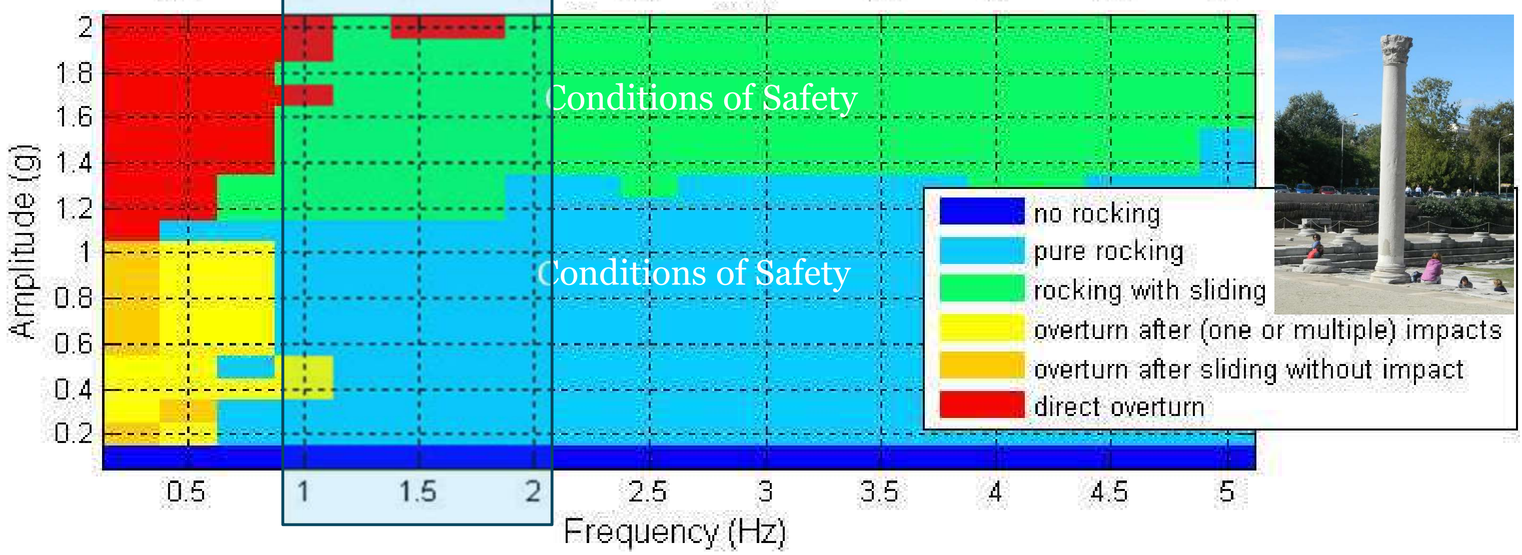
Bi-lateral Excitation

f= 0,25Hz, PGA=1.5g

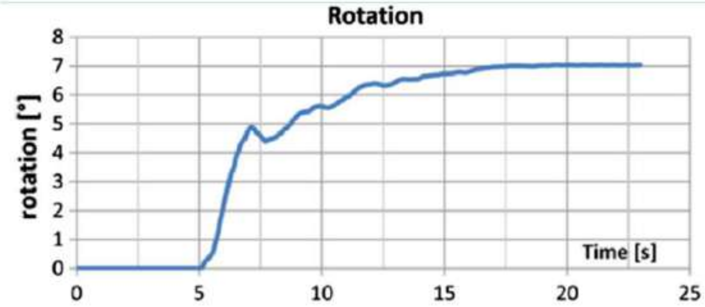


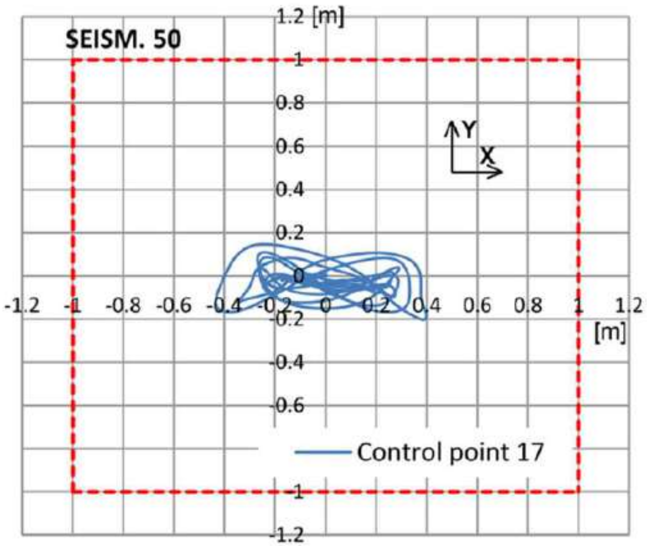
Rocking spectra for the Byzantine Wall residuum & the Roman colonnade

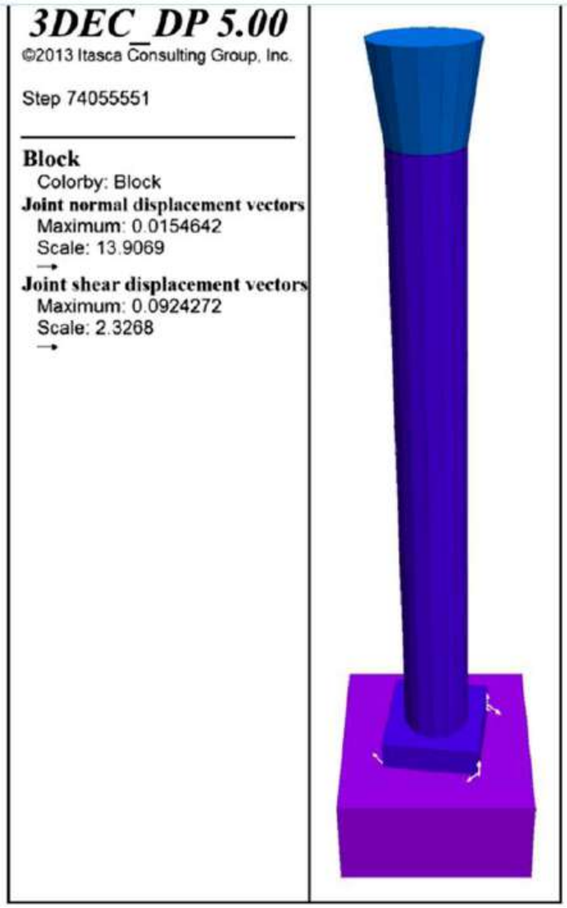


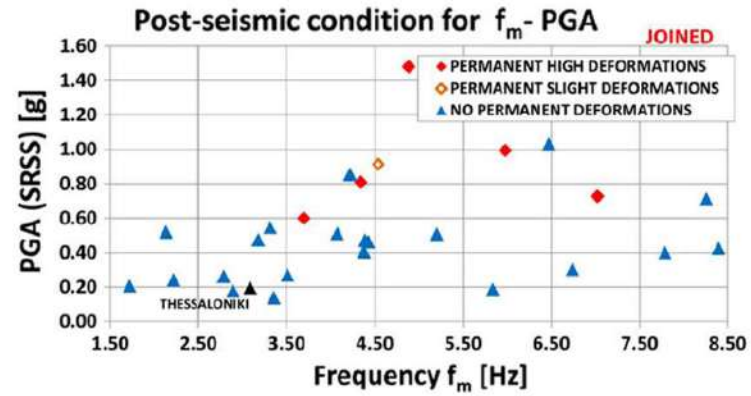


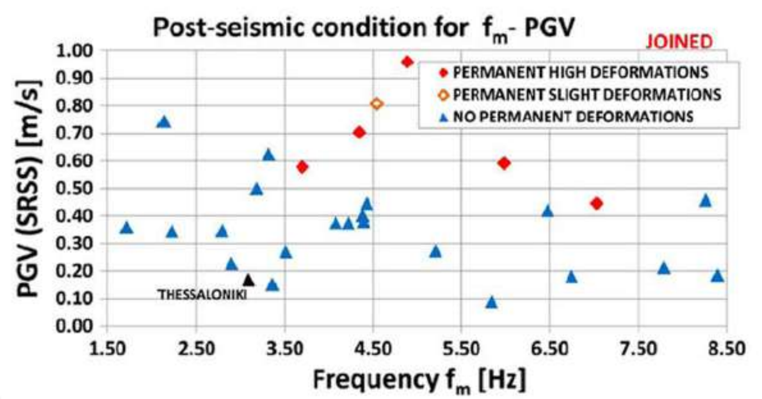
Efficiency of different Intensity Measures





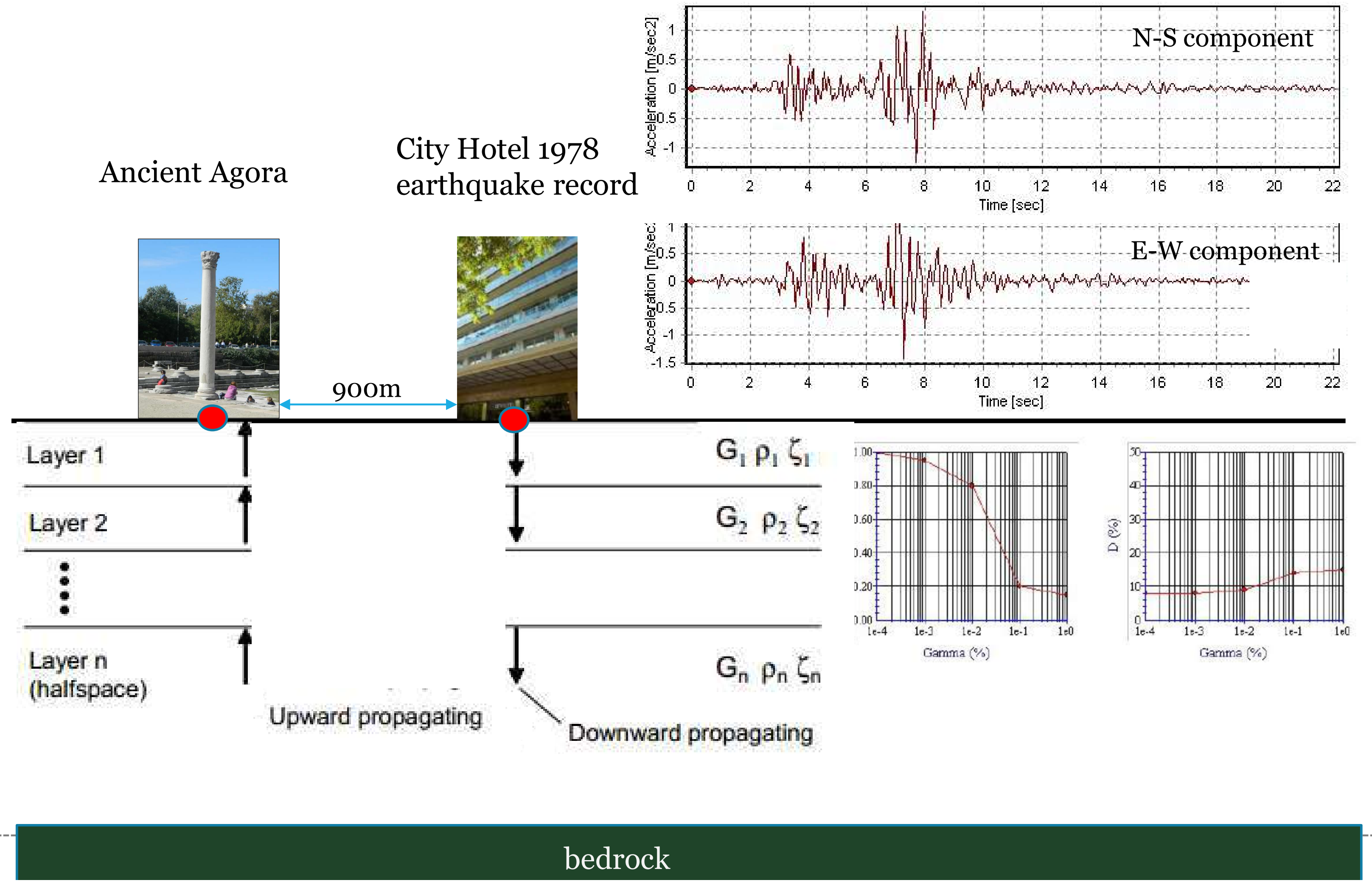






Pappas, A., Sextos, A. G., da Porto, F., & Modena, C. (2017). Efficiency of alternative intensity measures for the seismic assessment of monolithic free-standing columns. Bulletin of Earthquake Engineering, 15(4), 1635–1659.

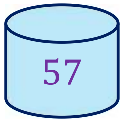
Deconvolution of the 1978 record and 1D site response



Disaggregation of Seismic Hazard

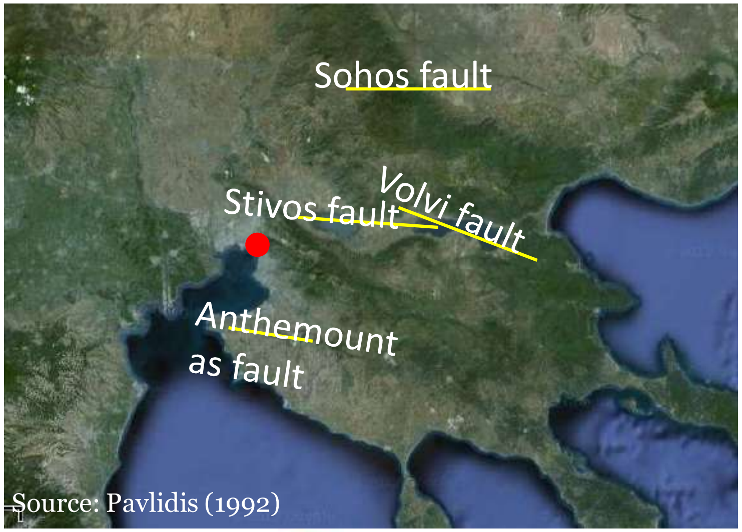
- 57 earthquake records (PEER-NGA database)

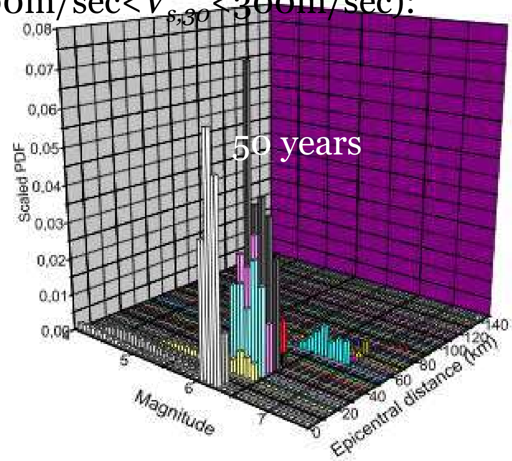
- Based on PSHA dissagregation:
- 6.0<M<6.5 & 10km<R<30km

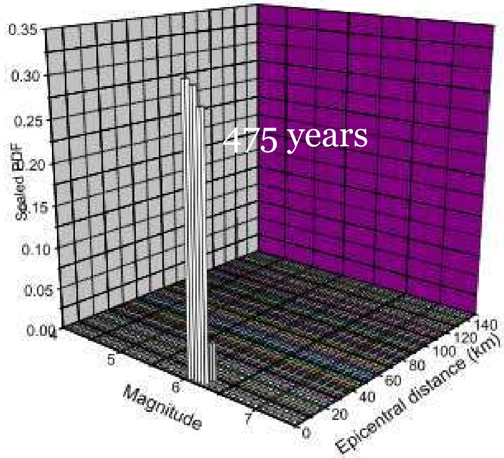


Four sets were formed:
- $0 < a_g < 0.1g$ (corresponding to T_R = 50years),
- $0.1g < a_g < 0.25g$ (corresponding to T_R=475years),
- $0.25g < a_g < 0.50g$
- $0.50g < a_g < 1.50g$

with 200m/sec< $V_{s,30}$ <300m/sec):

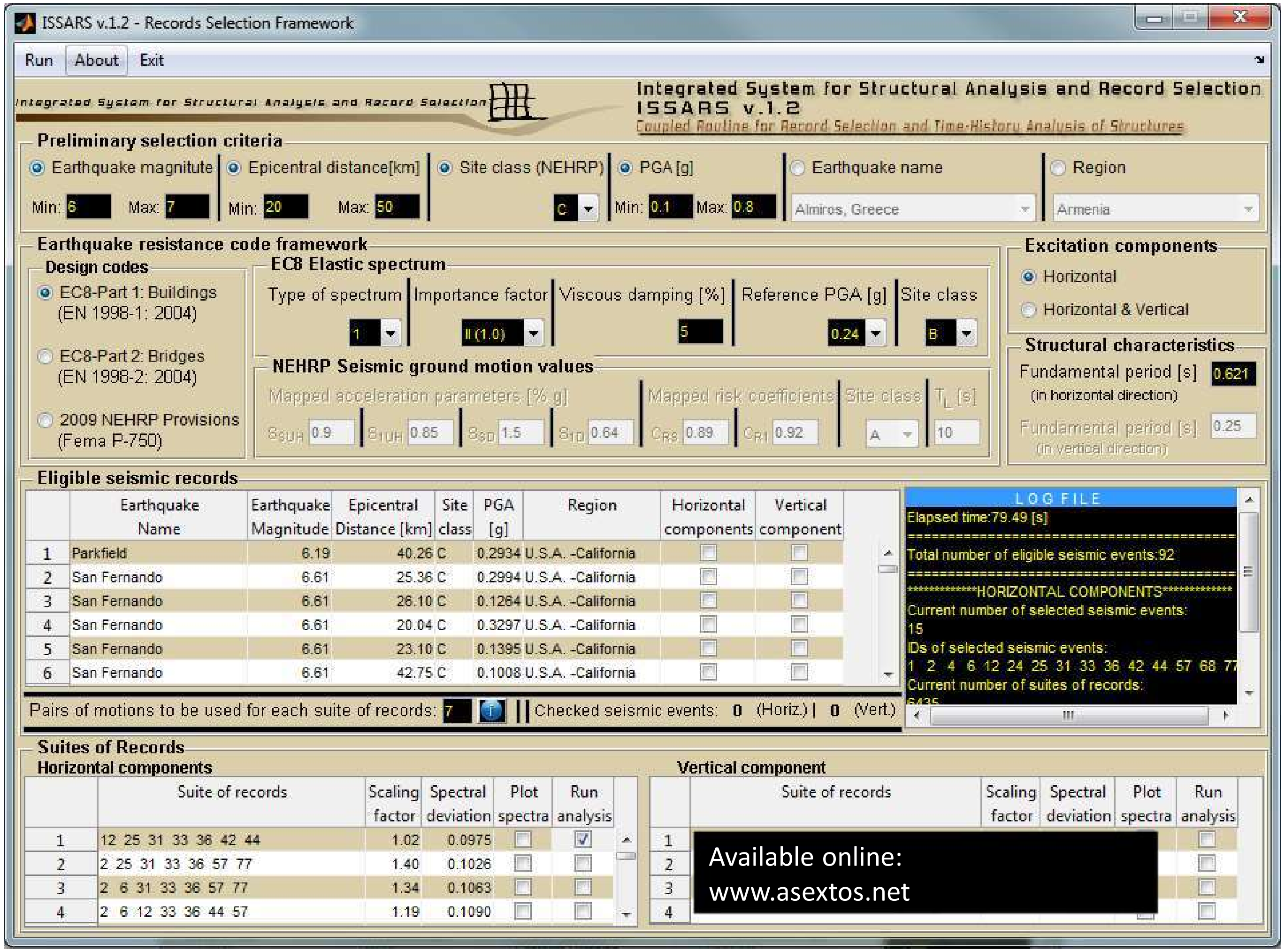






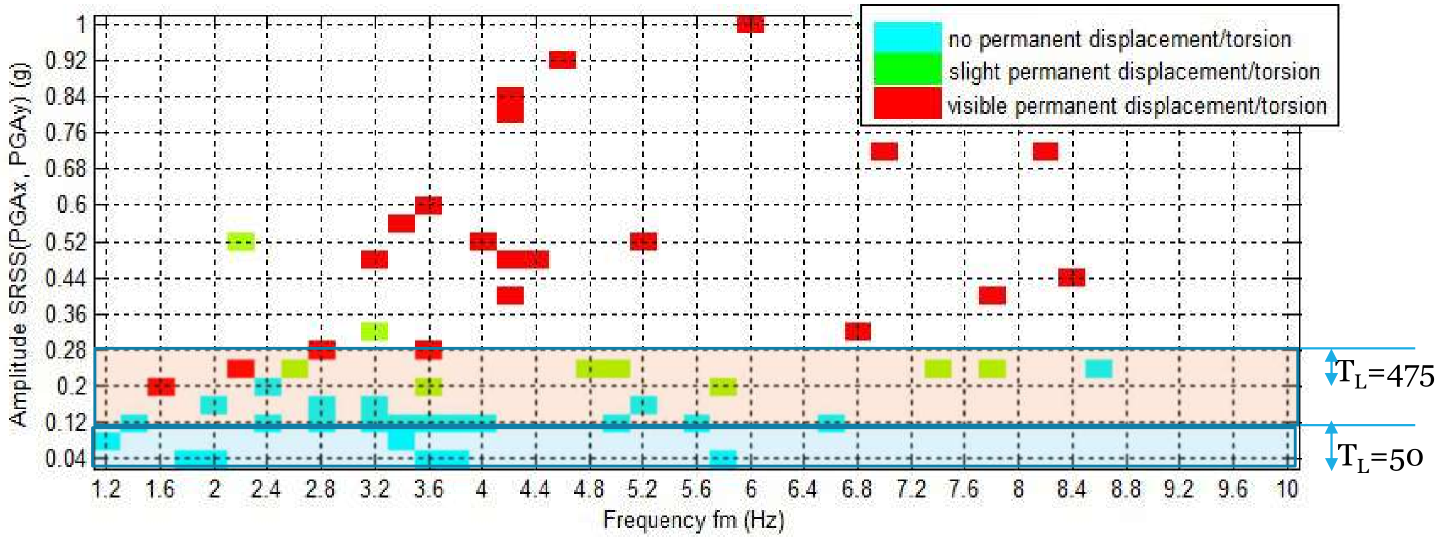
Source: Pitilakis, K.D., Cultrera, G., Margaris, B., Ameri, G., Anastasiadis, A., Franceschina, G., and Koutrakis, S. (2007). Thessaloniki Seismic Hazard Assessment: Probabilistic and deterministc approach for rock site conditions. 4th International Conference on Earthquake Geotechnical Engineering, June 25-28, 1701.

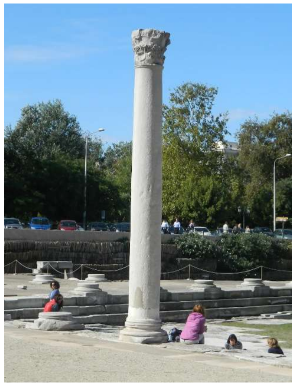
Ground Motion Selection & Scaling



Katsanos, E.I. and Sextos, A.G. (2013). ISSARS: An integrated software environment for structure-specific earthquake ground motion selection. Advances in Engineering Software 58, 70–85.

Colonnade response under seismic excitation





$$T_m = \frac{1}{f_m} = \frac{\sum C_i^2 \cdot \frac{1}{f_i}}{\sum C_i^2}$$

for $0.25\ Hz \le f_i \le 20\ Hz$ *with* $\Delta f \le 0.05\ Hz$

Colonnade response under seismic excitation

So what do we really know about Seismic Hazard at the site of interest?

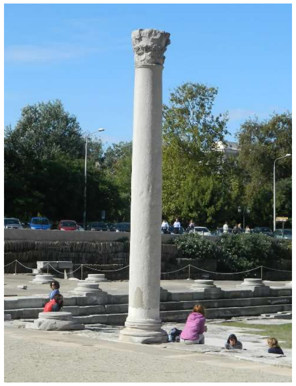
1. from Eurocode 8: (according to the Greek National Annex):

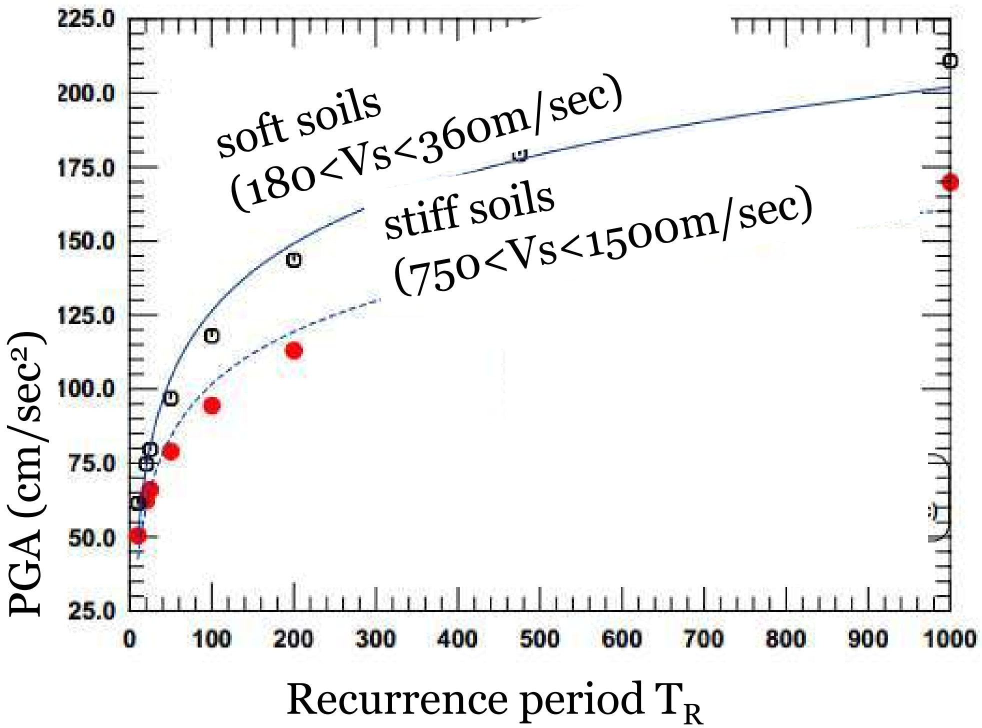
probability of 10% to exceed 0.16g within 50 years (corresponding to a period of recurrence of T_R = 475 years).

2. from experience: (given the re-establishement of the colonnade in 1969 and the 1978 earthquake):

probability of 0% to exceed 0.14g in 43 years because this is the only ground motion recorded

Colonnade response under seismic excitation



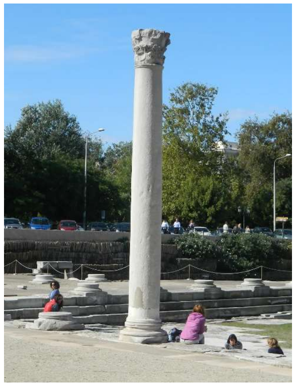


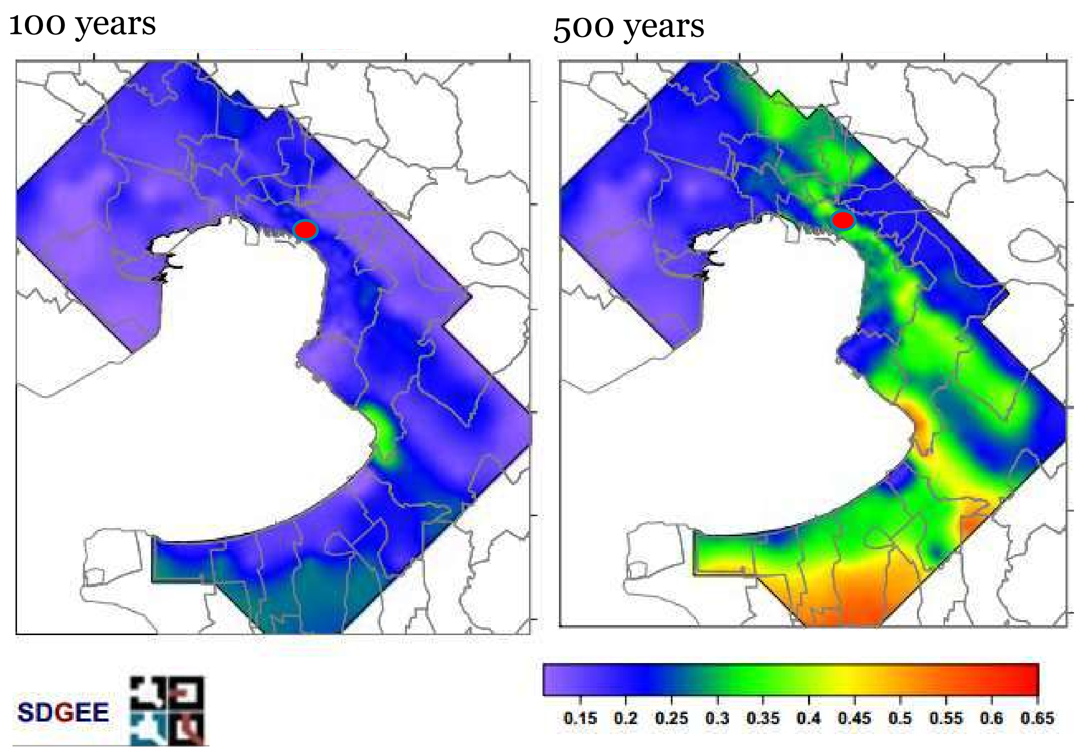
3. from Thessaloniki Microzonation study I (Leventakis, 2003):

probability of 10% to exceed 0.179g within 50 years (corresponding to T_R = 475 years)

probability of 15% to exceed 0.16g within 50 years (corresponding to T_R = 475 years)

Colonnade response under seismic excitation

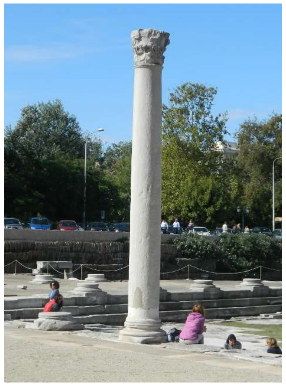


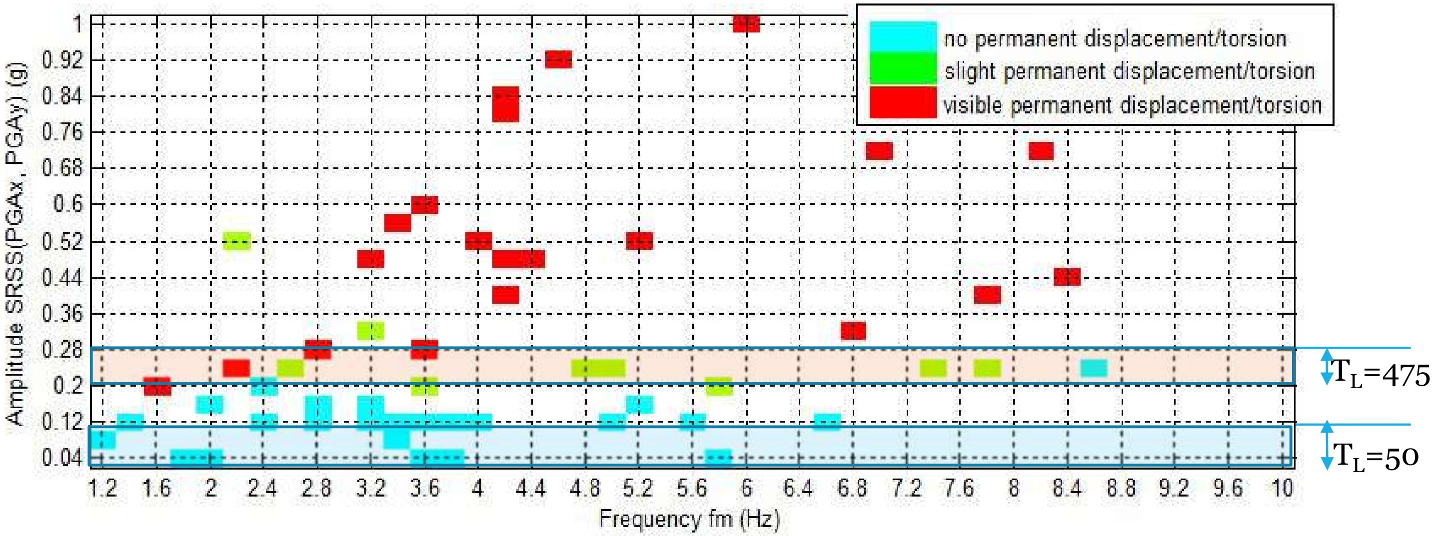


4. from Thessaloniki Microzonation study II (Pitilakis, 2011):

probability of 50% to exceed 0.22g within 50 years (corresponding to T_R = 100years)
probability of 10% to exceed 0.38g within 50 years (corresponding to T_R = 475 years)

Colonnade response under seismic excitation





5. from rocking response analysis (numerical experiment):

probability of 0% to have exceeded 0.52g* since 1969 as no permanent displacement or collapse has taken place

*0.47g if the maximum PGA of the two components instead of the SRSS of the two maxima)

Though this numerical vs. evidence experiment corresponds to only 43 years it is highly improbable that an event with PGA>0.28g would lead to visible permanent displacement or collapse.

Conclusions

The method could be potentially useful provided that ..

- we use more structures
- they are easier to overturn,
- they are well documented
- they are standing for >500y
- vertical component is taken into consideration
- the uncertainty in friction coefficient is considered

- It is back-verified that a PGA=0.47g has not been exceeded within the last 45 years *that we knew already ☺*
- the probability of permanent dislocation of the ancient colonnade *given* the 475 years scenario (10% tbe in 50y) of the city is found approximately equal to 30%

obviously did not occur during the 1978 earthquake

- Back analysis of historic structures within the city grid is an interesting tool towards the improvement of our understanding of historical seismic events, particularly when focusing to structures which stand still for significantly longer periods