Quantitative assessment of archeo-earthquakes from back analysis of historic masonry structures

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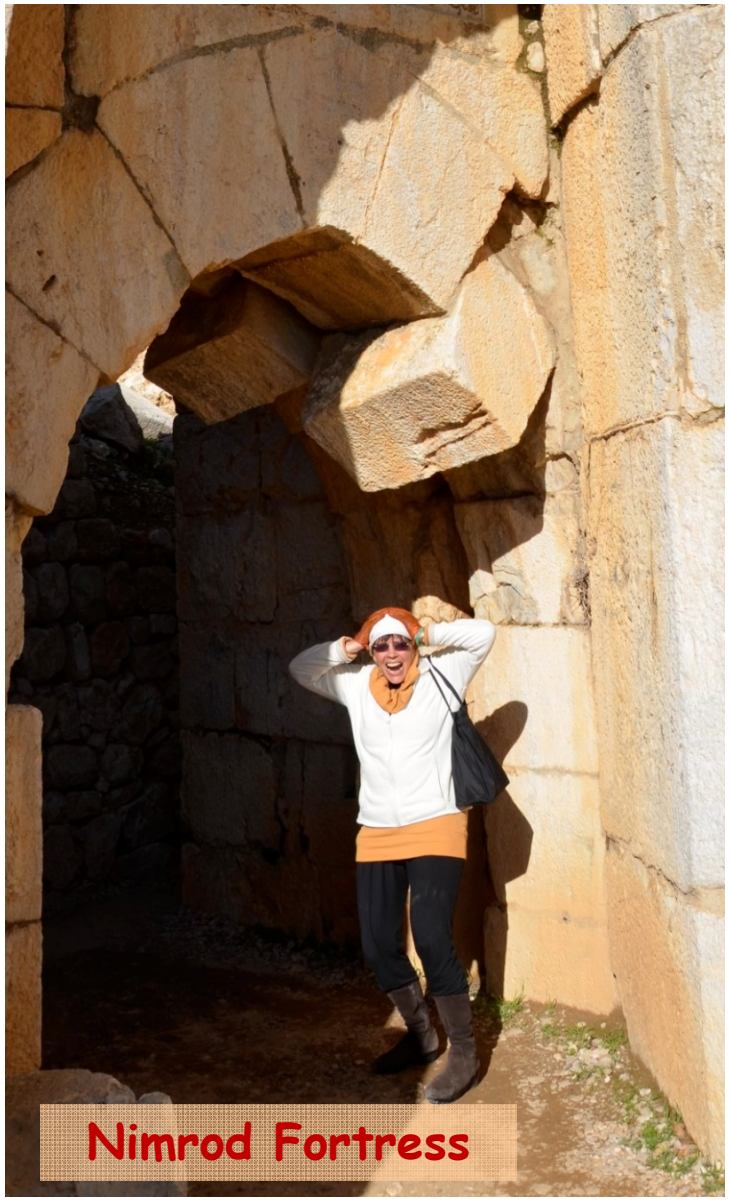
Acknowledgements

Prof. Yossef H. Hatzor

Dr. Gony Yagoda-Biran

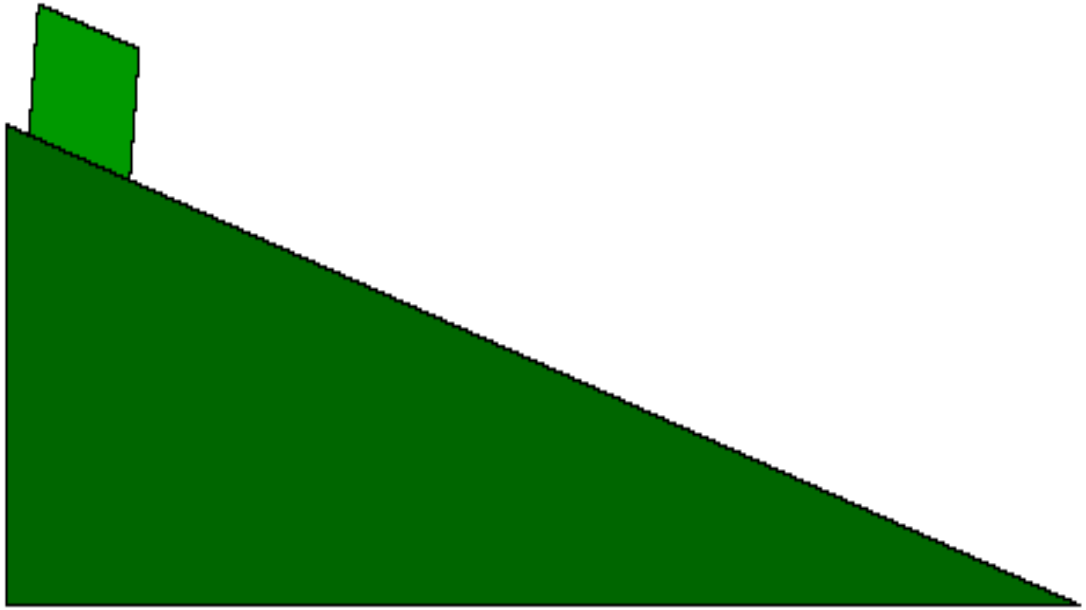
CULTURAL HERITAGE SITES AS RECORDERS OF HISTORIC SEISMICITY

Field Evidence of Seismically Driven Failures in Historic Masonry Structures



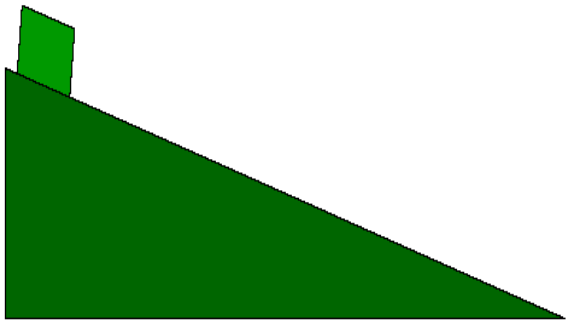
Talk Outline

- Research Method – the numerical, discrete element, Discontinuous Deformation Analysis (DDA) method: Verifications and validations.
- Constraining Paleo-PGA by back-analysis of stone displacements in arches and toppling of columns in historic masonry structures.
- Identifying Archeo-earthquakes in the region with consideration of local site effects
- Defficiencies in seismic-hazard evaluation in Israel

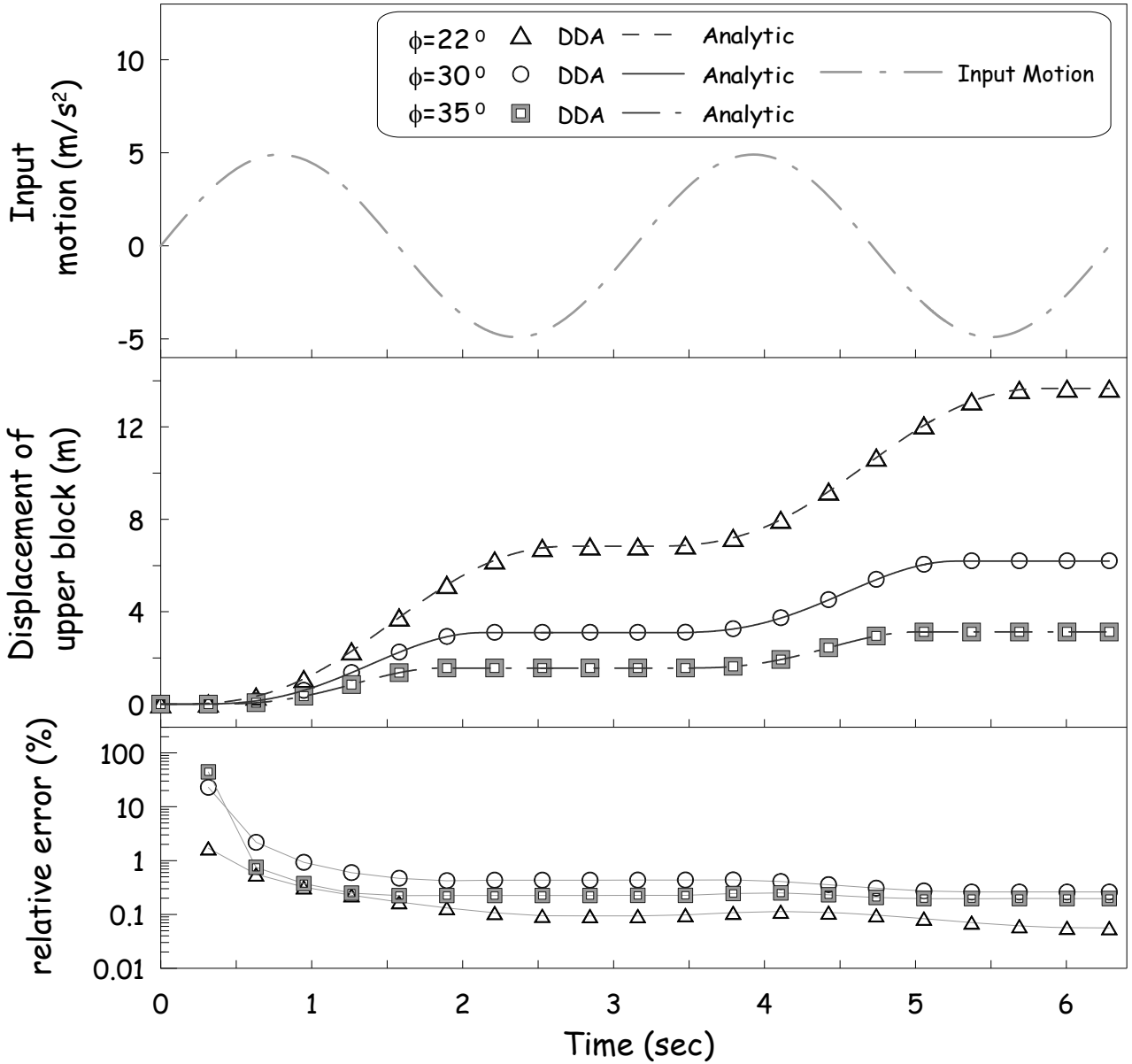


DISCONTINUOUS DEFORMATION ANALYSIS: VERIFICATIONS AND VALIDATIONS

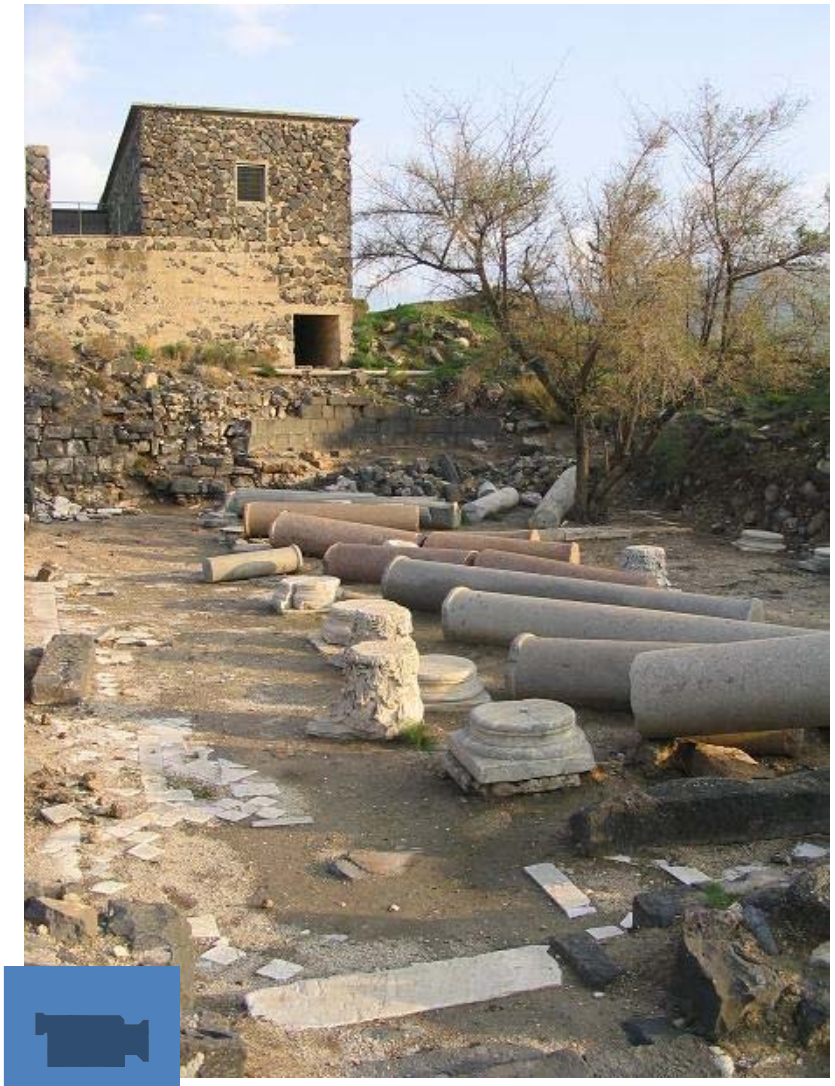
Single Face Sliding

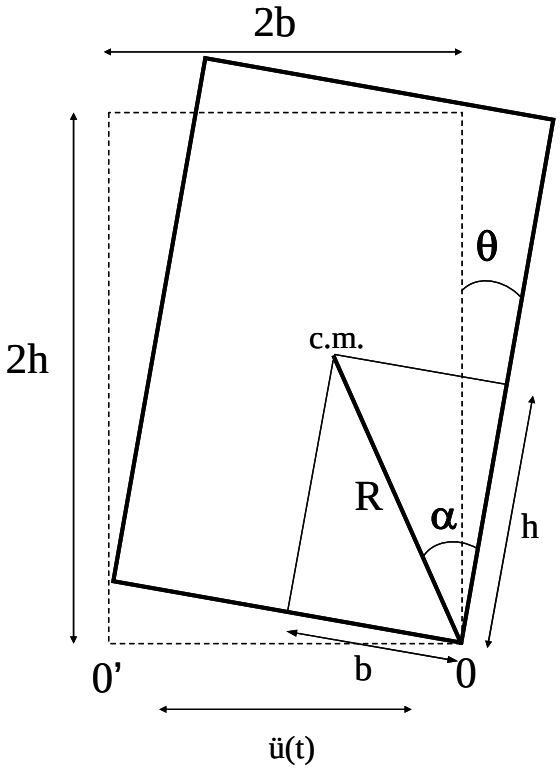


Dynamic sliding under gravitational load only was studied originally by Mary McLaughlin in her PhD thesis (1996) (Berkeley) and consequent publications with Sitar and Doolin 2004 - 2006. Sinusoidal input first studied by Hatzor and Feintuch (2001), *IJRMMS*. Improved 2D solution presented by Kamai and Hatzor (2008), *NAG*. Ning and Zhao (2012), *NAG* (From NTU) recently published a very detailed study of this problem.



Dynamic Block Rocking

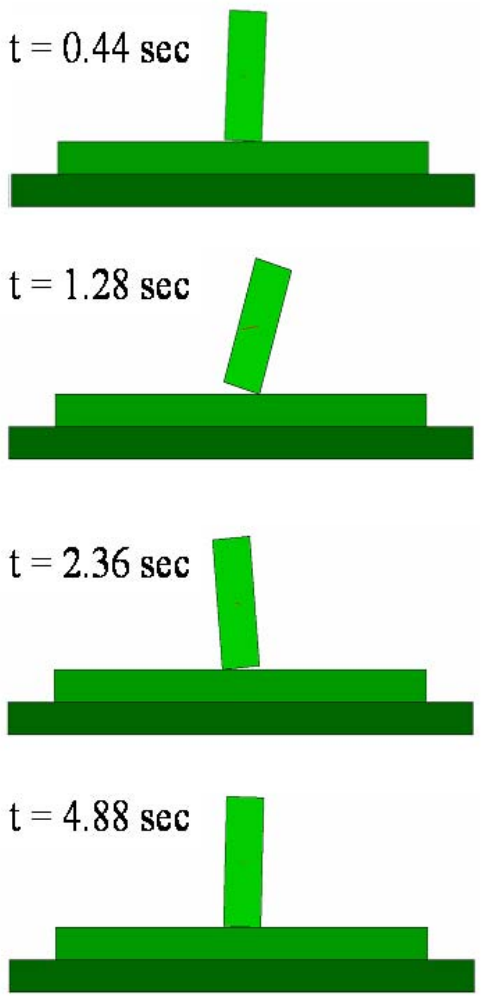


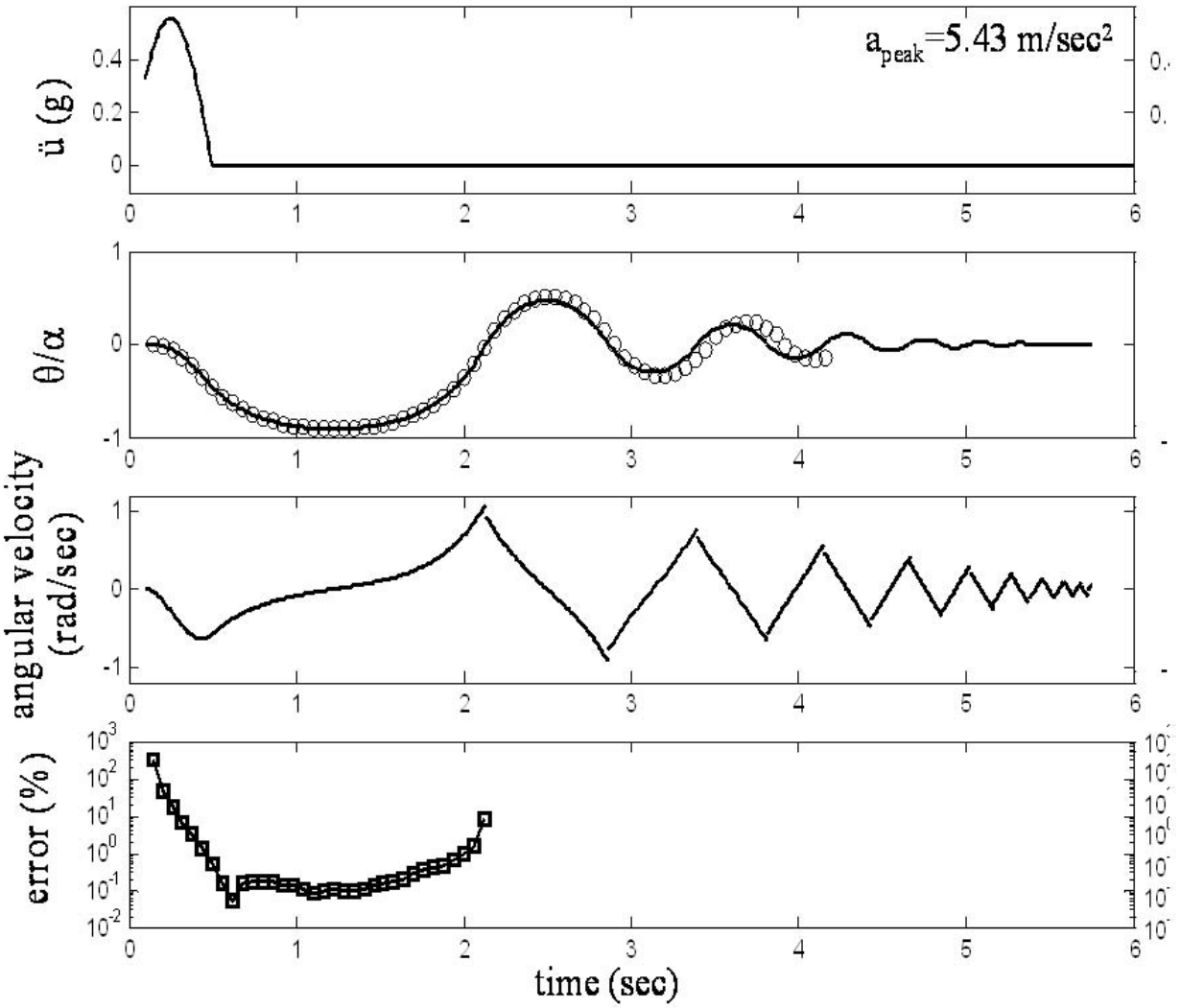


Analytical solution proposed by:
Makris and Roussos (2000), *Geotechnique.*

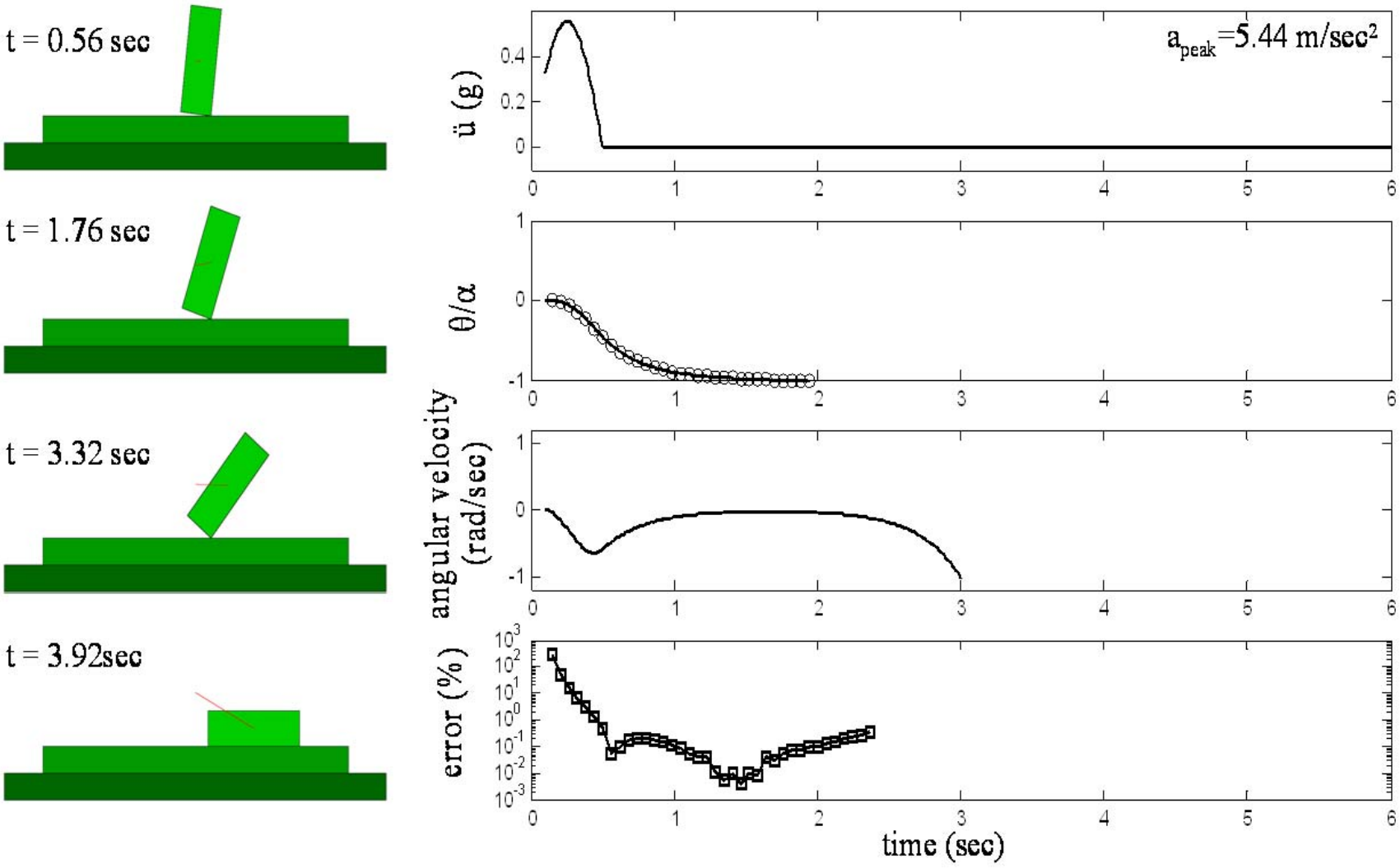
DDA validation with applications:
Yagoda-Biran and Hatzor (2010), *EESD*.

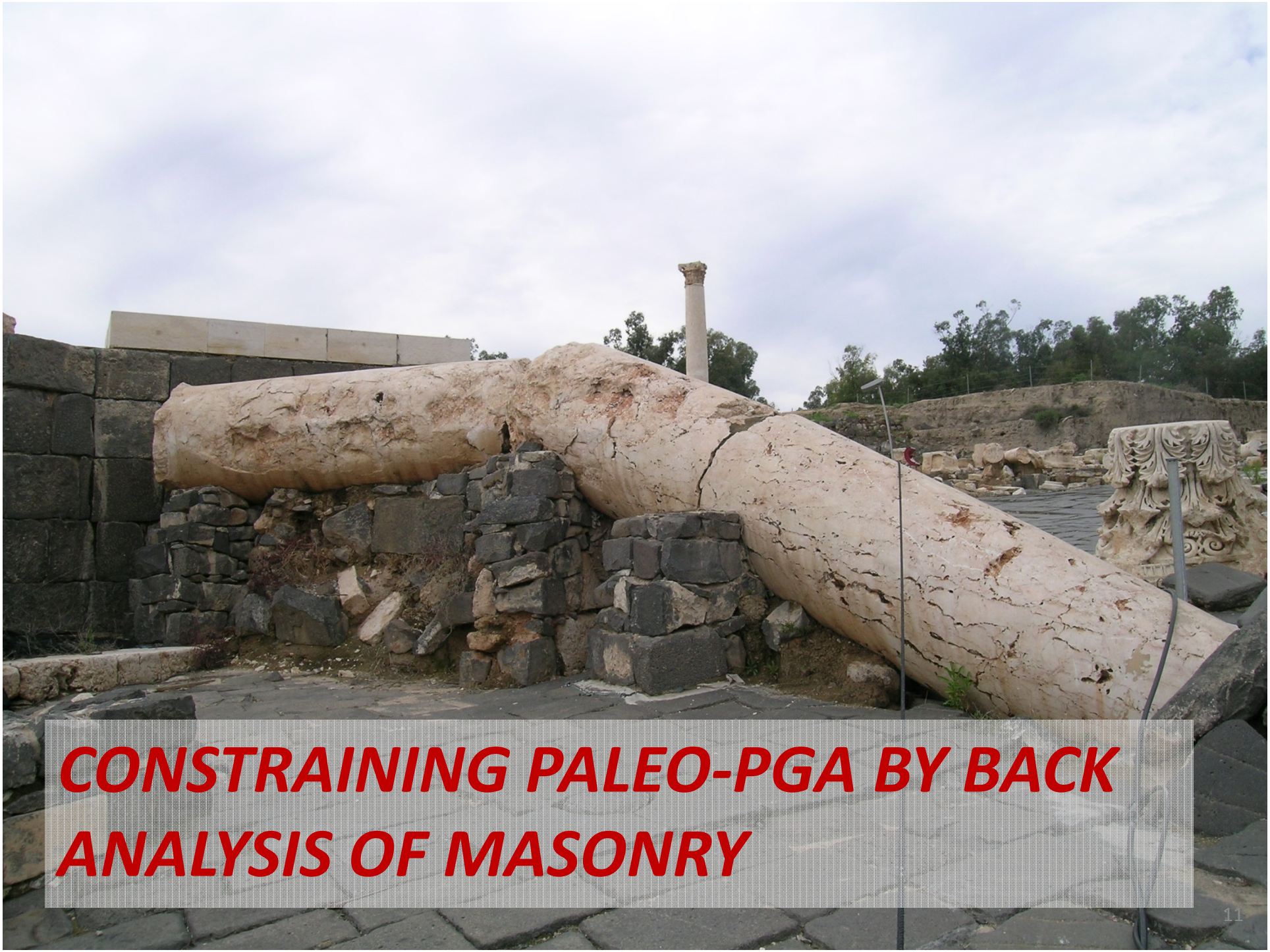
a_{peak} slightly lower than *PGA* required for toppling





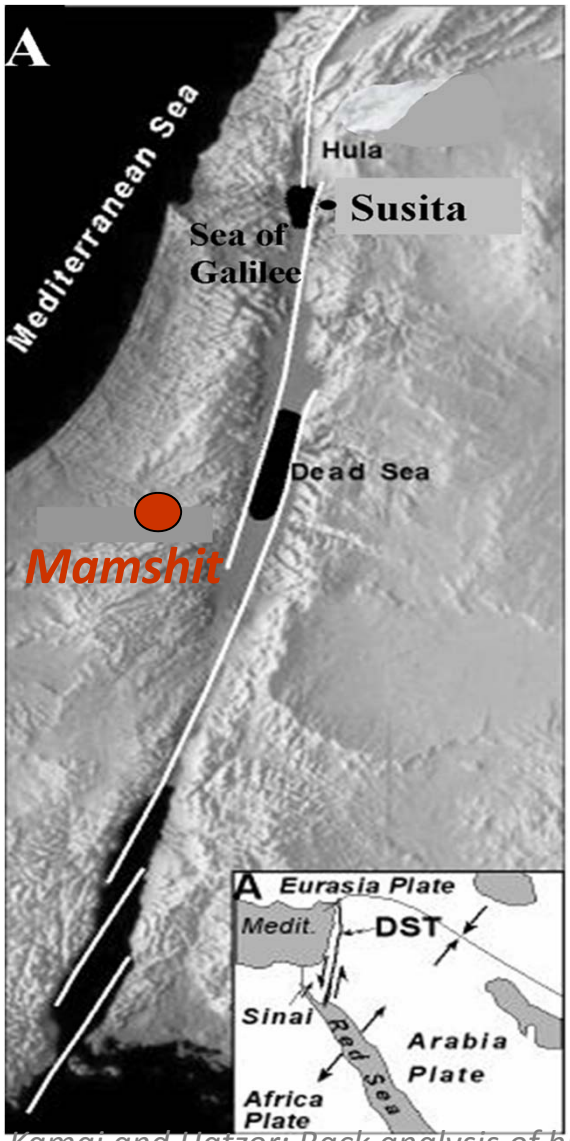
a_{peak} slightly higher than *PGA* required for toppling





CONSTRAINING PALEO-PGA BY BACK ANALYSIS OF MASONRY

Mamshit - Nabatean to Byzantine Period



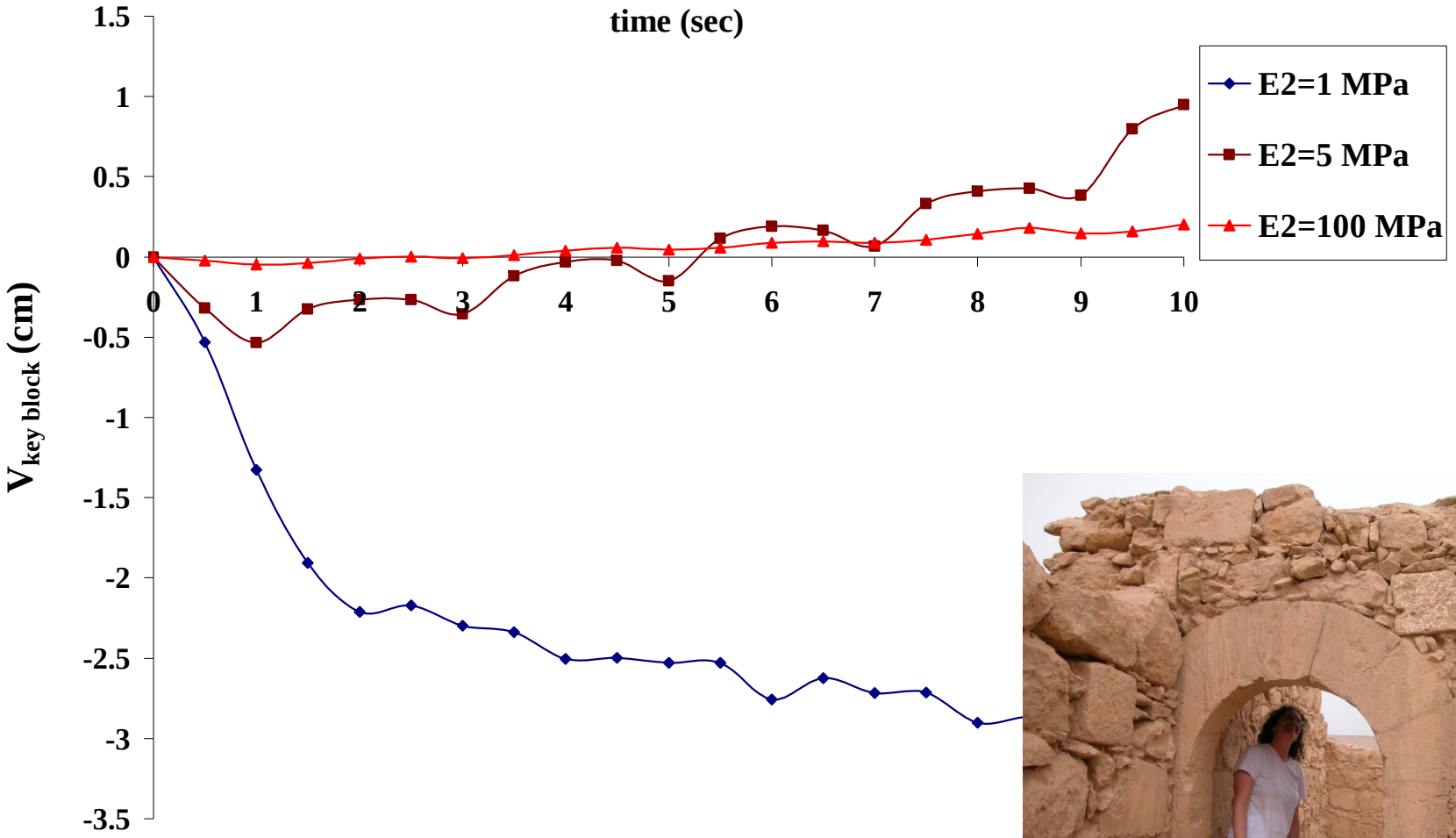
Kamai and Hatzor, 2008. *NAG.*

Generation of DDA mesh

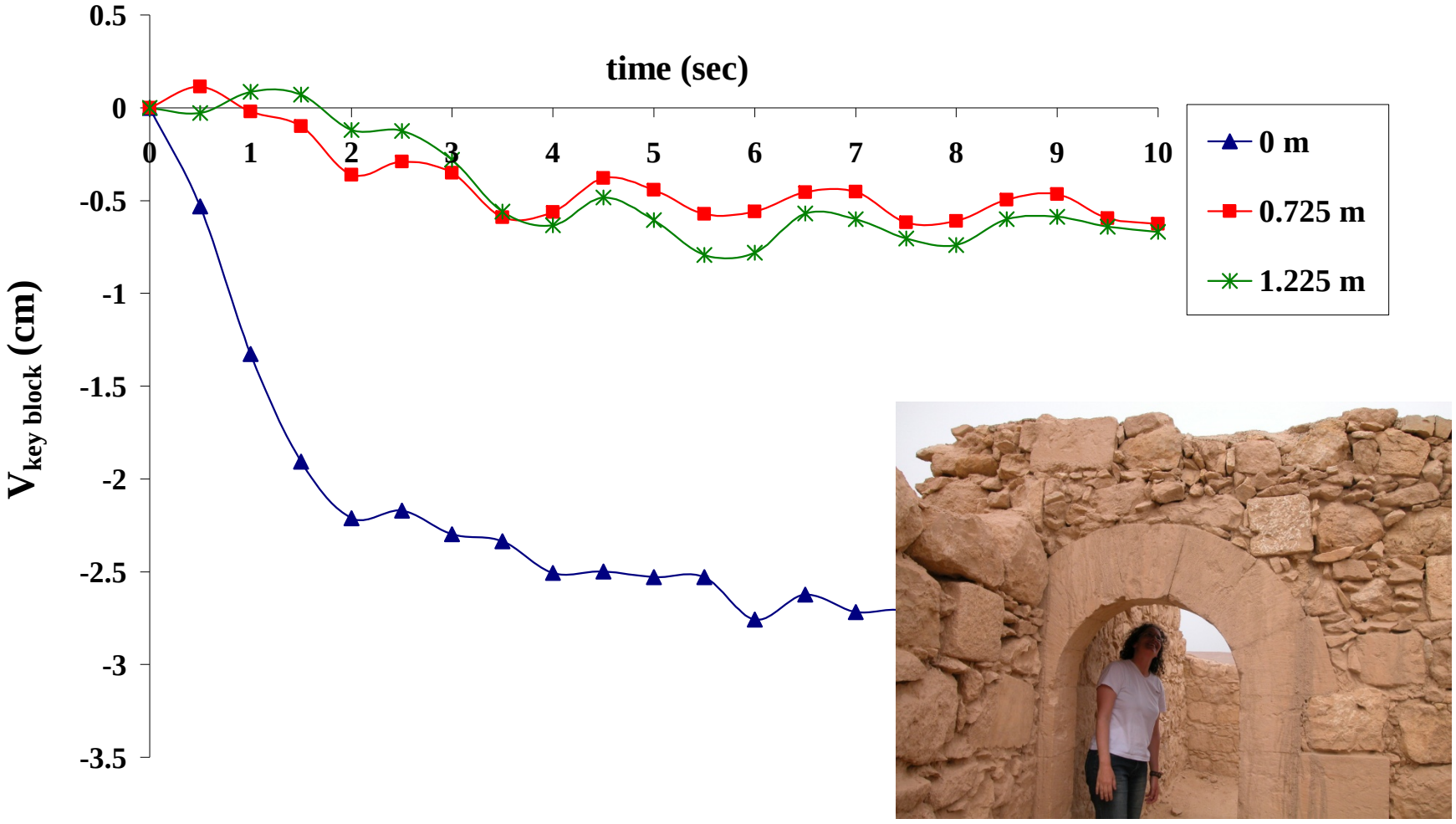
The model:

- heterogeneous wall - material lines define different parameters for arch and wall
- fixed points in foundation block
- measurement point in keystone

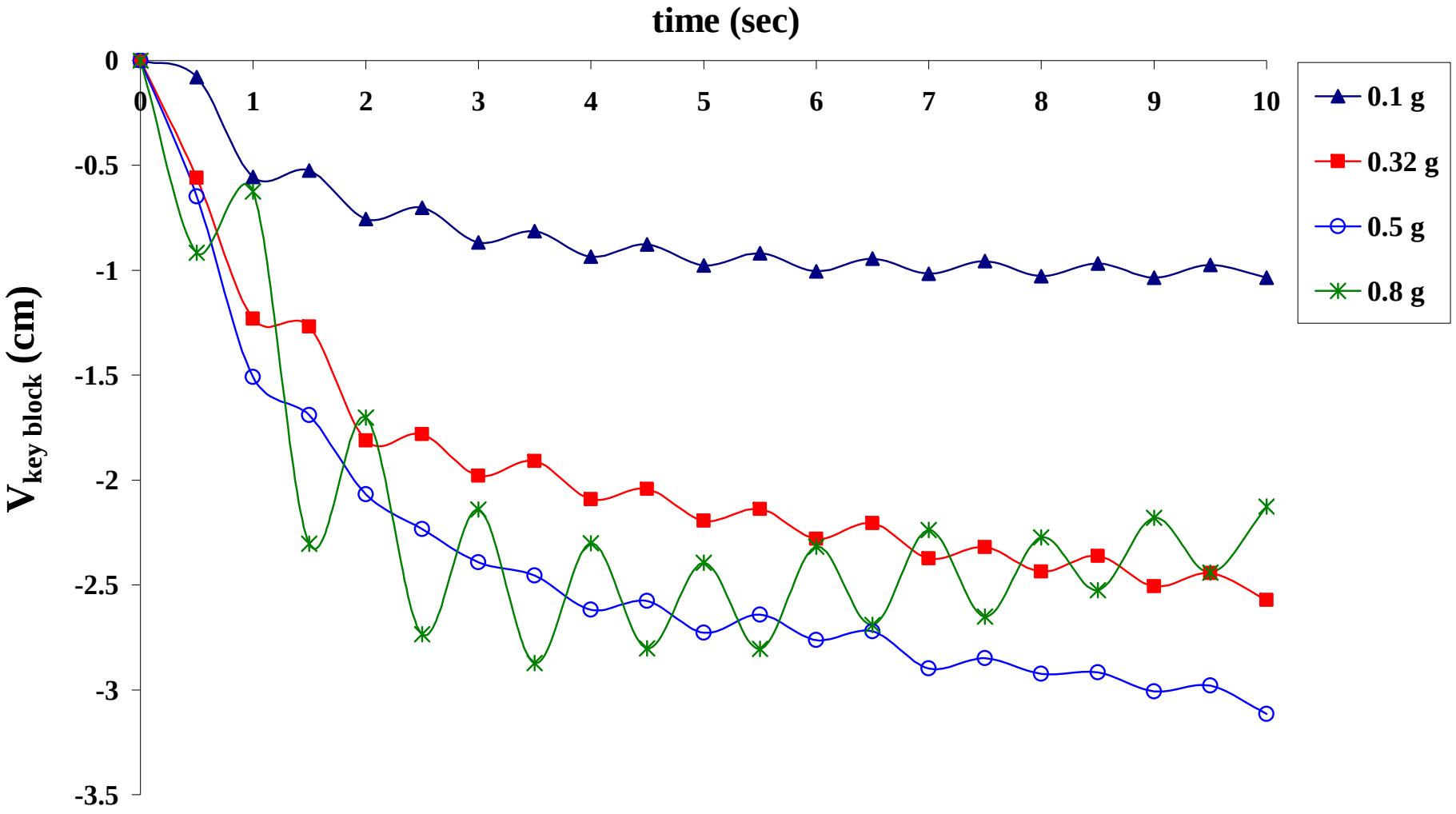
Influence of wall stiffness
f = 1.5 Hz, A = 0.5 g, E_{arch}=17 GPa



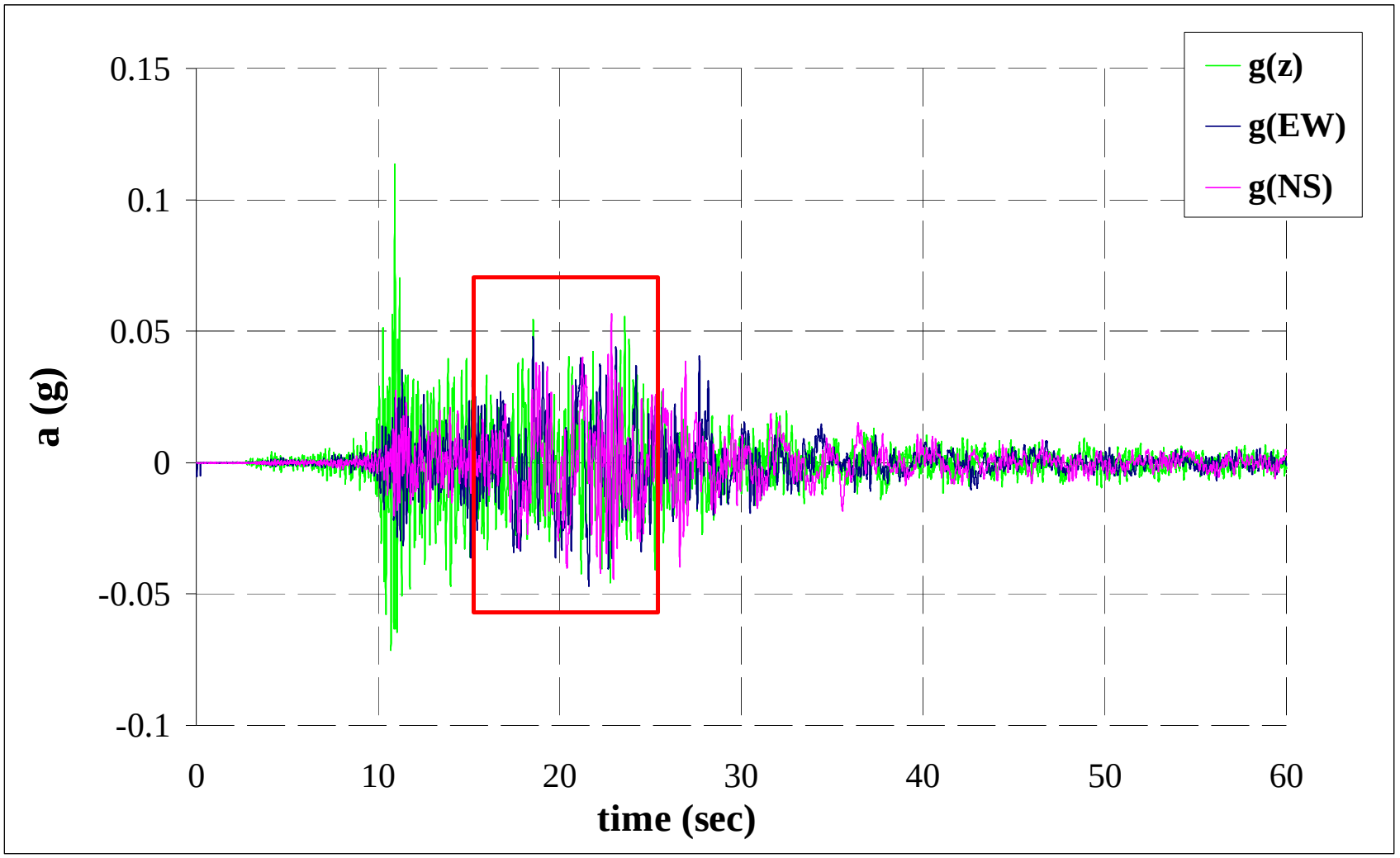
Influence of overburden (h)
f = 1.5 Hz, A = 0.5 g



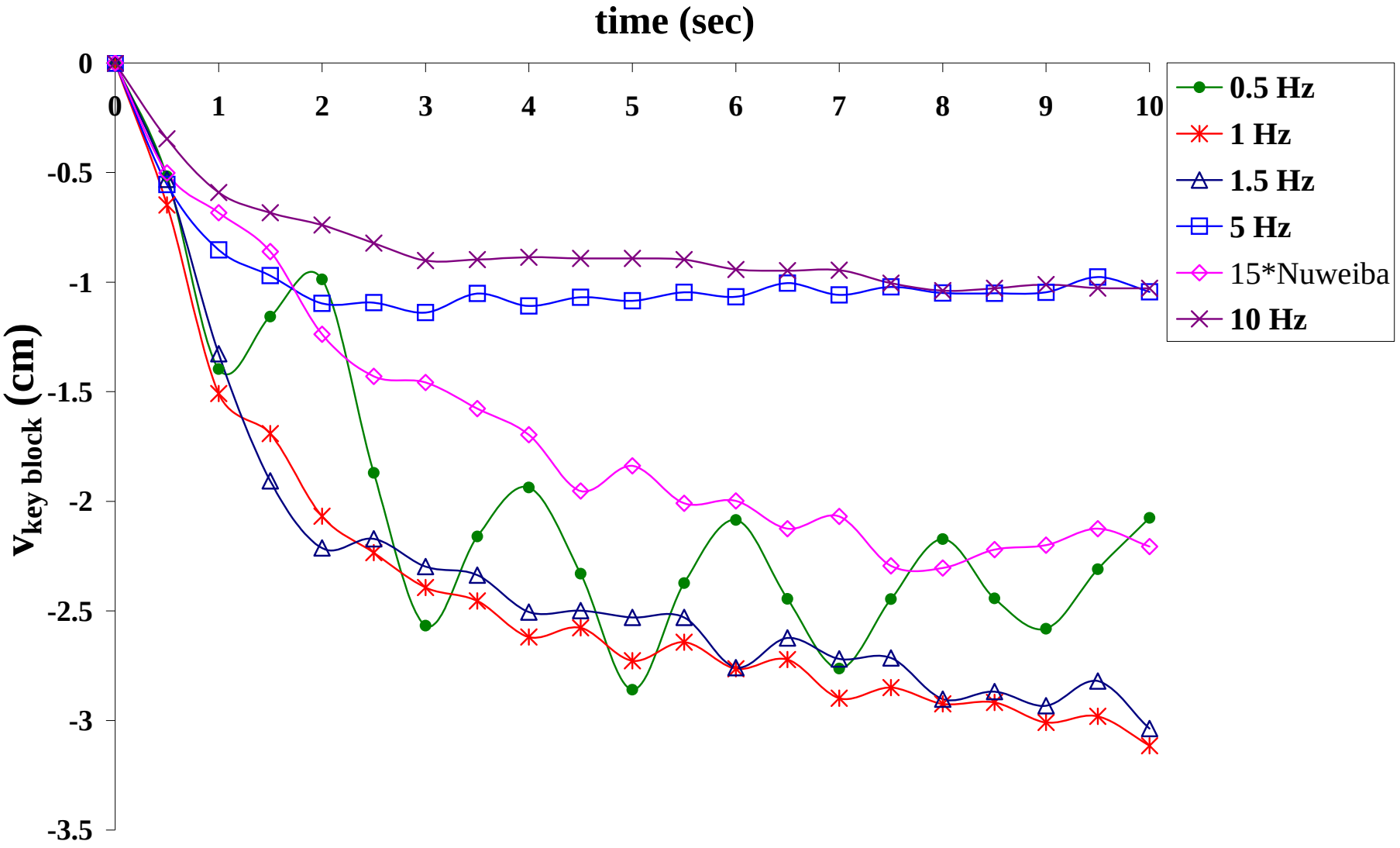
Influence of input motion amplitude (A)
f = 1 Hz



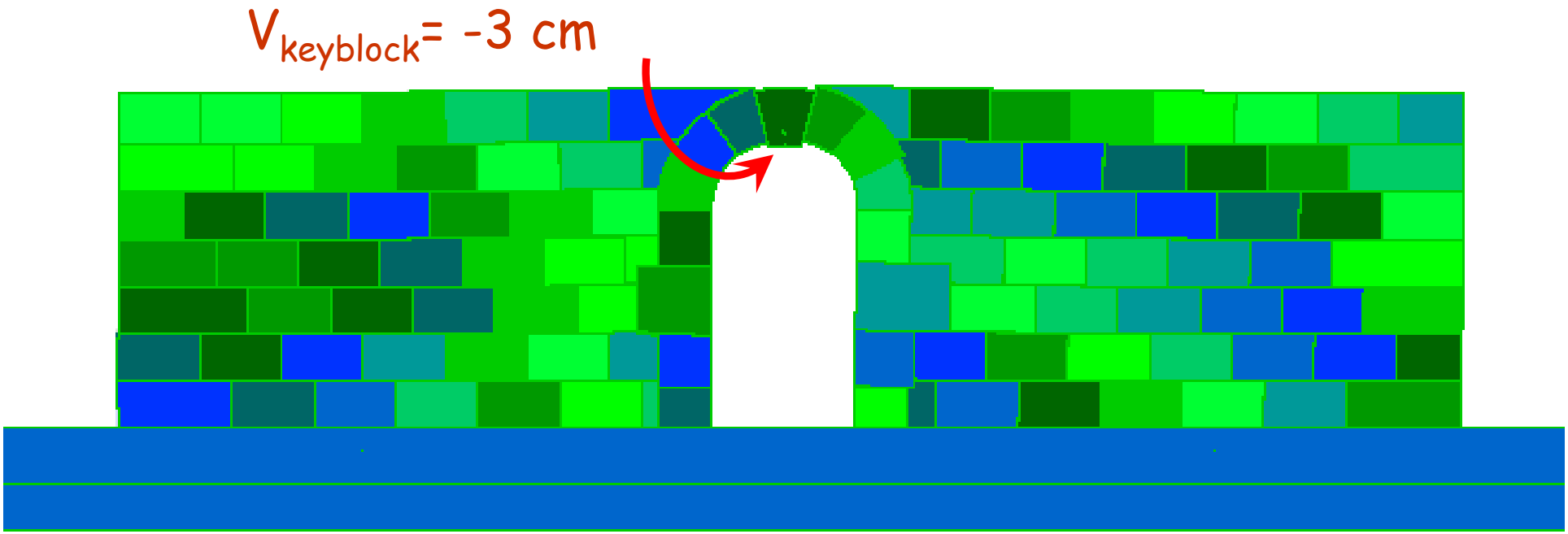
Real Input motion, the M = 7.1 Nuweiba earthquake



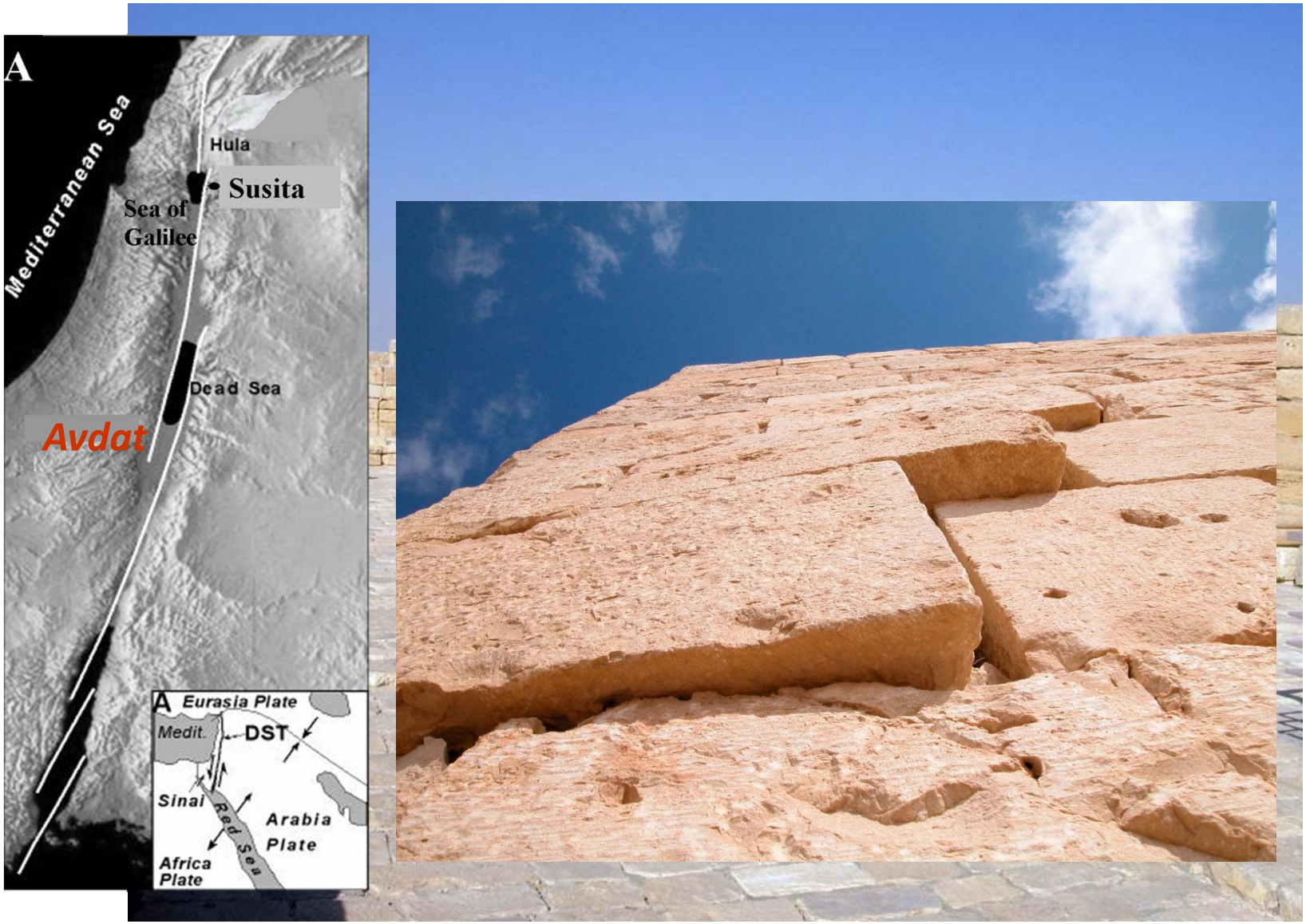
Influence of input frequency (*f*)
A = 0.5 *g*



Our Best Estimate Motion Parameters: Duration ~ 10 sec., f =1.5 Hz, a_{peak} = 0.5 g

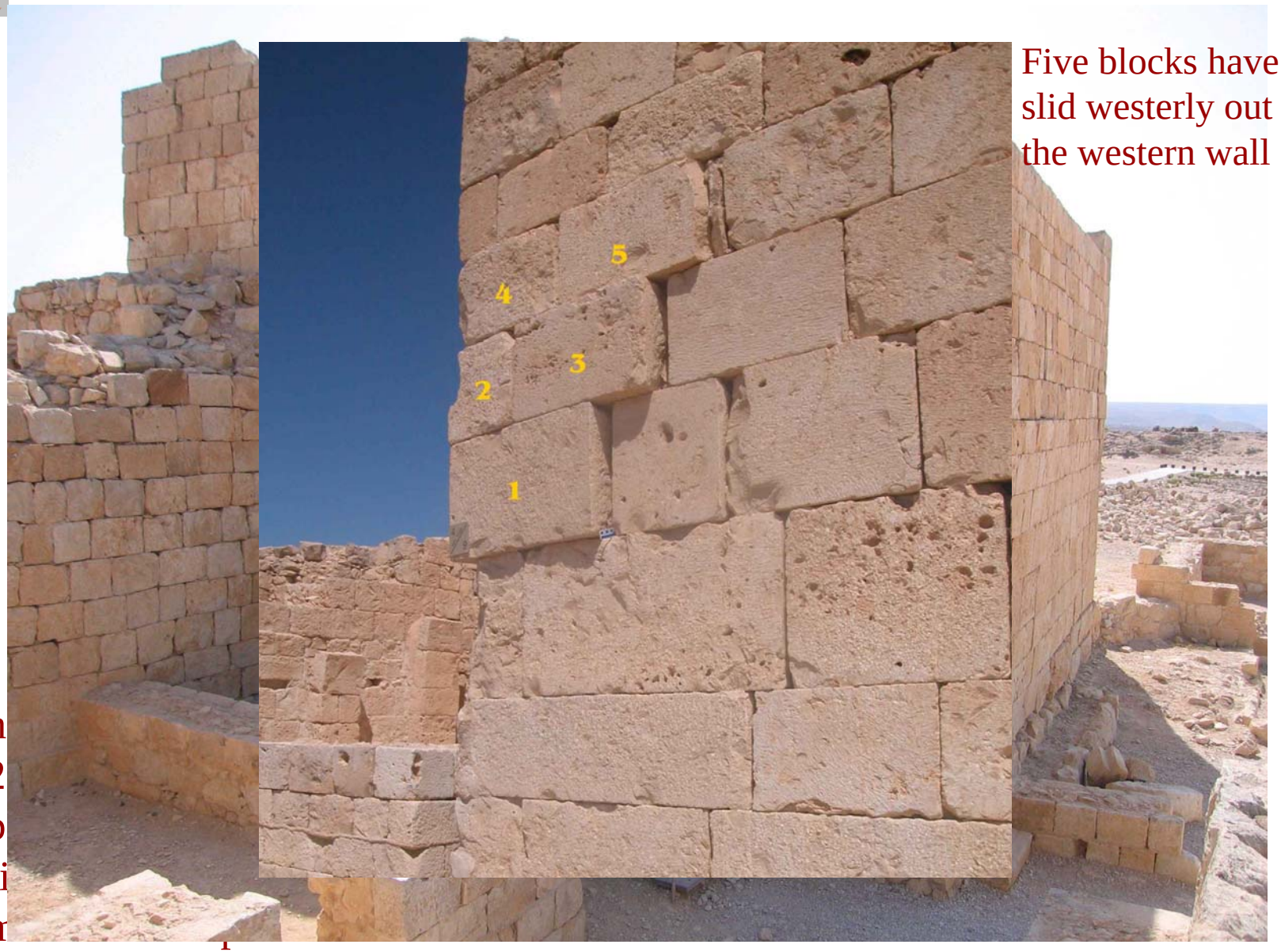


Avdat – Nabatean to Byzantine Period



Kamai and Hatzor: Back analysis of historic masonry structures. January 20th, 2014, Tower of David, Jerusalem.

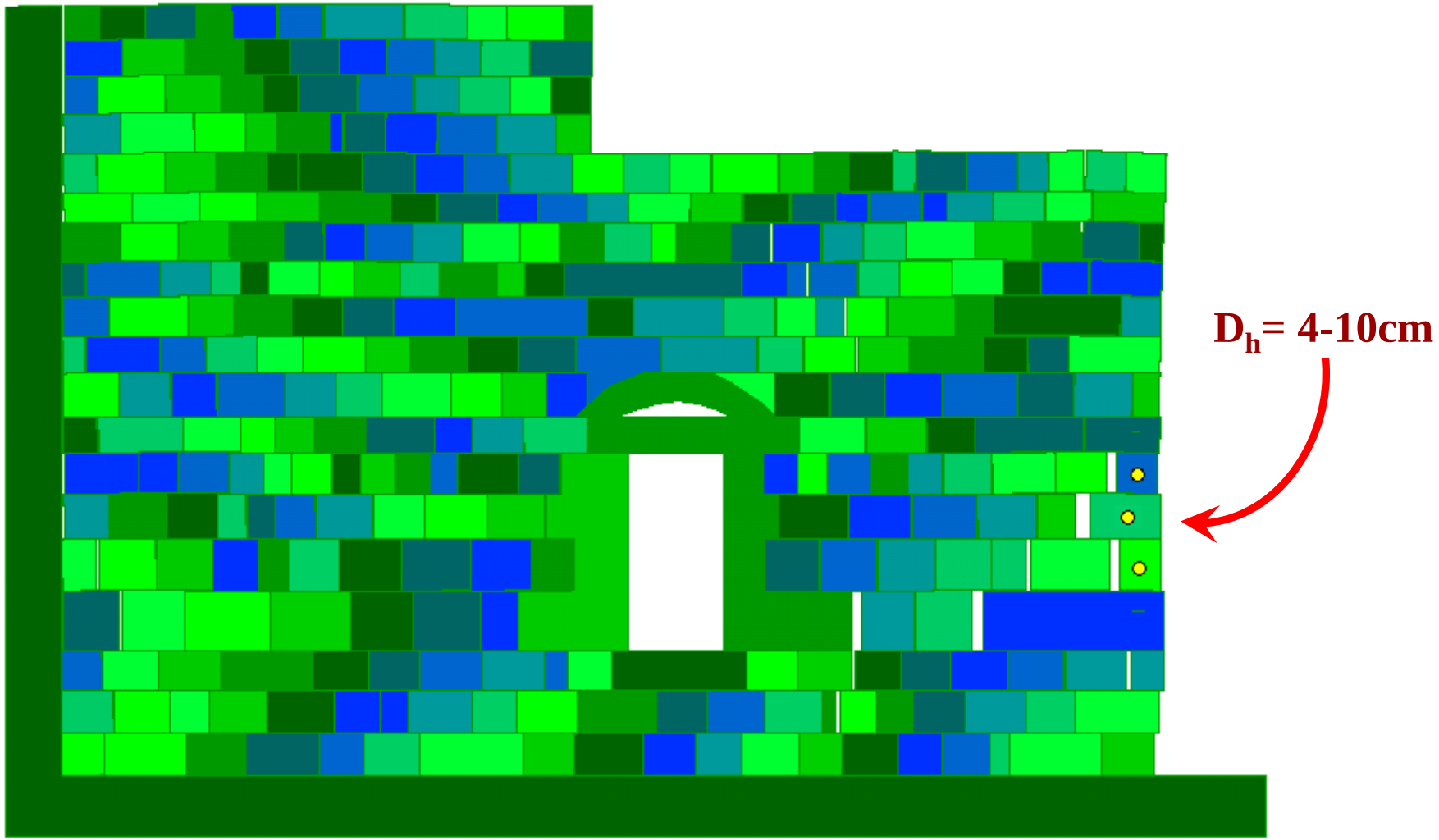
Displacement of 5 blocks from wall



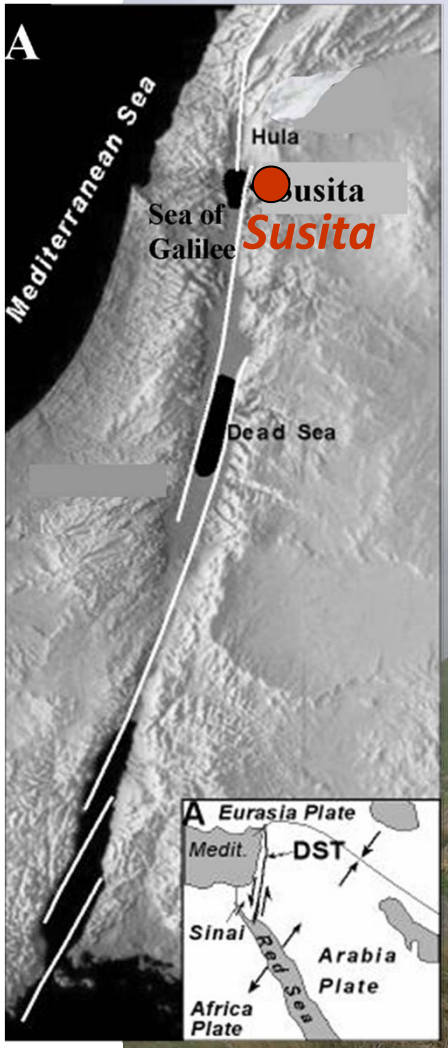
Five blocks have slid westerly out of the western wall

Th
- 2
- b
- fi
- m

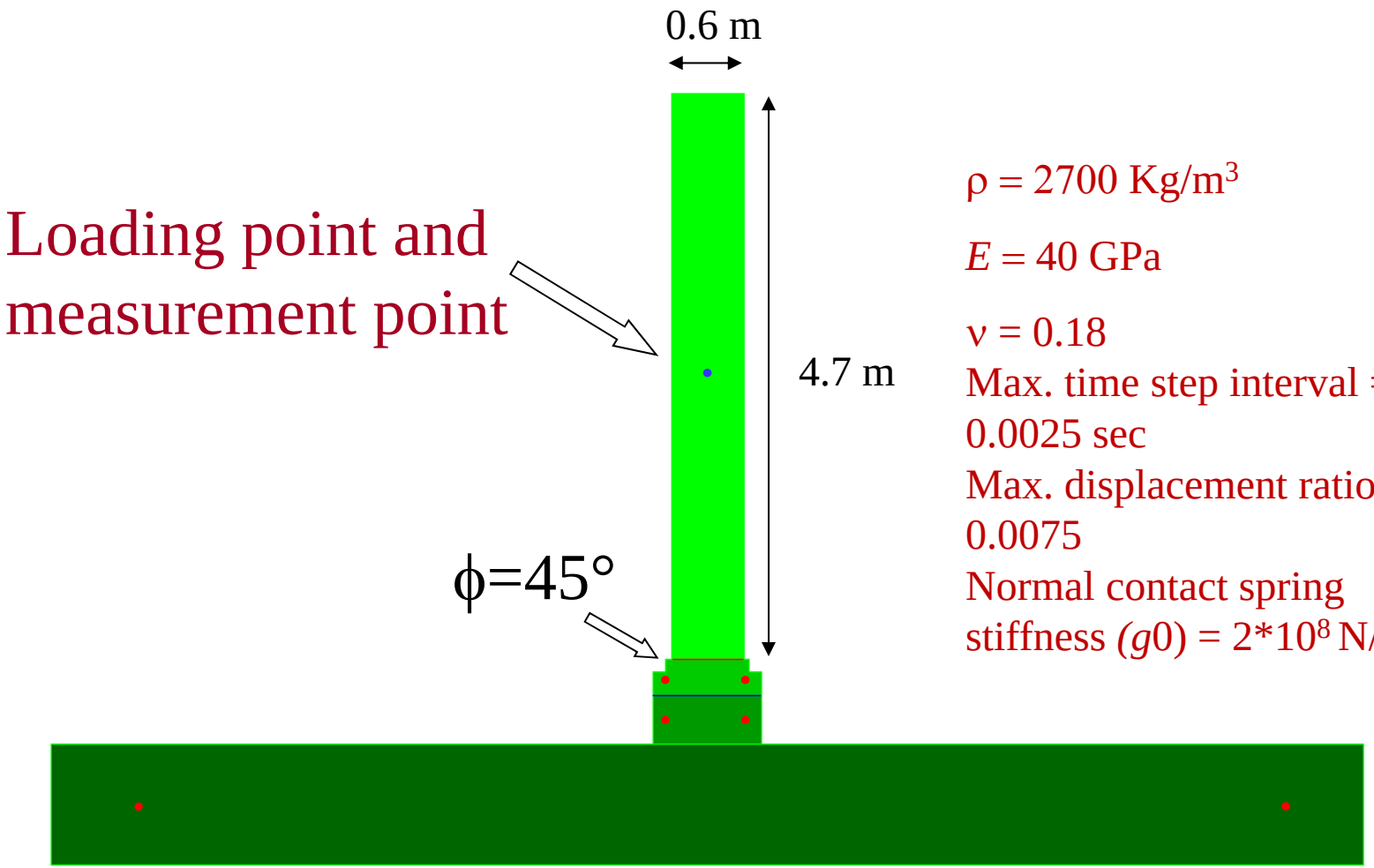
Best fit to field evidence after 10sec obtained with: f =3 Hz, A = 1g



Susita - Byzantine Period



DDA model for free standing column



$\rho = 2700$ Kg/m^3

$E = 40$ GPa

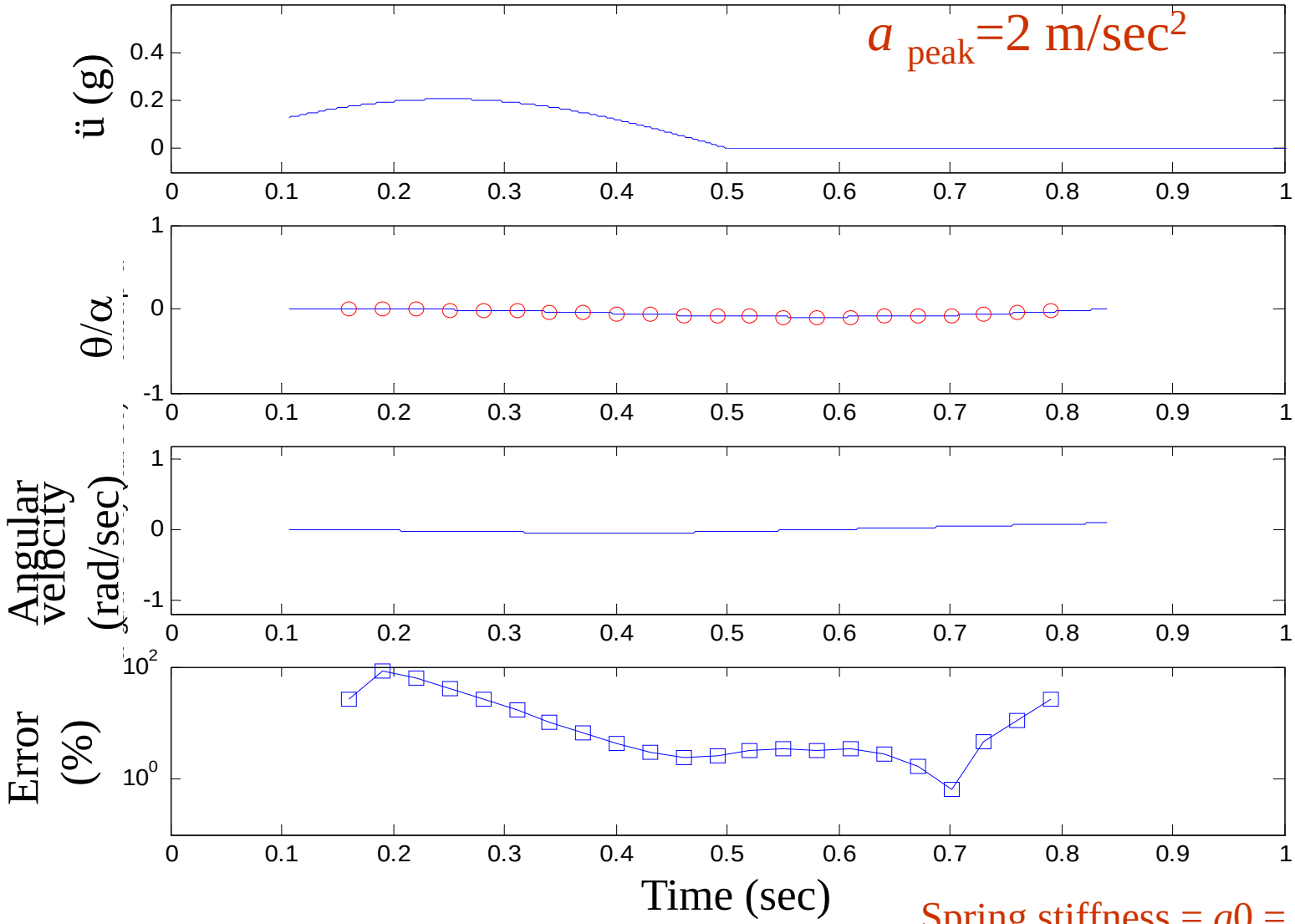
$\nu = 0.18$

Max. time step interval = 0.0025 sec

Max. displacement ratio = 0.0075

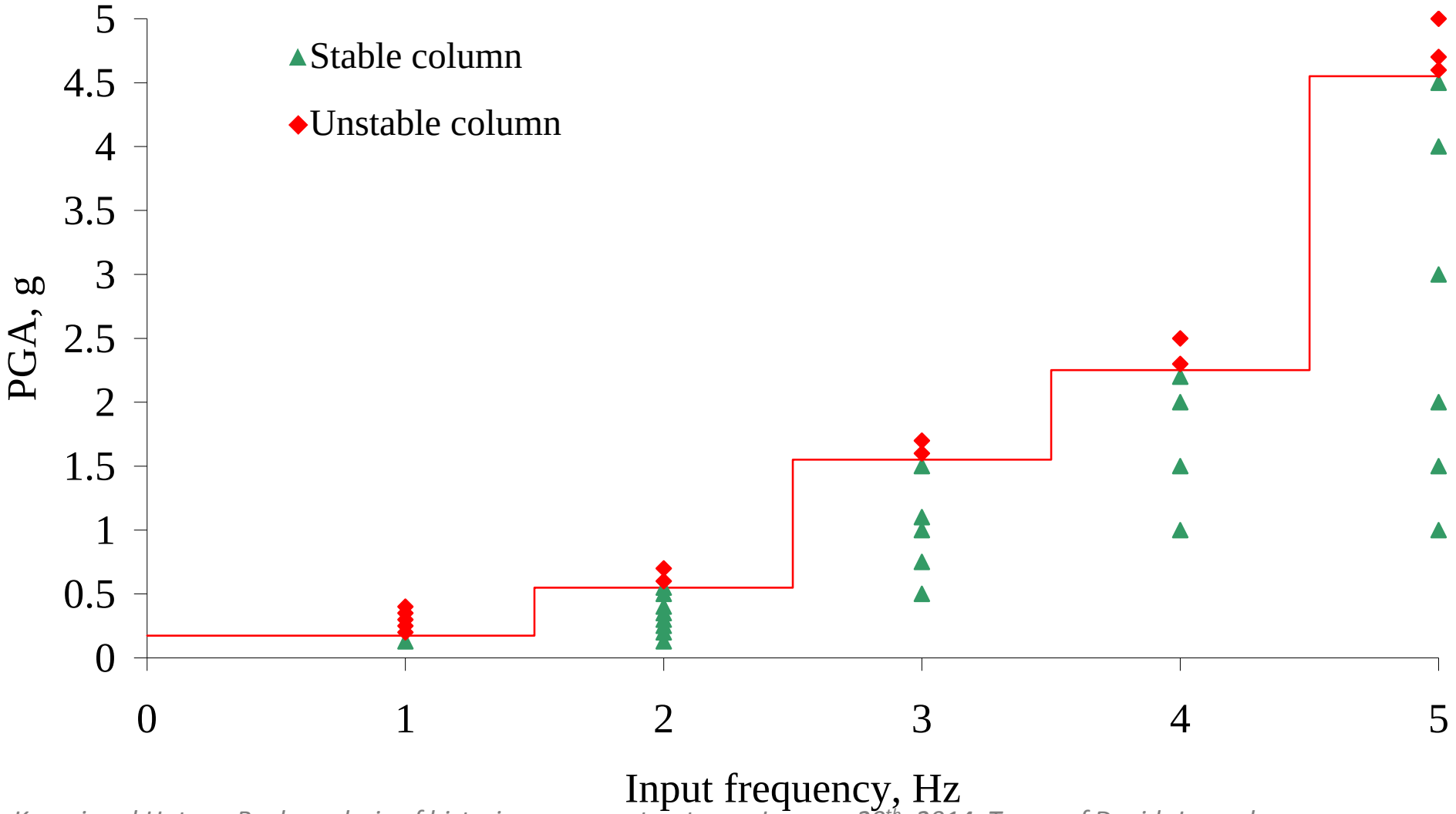
Normal contact spring stiffness ($g0$) = $2*10^8$ N/m

Optimizing contact spring stiffness

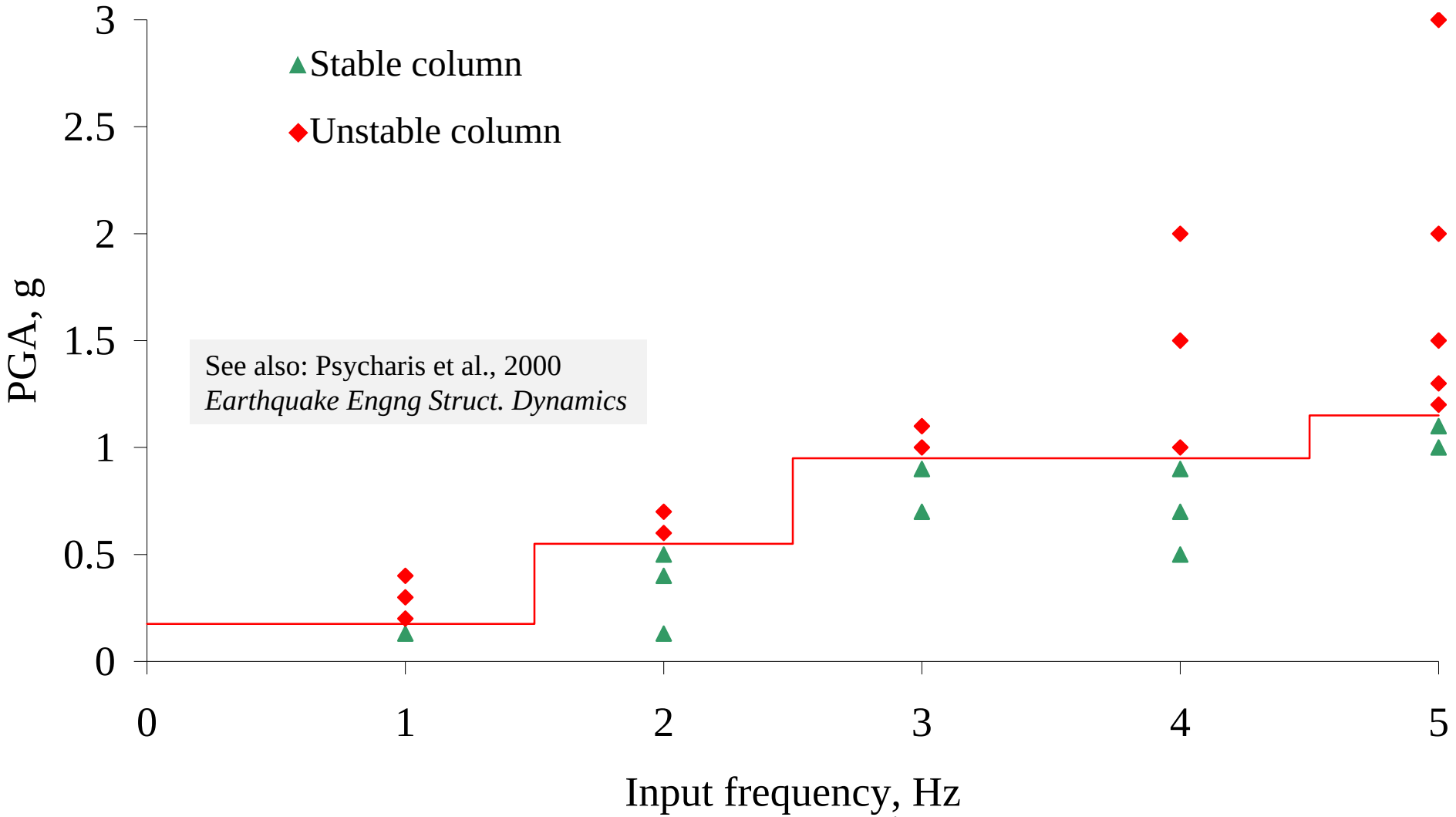


Spring stiffness = $g0$ = 2*10^8 N/m

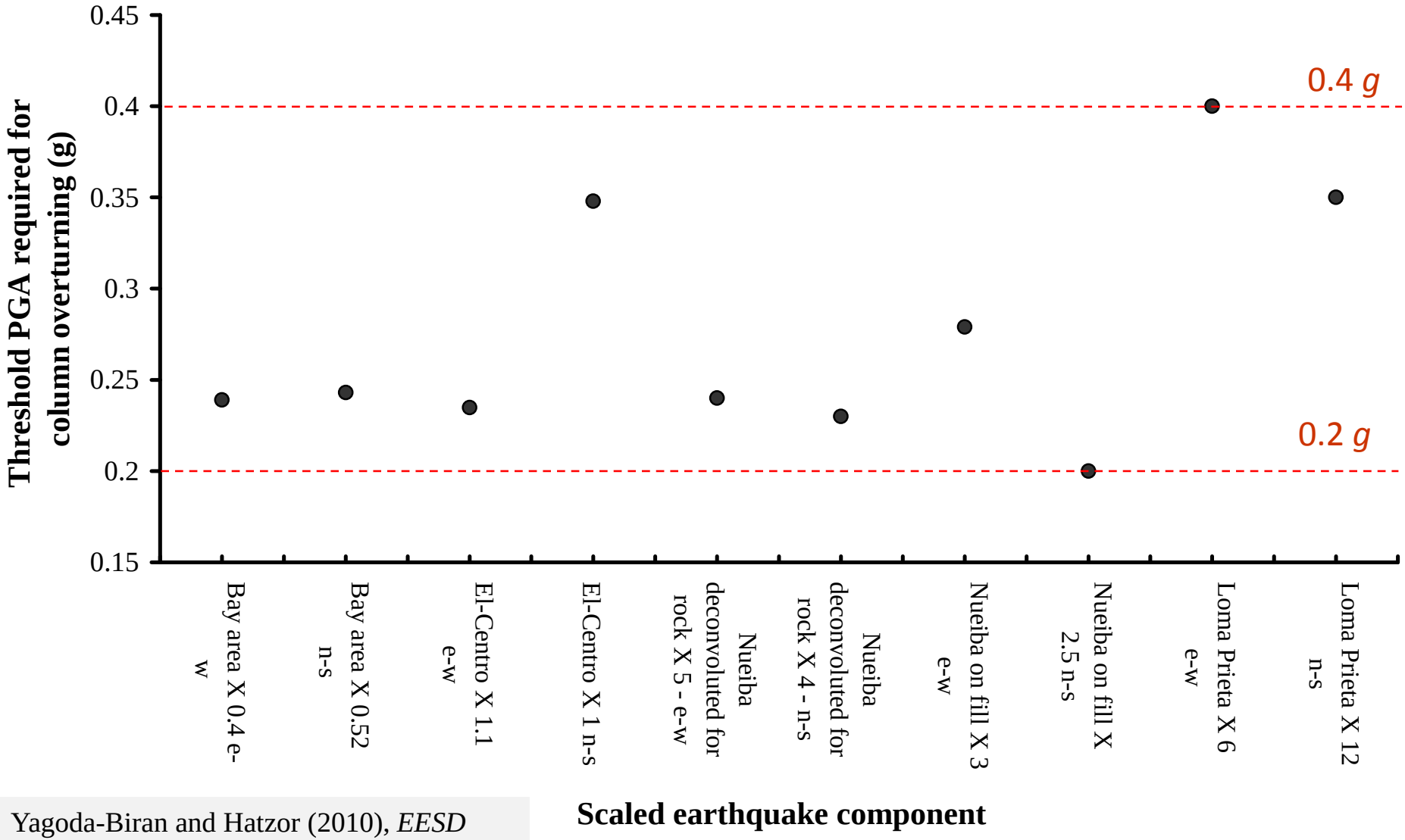
Frequency dependent PGA results
1 sinusoidal input cycle



Frequency dependent PGA results
3 sinusoidal input cycles

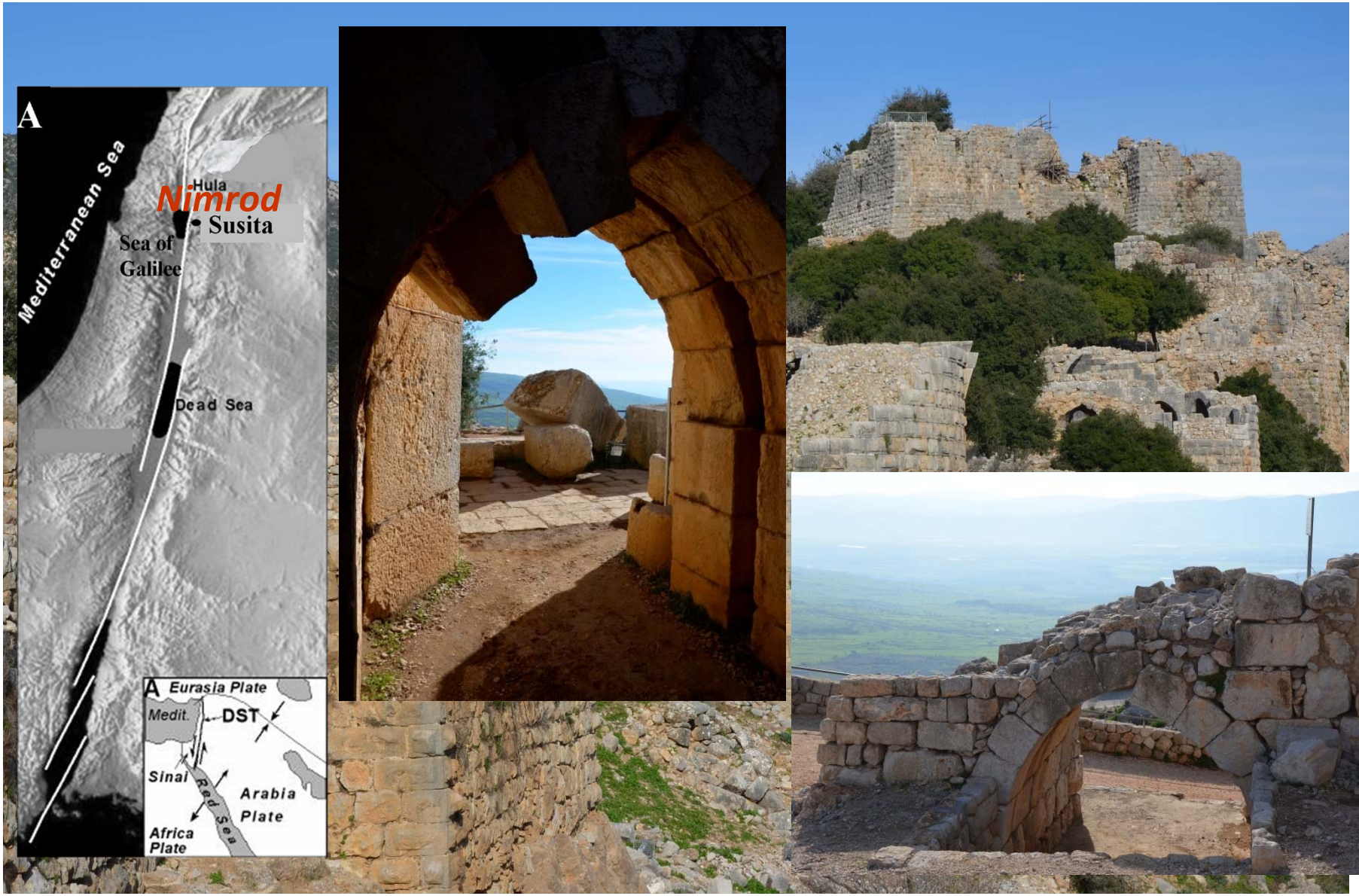


Constraining paleo-seismic PGA by application of true earthquake records



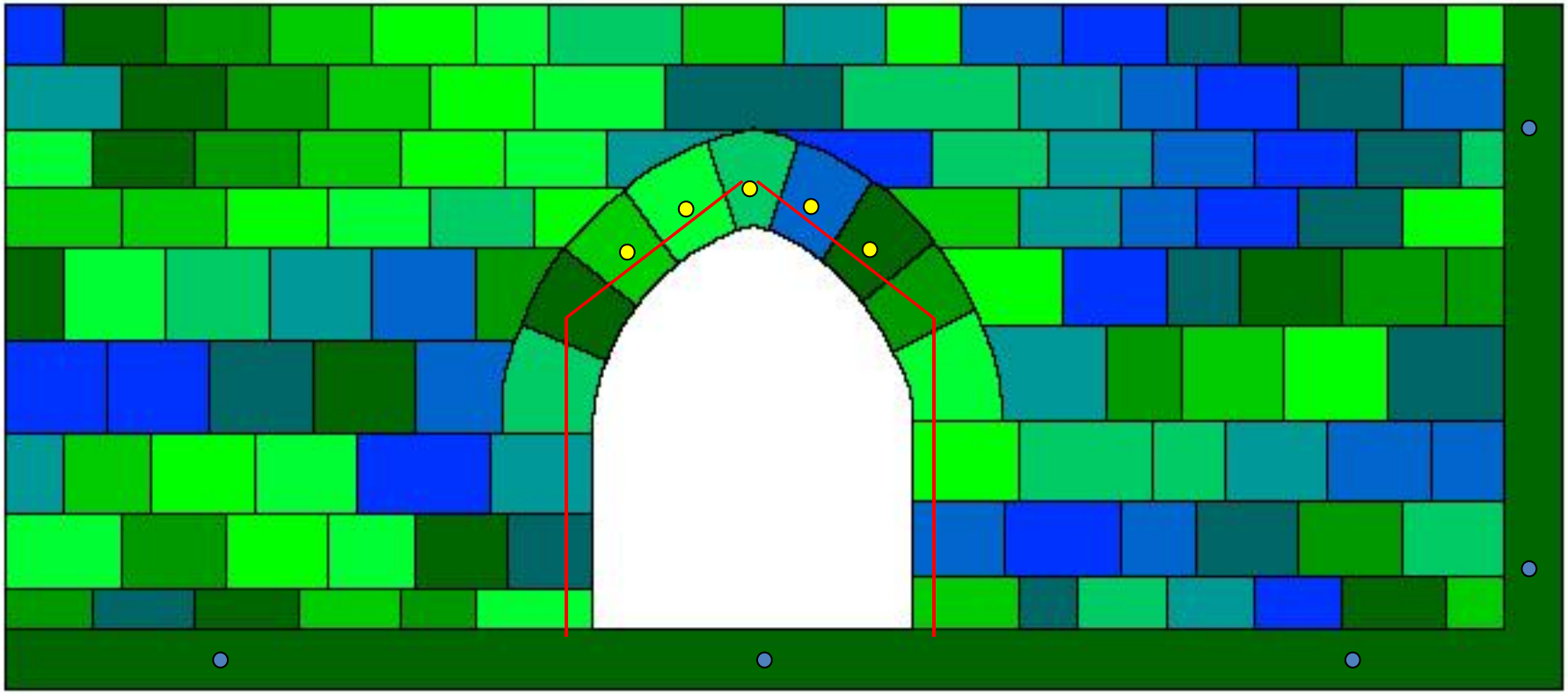
Yagoda-Biran and Hatzor (2010), *EESD*

Nimrod Fortress: Ayyubid - Crusaders Period



Asymmetric block displacement in arch

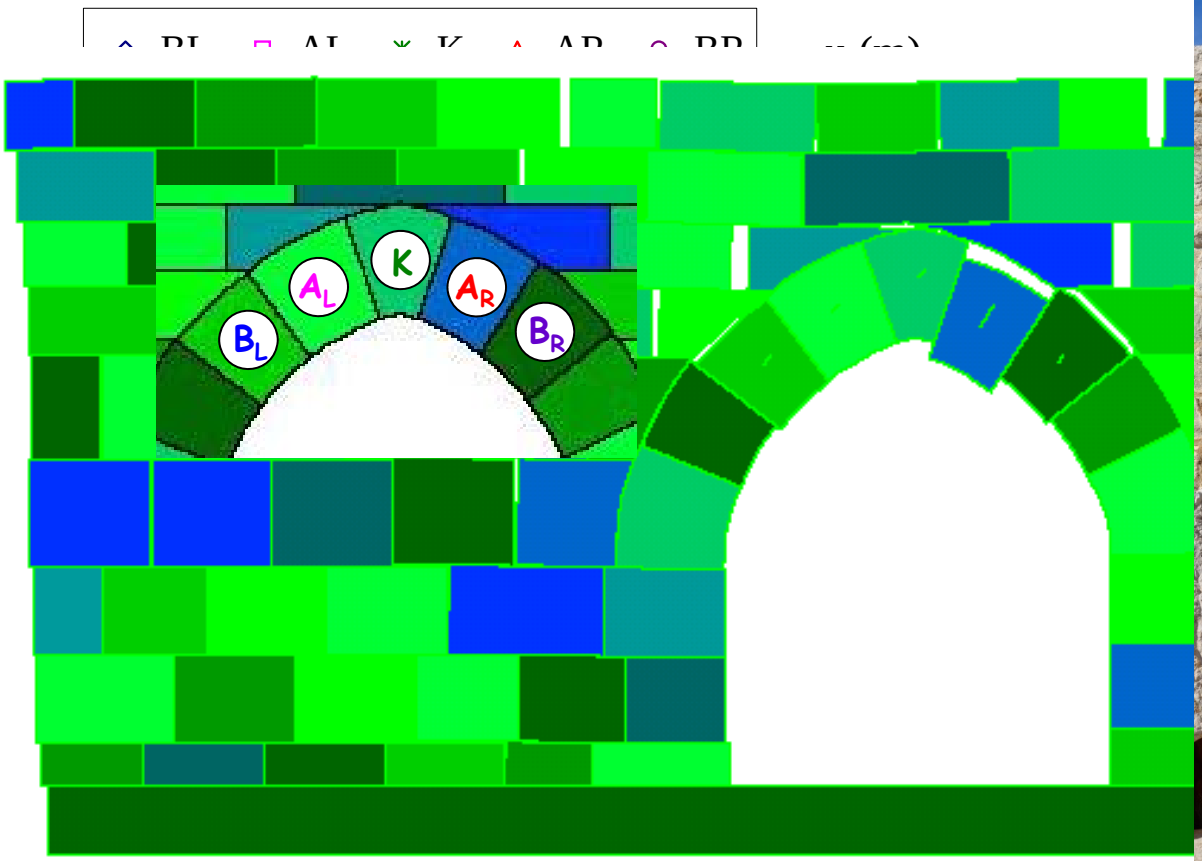
DDA Model



The model:

- boundary block on right represents geographical asymmetries
- fixed points in boundary block
- measurement points in five of the arch stones

‘Best fit’ to field evidence obtained with:
f = 2 Hz , A = 1g , $E_2/E_1 = 10^4$, h > 0 , t = 40 s.



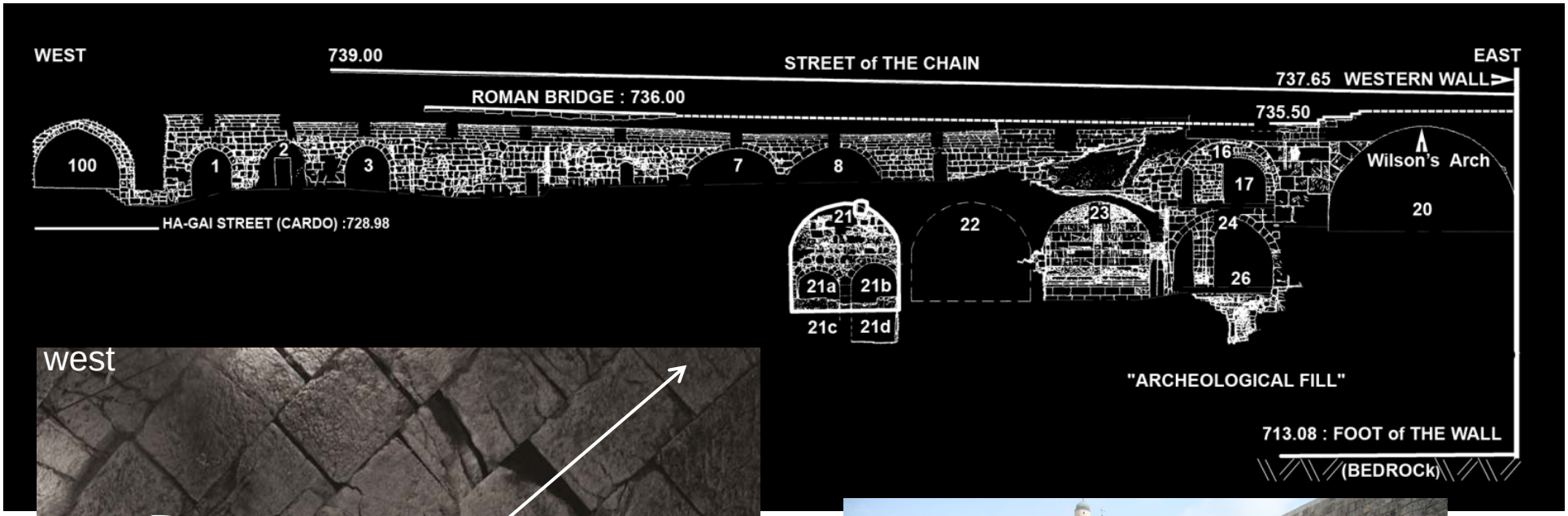
-0.1

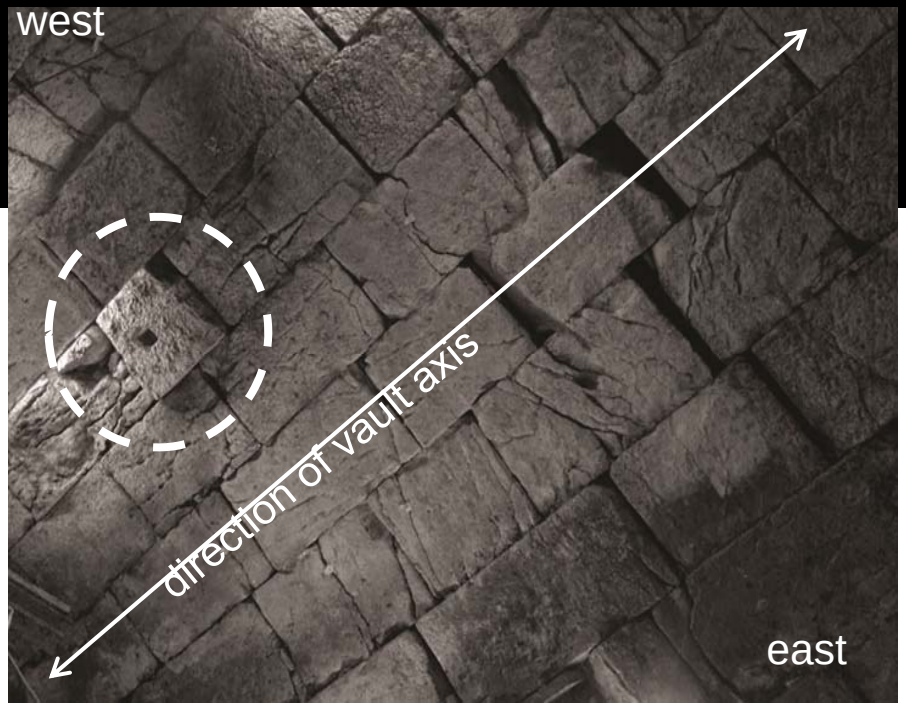
-0.14

Kamai and Hatzor, 2008. *NAG*.

IDENTIFYING ARCHEO-EARTHQUAKES: THE CASE OF THE WESTERN WALL TUNNELS, JERUSALEM

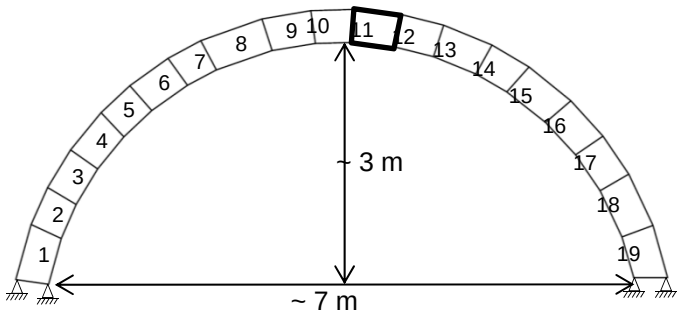
The great causeway discovered in the WWT





Kamai and Hatzor: Back analysis of historic masonry structures. January 20th, 2014, Tower of David, Jerusalem.

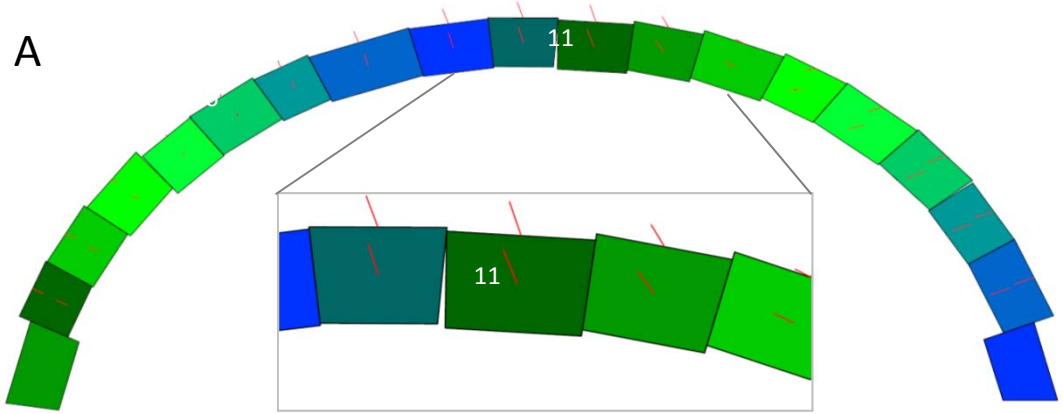
Back analysis of mapped stone displacement



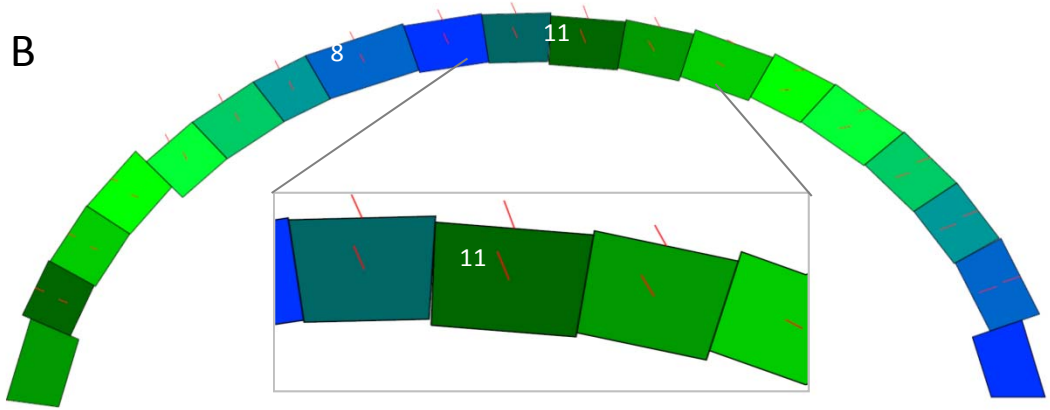
1183 DDA sensitivity analyses changing:

1. Overload conditions: from surficial structure (old) to buried structure (today).
2. Selective overload removal from keystones to simulate local erosive patterns
3. Friction angle of block interfaces
4. PGA of input earthquake (the M=7.1 Nuweiba E.Q.

A



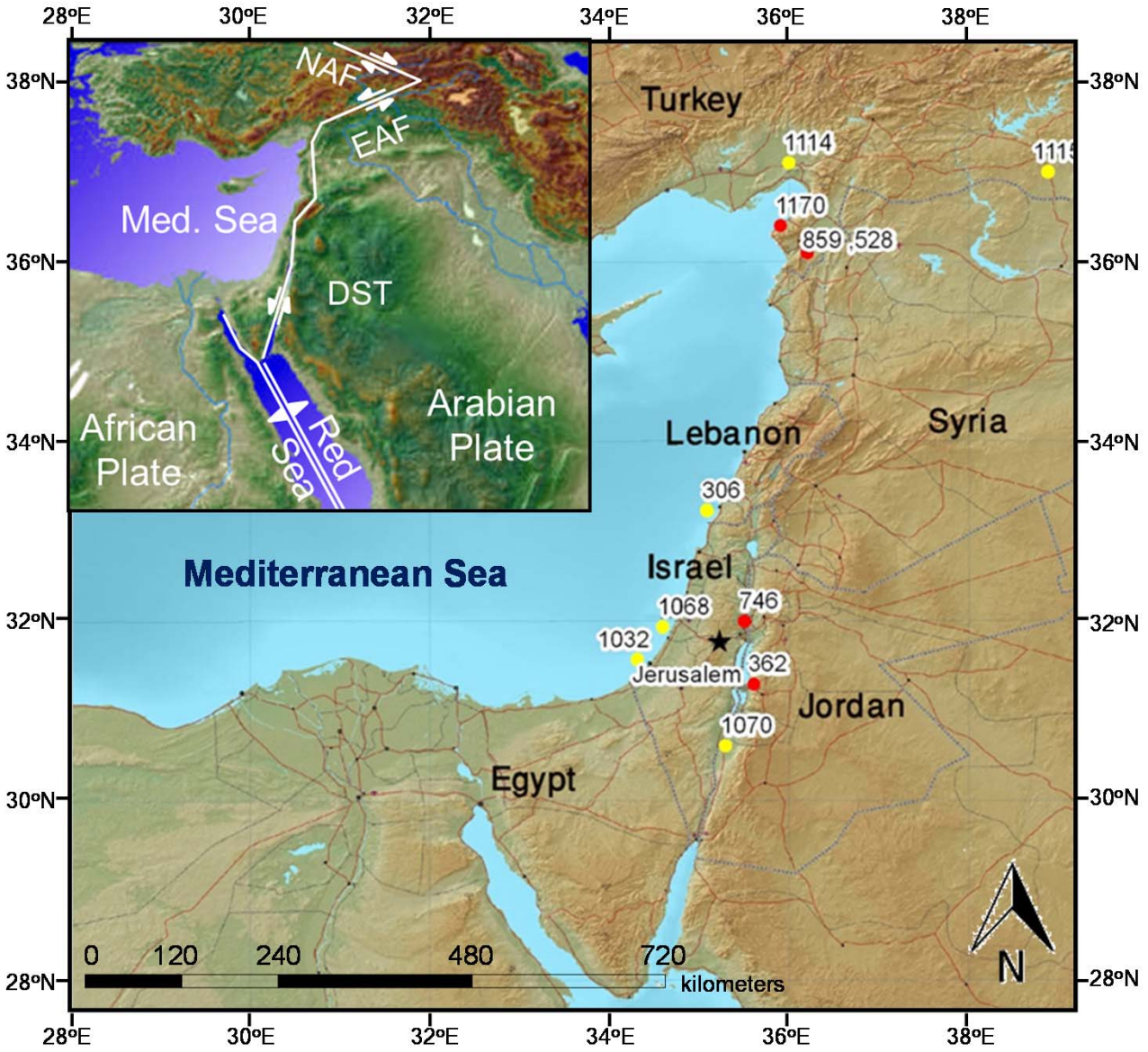
B



Required PGA for best fit solution: 1.5g – 2g

Note: the results are for the *top* of the structure! namely, the obtained threshold PGA includes *both* structural amplifications *and* local site effects.

Candidate Historic Earthquakes



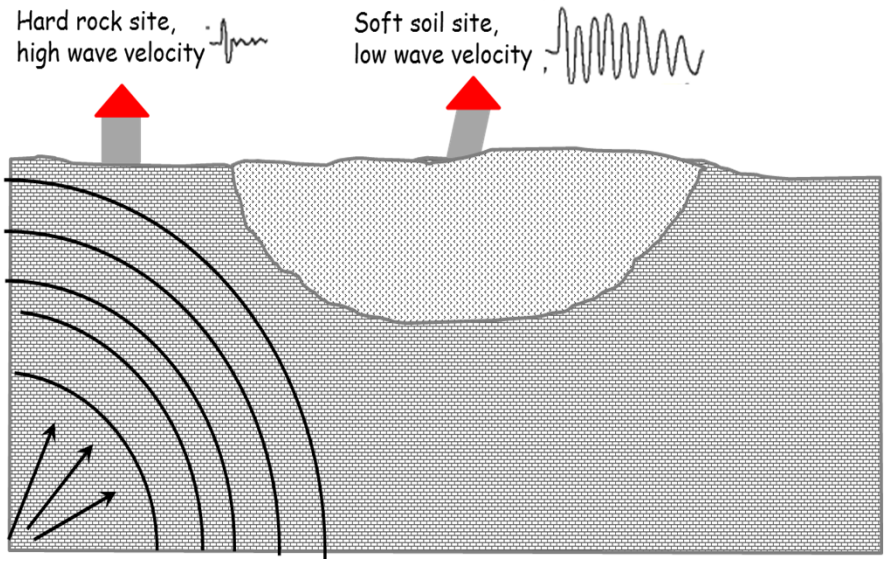
Bulletin of Historic Earthquakes

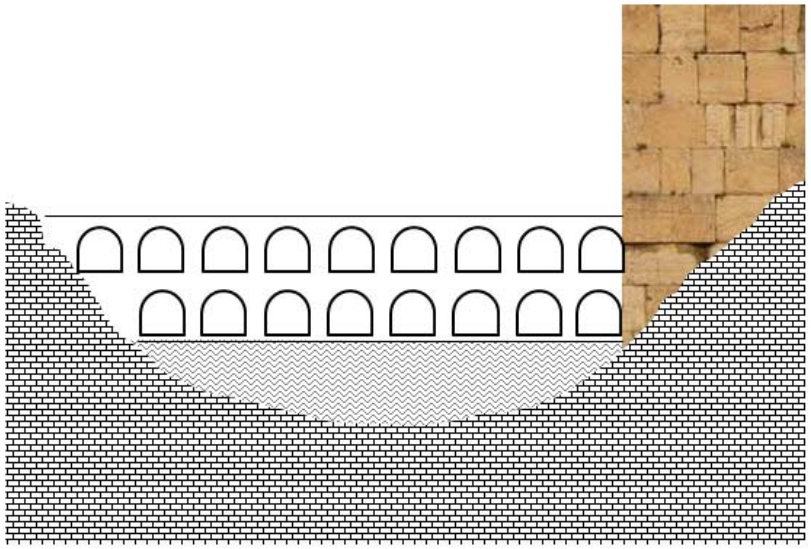
Date	Location	M_L	Distance to Jerusalem (km)	PGA (g) Ben- Menahem (1991)
306 AD	Off coast Sur	7.1	170	0.06
362	31.3N 35.6E	6.7	63	0.14
447	40.2N 28E	7.5	1100	0.0009
528	36.2N 36.1E	7.1	500	0.007
746	32N 35.5E	7.3	38	0.48
859	36.2N 36.1E	8	500	0.02
1032	Off coast Gaza	6.9	130	0.07
1068	Off coast Yavne	7	80	0.15
1070	Arava	6	170	0.016
1170	35.9N 36.4E	7.5	470	0.014

A discrepancy by a factor of 10 between numerically computed and empirically constrained PGA values!!

Data From: Ben-Menahem, A., 1991, Four thousand years of seismicity along the Dead Sea Rift: *J. Geophys. Res.*, v. 96, no. B12, p. 20,195-20,216.

The significance of local site effect





As a rule of thumb…

$$A_0 = \frac{\rho_B \cdot v_B}{\rho_S \cdot v_S}$$

Layer	parameters	
	density (kg/m^3)	shear wave velocity (m/sec)
Bedrock	2500	2000 - 3000
archeological fill (adopted alluvium values)	1800	100 - 500

From Gony Yagoda Biran, Ph. D. Thesis , 2013 (recently completed)

Needed research

- Improve seismic hazard evaluation in Israel:
  - Develop updated Ground Motion Prediction Equation (GMPE) for Israel, either by adjusting NGA or by supplementing database with synthetic earthquakes
  - Site response studies
    - Put instruments on *SOIL* and not only *ROCK*
    - Vertical and horizontal arrays
    - Evaluate linear and nonlinear soil response for input into GMPE

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Tower of David | Museum of the History of Jerusalem
برج داود | متحف تاريخ أورشليم القدس

ISRAEL ANTIQUITIES AUTHORITY רשות העתיקות

ועדת ההיגוי הבין-משרדית להערכות לרעידות אדמה
National Steering Committee for Earthquake Preparedness

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Thank you for your attention, and enjoy your stay in Israel!