Conservation of Cultural Heritage Monuments in Rock Sites: Case Studies from Israel

Special seminar sponsored by ISRM Commission on Preservation of Ancient Sites,
Commission President: Prof. Wang Xudong

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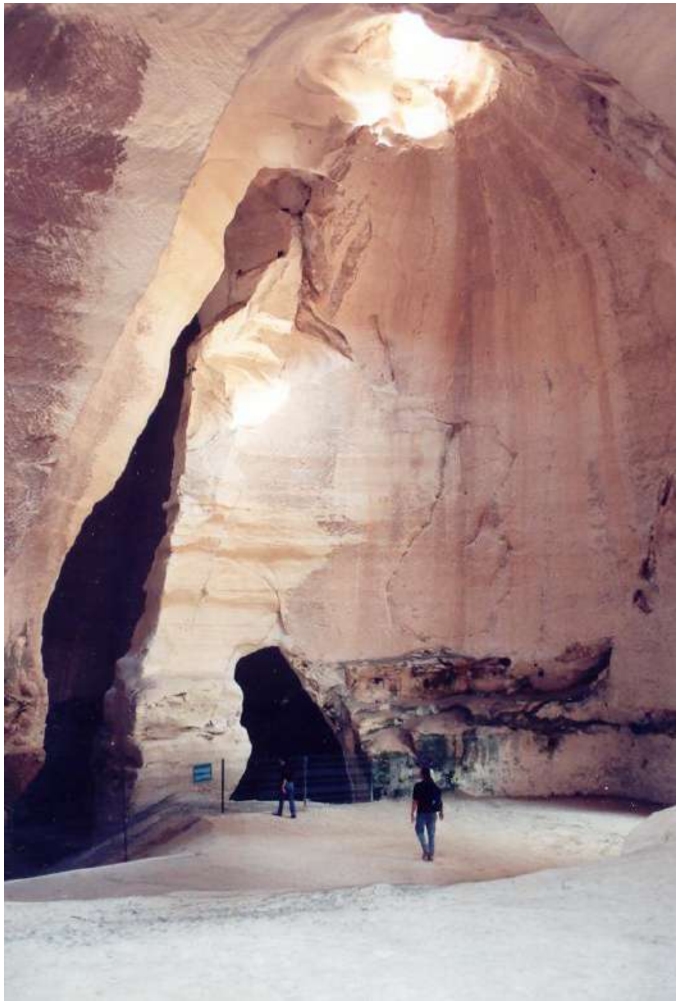
Talk Outline

- Ancient monuments excavated underground
  - 1000 year old bell shaped caverns, Bet Guvrin
  - 2000 year old underground quarry, Jerusalem
  - 3000 year old underground water reservoir, Beer Sheva
  - Lessons learned: critical relationship between cavern span and overburden height
  - Application to preservation of a Pleistocene karstic cave underneath an active open pit mine
- Ancient monuments on rock slopes
  - The case of Masada World Heritage Site
- Ancient monuments as recorders of historic seismicity
  - The Nabatean (2000 year old) city of Mamshit
  - The Byzantine (1300 year old) cathedral of Susita
  - The Crusaders (900 year old) fortress of Nimrod

CONSERVATION OF CULTURAL HERITAGE MONUMENTS EXCAVATED UNDERGROUND

Case 1: The Bet Guvrin bell-shaped caverns



Hatzor, Y. H., Talesnick, M. L., and M. Tsesarsky, 2002. Continuum and Discontinuum Stability Analysis of the Bell Shaped Caverns at Bet Guvrin, Israel.. *Int. J. Rock Mech. Min. Sci.*

The Challenges

- **Rock Mechanics Challenge:**

Extremely high span and height opening (40 meters/ 20 meters) excavated in a discontinuous and very weak rock that exhibits ***time dependency***

- **Preservation Challenge:**

The system is at an advanced stage of disintegration – can it be saved without ruining it?

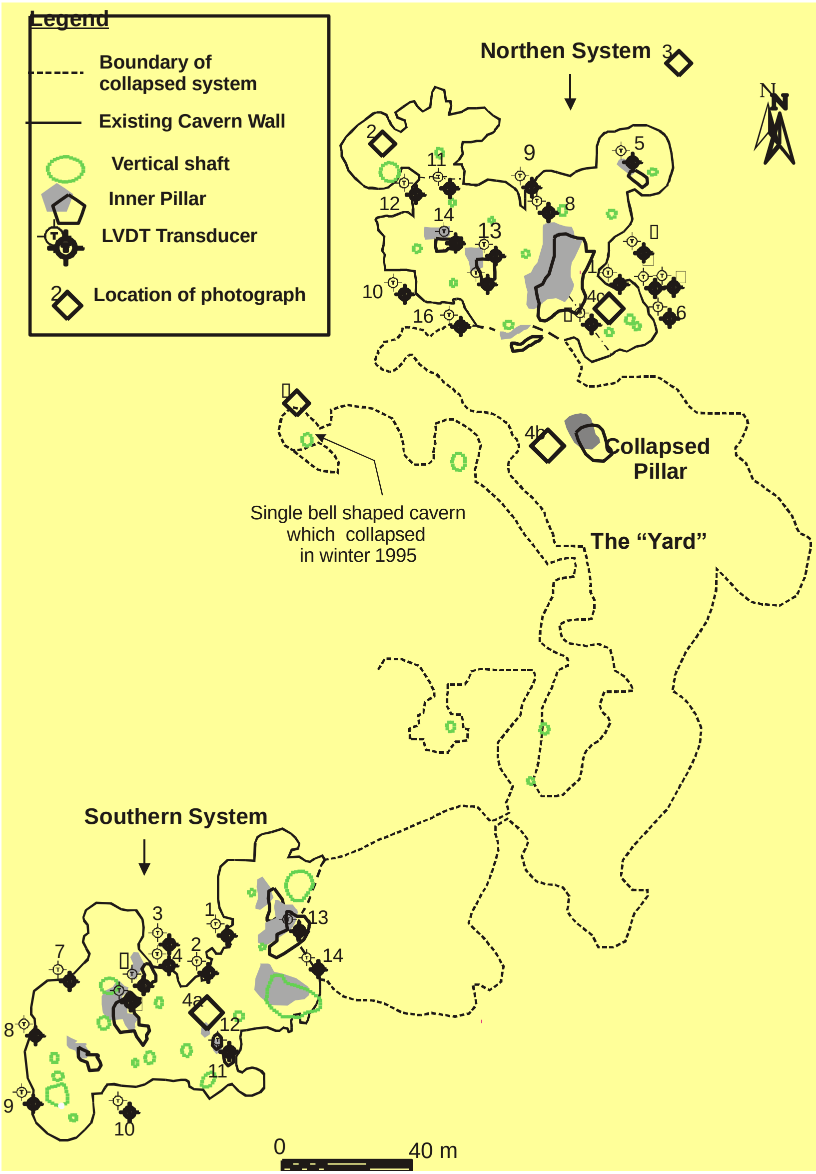
- **Approach:**

  Geometrical Model

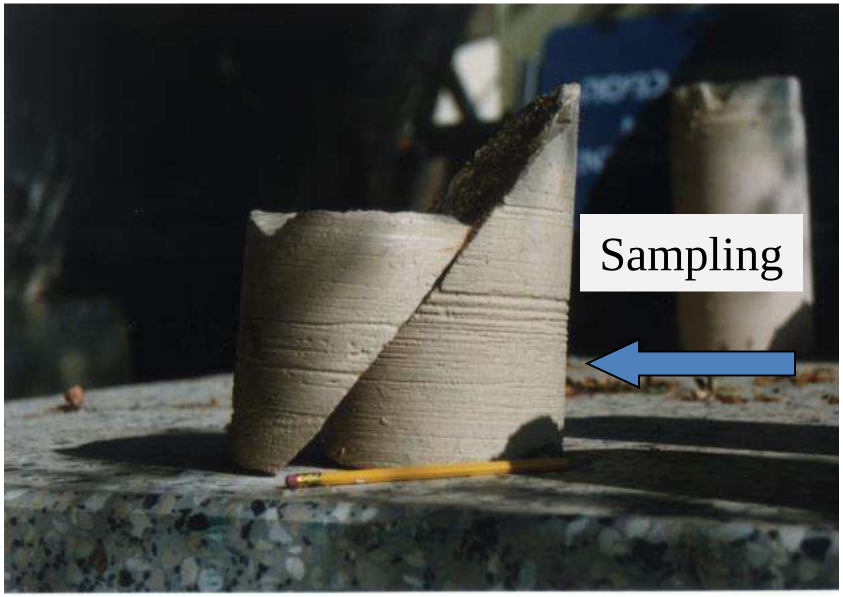
  Mechanical Properties

  Stability Analysis

System Layout



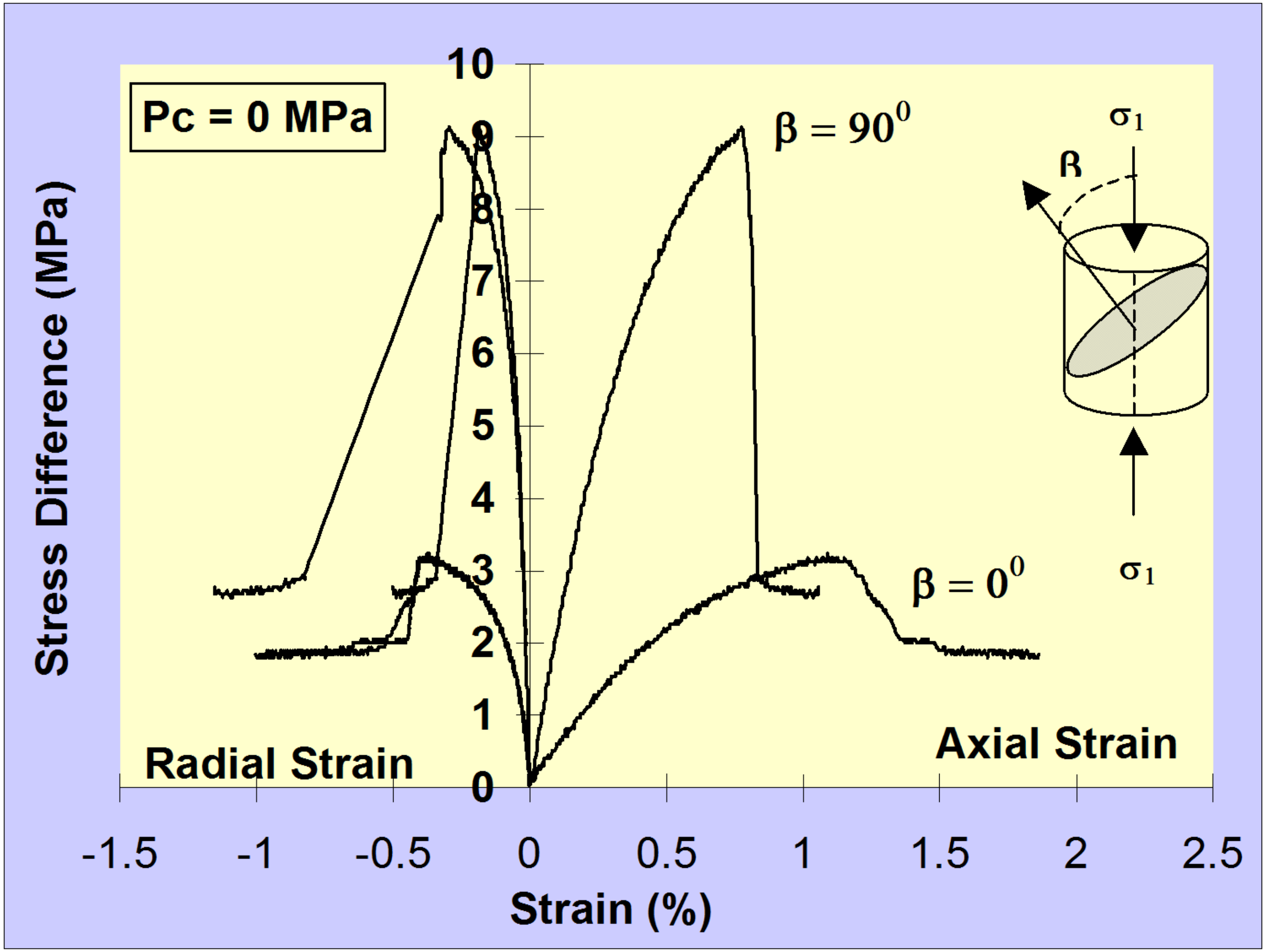
Determination of Mechanical Properties of Rock

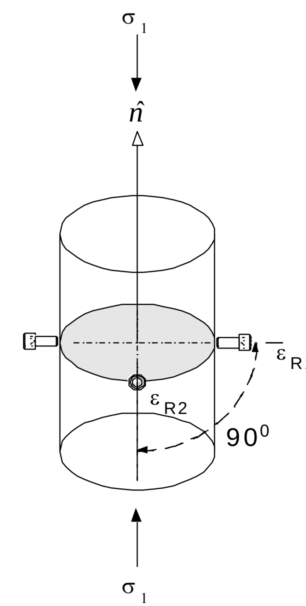


Rock Testing

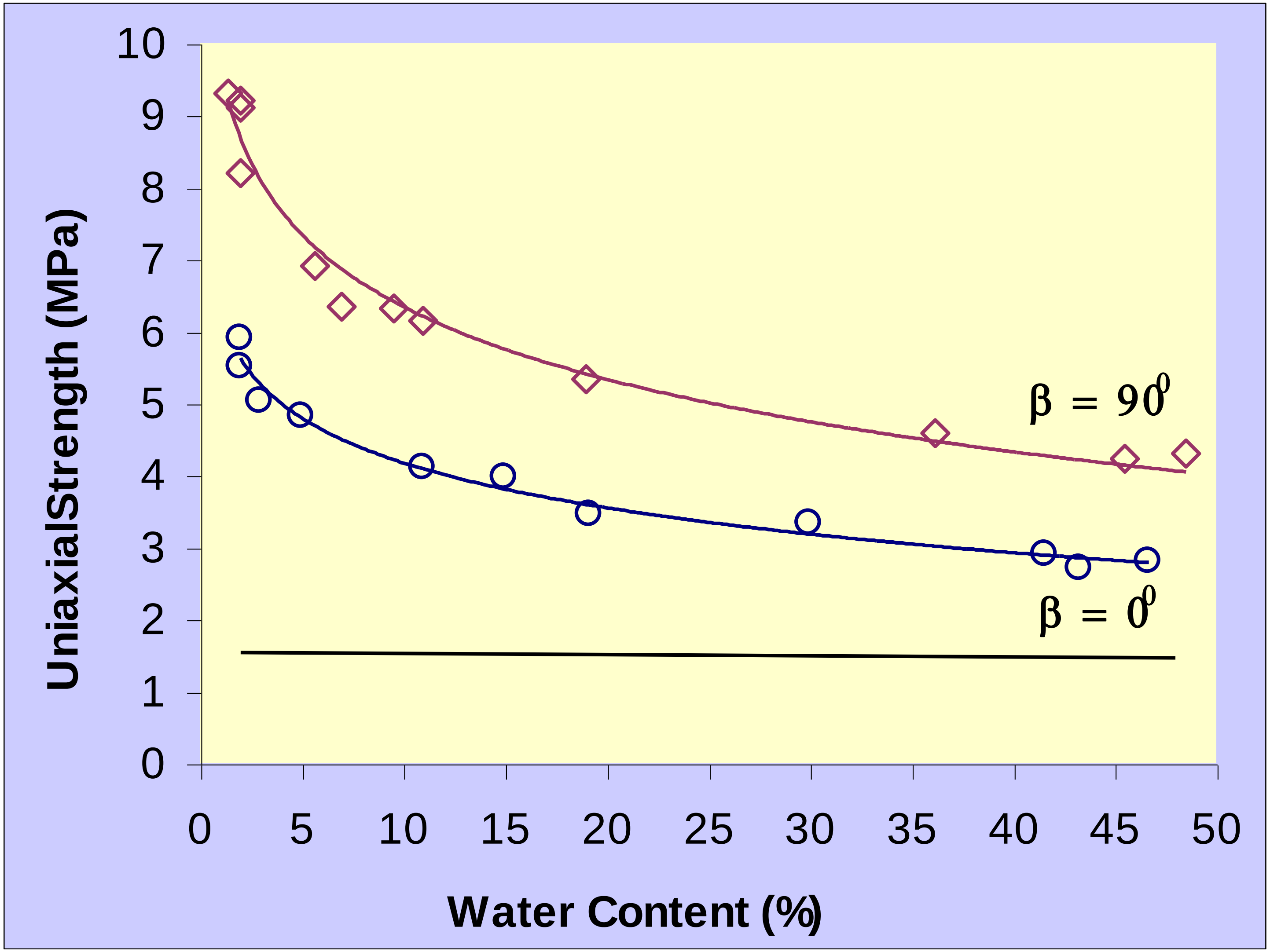
Test Preparation

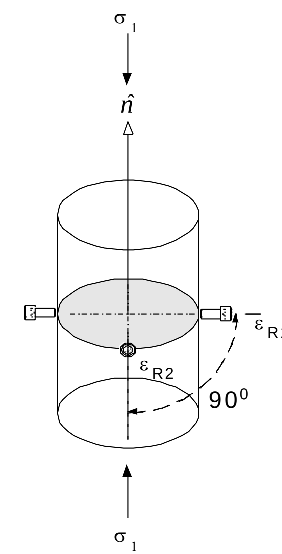
Influence of Anisotropy on Strength





Influence of Water Content on Strength





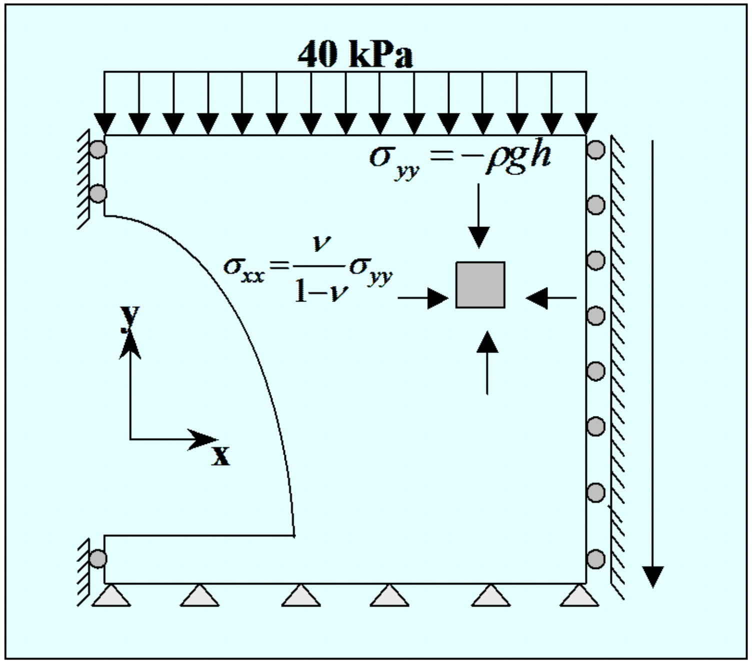
After: Talesnick, M. L., Y. H. Hatzor, and M. Tsesarsky, 2001. The elastic deformability and strength of a high porosity, anisotropic, chalk.. *Int. J. Rock Mech. Min. Sci.*

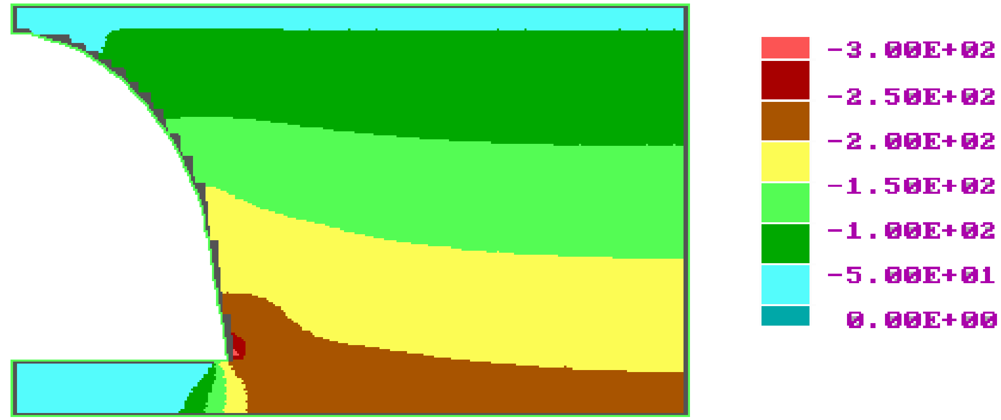
Summary of Mechanical Properties

- Peak compressive strength parallel to bedding 9 MPa
- Peak compressive strength normal to bedding 5 MPa
- 50% reduction in rock strength with water content increase from 3% to 50% in both states
- Peak tensile strength parallel to bedding = 1 MPa
- Decrease in tensile strength due to water content same as in compression

Now, let's check Factors of Safety against failure in compression and tension

Stress Distribution Analysis
Single Opening, Maximum Free Span 24m





Vertical stress distribution

Horizontal stress distribution

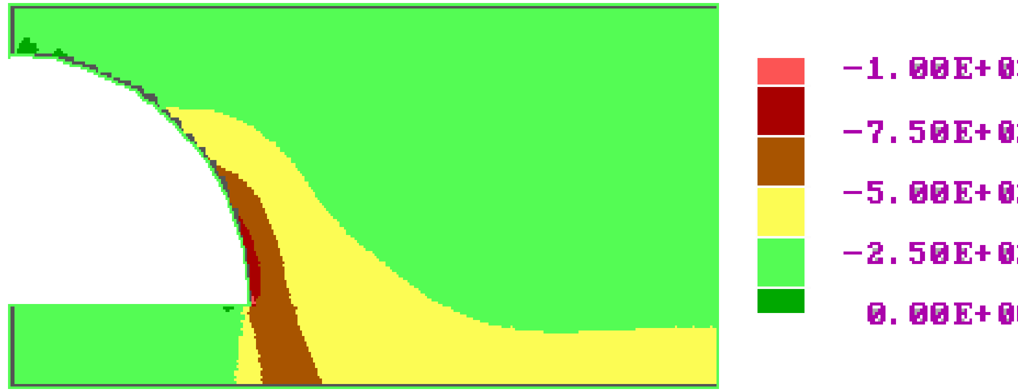
Factor of safety against crushing at roof = 40

Factor of safety against crushing at abutments = 17

Two Overlapping Openings
Maximum Free Span 34 meter

Factor of safety against crushing at roof = 13

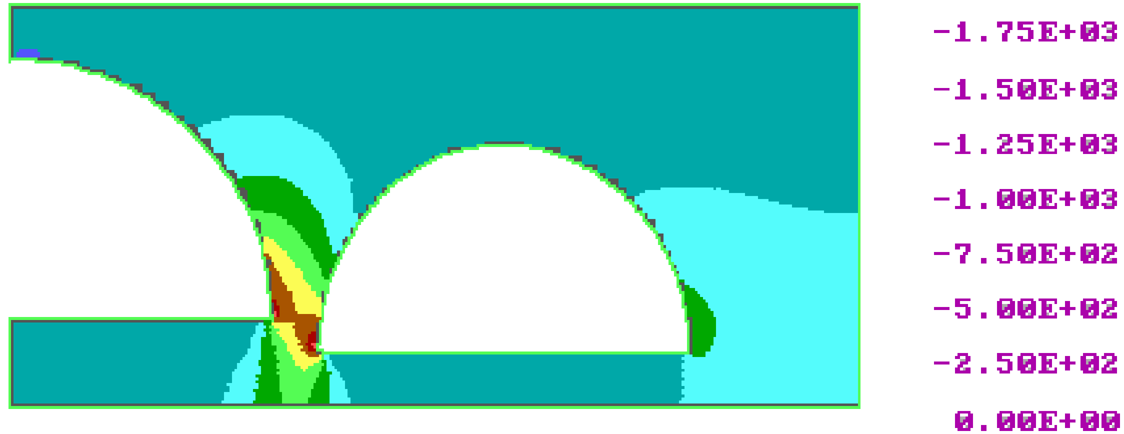
Factor of safety against crushing at abutments = 6



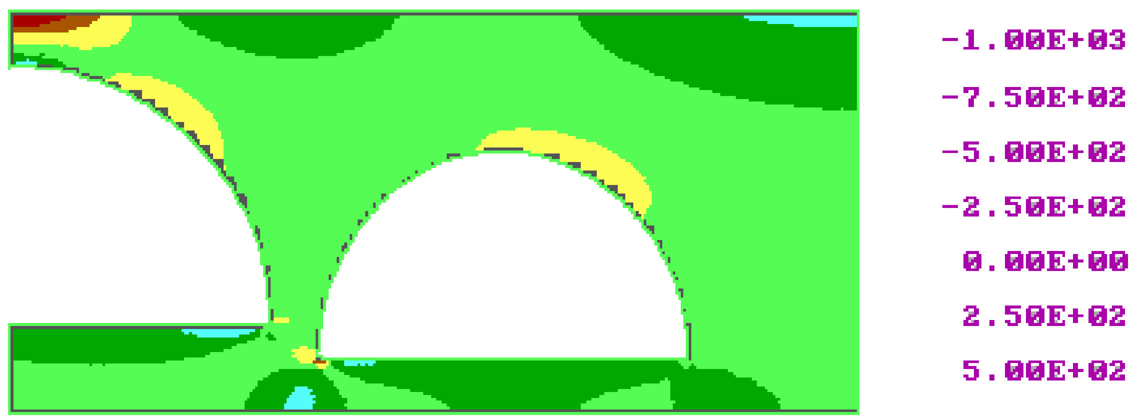
Vertical stress distribution

Horizontal stress distribution

Two Adjacent Openings



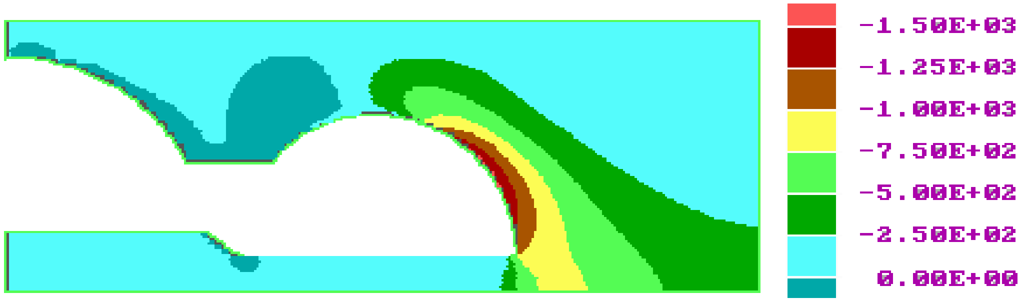
Vertical stress distribution

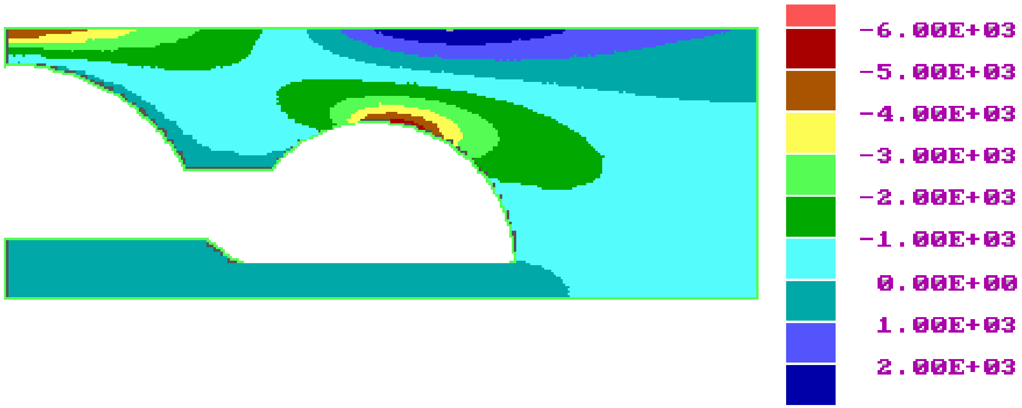


Horizontal stress distribution

Factor of safety against crushing at common side wall:
F.S. = 3 (Wall thickness = 3m)
F.S. = 2 (Wall thickness = 2m)

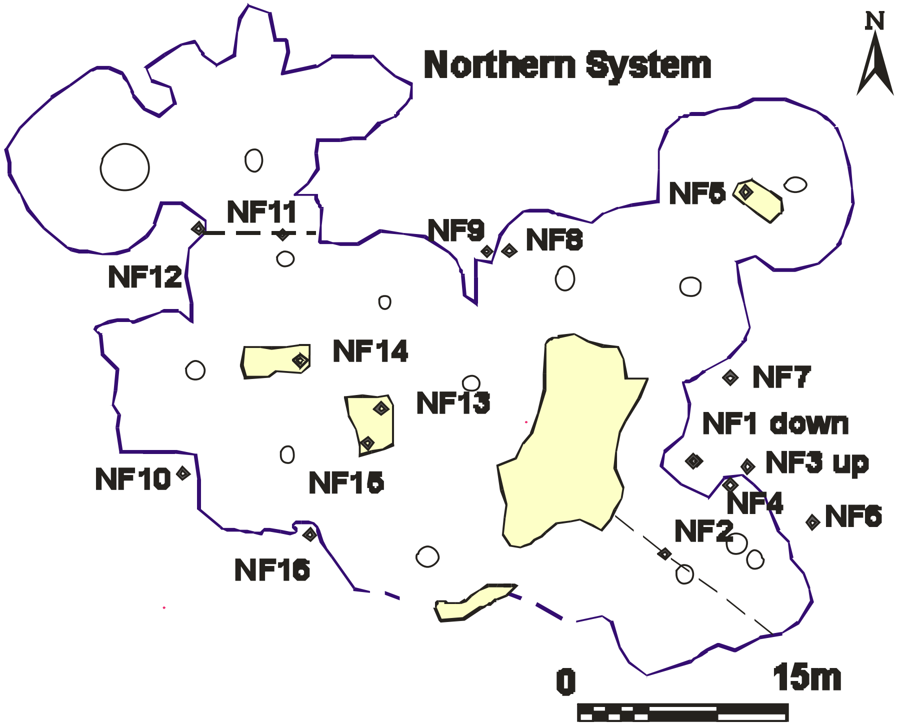
Stress Re-Distribution after Collapse of Common Side Wall: Free Span = 64 meter

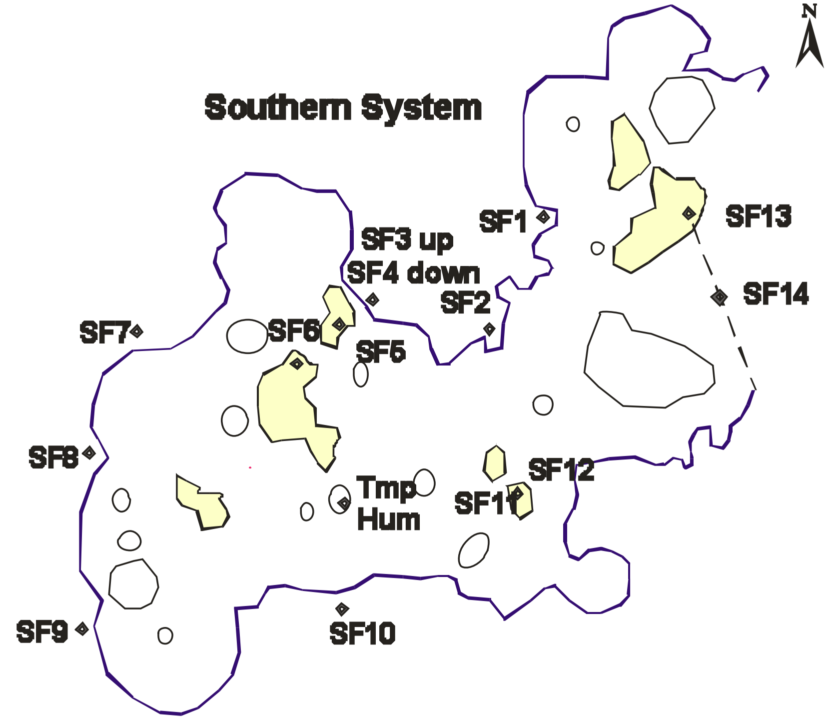




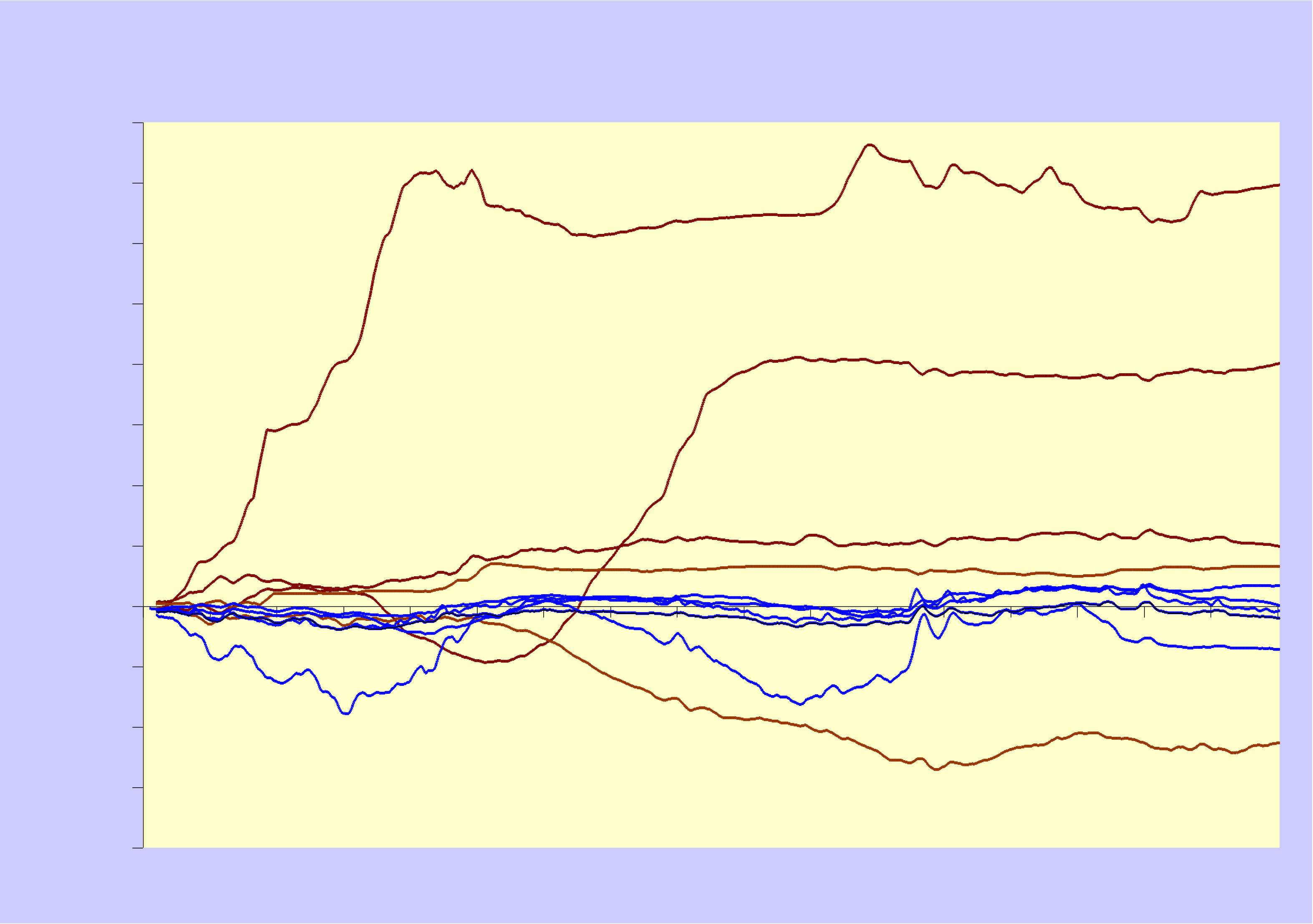
- Factor of safety against crushing at roof = 2
- Factor of safety against crushing at abutments = 4
- Factor of safety against tensile rupture in roof = 0.5!

Monitoring *In-Situ* Cavern Wall Performance

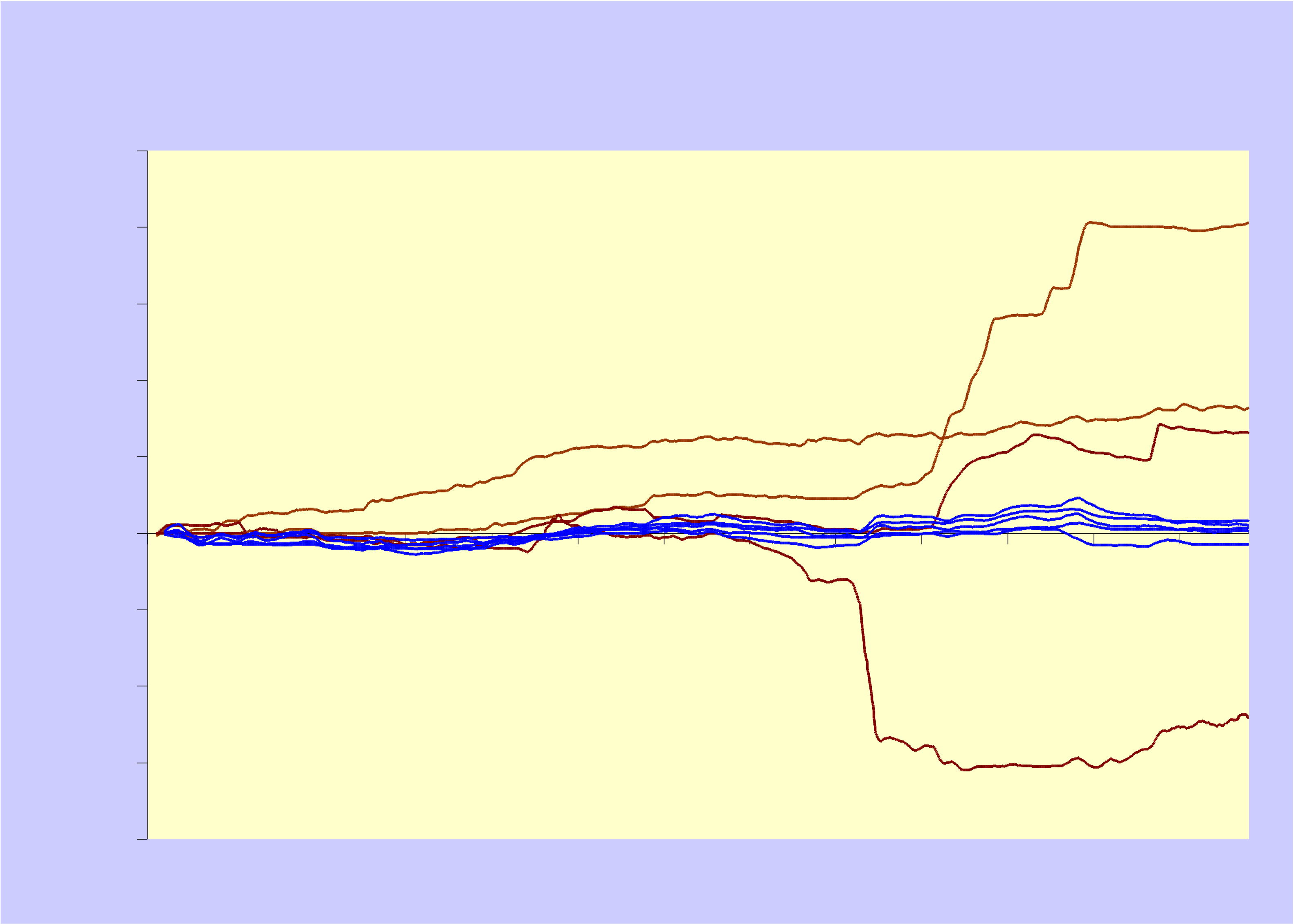




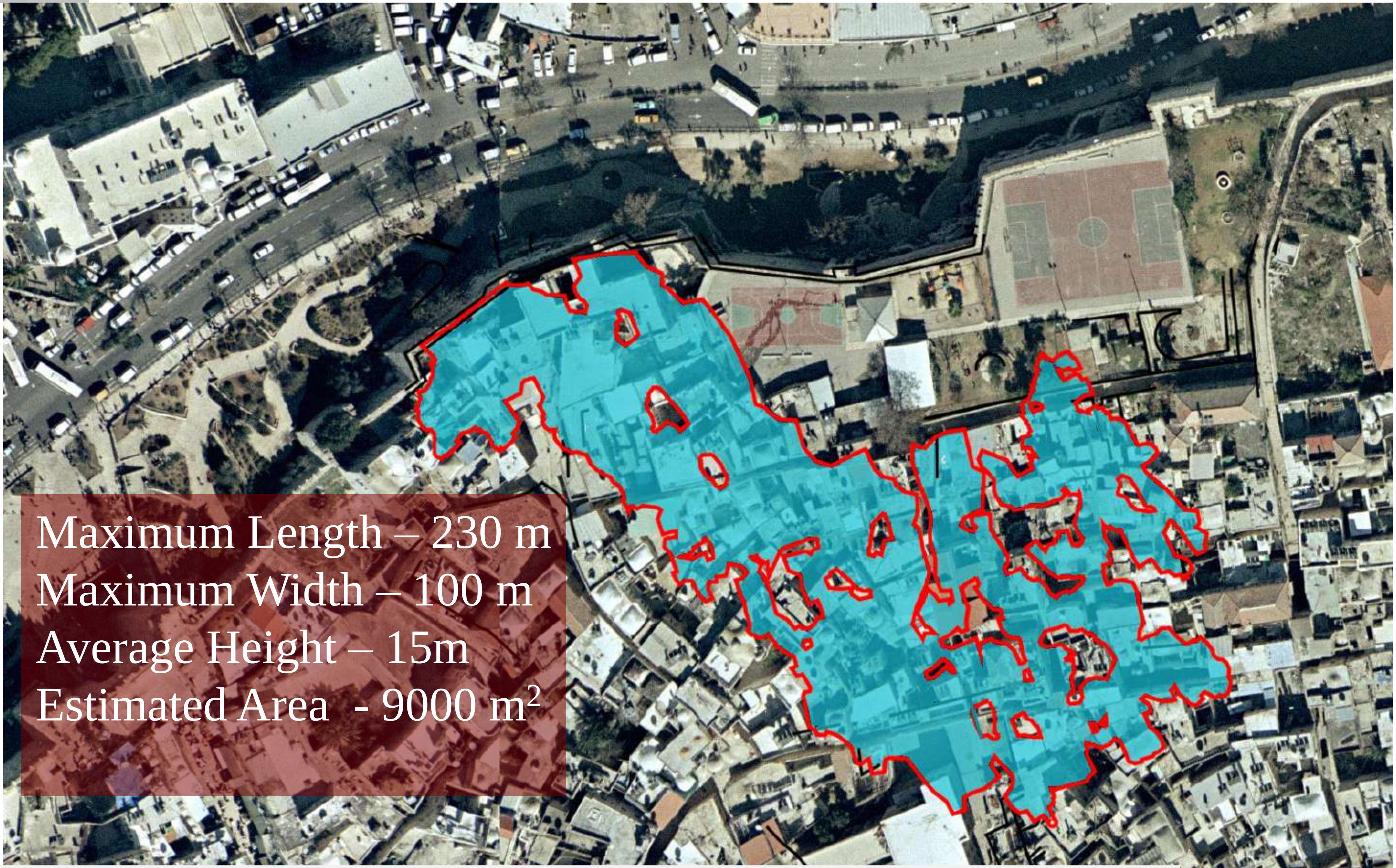
Monitoring Results – Southern System



Monitoring Results – Northern System

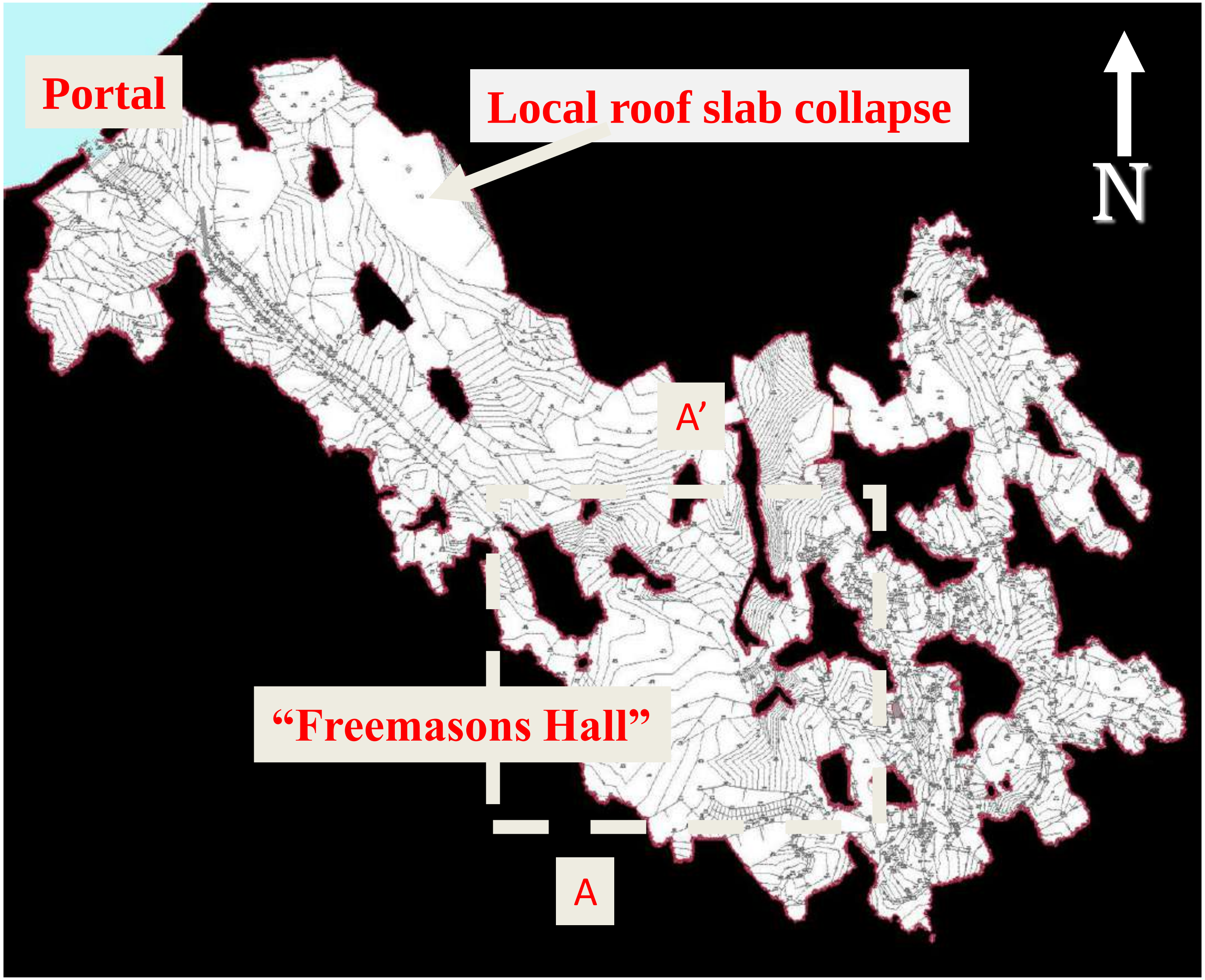


Case 2: Zedekiah cave, old city of Jerusalem

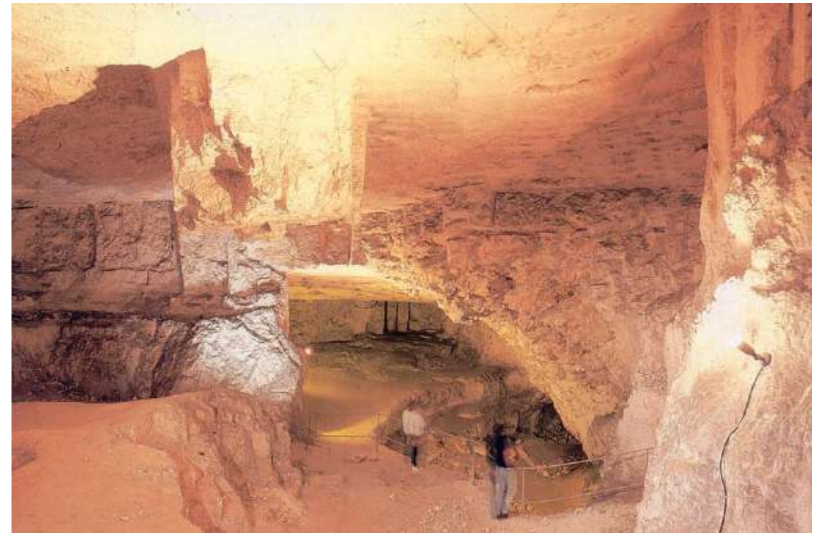


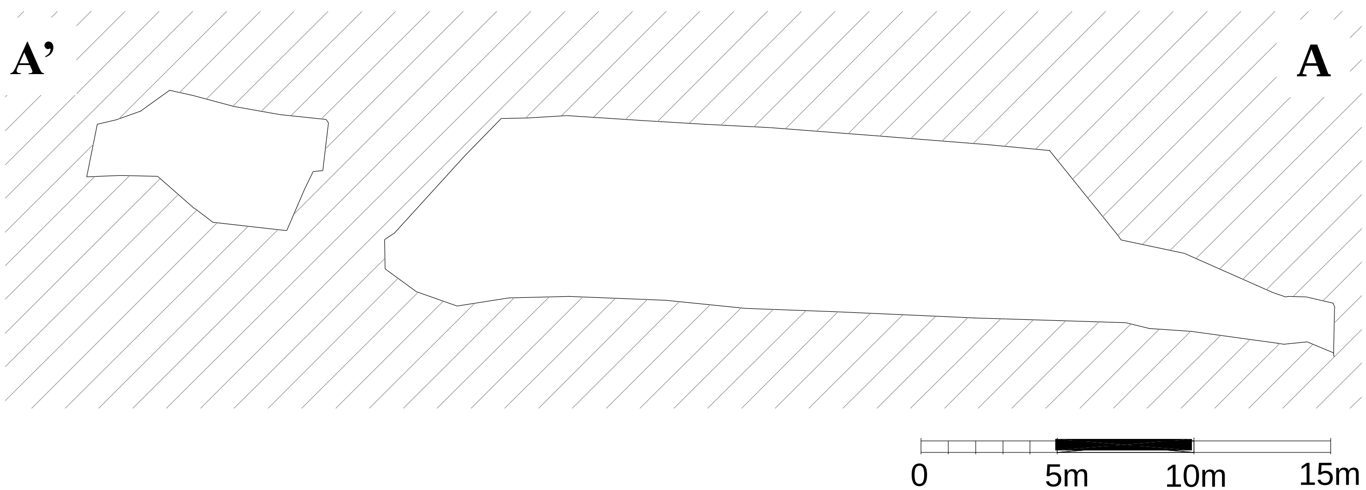
Bakun-Mazor, D., Hatzor, Y. H. and W. S. Dershowitz, 2009. Modeling mechanical-layering effects on stability of underground openings in jointed sedimentary rocks. *Int. J. Rock Mech. Min. Sci.*

Layout of the cave

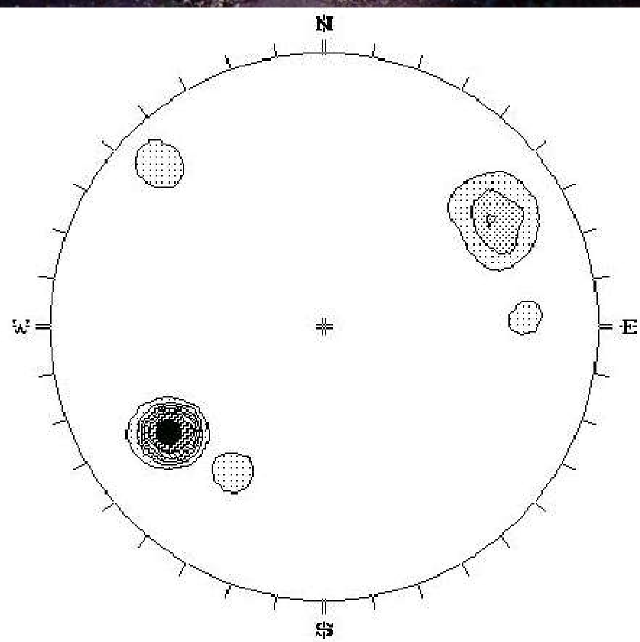


Cross section through main chamber





Rock Mass Structures

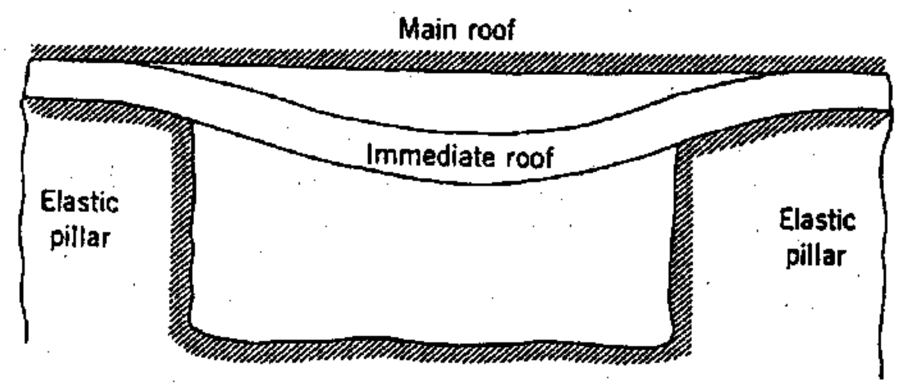


Set	Type	Dip	Spacing
1	Bedding	08/091	0.85
2	Shears	71/061	0.79
3	Shears	67/231	1.48
4	Joints	75/155	1.39

Roof stability assuming bedding planes only

Free span (*L*)	30 m
Beam thickness (*t*)	0.85 m
Unit weight (γ)	19.8 kN/m^3
Elastic modulus (*E'*)	8*10^3 MPa
Uniaxial compressive strength (σ_c)	16.4 MPa (bedding parallel)
Tensile strength (σ_t)	2.8 MPa

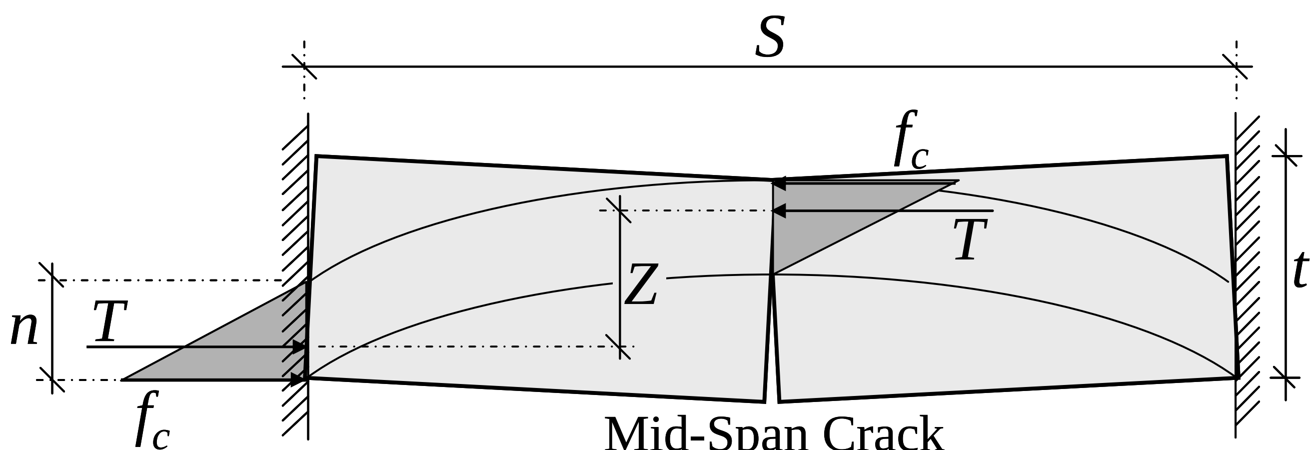
Maximum deflection at centerline (η)	8.67 cm
Maximum shear stress at abutments (τ_{max})	0.445 MPa
Maximum axial stress (σ)	10.5 MPa



The roof should have failed in tension…

Roof stability assuming the Voussoir analogue

Since the tensile strength of the material is exceeded in at the lowermost layers of the roof a vertical crack may propagate and decompose the continuous roof slab into two blocks, thus forming the so called "Voussoir Bean" (See Ray Sterling PhD thesis and Brady and Brown, 2004):



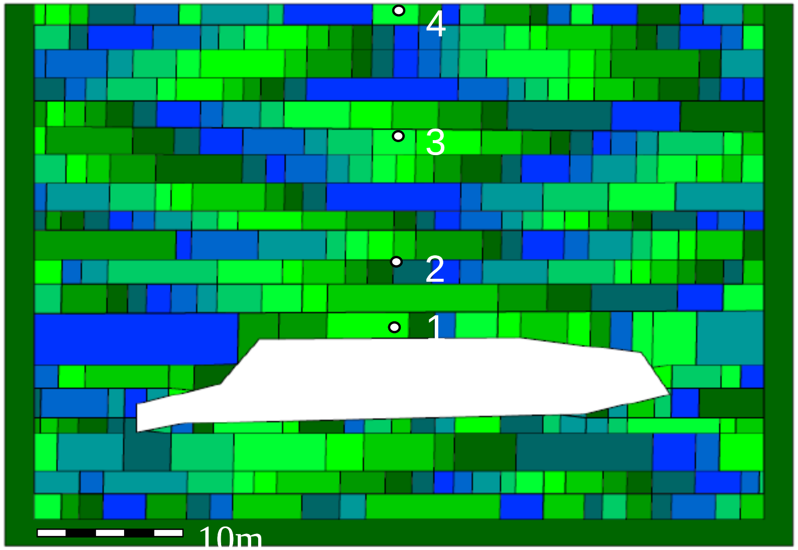
With the given dimensions the roof should undergo buckling culminating in a "snap – through" mechanics ($Z < 0$).

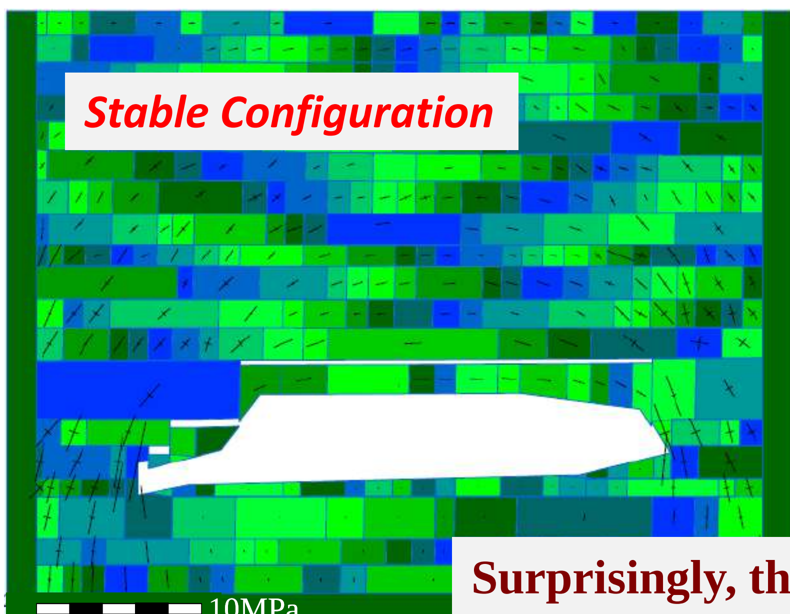
So, what is keeping the roof stable?...

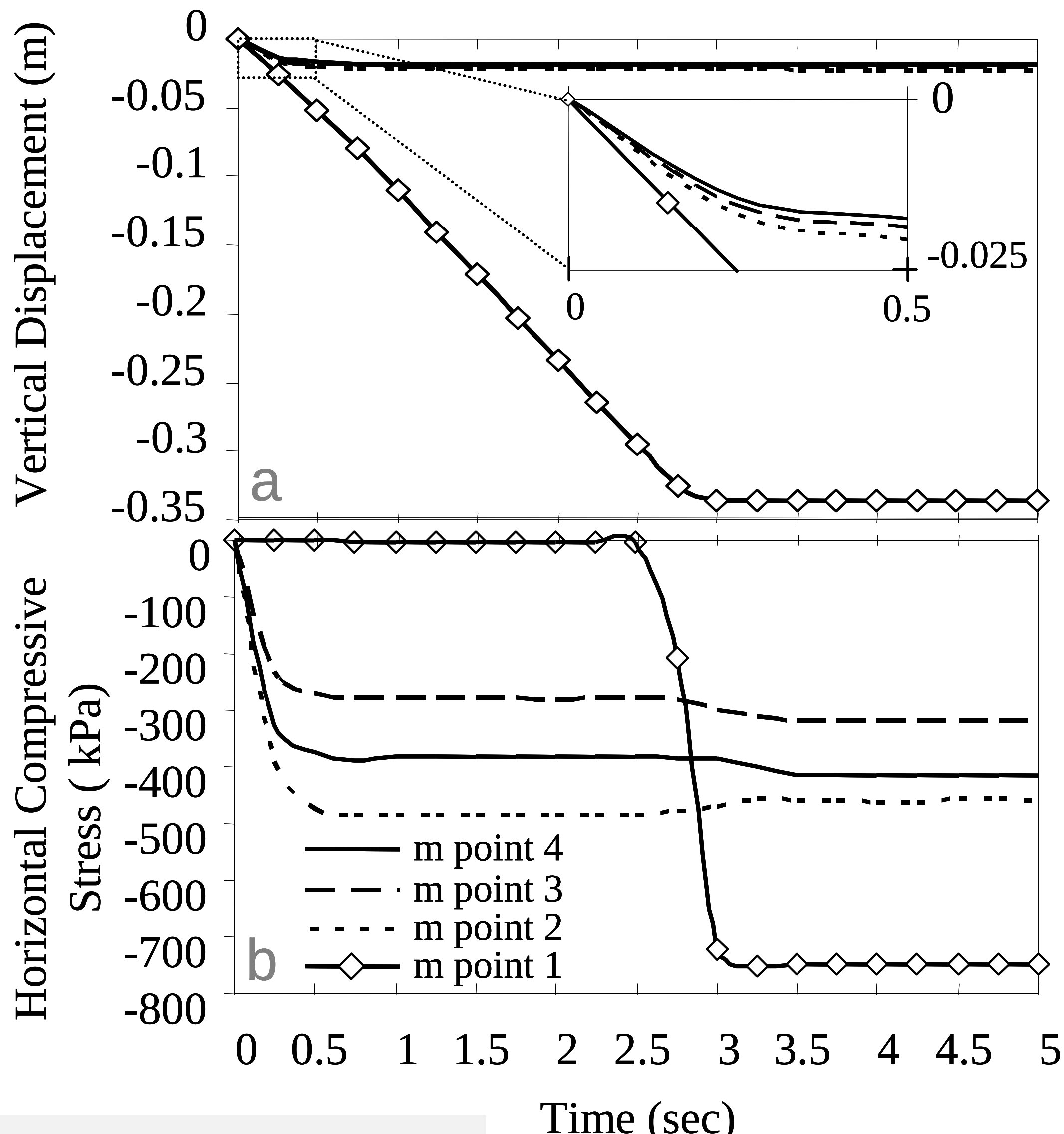
Modeling multiple block interaction with DDA

Mechanical properties	
Elastic Modulus	10 GPa
Poisson's Ratio	0.184
Density	2500 kg/m^3
Numerical control parameters	
Dynamic control parameter	0.98
Number of time steps	20000
Time interval	0.00025 (sec)
Assumed max. disp. ratio	0.0004
Penalty stiffness	$5*10^9$ N/m
Friction angle	41^o

Results of forward modeling with DDA

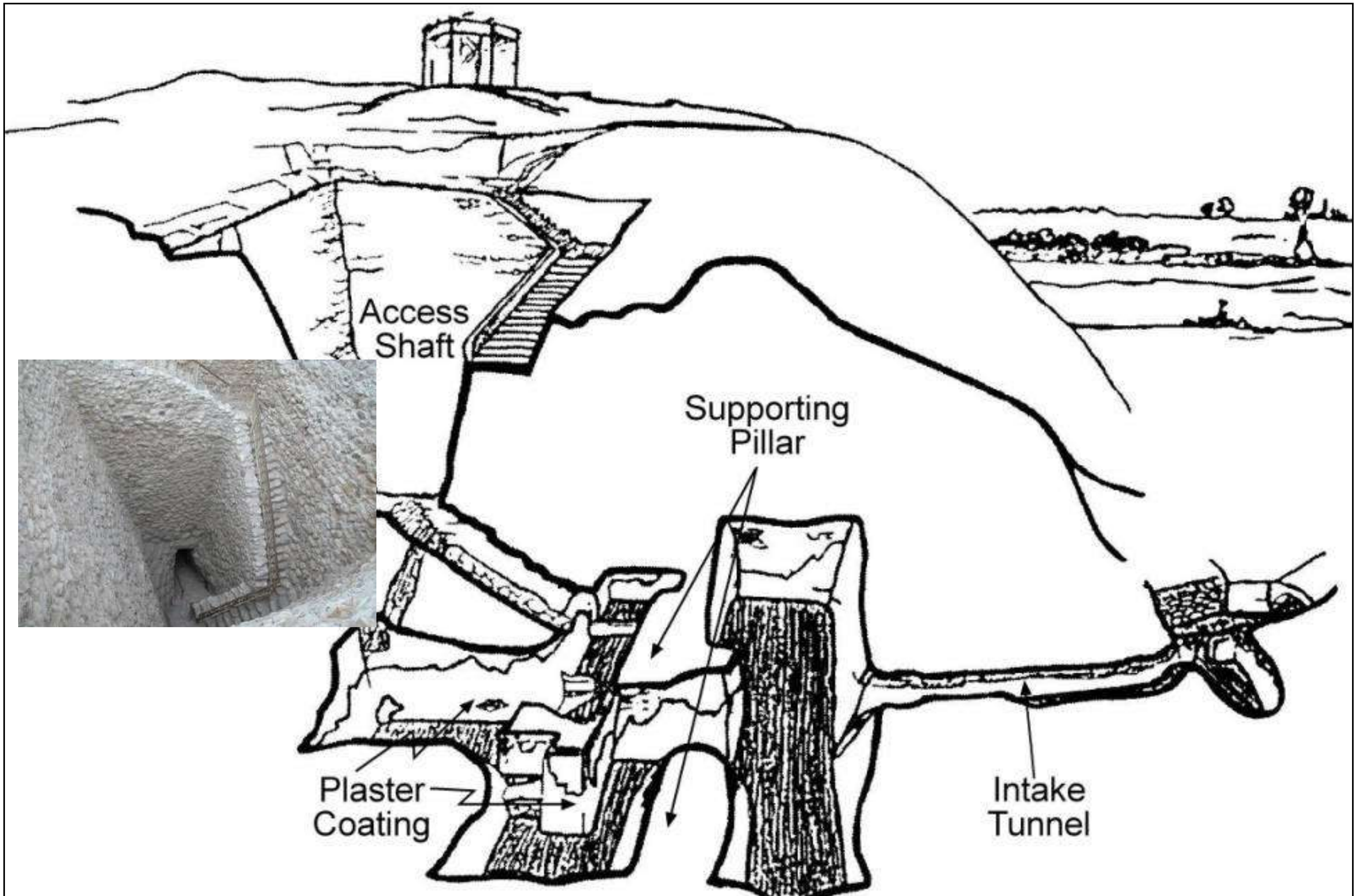






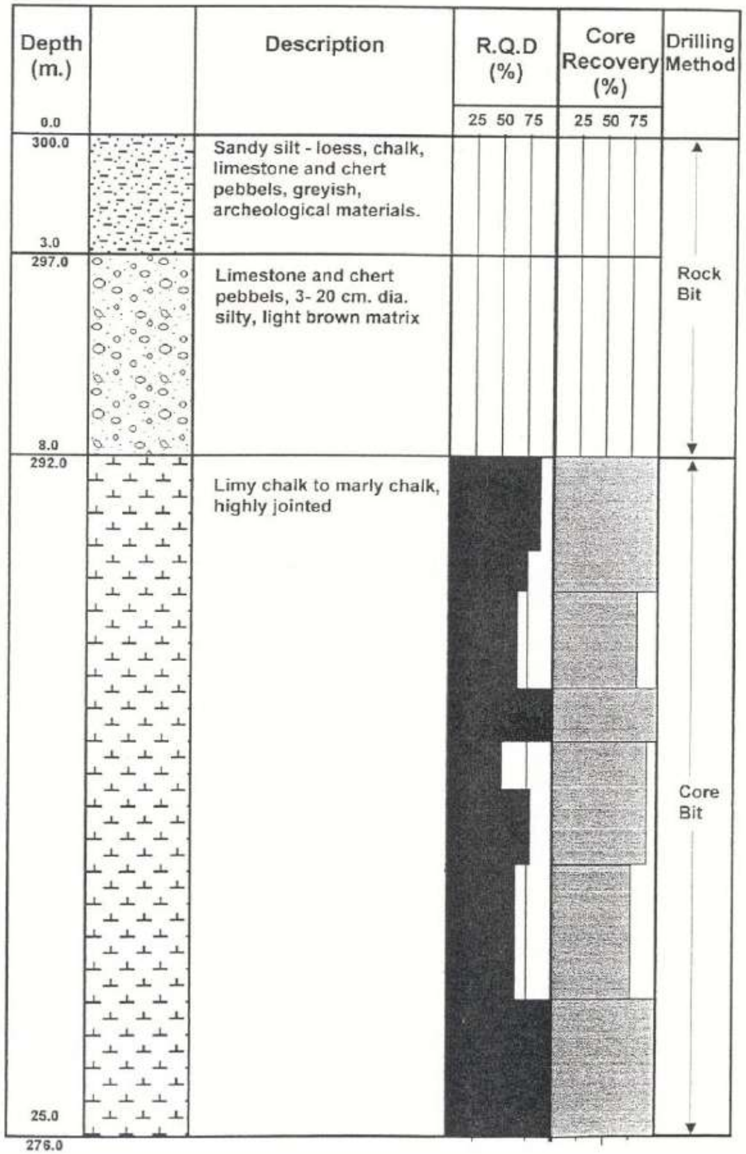
Surprisingly, the jointing patterns keeps the roof stable…

Case 3: Tel Beer-Sheva

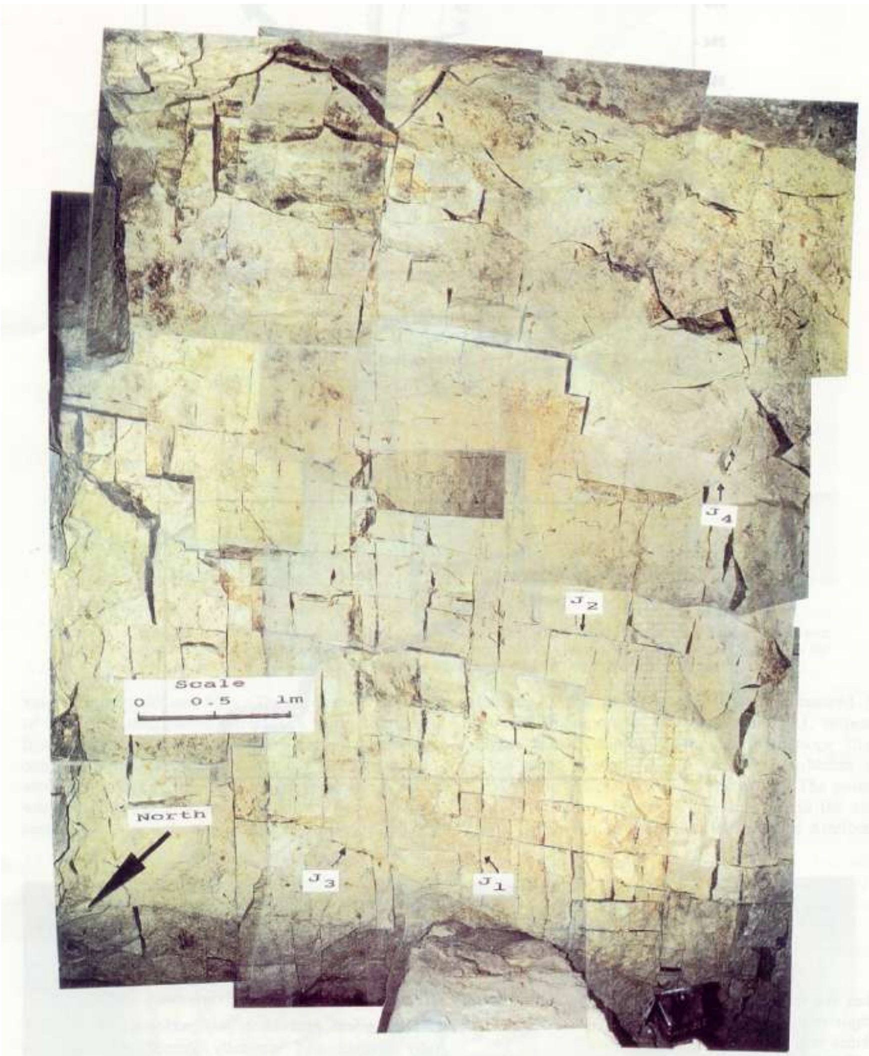


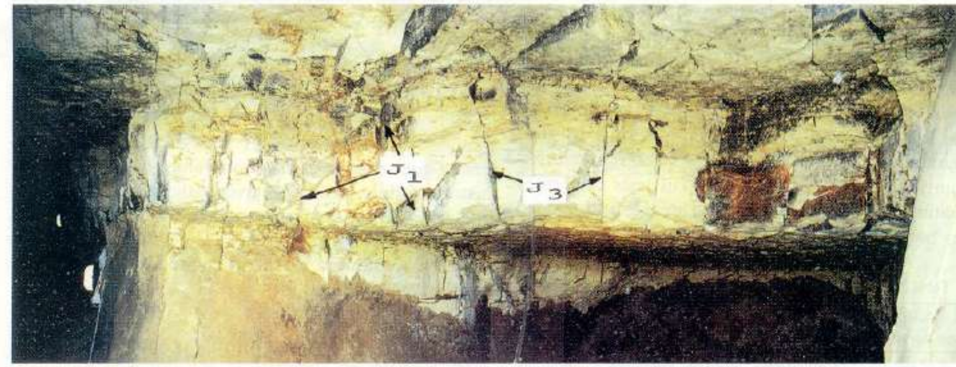
Hatzor, Y. H. and R. Benary, 1998. Stability of a laminated Voussoir beam: back analysis of a historic roof collapse using DDA. *Int. J. Rock Mech. Min. Sci.*

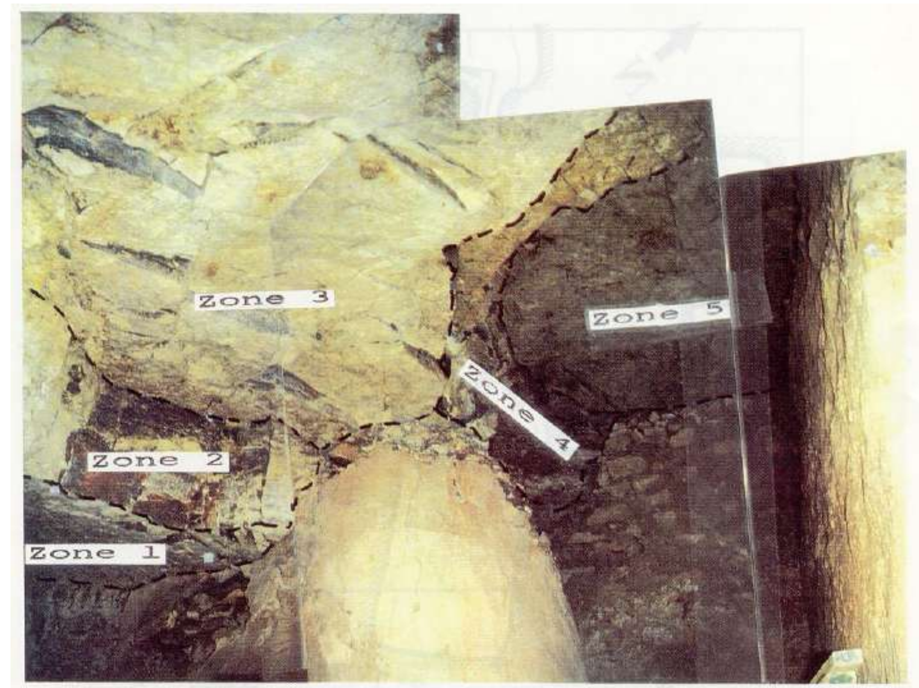
The Geological Cross Section at the Site



Inside View – The Discontinuous Roof

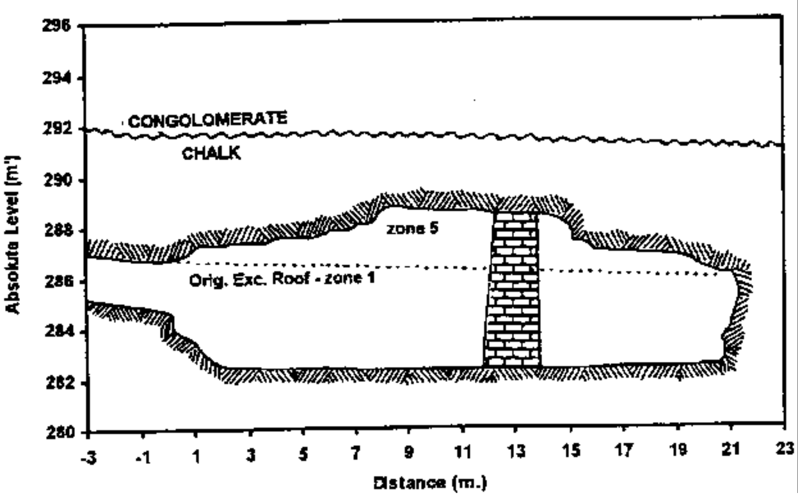




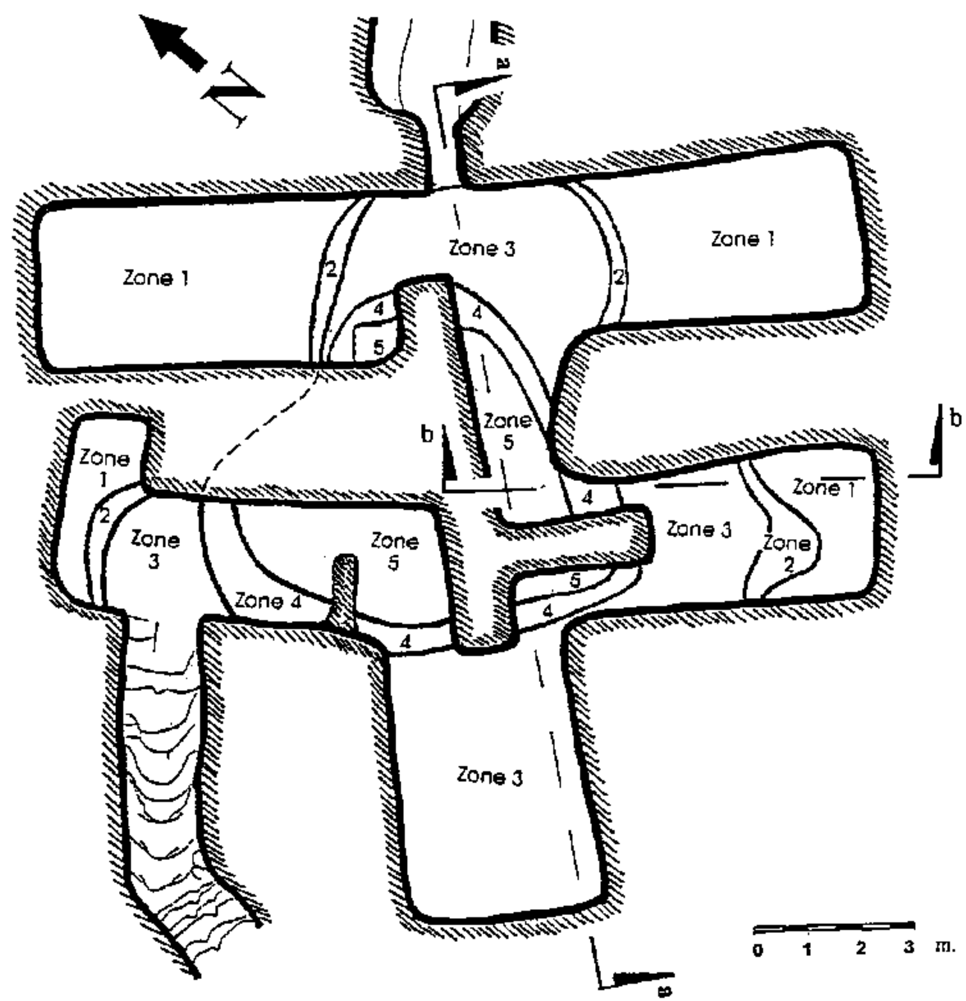


System Layout

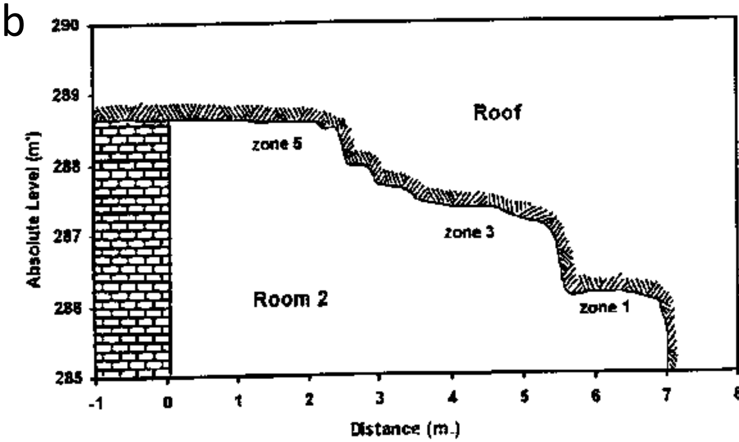
a



a

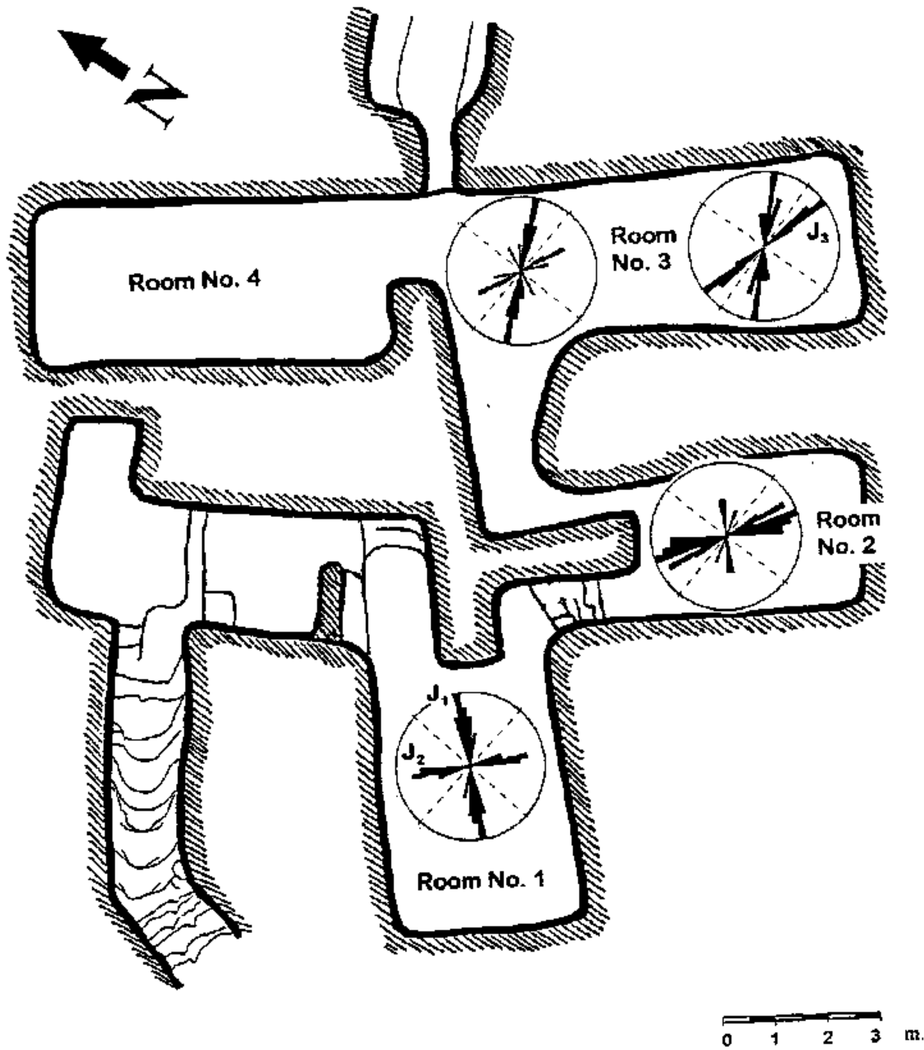


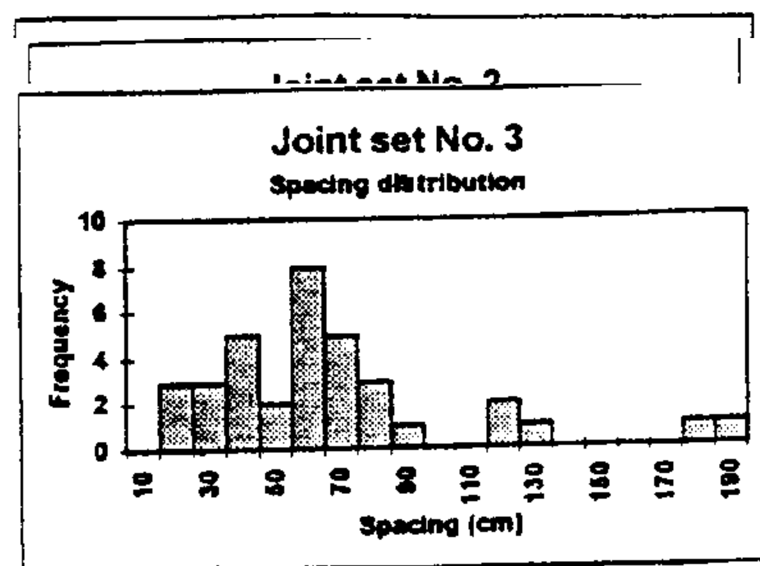
b



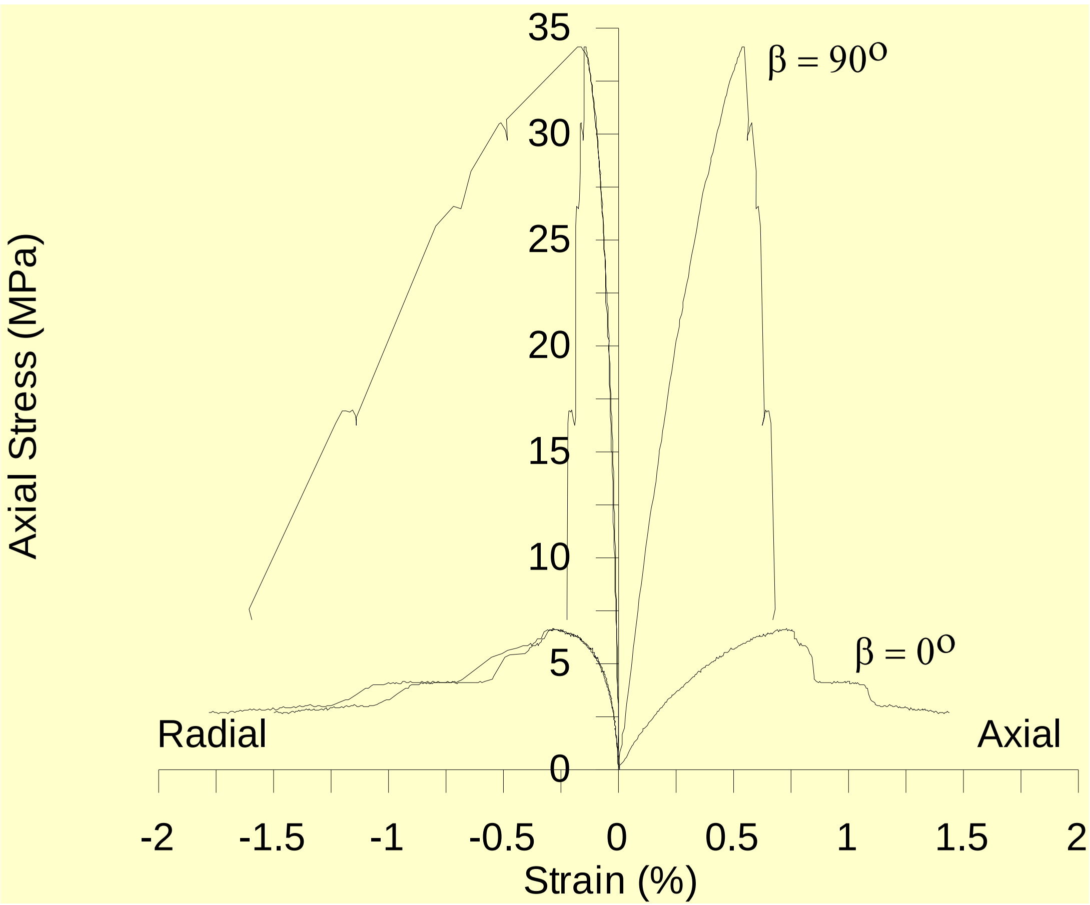
b

Influence of Rock Structure on Excavation

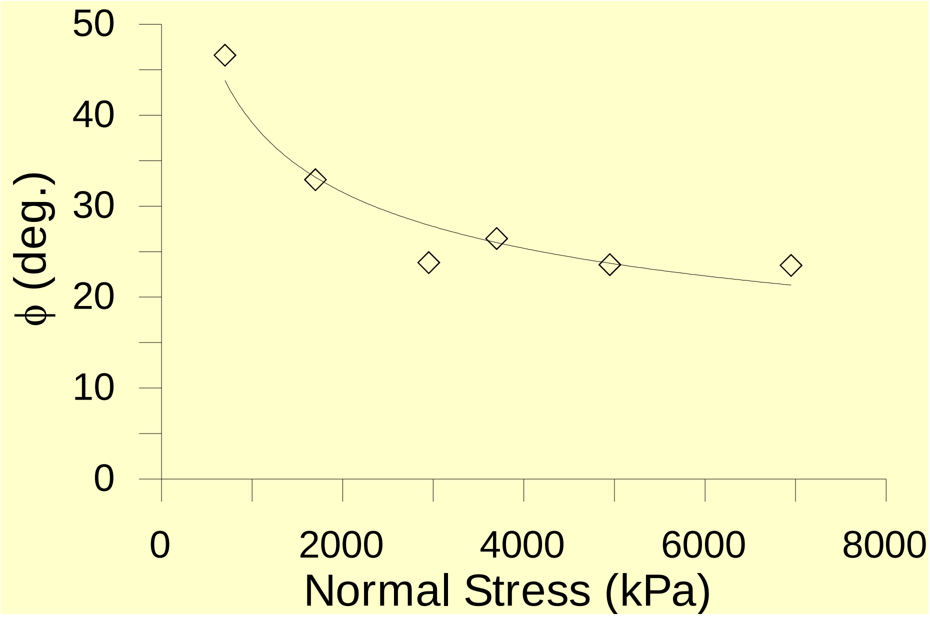


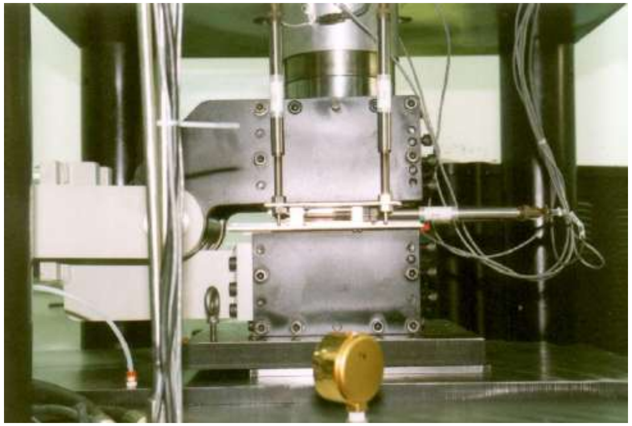


Compressive Rock Strength



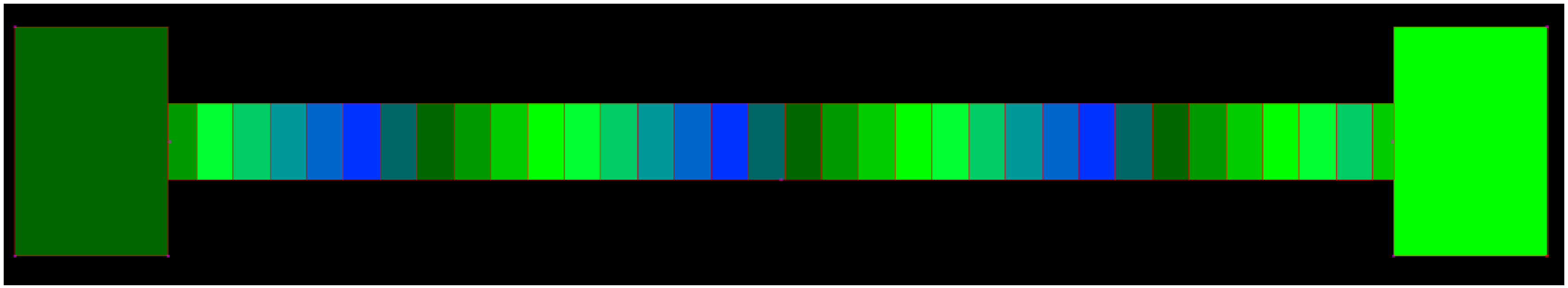
Shear Strength of Discontinuities





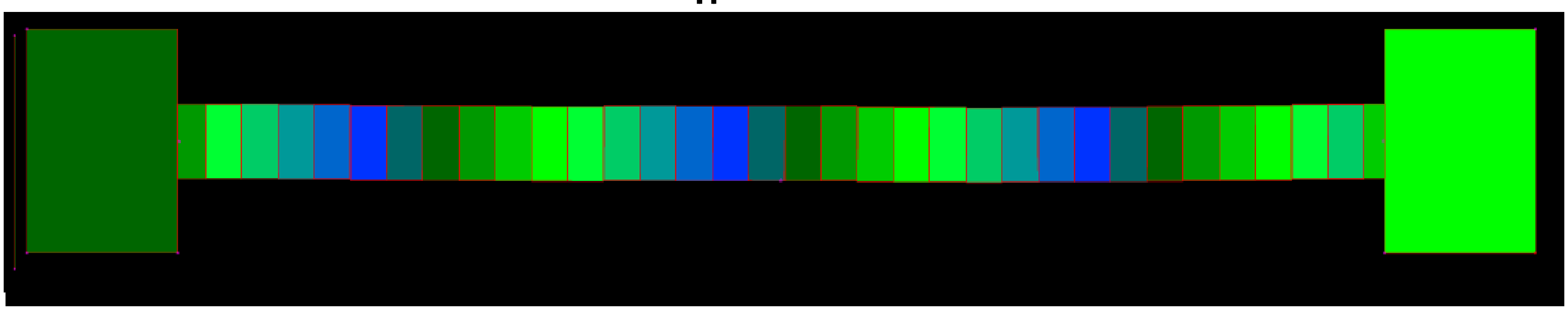
Kinematics of a Jointed Beam (Voussoir)

$S = 8m,\ t = 0.5m,\ S_j = 0.25m$



Initial Geometry

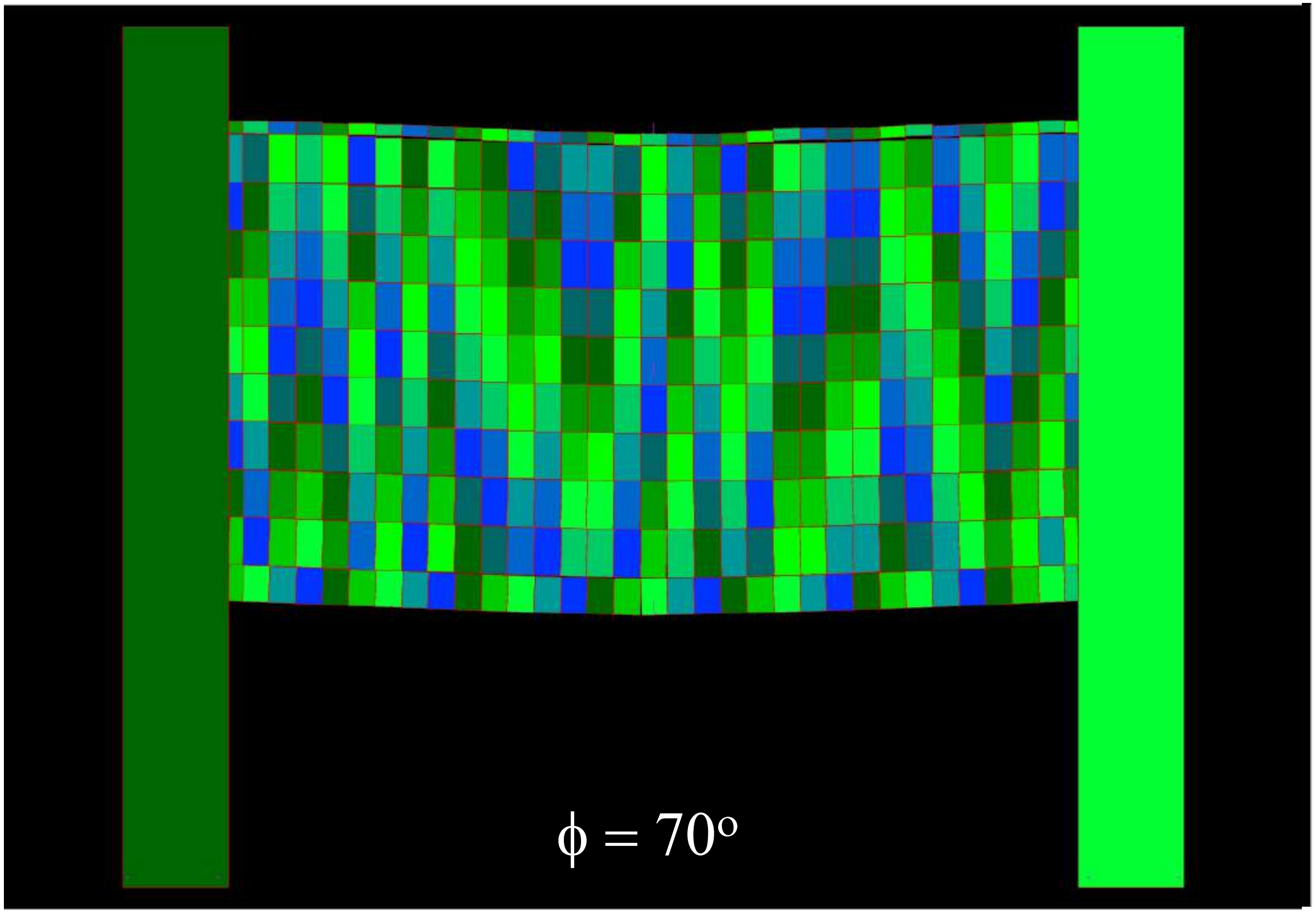
$\phi =$ [illegible]°



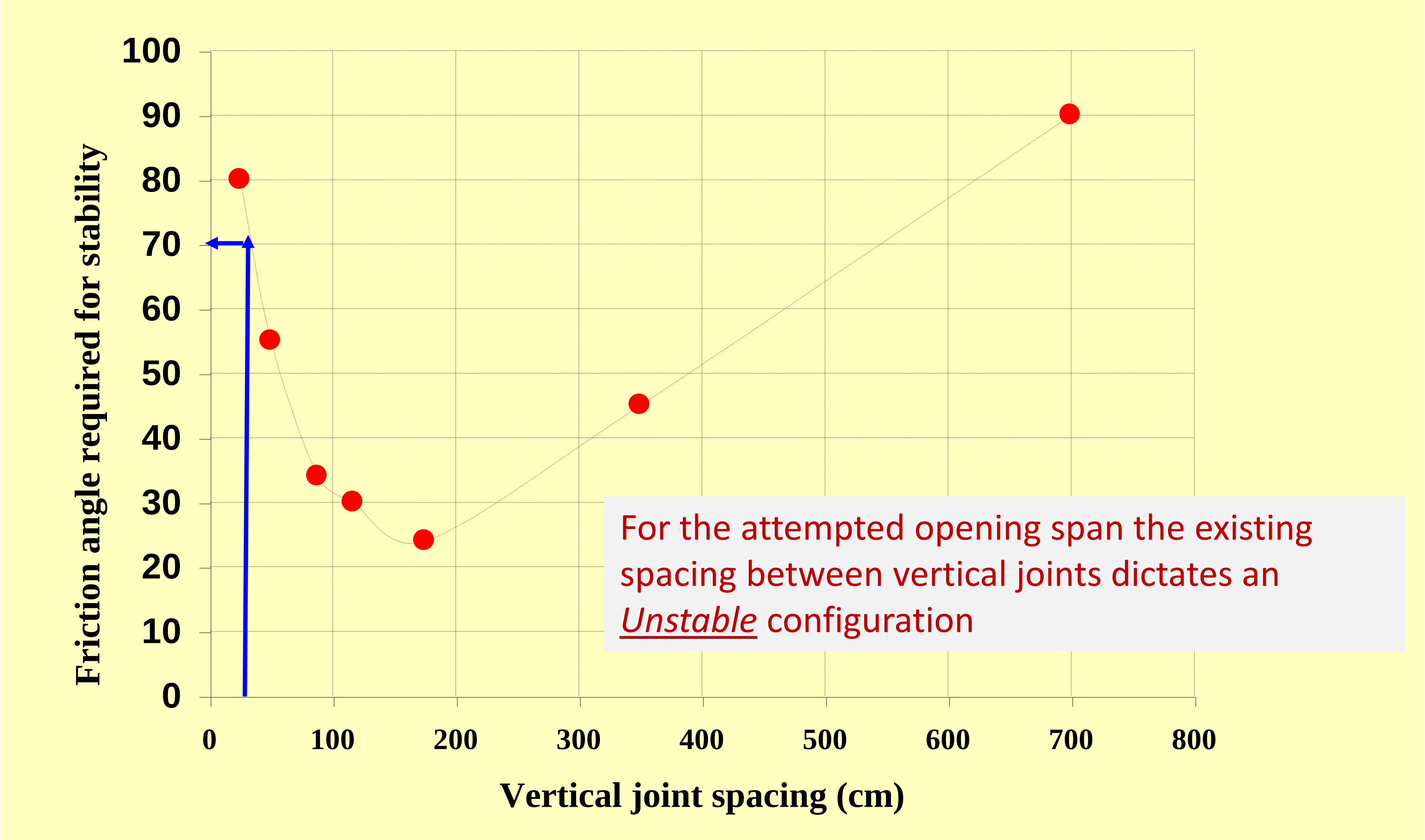
Deformed state

Kinematics of a Layered, Jointed Beam (Laminated Voussoir)

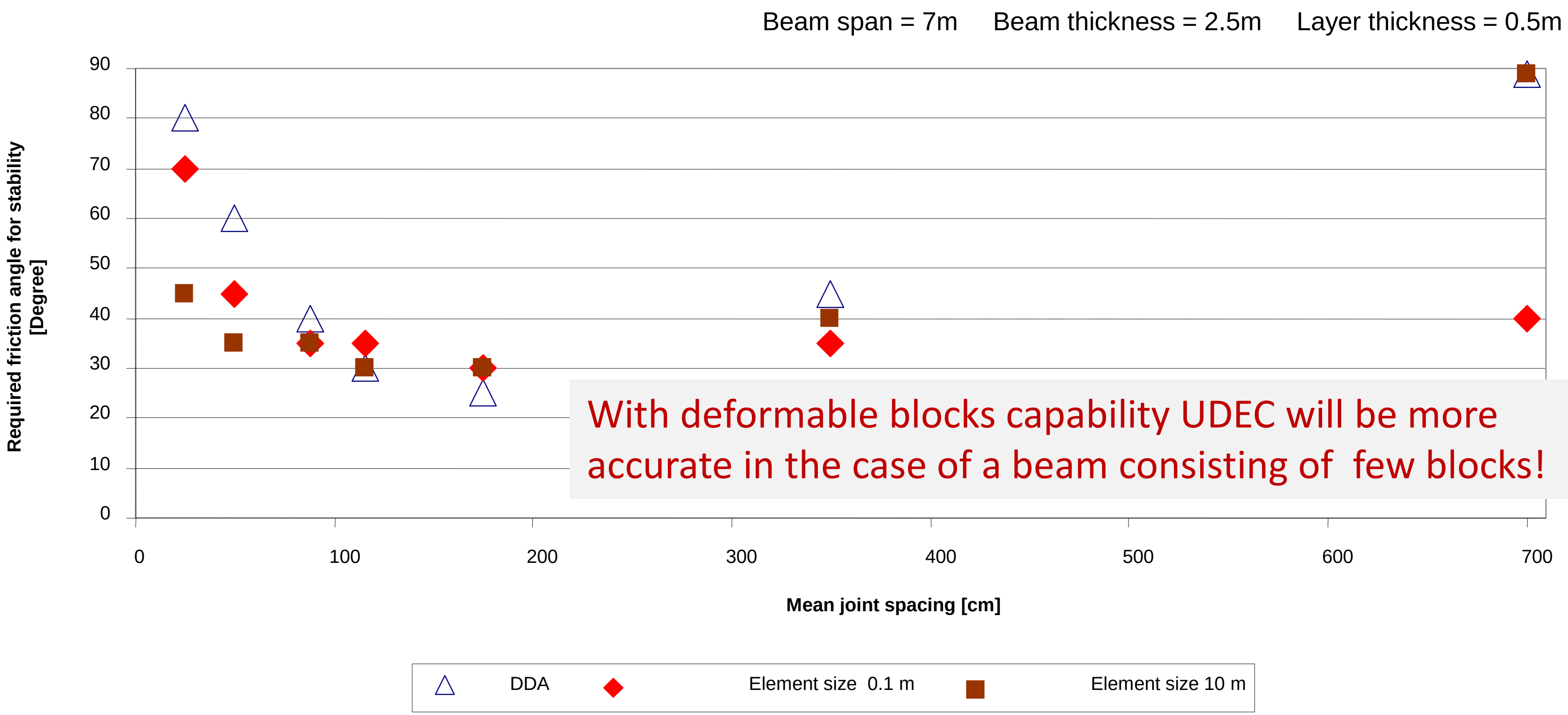
(S = 8m, t = 0.5m, T = 6m, S_j = 0.25m)



Forward DDA modeling results proves to be a function of vertical joint spacing and friction angle



DDA vs. UDEC

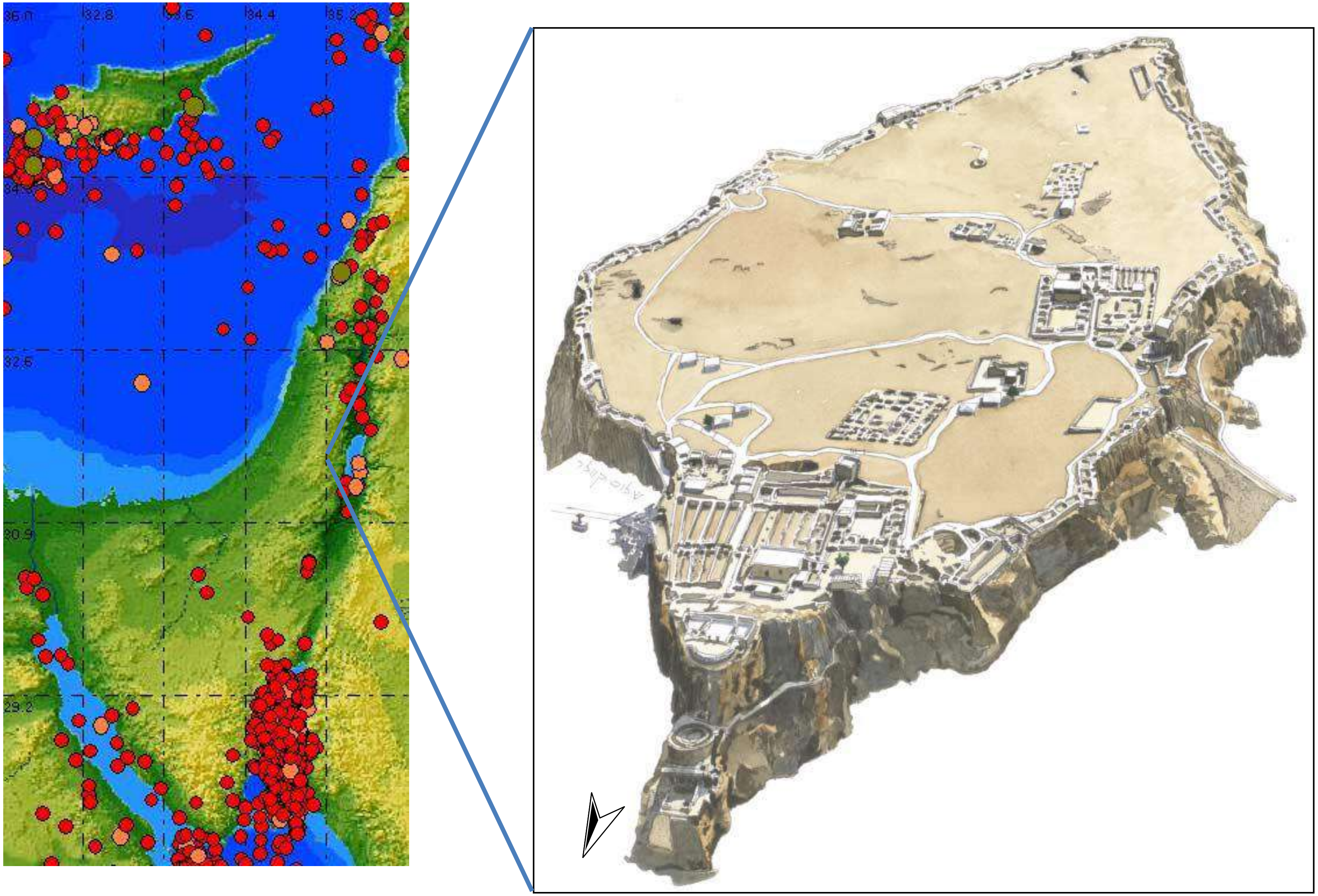


With deformable blocks capability UDEC will be more accurate in the case of a beam consisting of few blocks!

Barla, Monacis, Perino, and Hatzor (2010), *Rock Mechanics & Rock Engineering.*

CONSERVATION OF CULTURAL HERITAGE SITES IN ROCK SLOPES: THE CASE OF MASADA WORLD HERITAGE SITE

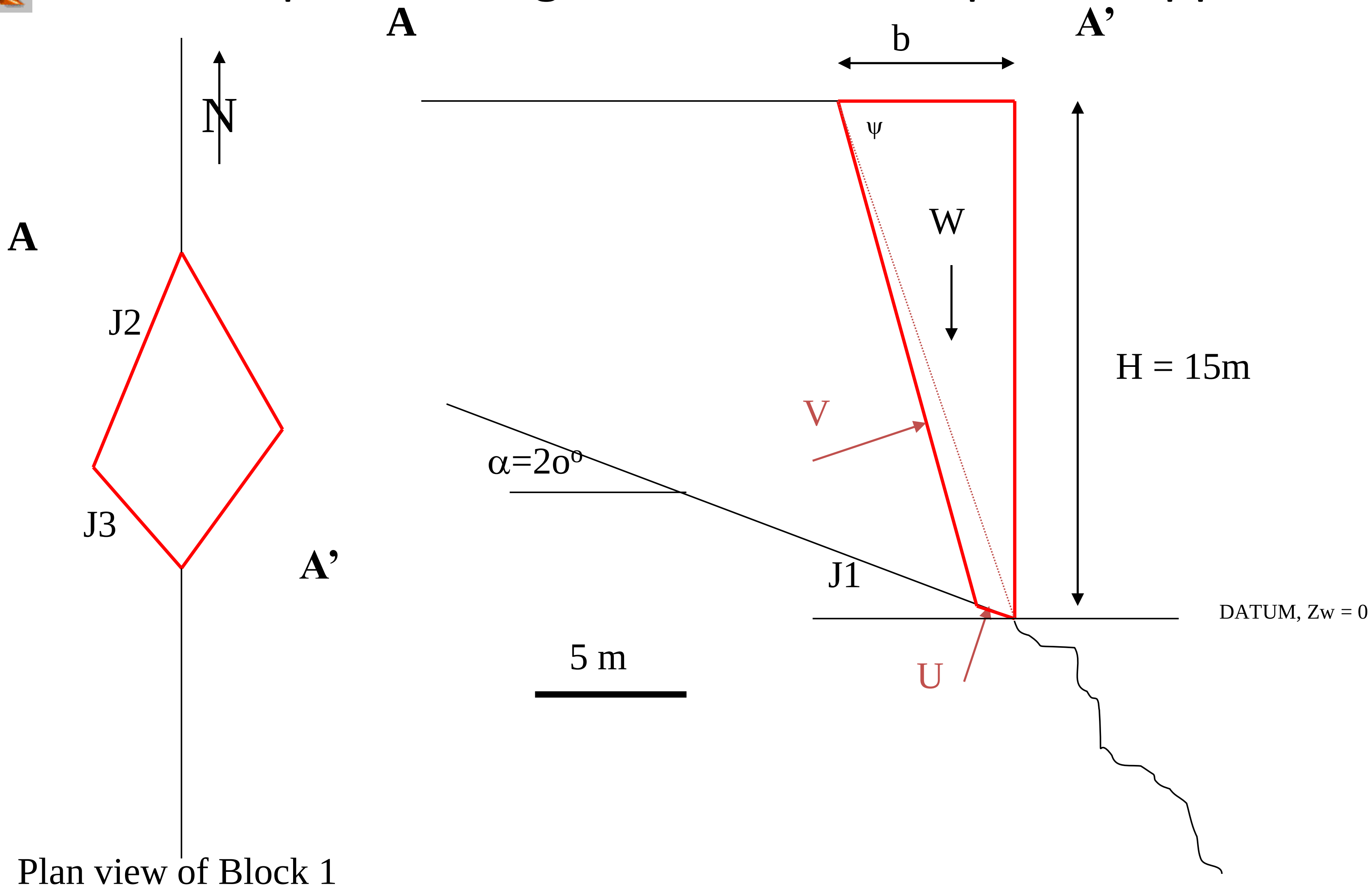
Masada is located in a seismically active zone



Large discrete blocks form the East slope

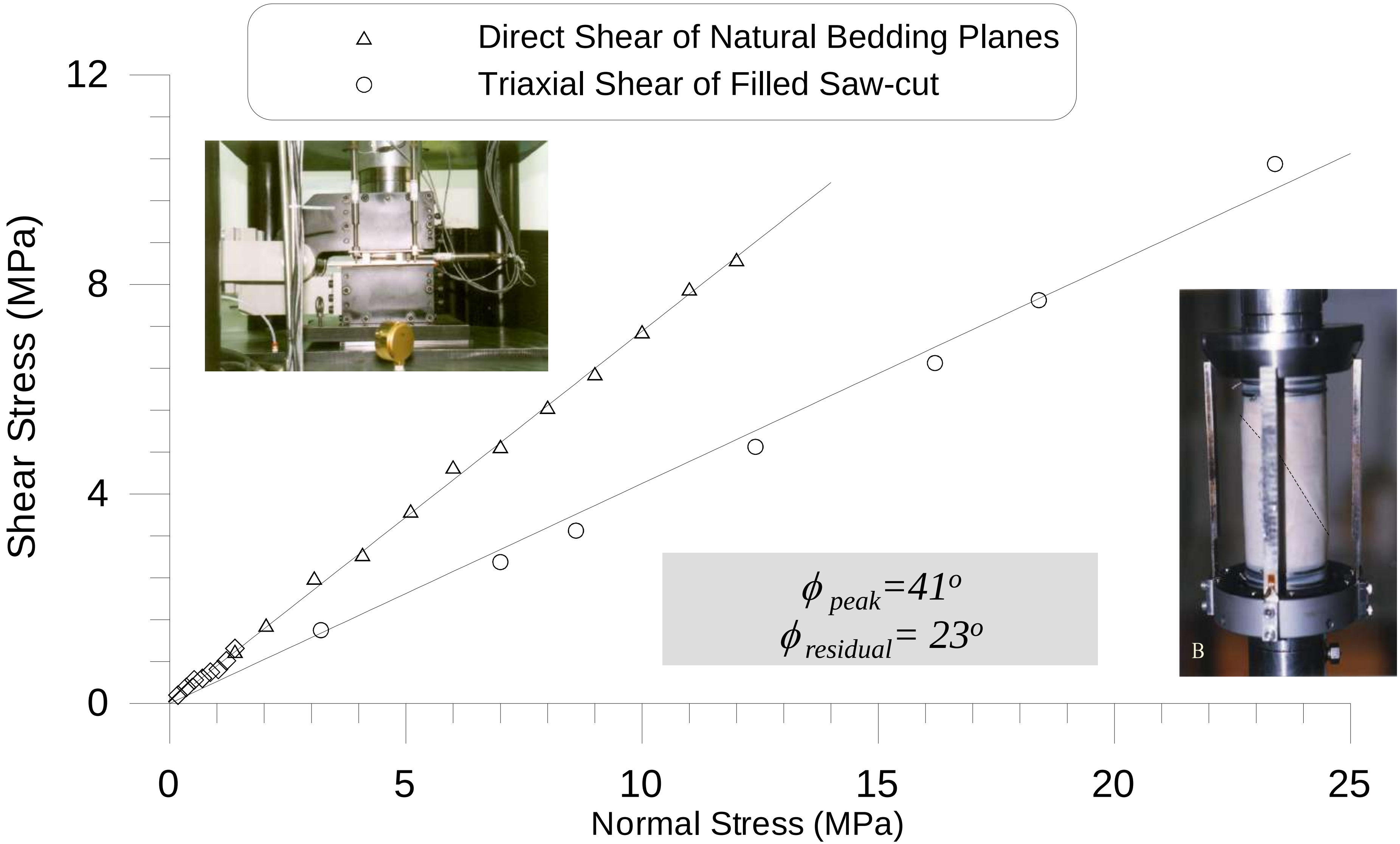
Hatzor, Y. H. 2003. Keyblock stability in seismically active rock slopes – the Snake Path cliff – Masada. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*

Example of a large block which requires support

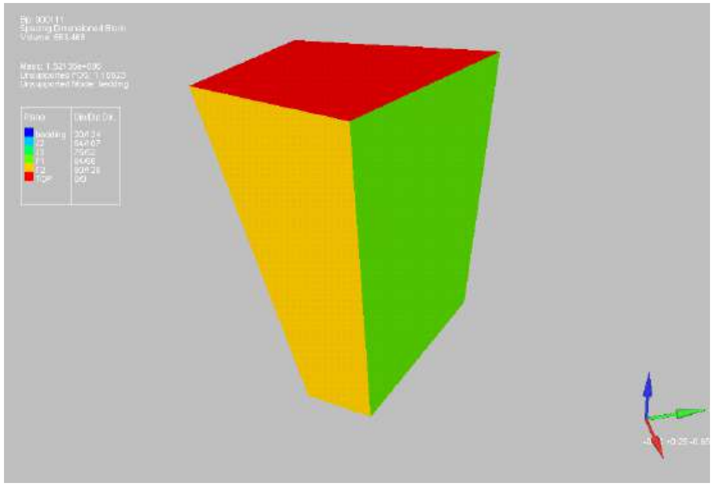


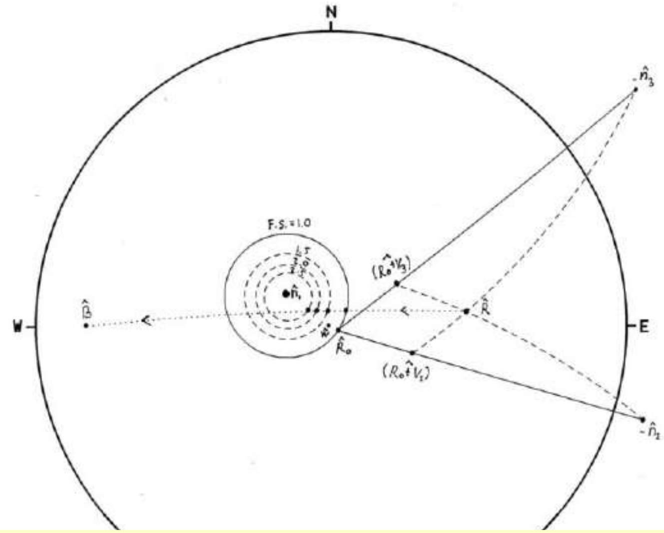
Shear Strength of Discontinuities

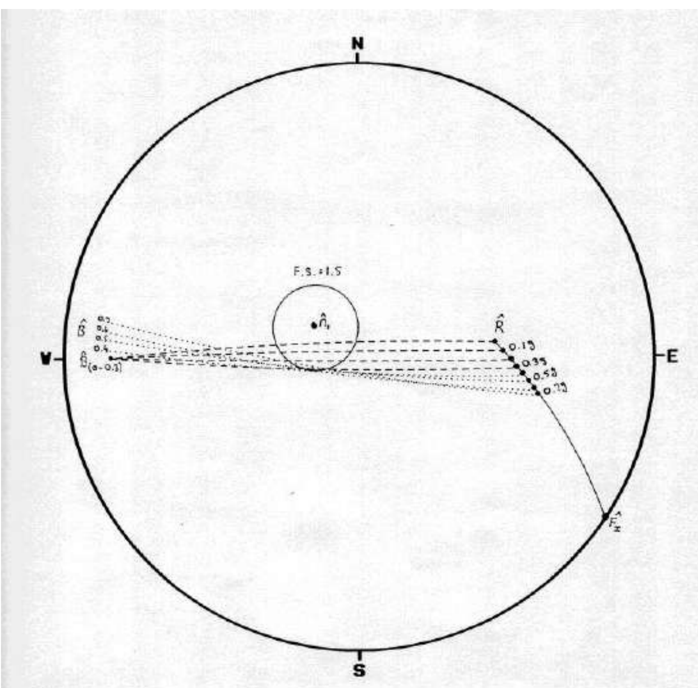
Failure envelope of smooth and rough surfaces

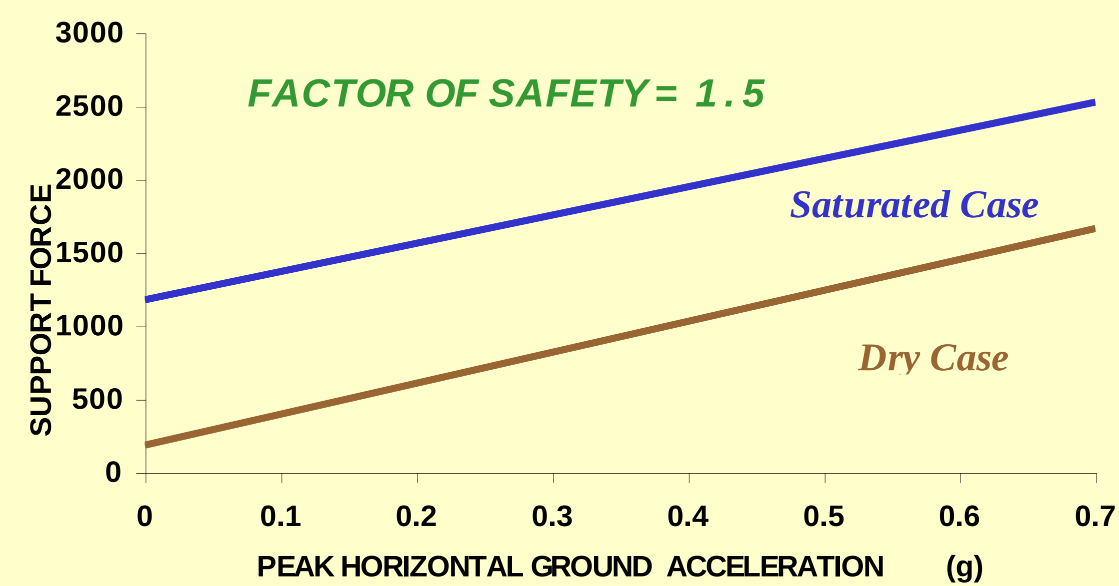


3D pseudo-static LEA assuming plane failure

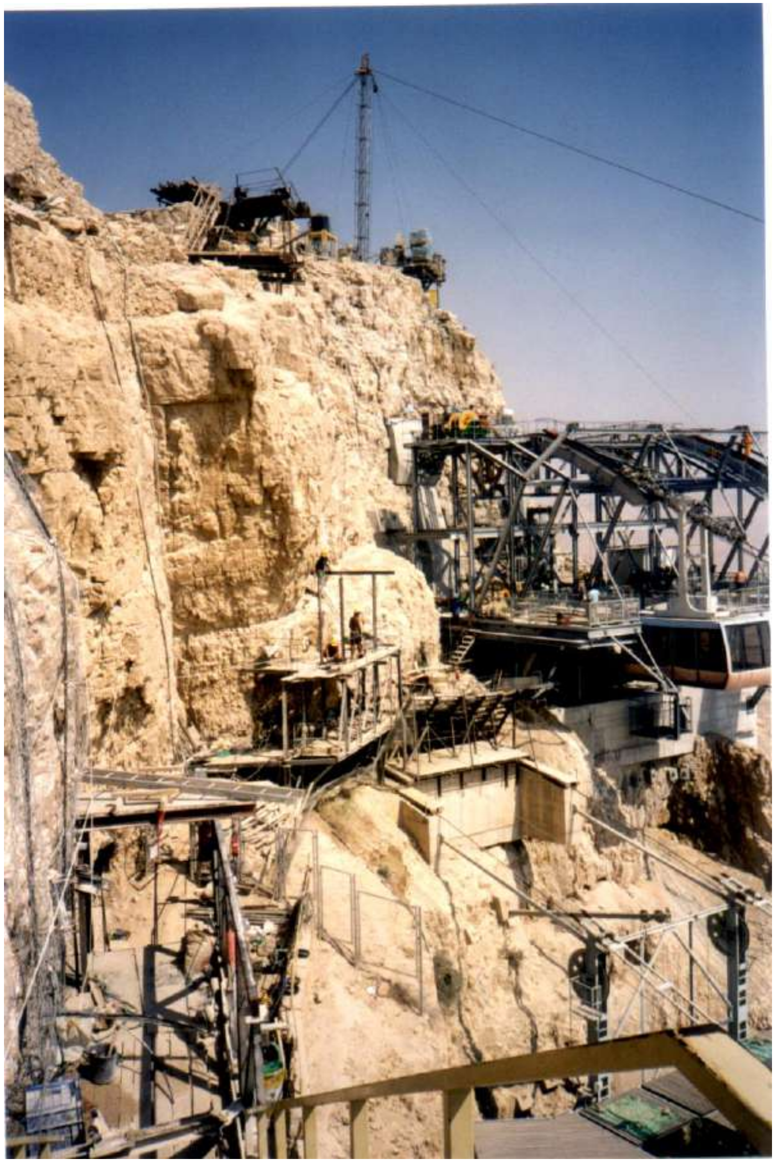






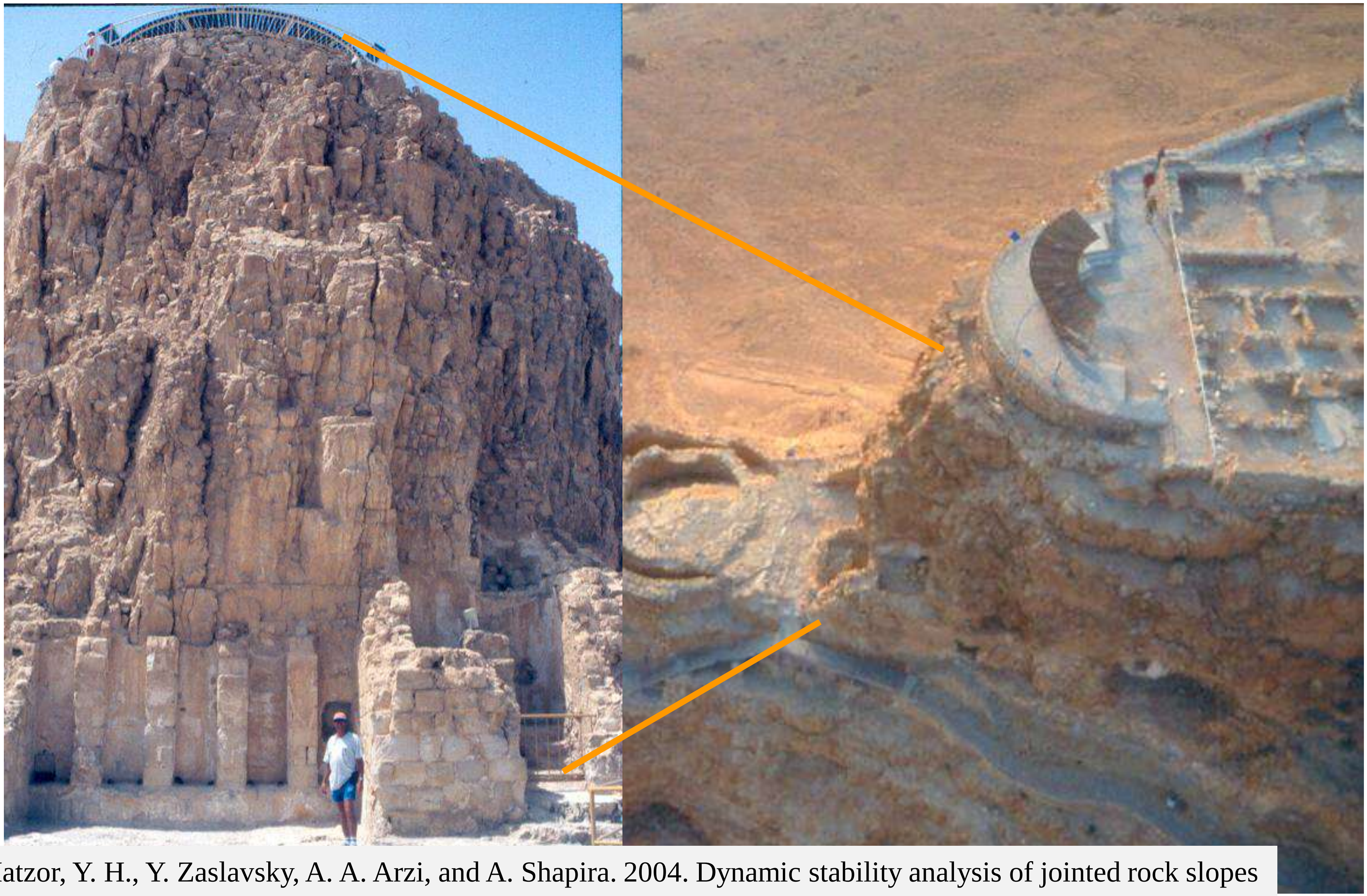


Support Installation



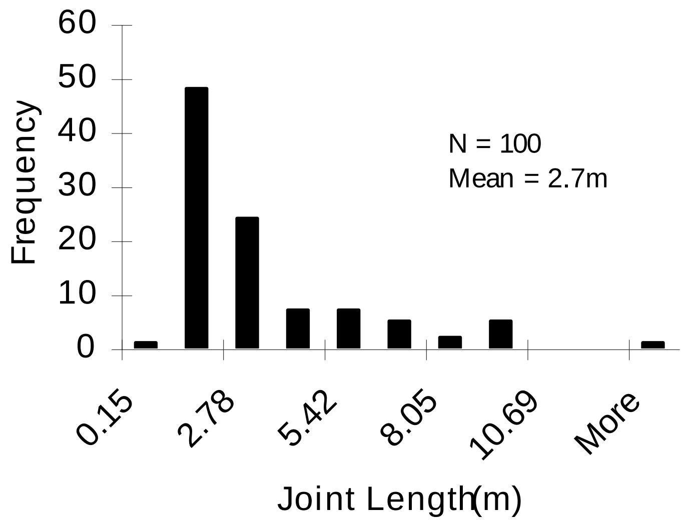
The Final Product at the East Slope

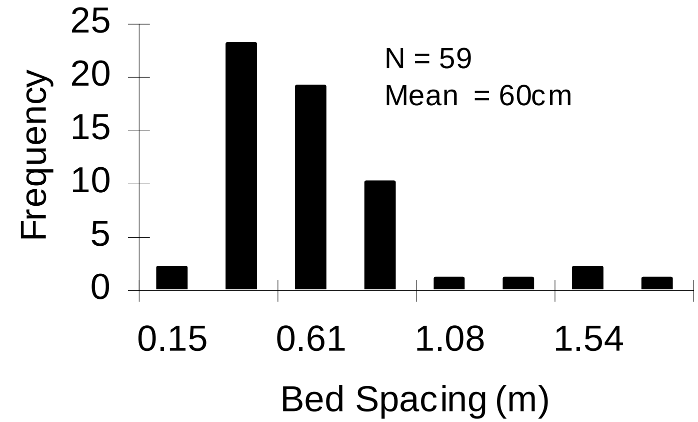
Fully dynamic analysis of multiple blocks

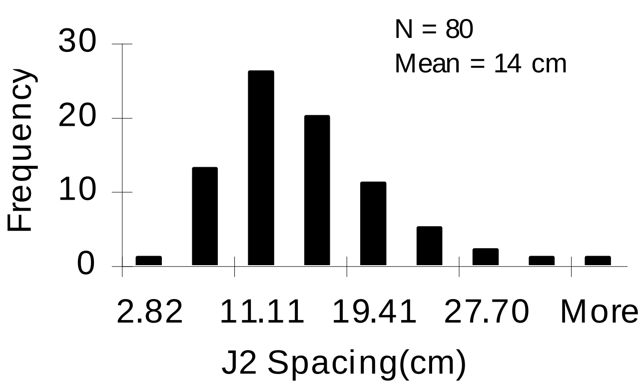


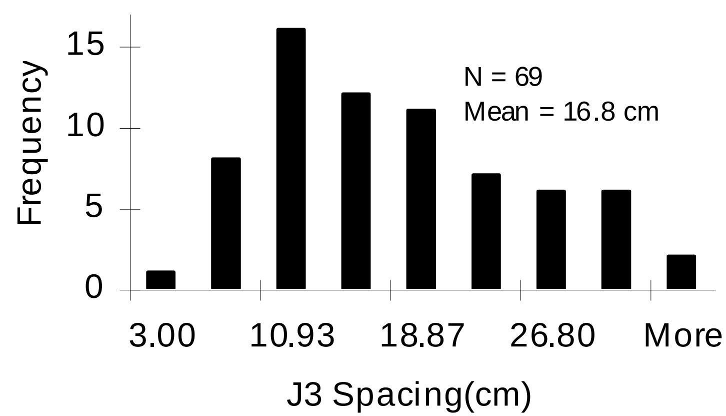
Hatzor, Y. H., Y. Zaslavsky, A. A. Arzi, and A. Shapira. 2004. Dynamic stability analysis of jointed rock slopes using the DDA method: King Herod's palace, Masada. *Int. J. Rock Mech. Min. Sci.*.

Generation of Rock Mass Structure

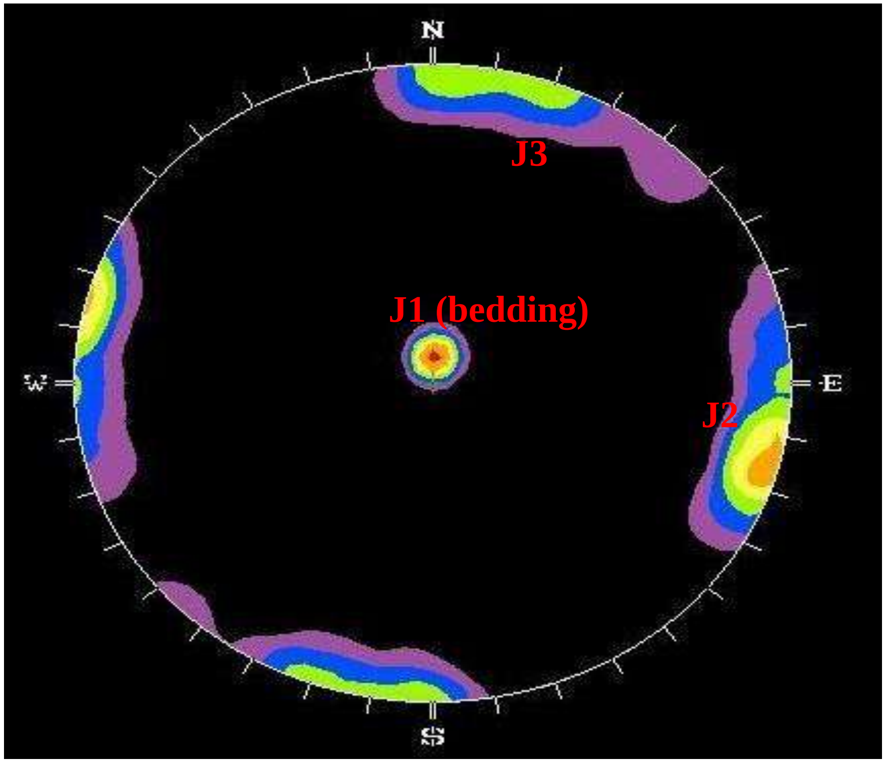


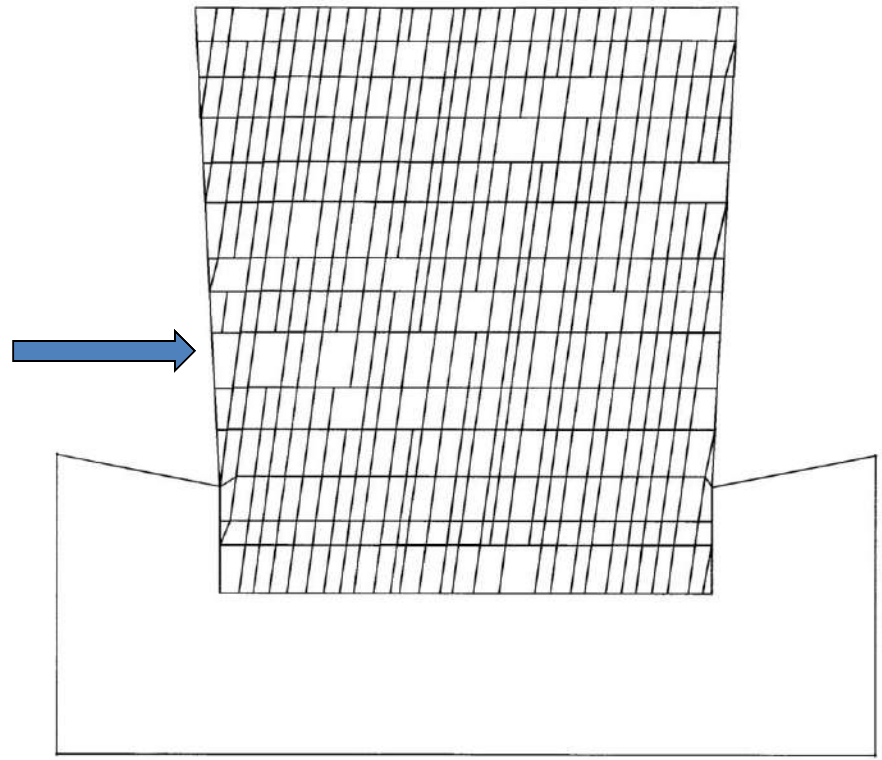




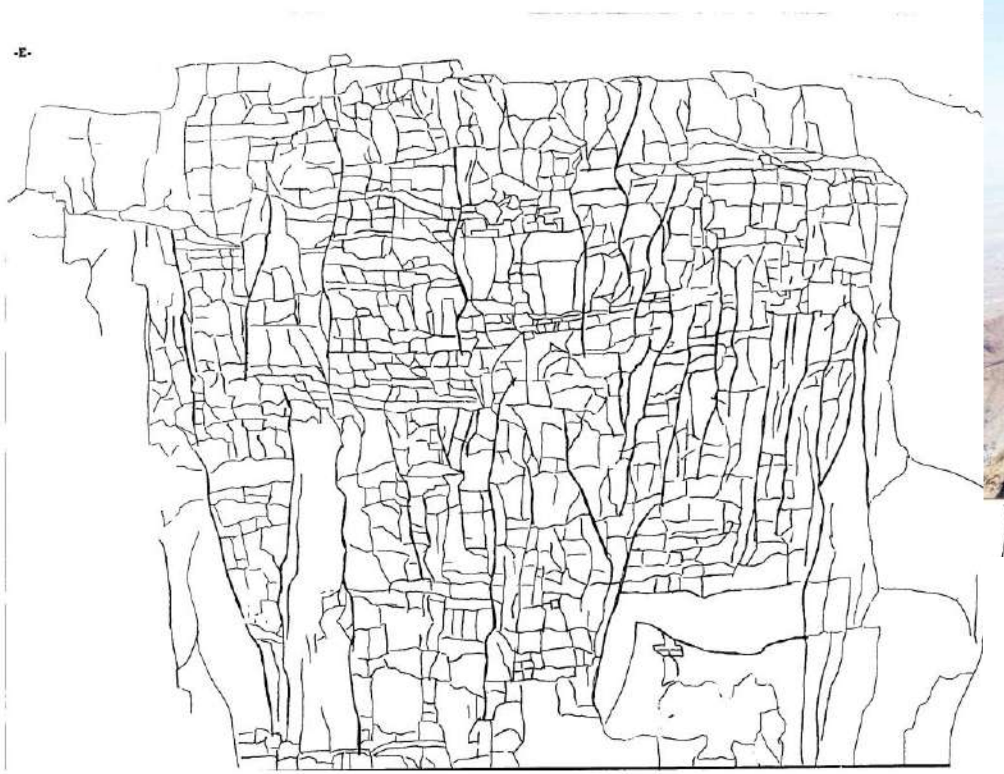


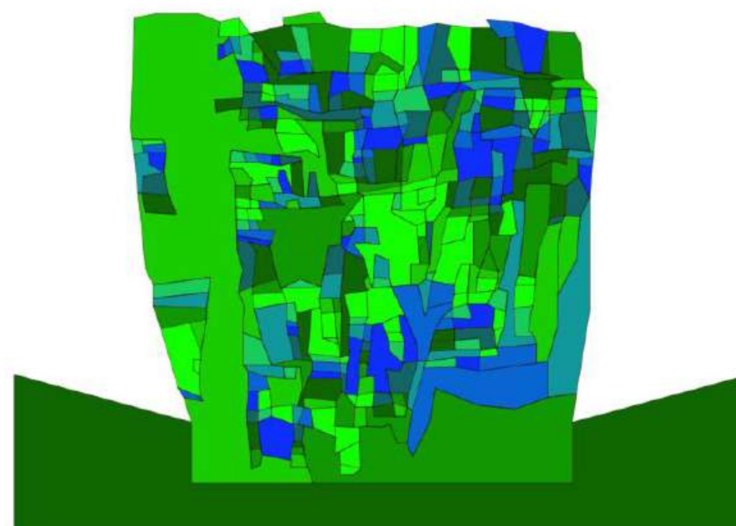
Statistical Joint Trace Generation



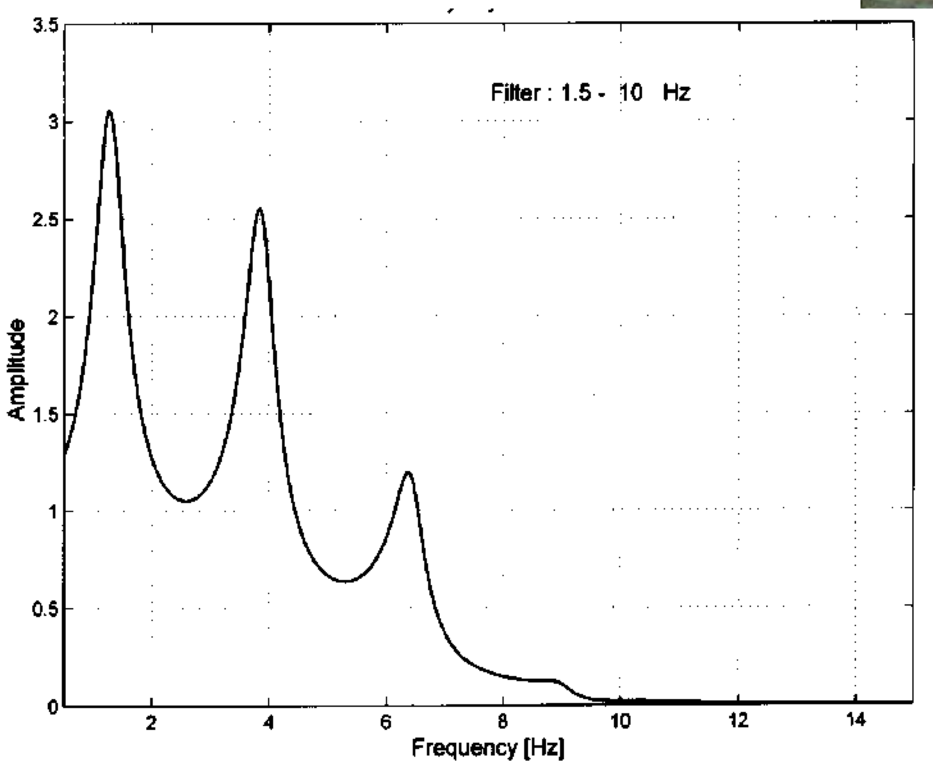


But the reality is more complicated…

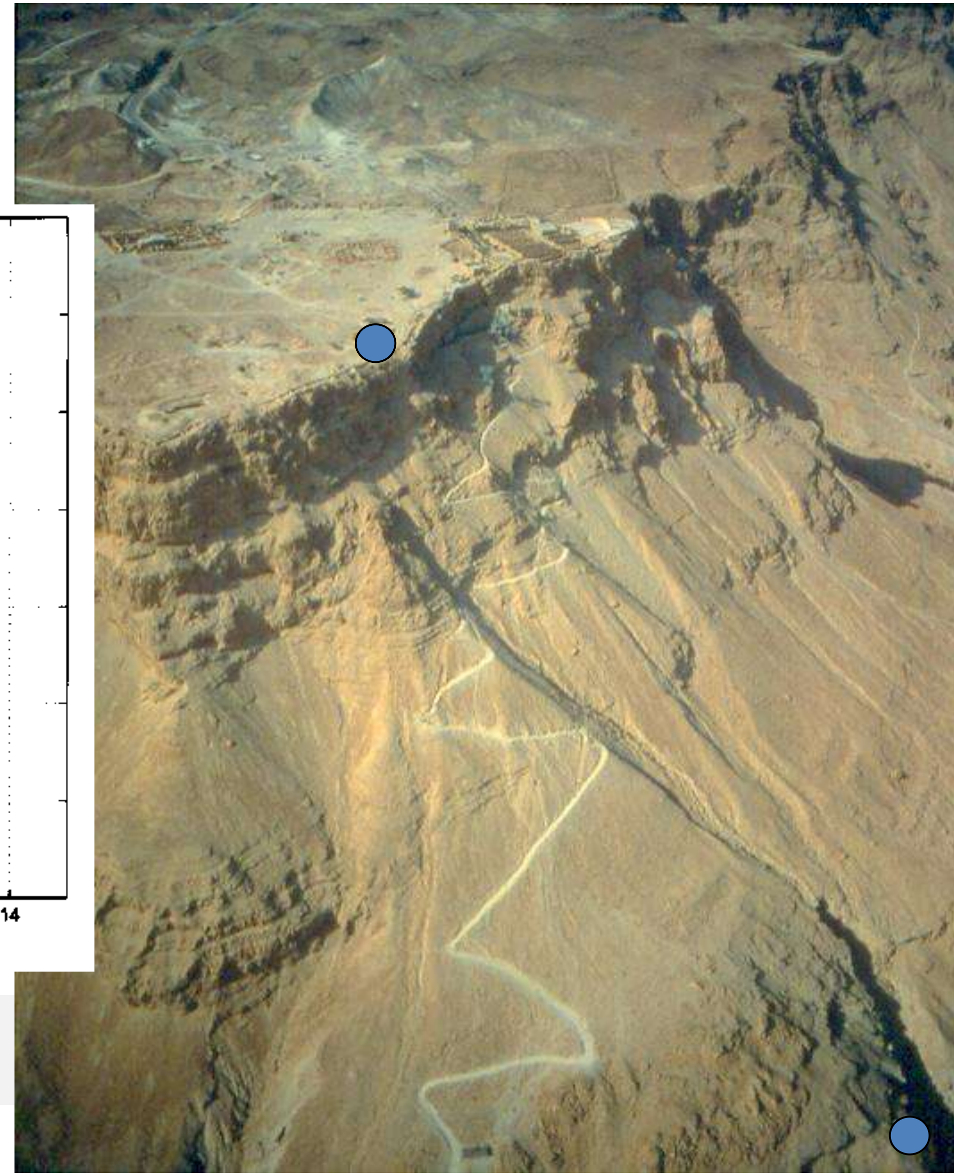




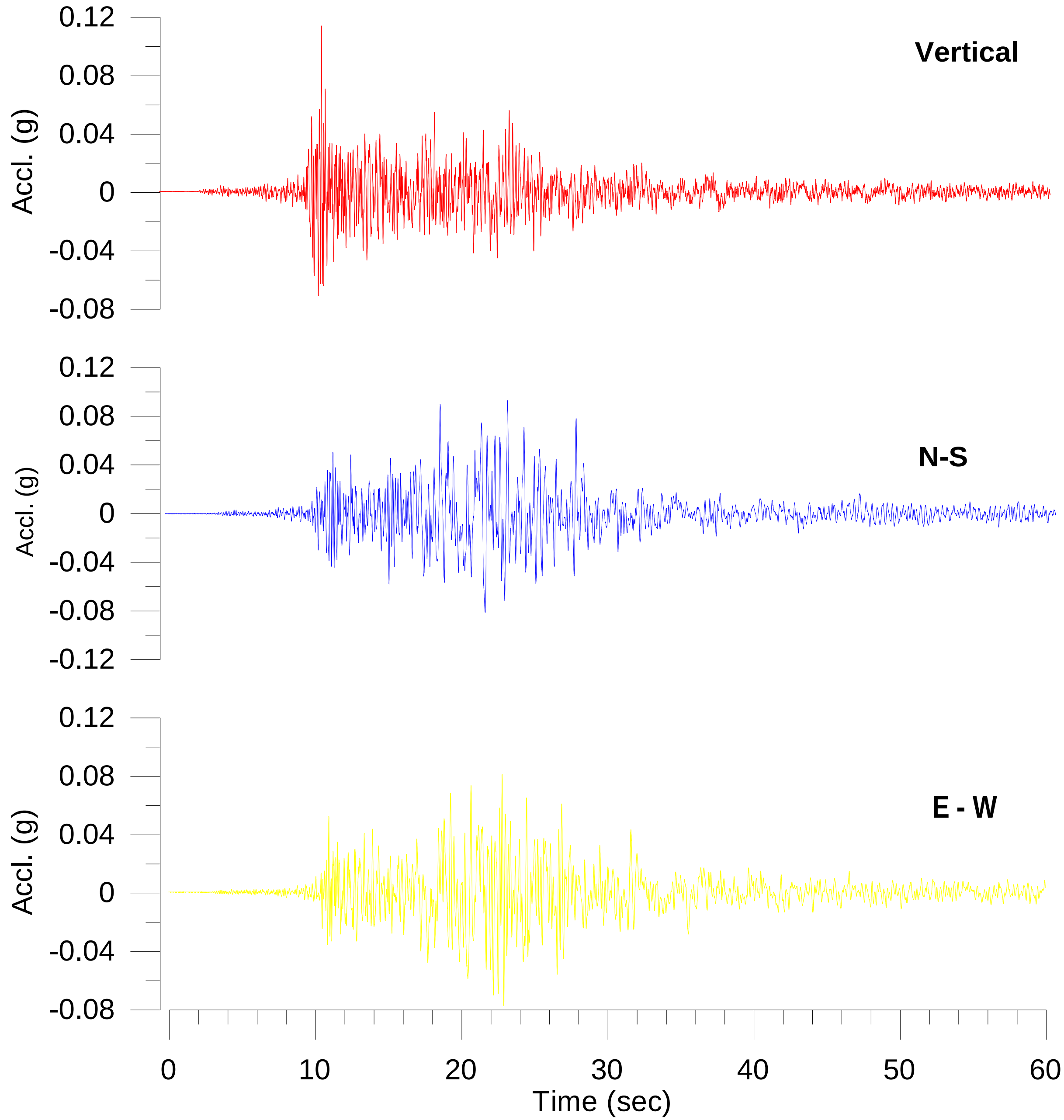
Input Motion: Consideration of Topographic Site Effect



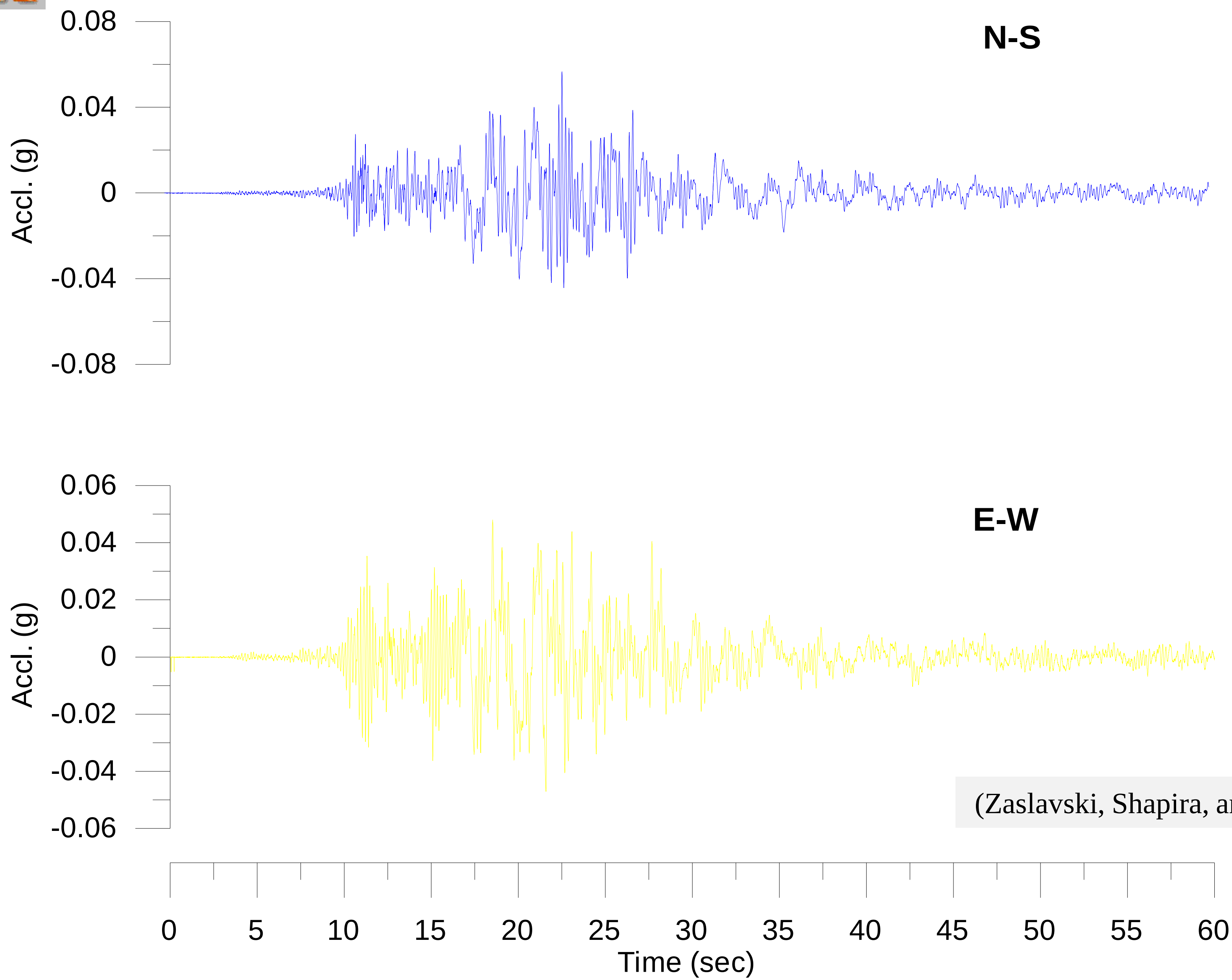
Empirical response function for the topographic site effect at Masada (Zaslavsky and Shapira, 2000).



The Nuweiba 7.1 Earthquake of Nov. 1995

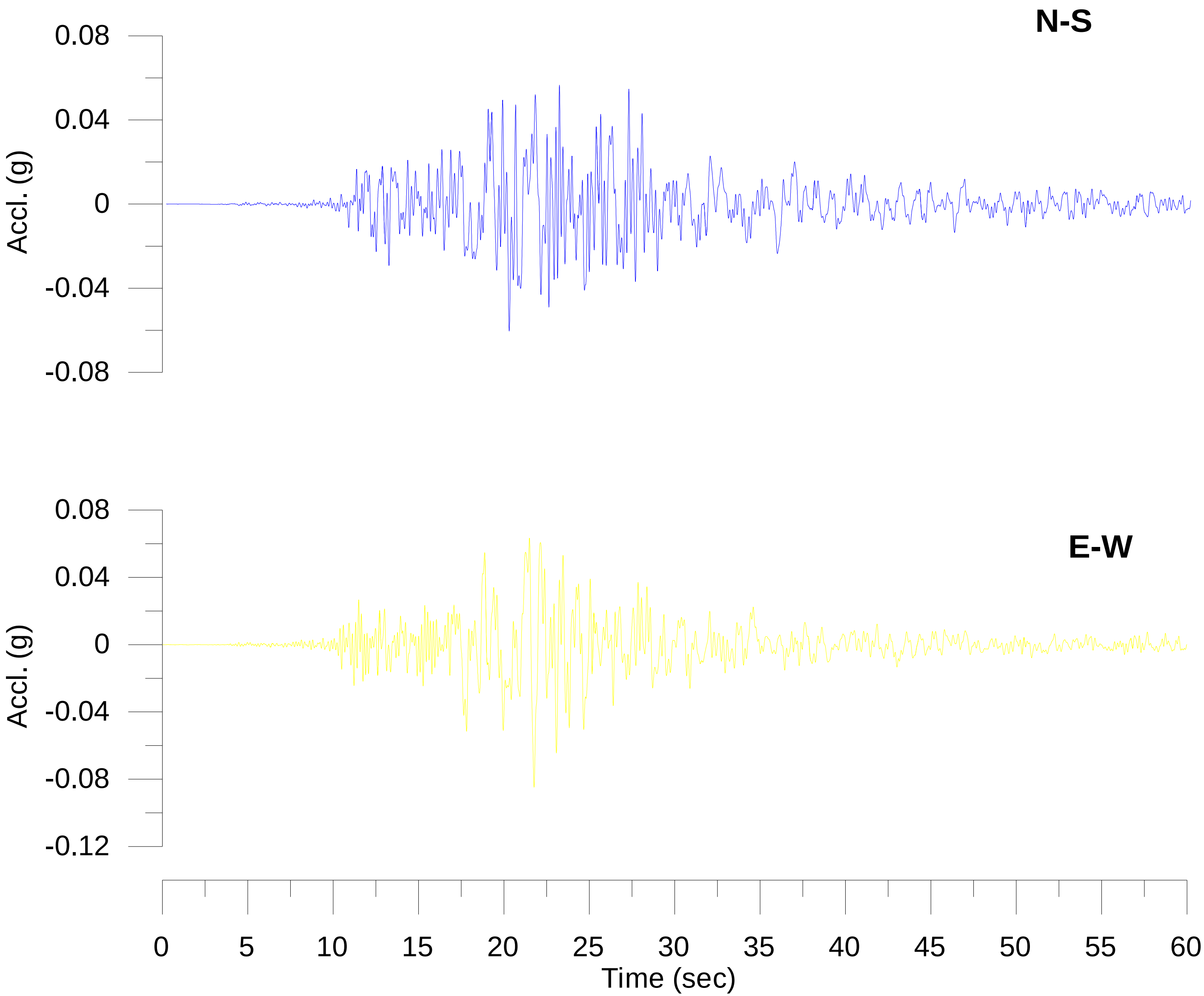


De-convolution: Bed-Rock Response

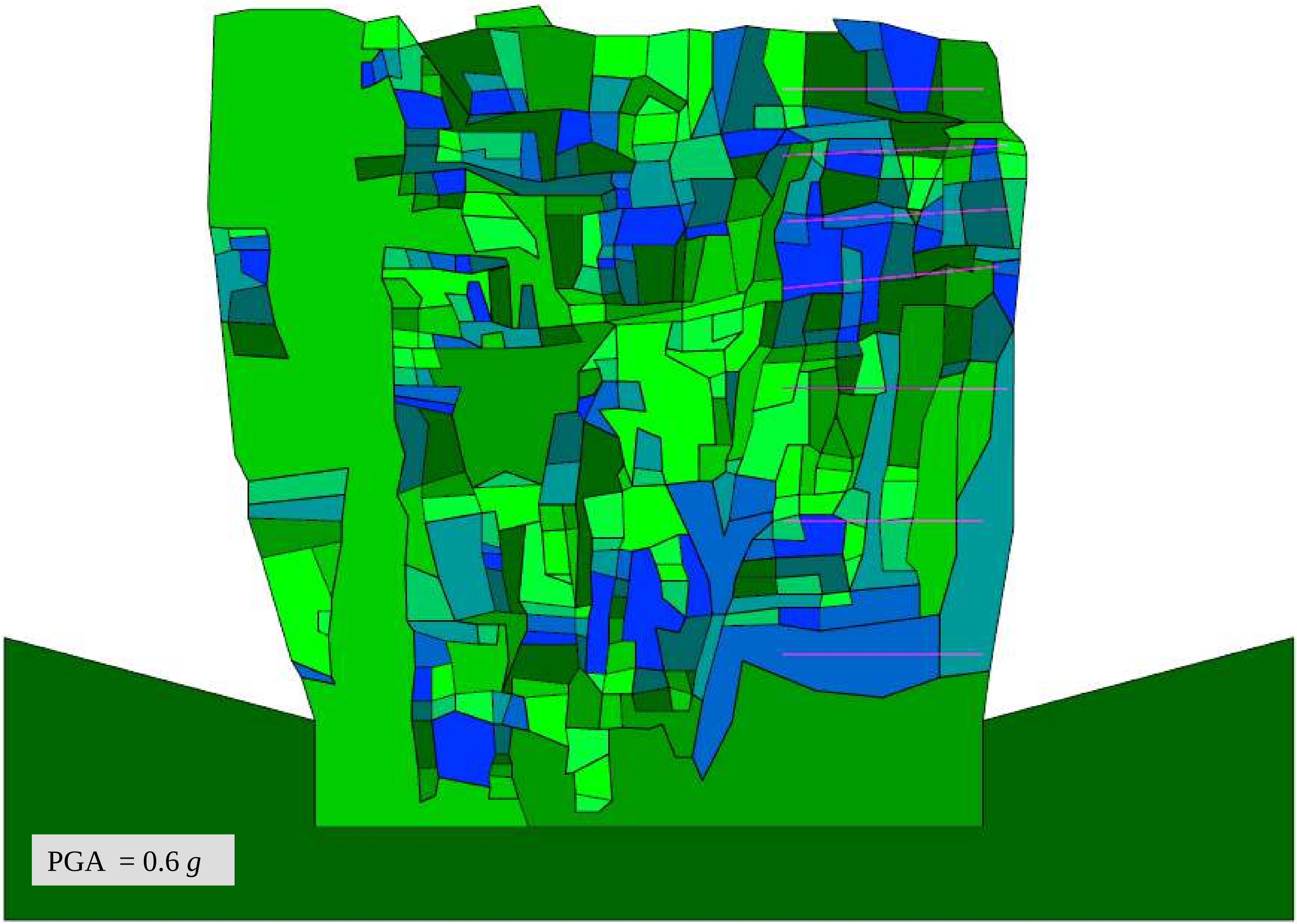


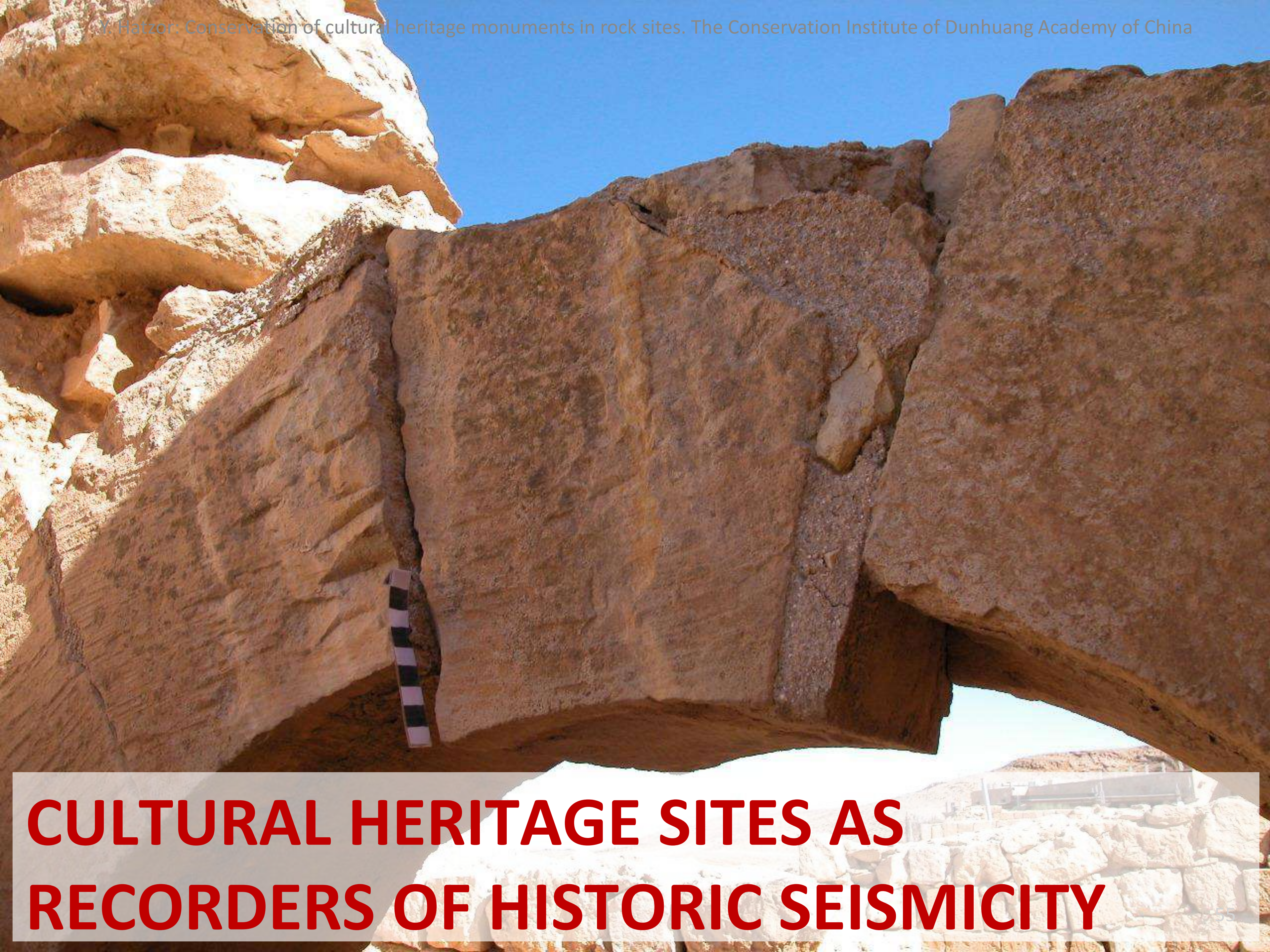
(Zaslavski, Shapira, and Arzi, 2000)

Convolution: Topographic Site Effect



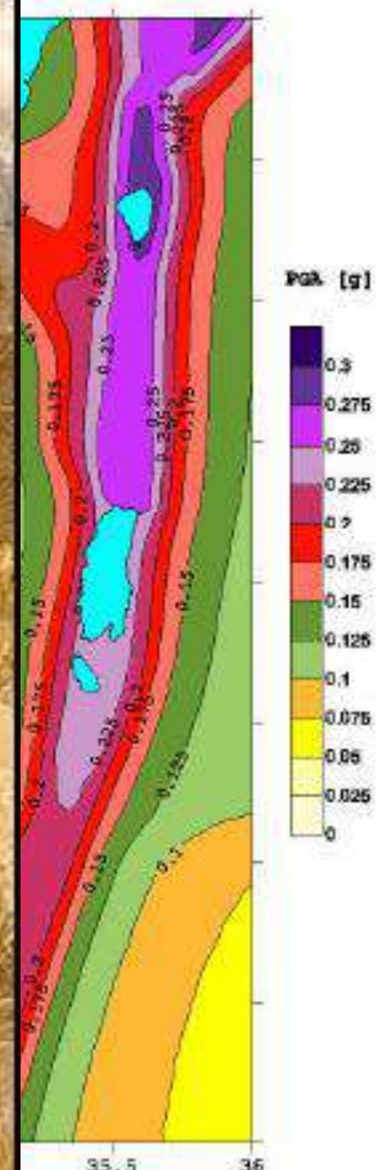
Dynamic DDA Modeling Results





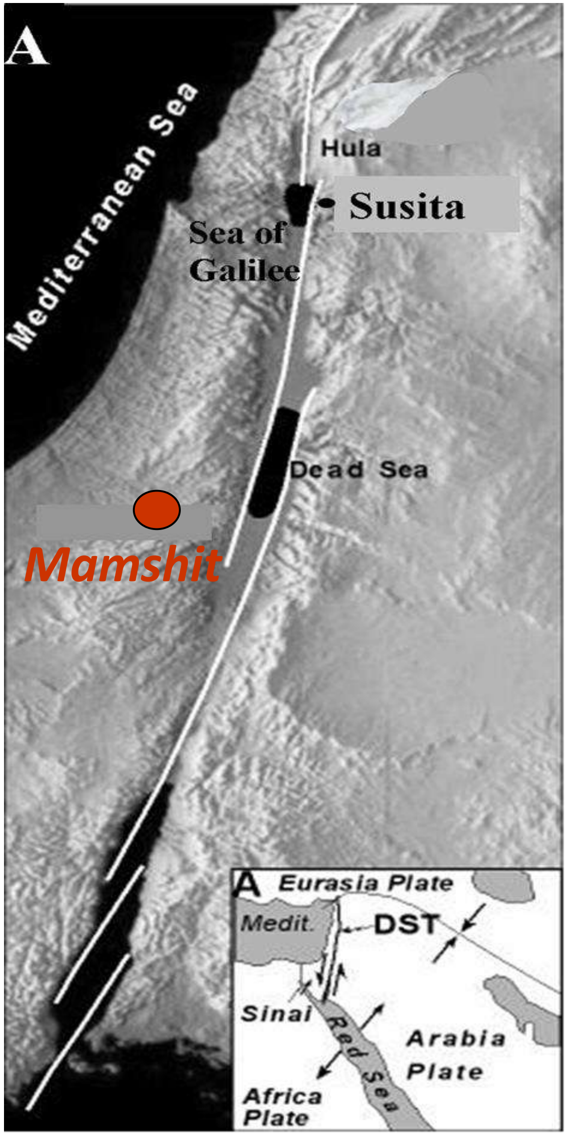
CULTURAL HERITAGE SITES AS RECORDERS OF HISTORIC SEISMICITY

Location Map of Key Sites



Field Evidence of Seismically Driven Failures in Historic Masonry Structures

Mamshit - A Nabatean City (-100 BC to 200 AD)



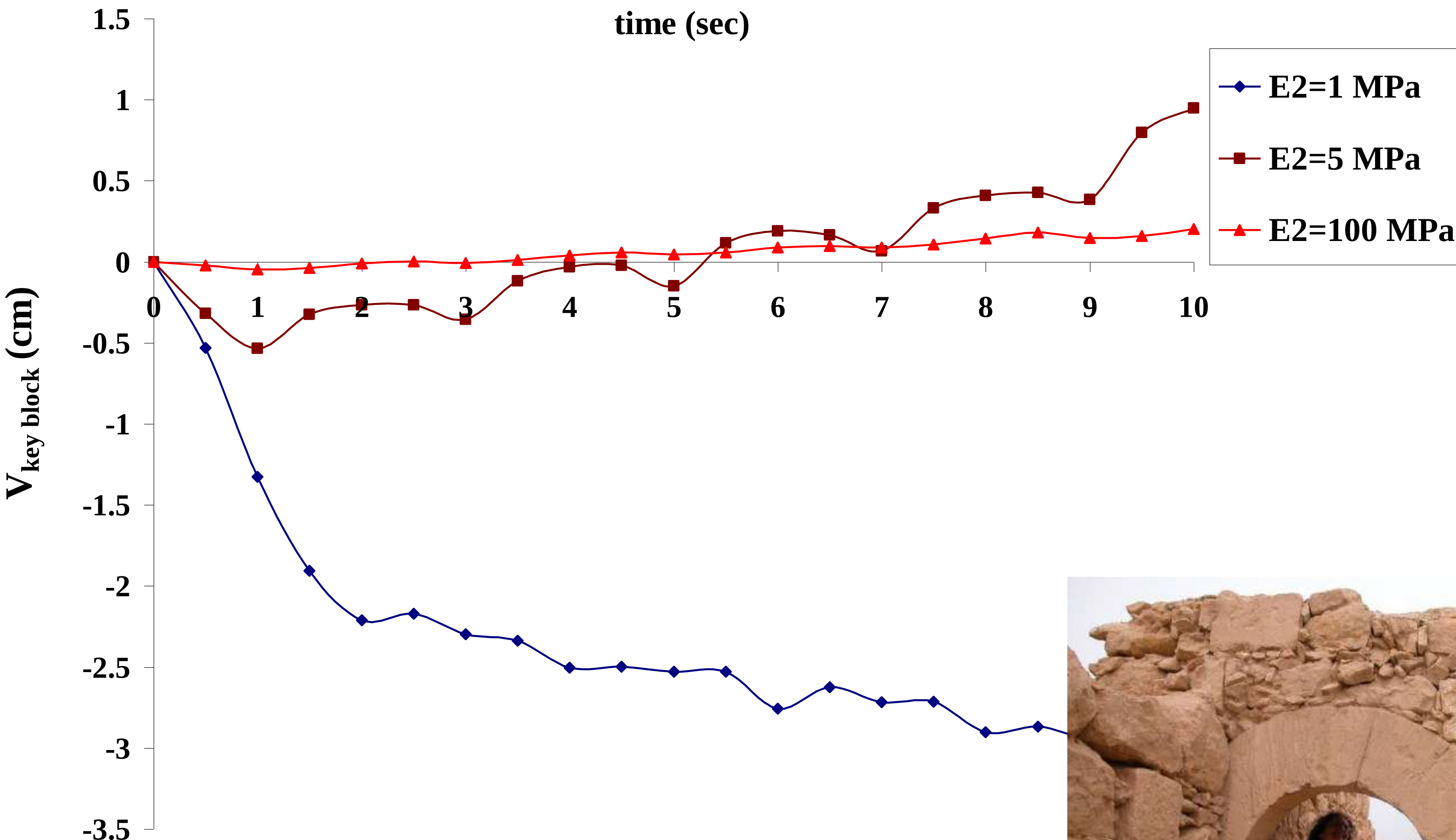
Kamai, R., and Y. H. Hatzor, 2008. Numerical analysis of block stone displacements in ancient masonry structures: a new method to estimate historic ground motions. *International Journal for Numerical and Analytical Methods in Geomechanics*

Generation of DDA mesh

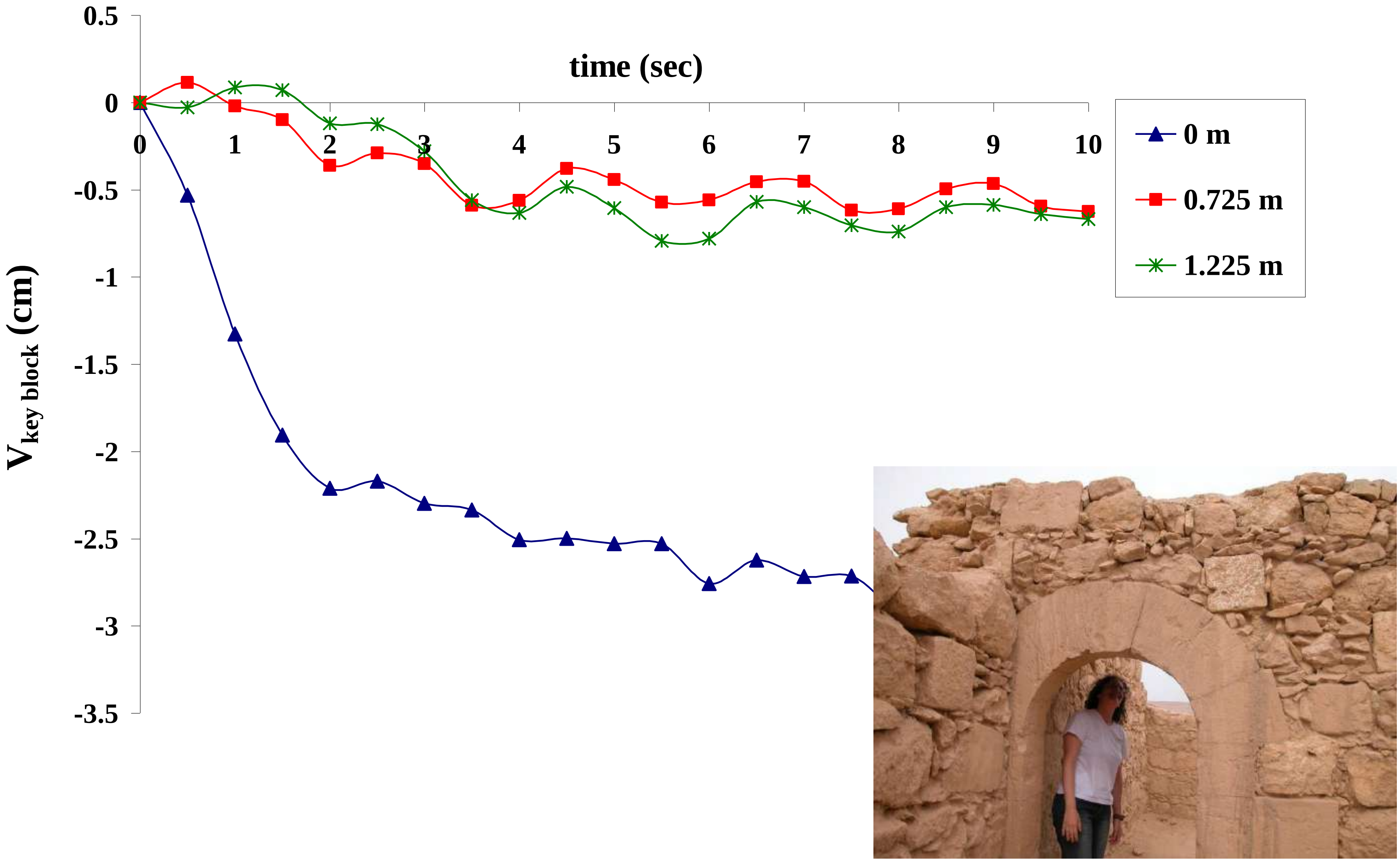
The model:
- heterogeneous wall - material lines define different parameters for arch and wall
- fixed points in foundation block
- measurement point in keystone

Influence of wall stiffness

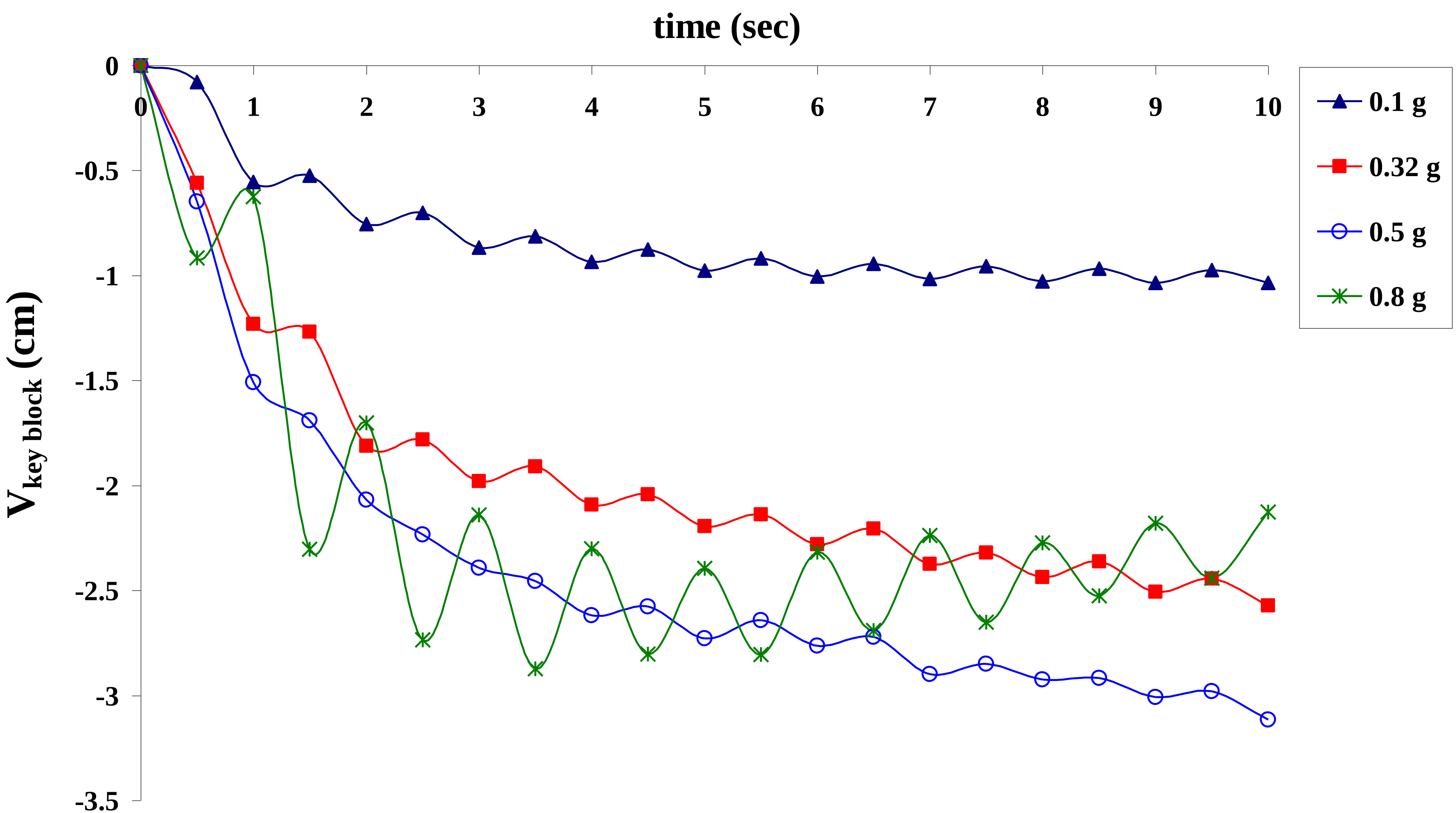
f = 1.5 Hz, A = 0.5 g, E_{arch}=17 GPa



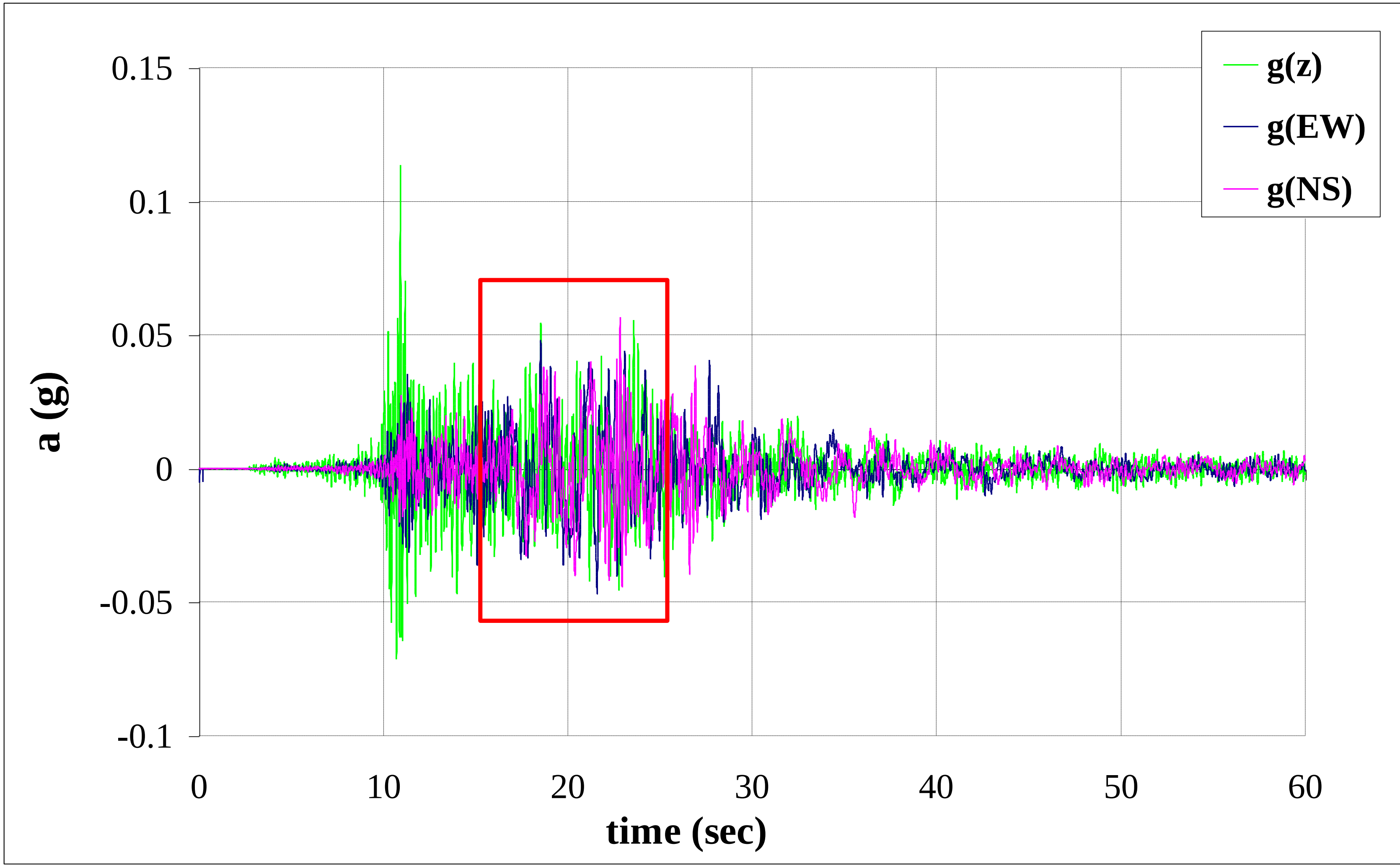
Influence of overburden (h)
f = 1.5 Hz, A = 0.5 *g*



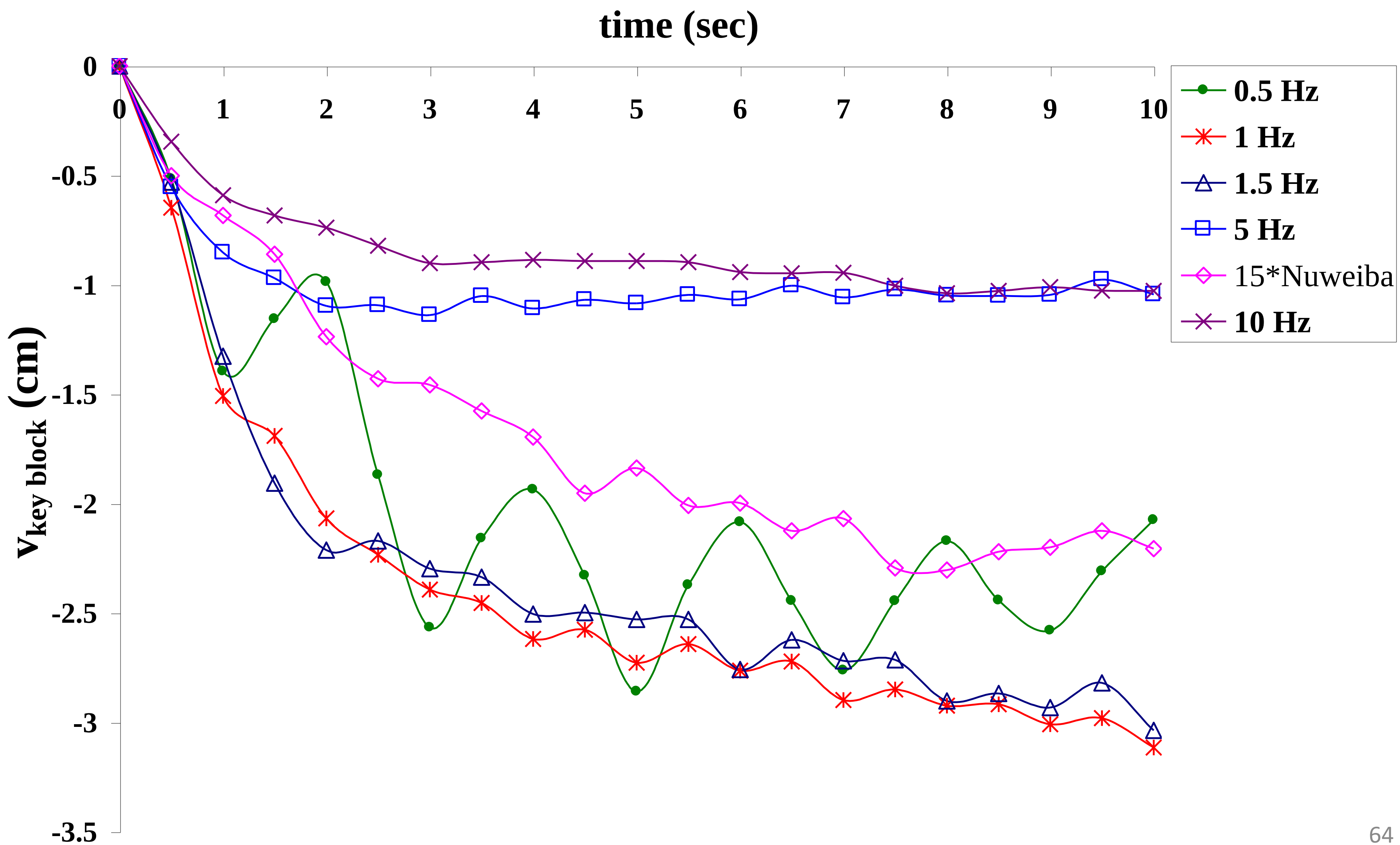
Influence of input motion amplitude (A)
f = 1 Hz



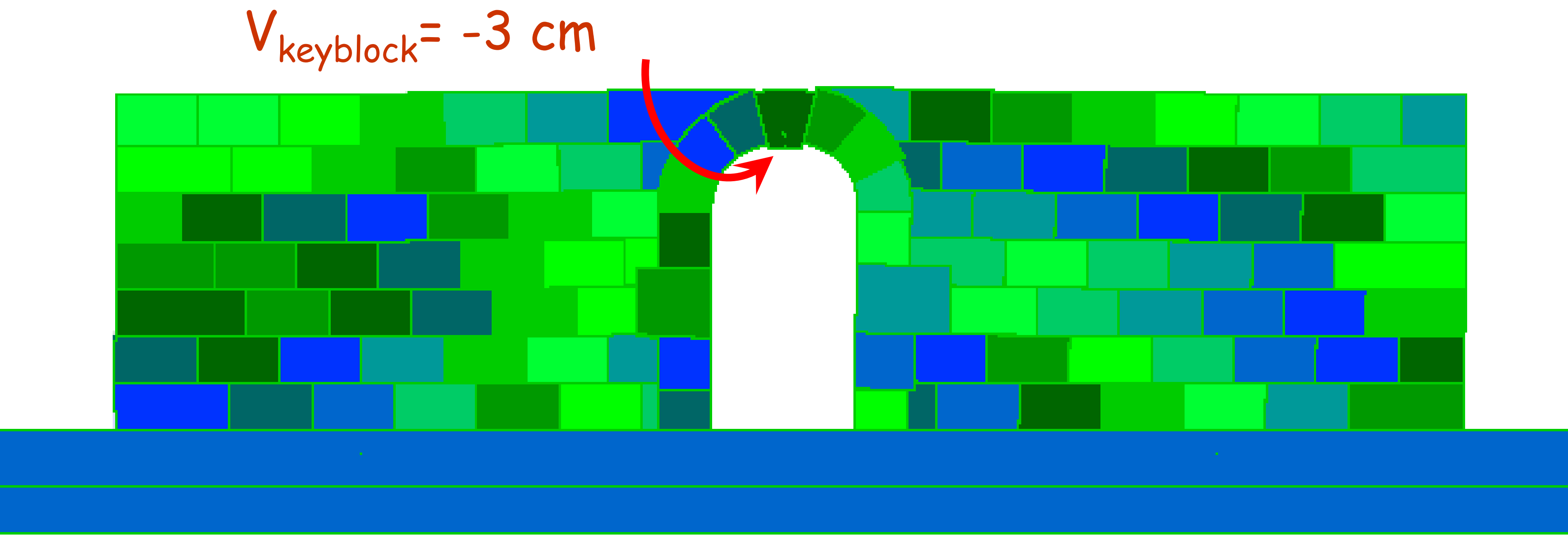
Input motion, the M = 7.1 Nuweiba earthquake



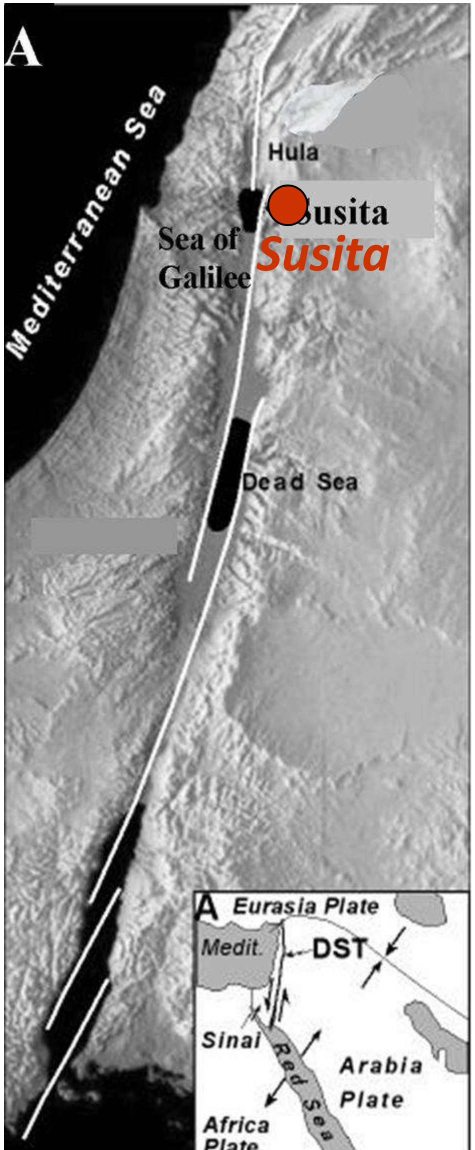
Influence of input frequency (*f*)
A = 0.5 *g*



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

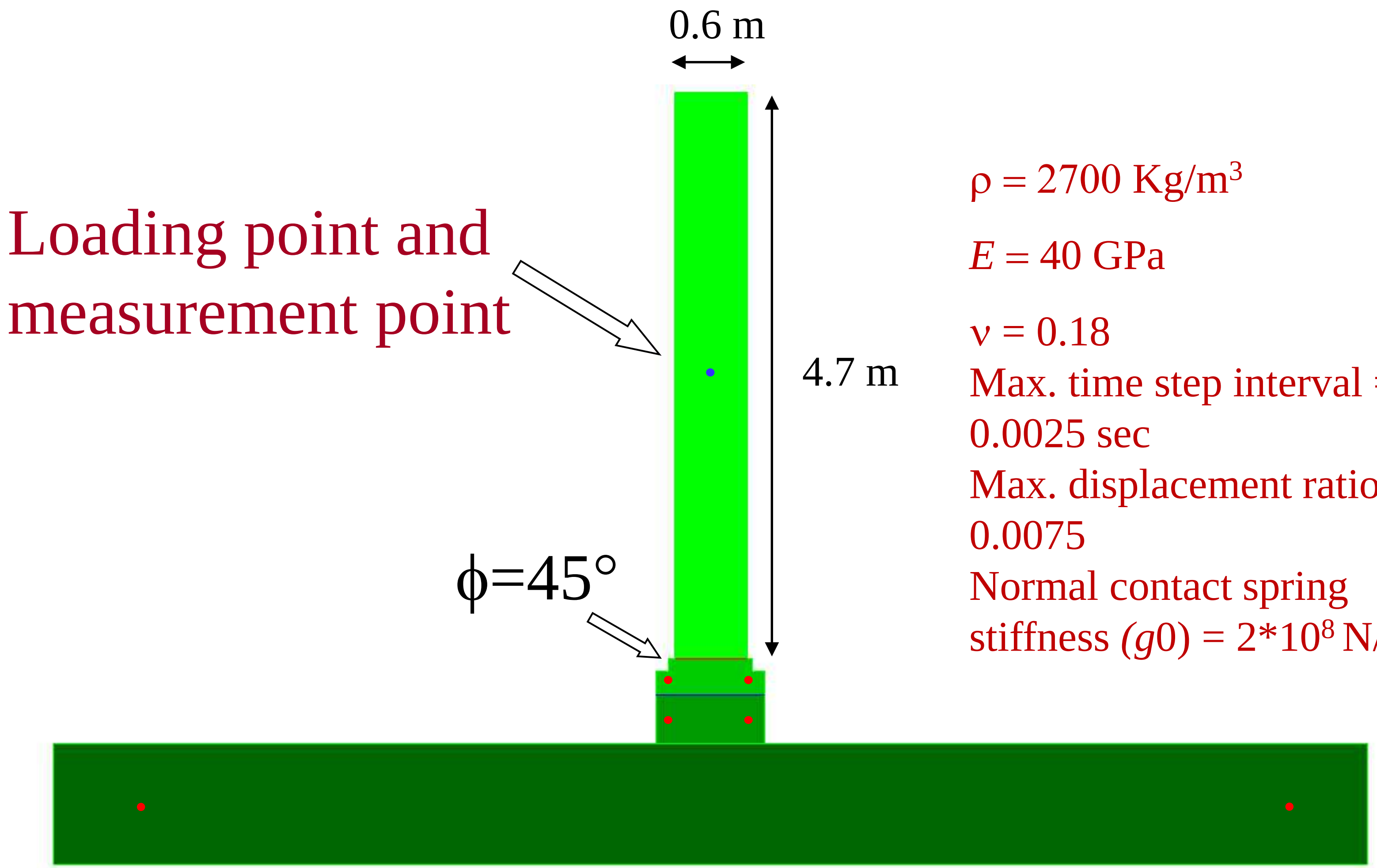


Susita - Byzantine Cathedral (591 A.D)



Yagoda-Biran, G. and Y. H. Hatzor. 2010. Constraining paleo PGA values by numerical analysis of overturned columns. *Earthquake Engineering and Structural Dynamics*

DDA model for free standing column



ρ = 2700 Kg/m^3

E = 40 GPa

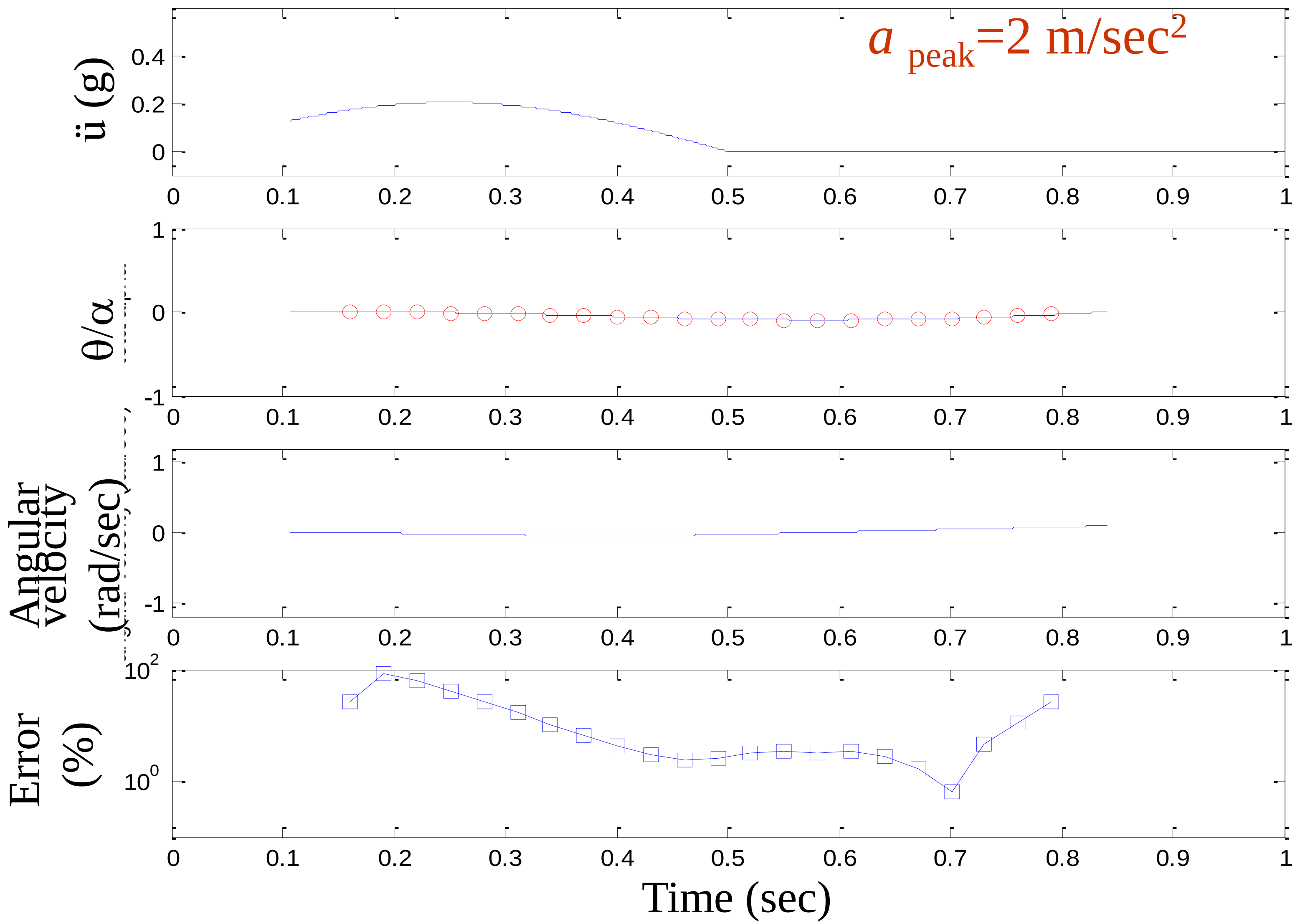
ν = 0.18

Max. time step interval = 0.0025 sec

Max. displacement ratio = 0.0075

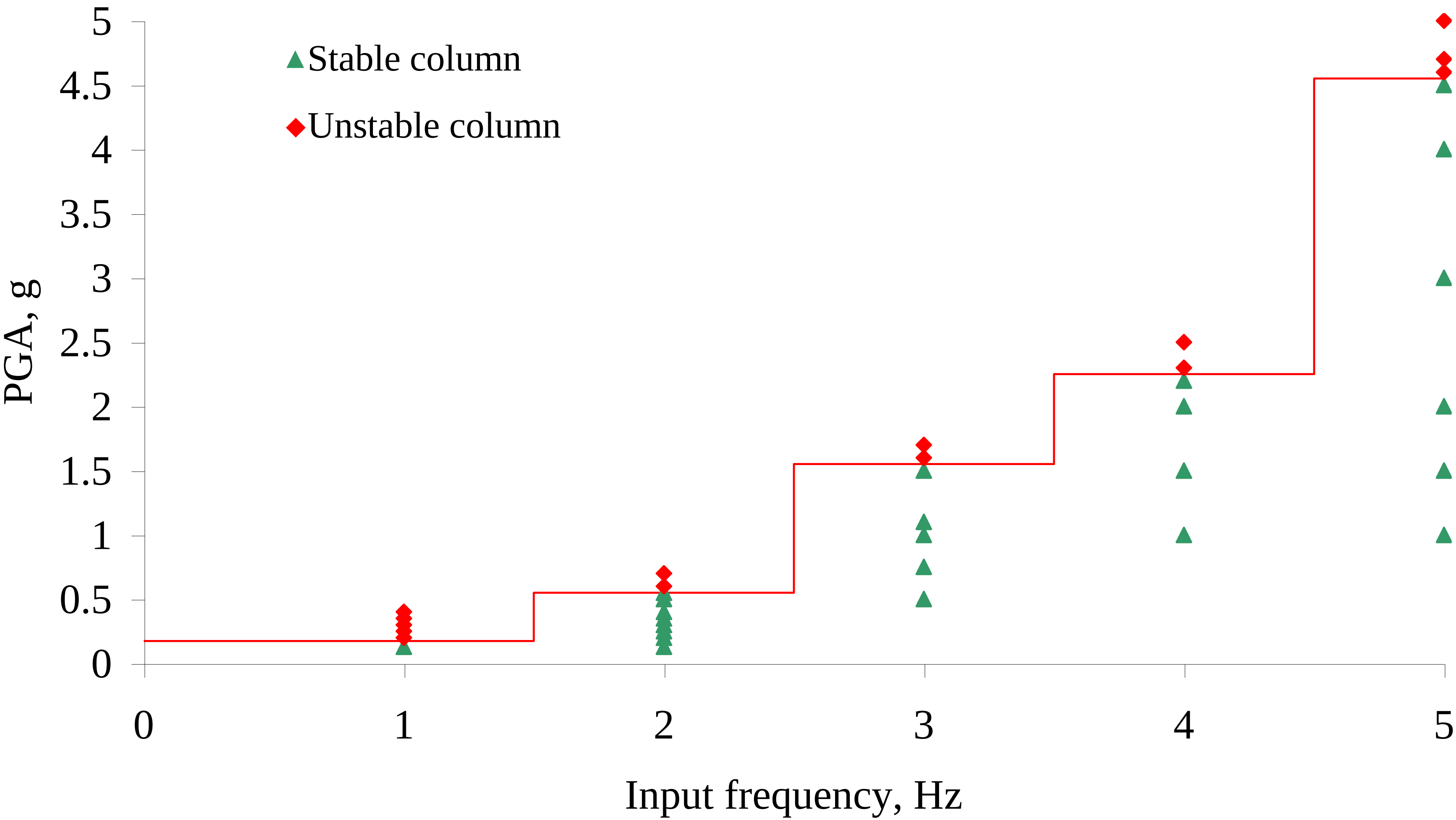
Normal contact spring stiffness ($g0$) = 2*10^8 N/m

Optimizing contact spring stiffness

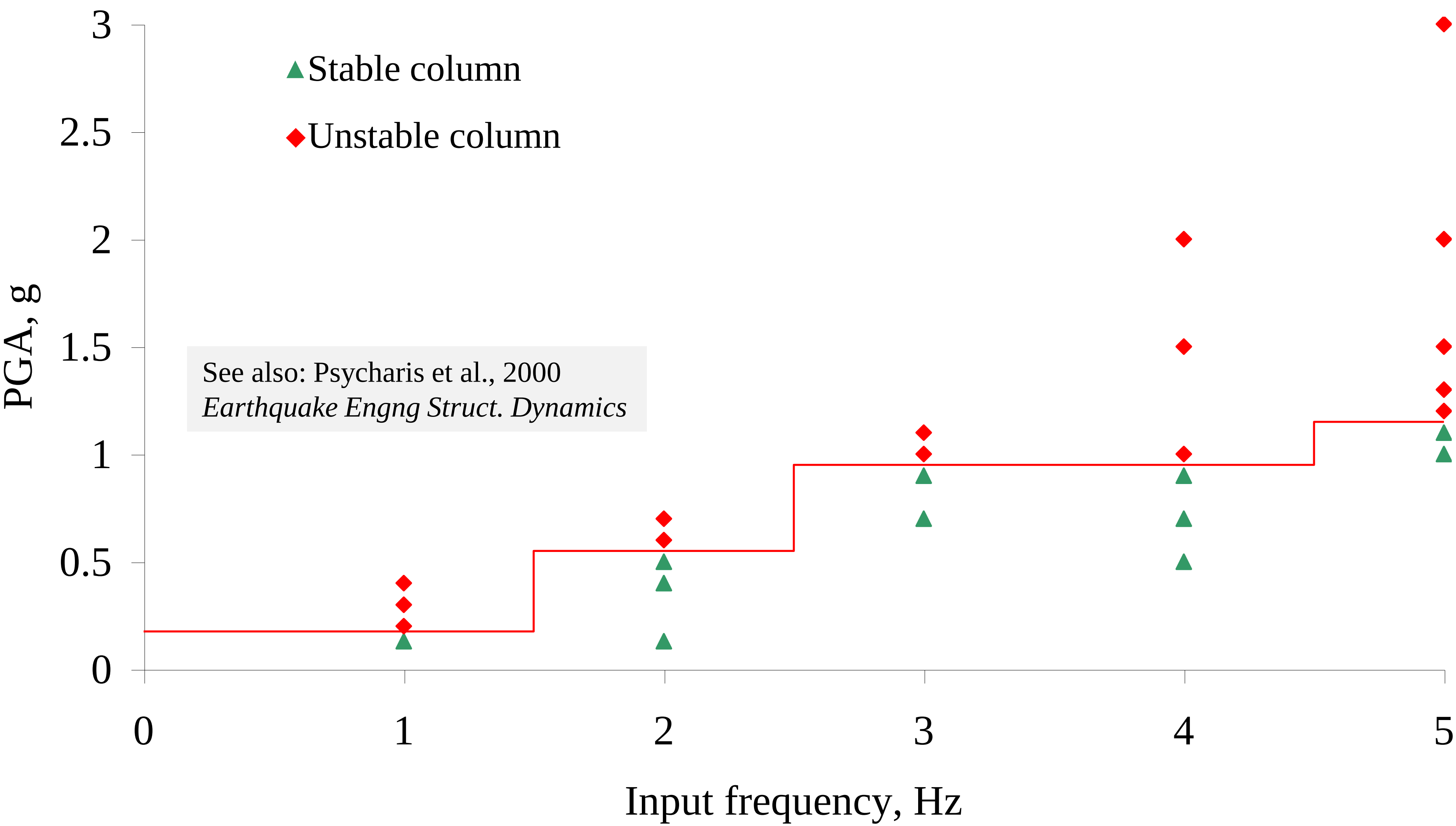


Spring stiffness = $g0$ = $2*10^8$ N/m

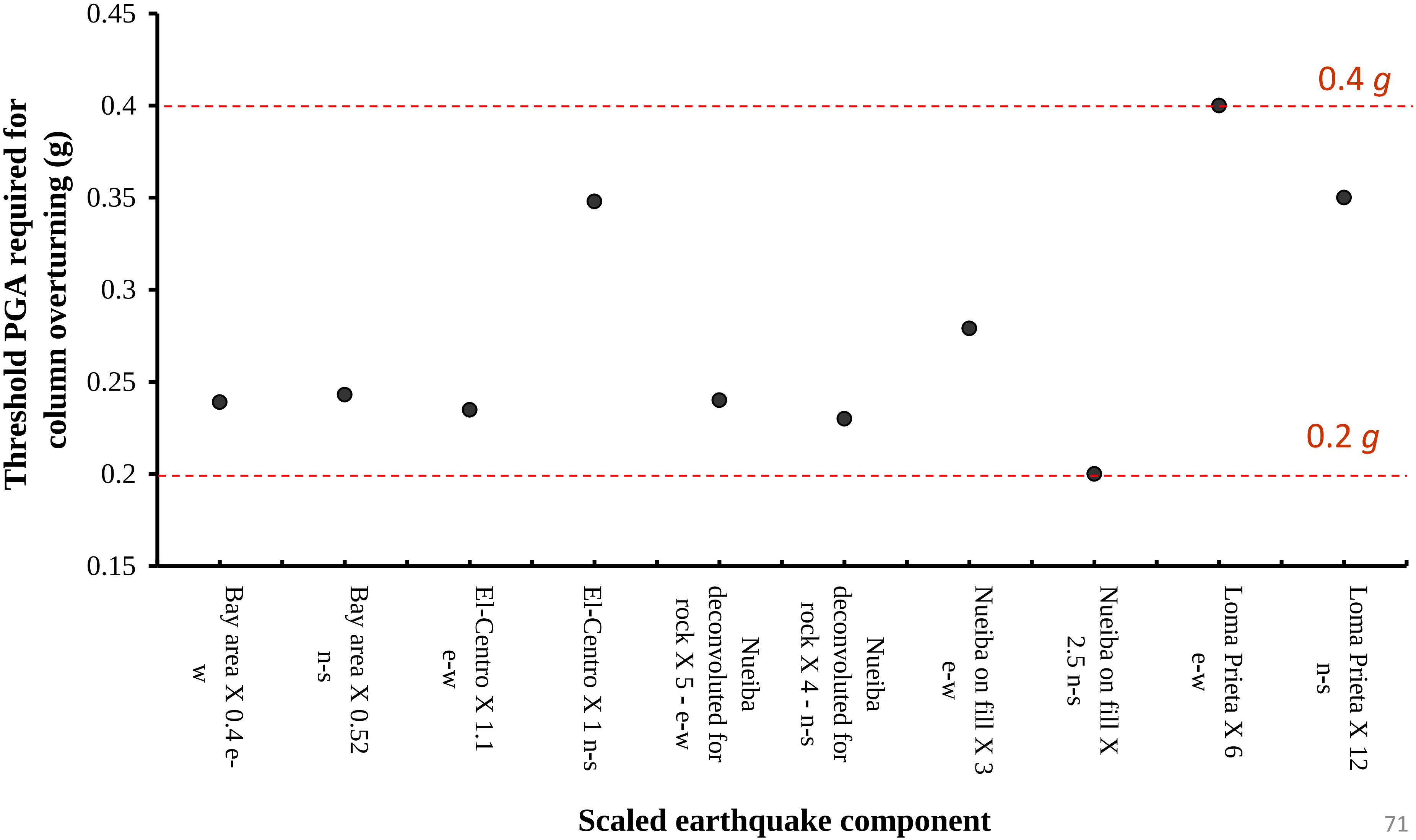
Frequency dependent PGA results
1 sinusoidal input cycle



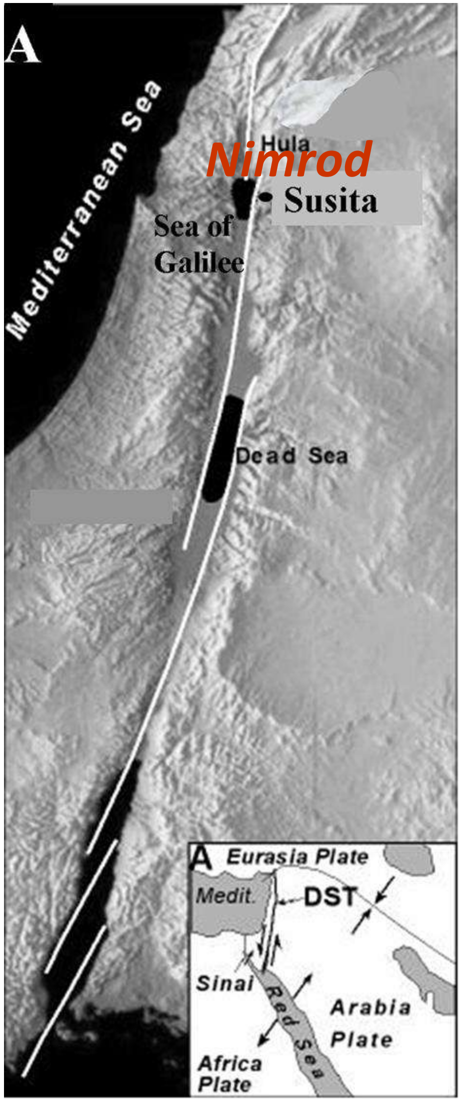
Frequency dependent PGA results
3 sinusoidal input cycles

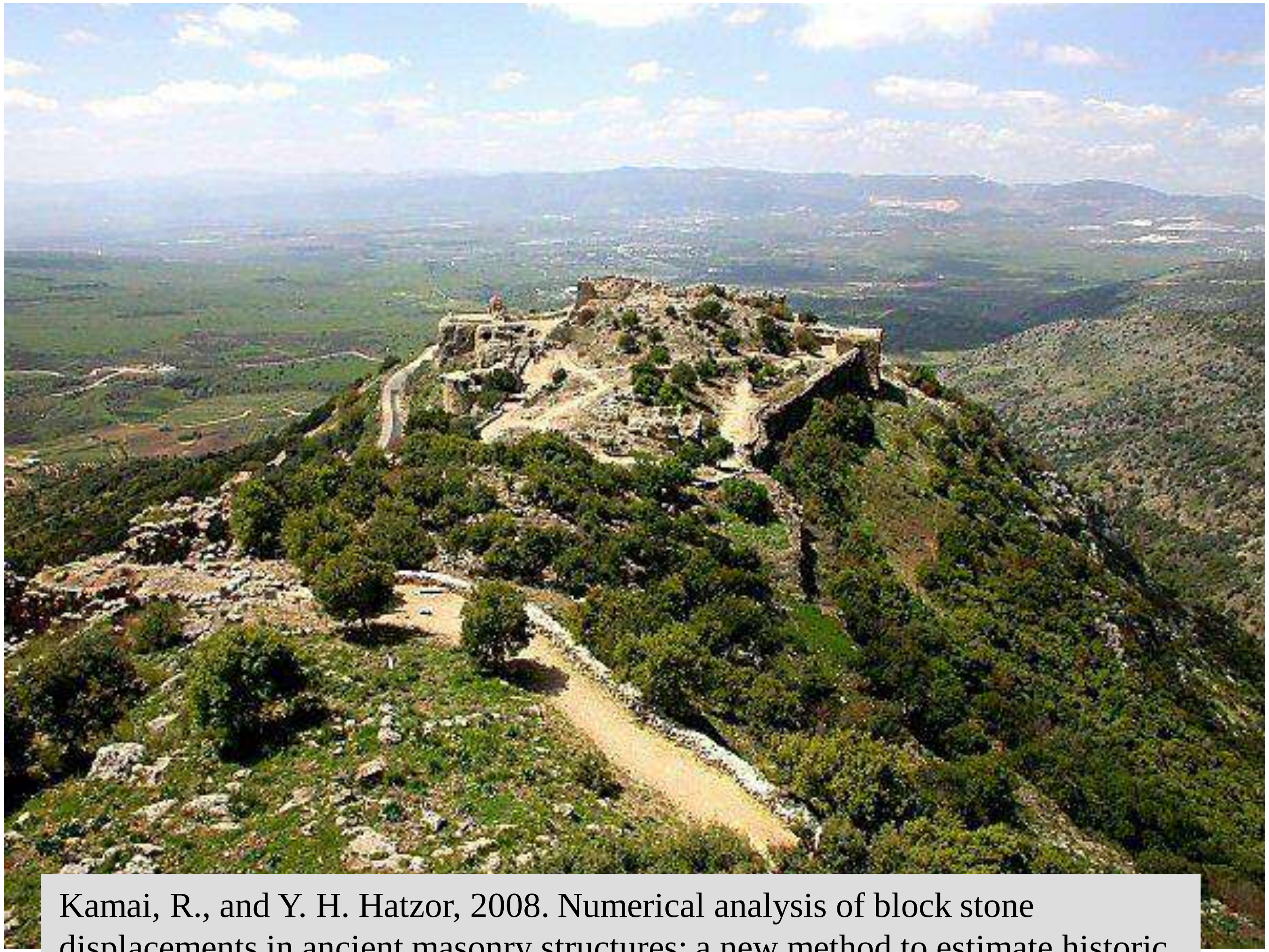


Constraining paleo-seismic PGA by application of true earthquake records



Nimrod – A Crusaders Fortress (1000 – 1200 AD)

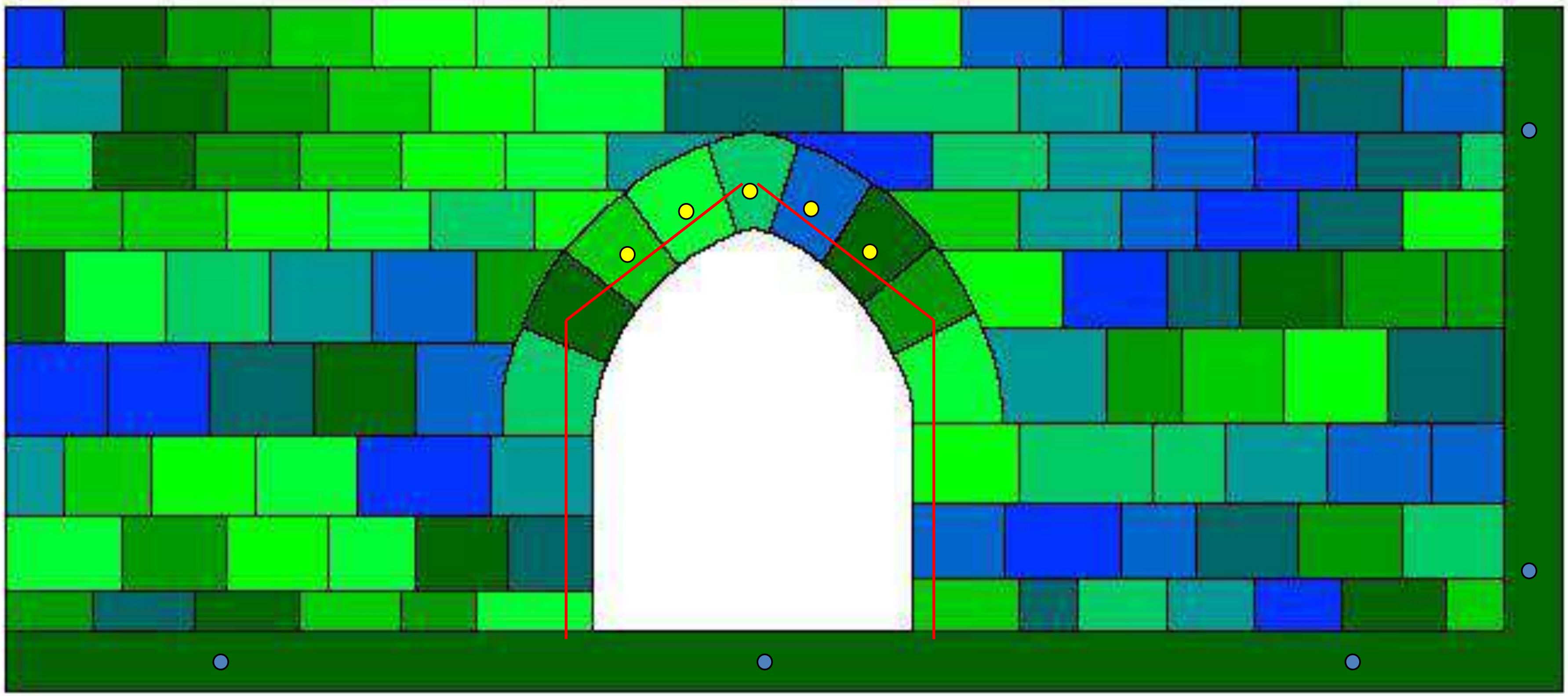




Kamai, R., and Y. H. Hatzor, 2008. Numerical analysis of block stone displacements in ancient masonry structures: a new method to estimate historic ground motions. *International Journal for Numerical and Analytical Methods in Geomechanics*

Asymmetric block displacement in arch

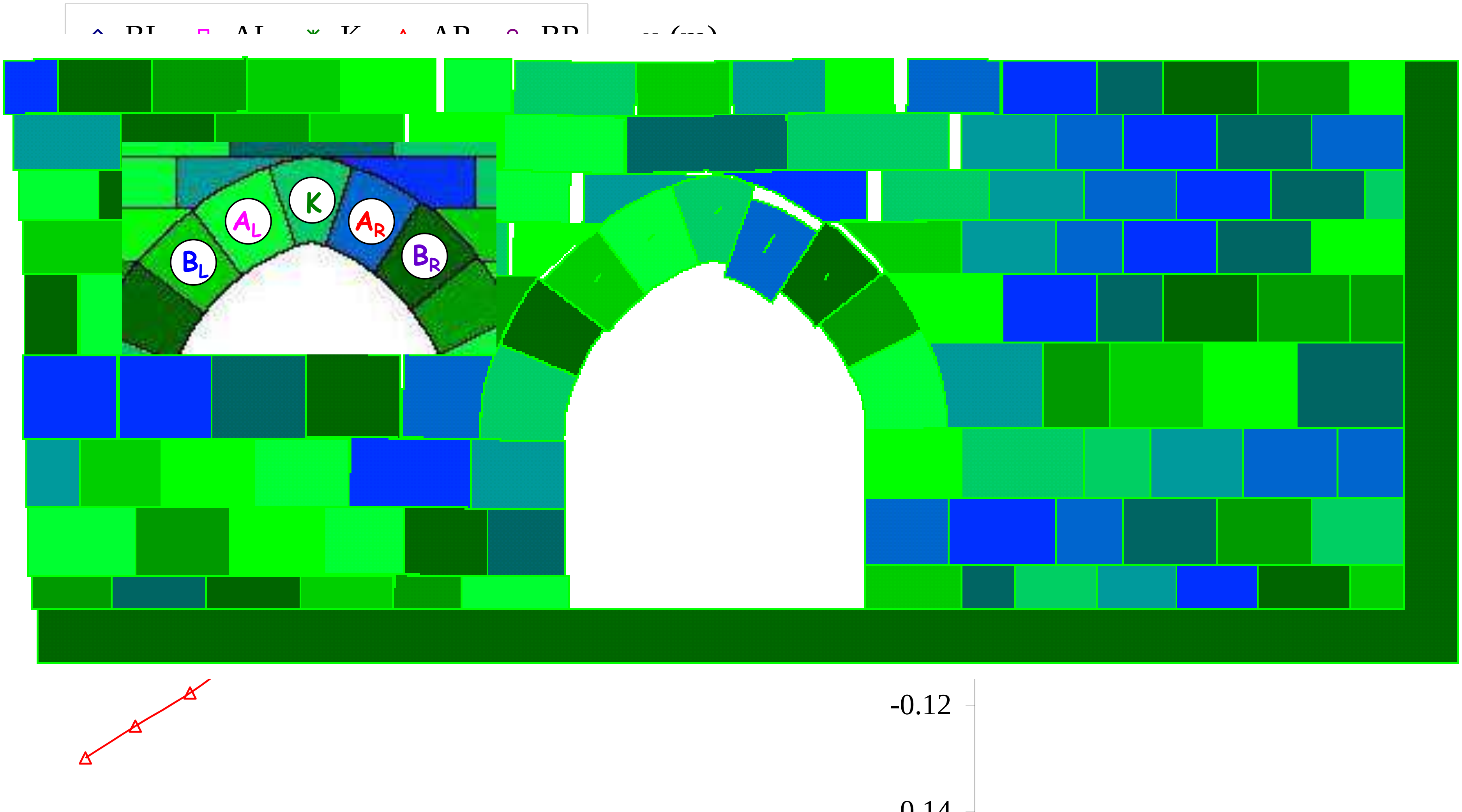
DDA Model



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.



Thank you for your attention, and welcome to Israel!