International Conference Vajont 1963 – 2013
Thoughts and analyses after 50 years since the catastrophic landslide
October 8 – 10, 2013 , Padua, Italy

Thermally vs. Seismically Induced Block Displacements in Jointed Rock Slopes

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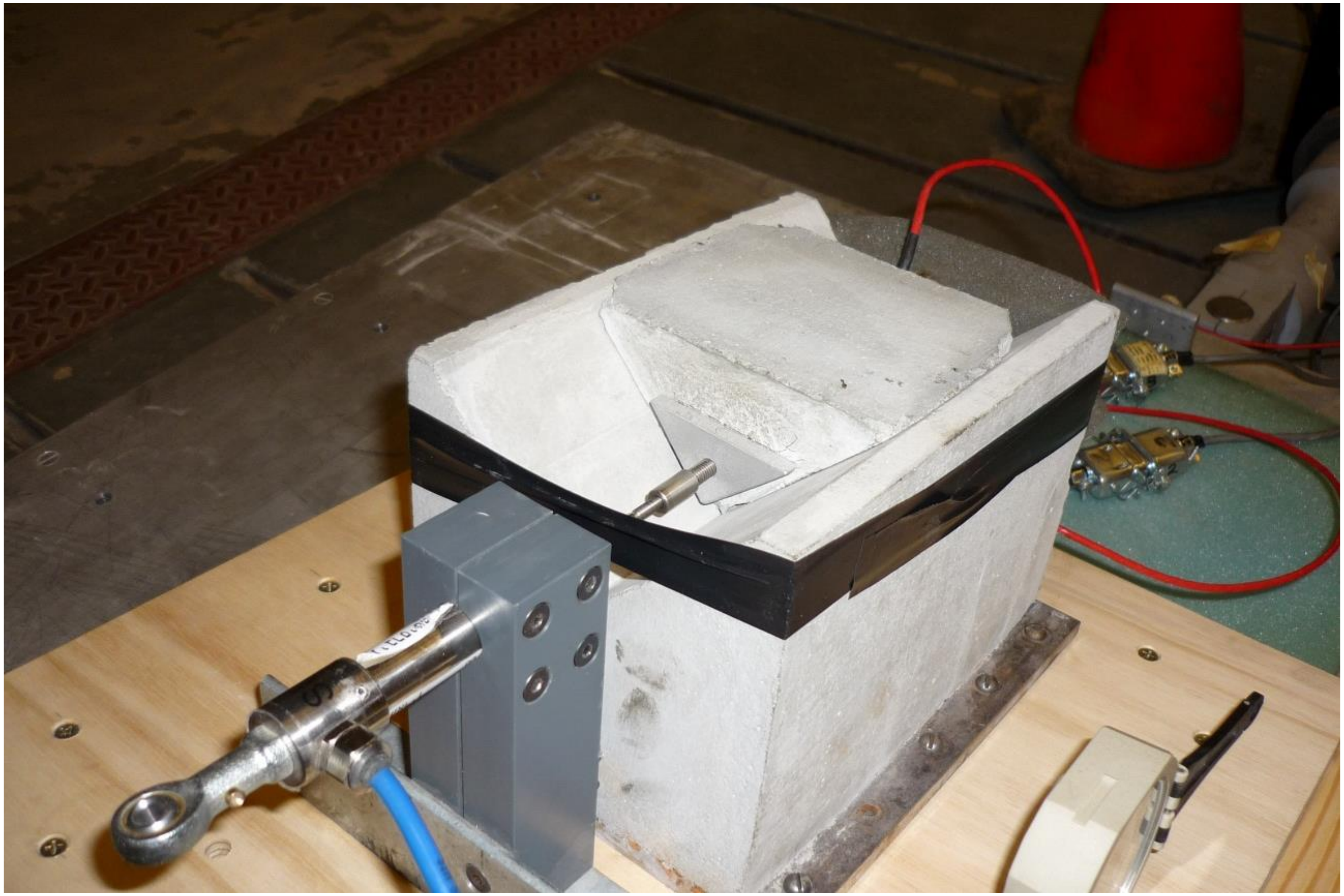
Talk Outline

Seismic Triggering: Verifications and Validations

- ❑ Single Plane Sliding
- ❑ Double Plane Sliding
- ❑ Shaking Table Experiments
- ❑ Velocity Dependent Friction Degradation

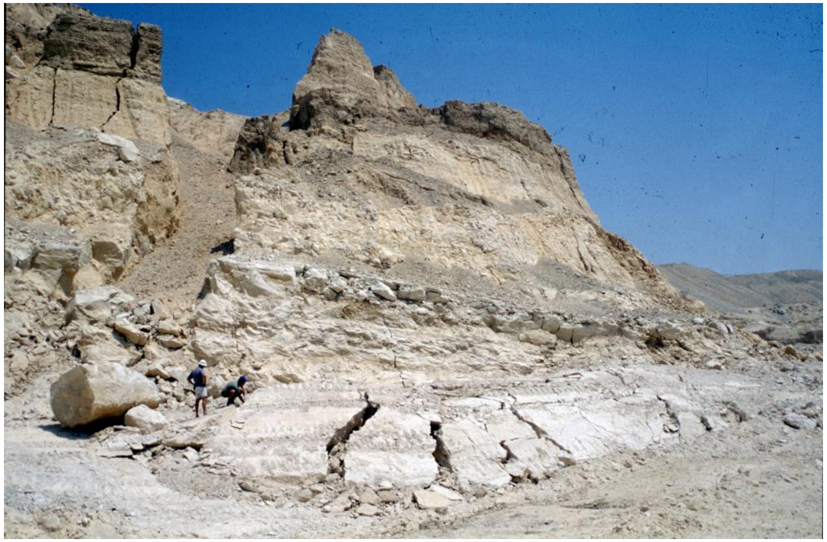
Climatic Triggering: Field Monitoring and Theoretical Model

- ❑ Masada World Heritage Site as a Field Station
- ❑ Monitored Rock Mass Response to Thermal Fluctuations
- ❑ Thermally Induced Ratcheting Mechanism
- ❑ Seismic vs. Thermal Triggering



Dynamic Sliding: Verifications and Validations

Single Plane Sliding



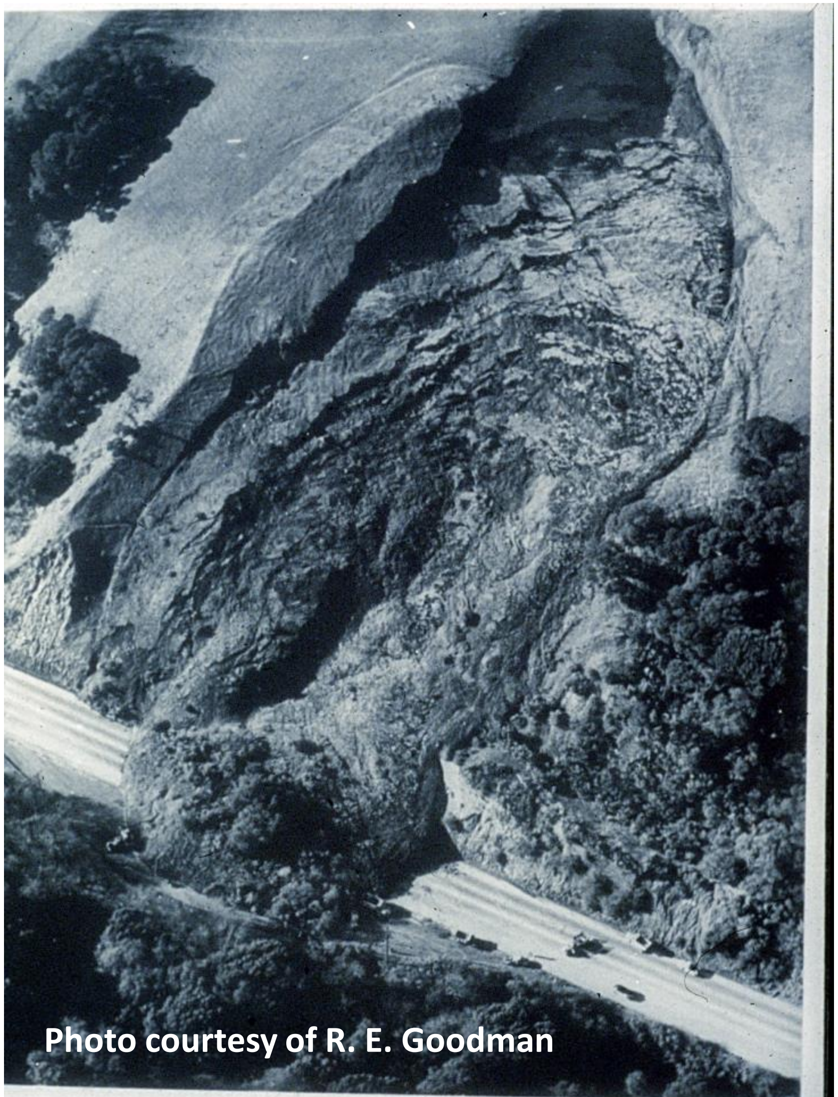
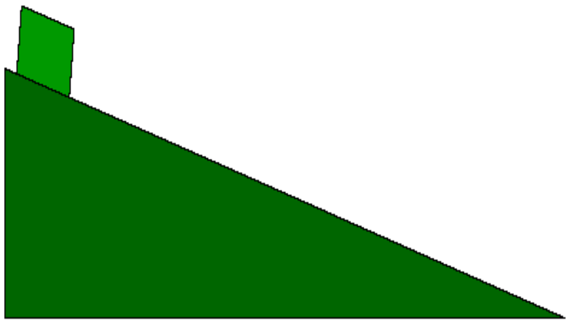
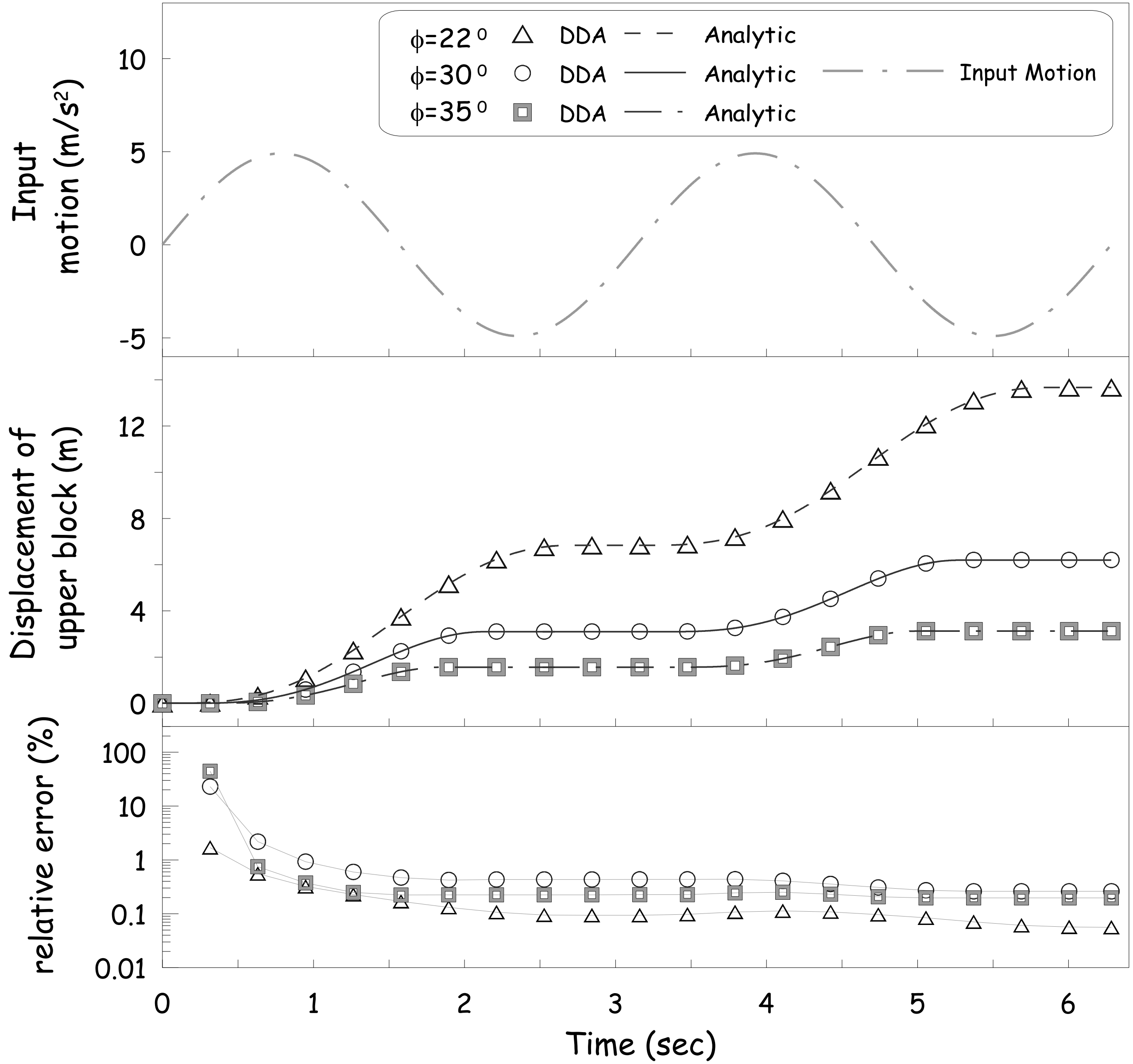


FIG. 7. LANDSLIDE NEAR ORINDA, CALIFORNIA, 1951

Verification of Single Plane Sliding

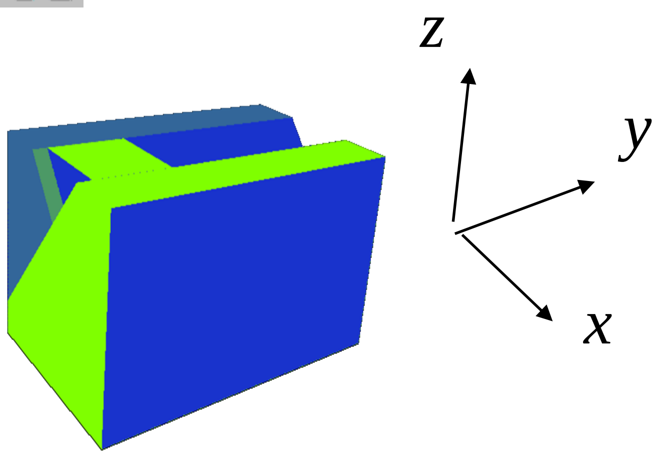


Dynamic sliding under gravitational load only was studied originally by Mary McLaughlin in her PhD thesis (1996) (Berkeley) and consequent publications with Sitar and Doolin 2004 - 2006. Sinusoidal input first studied by Hatzor and Feintuch (2001), *IJRMMS*. Improved 2D solution presented by Kamai and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



Double Plane Sliding

Verification of Dynamic Wedge Sliding



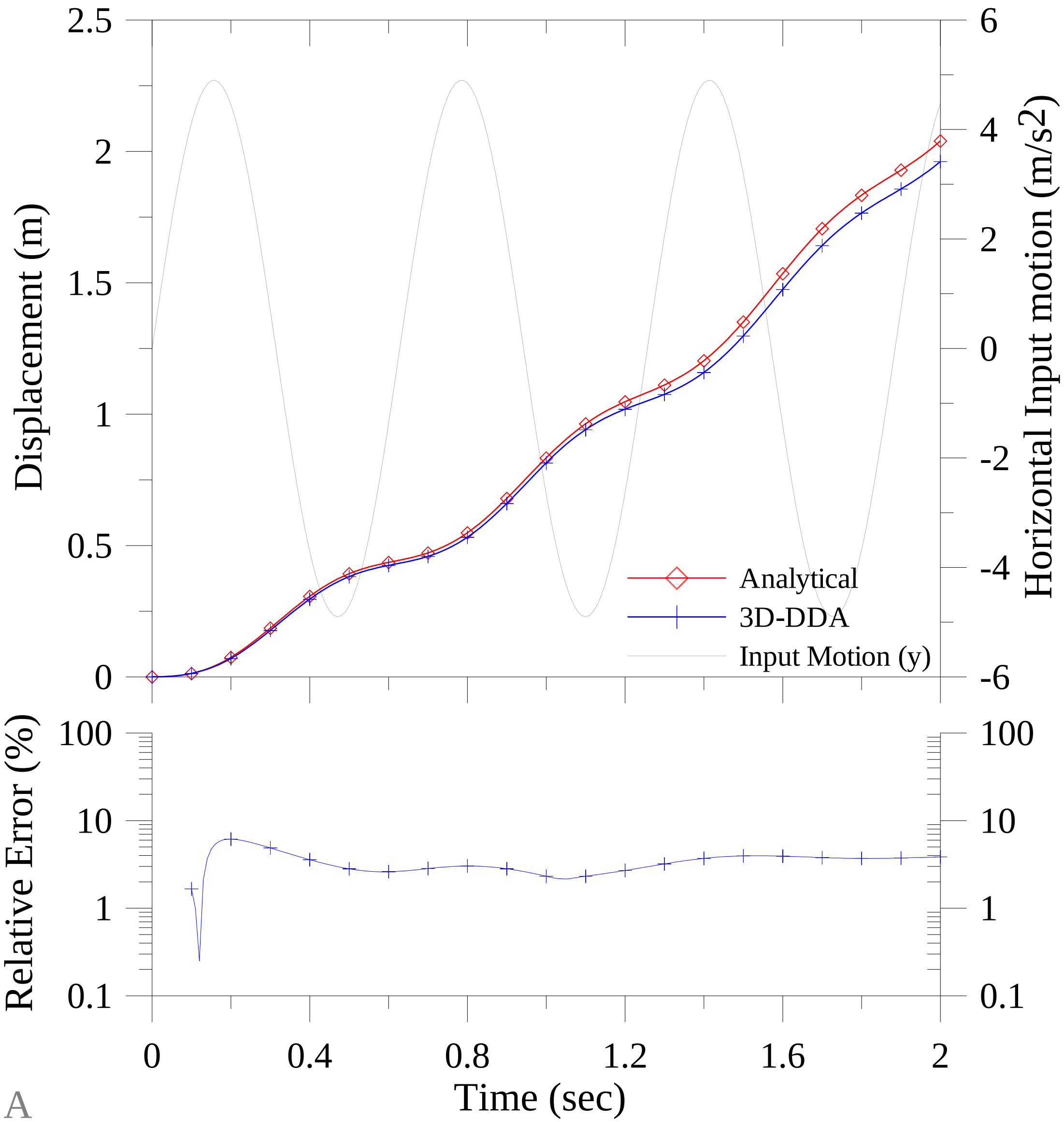
Wedge parameters:

P_1=52/063, P_2=52/296

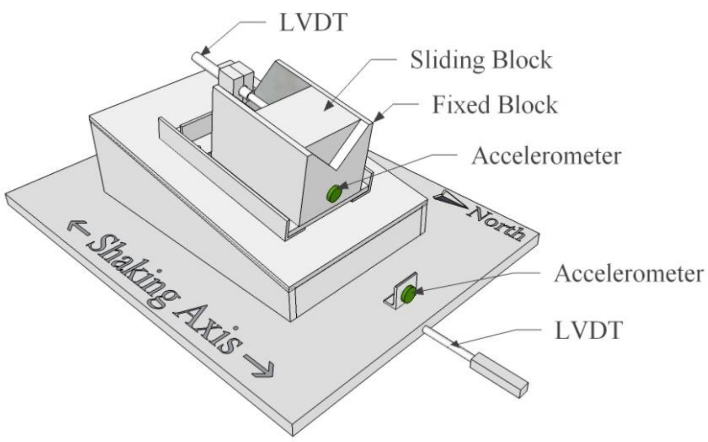
$\phi_1=\phi_2=30^o$

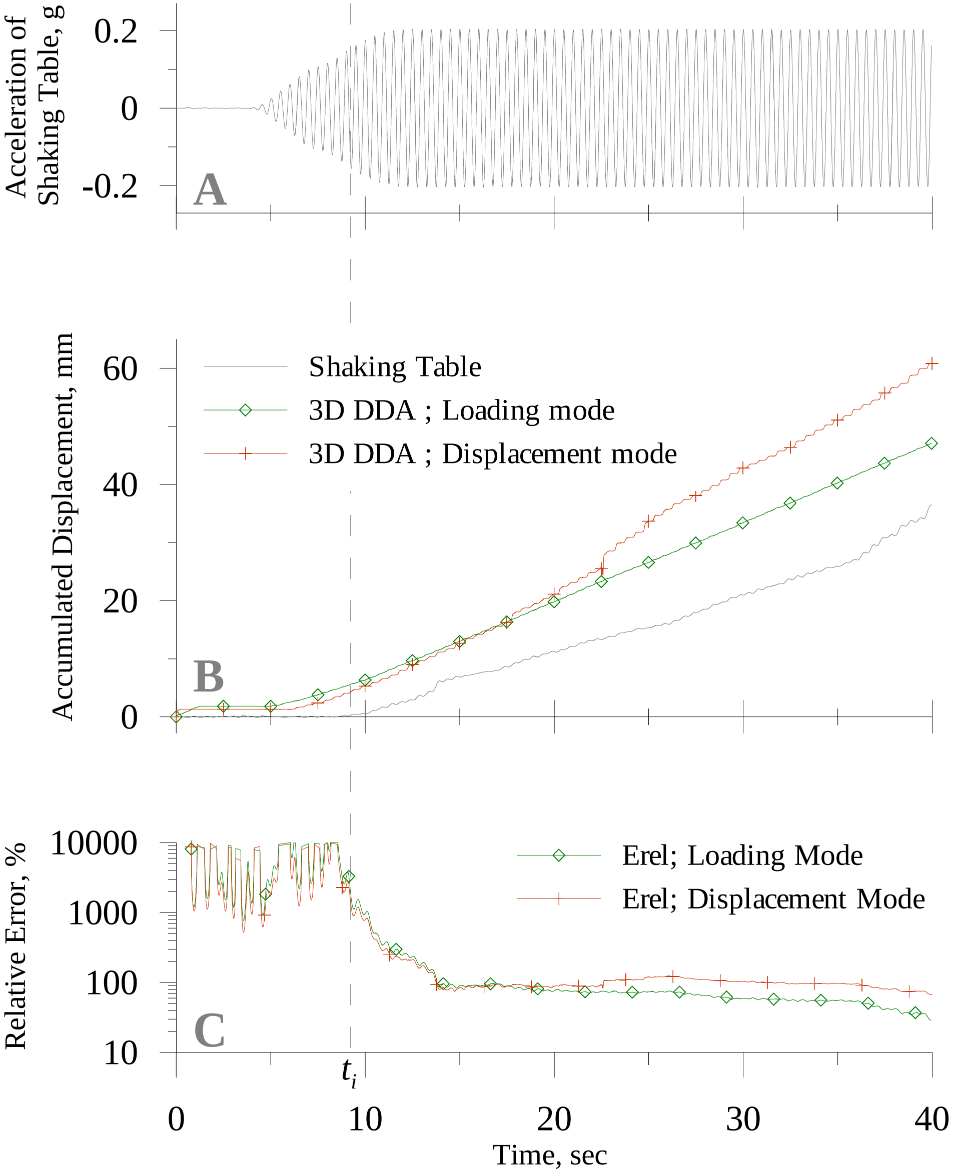
DDA validation originally investigated by Yeung M. R., Jiang Q. H., Sun N., (2003) *IJRMMS* using physical tests.

Analytical solution proposed and 3D DDA validation performed by Bakun-Mazor, Hatzor, and Glaser (2012), *NAG*.

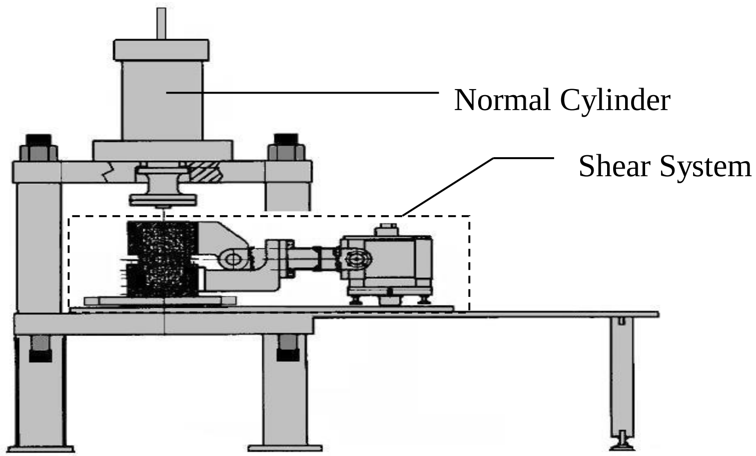


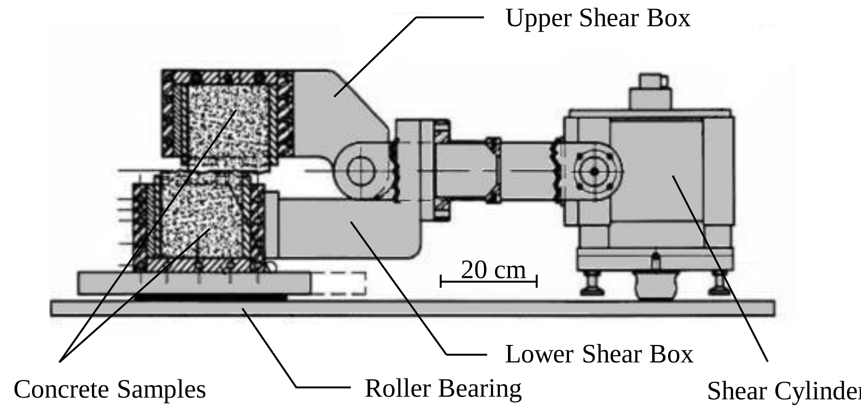
Shaking Table Experiments

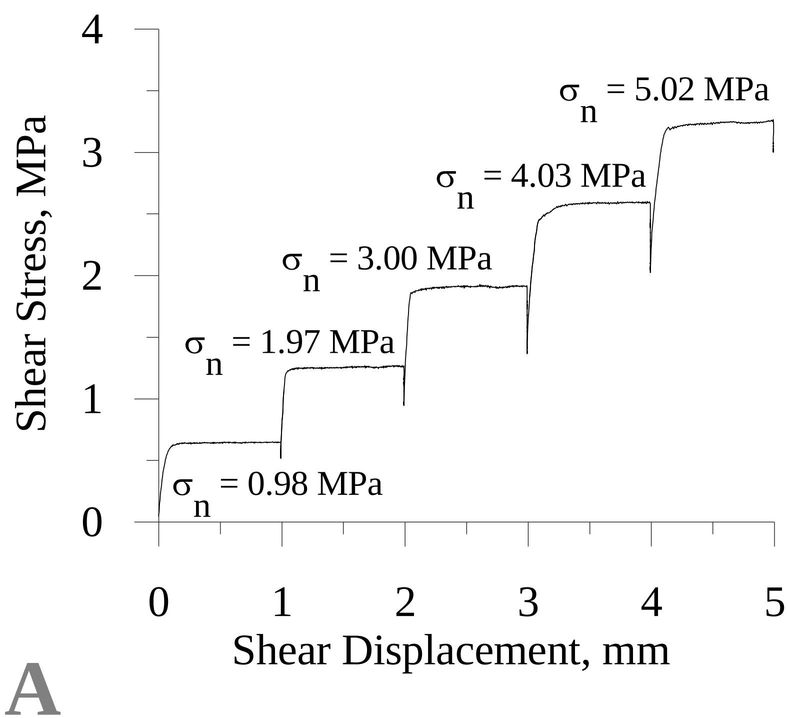


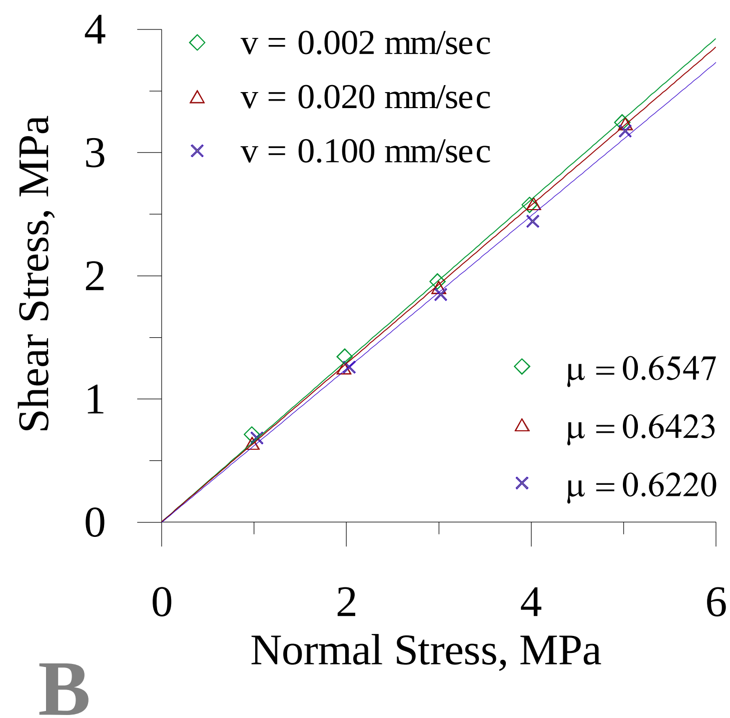


Rate Dependent Friction

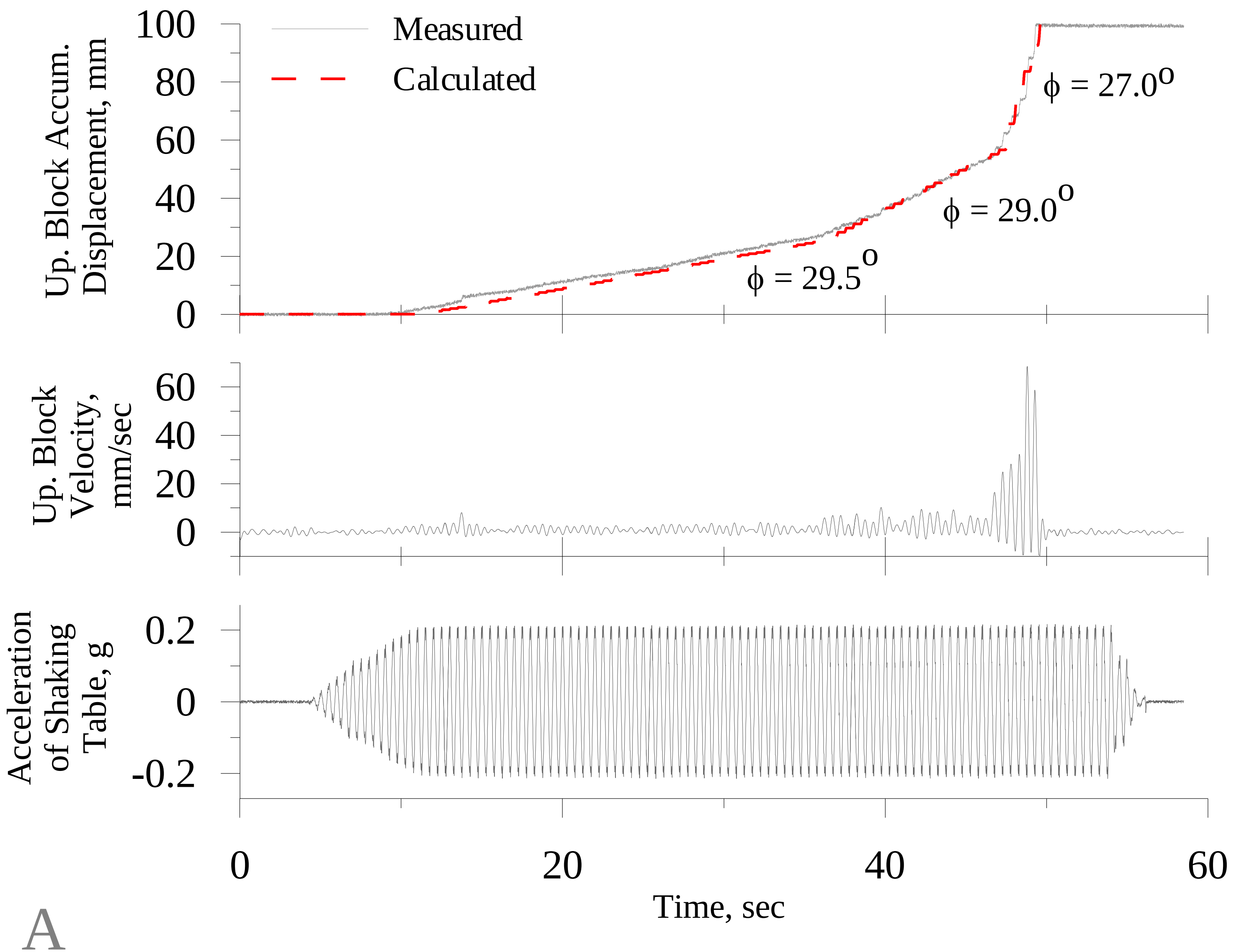




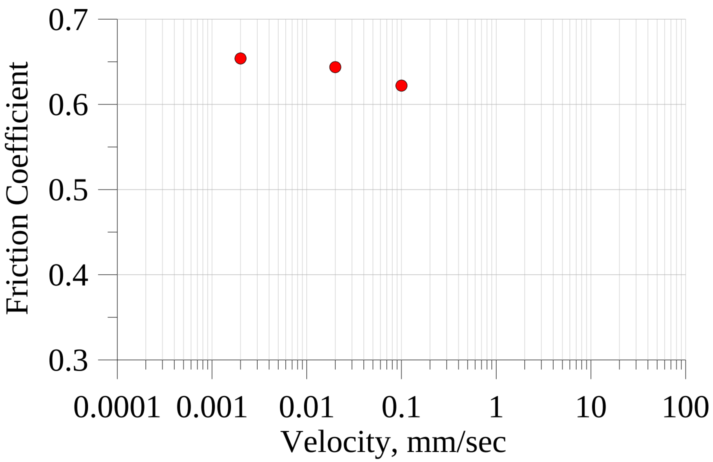


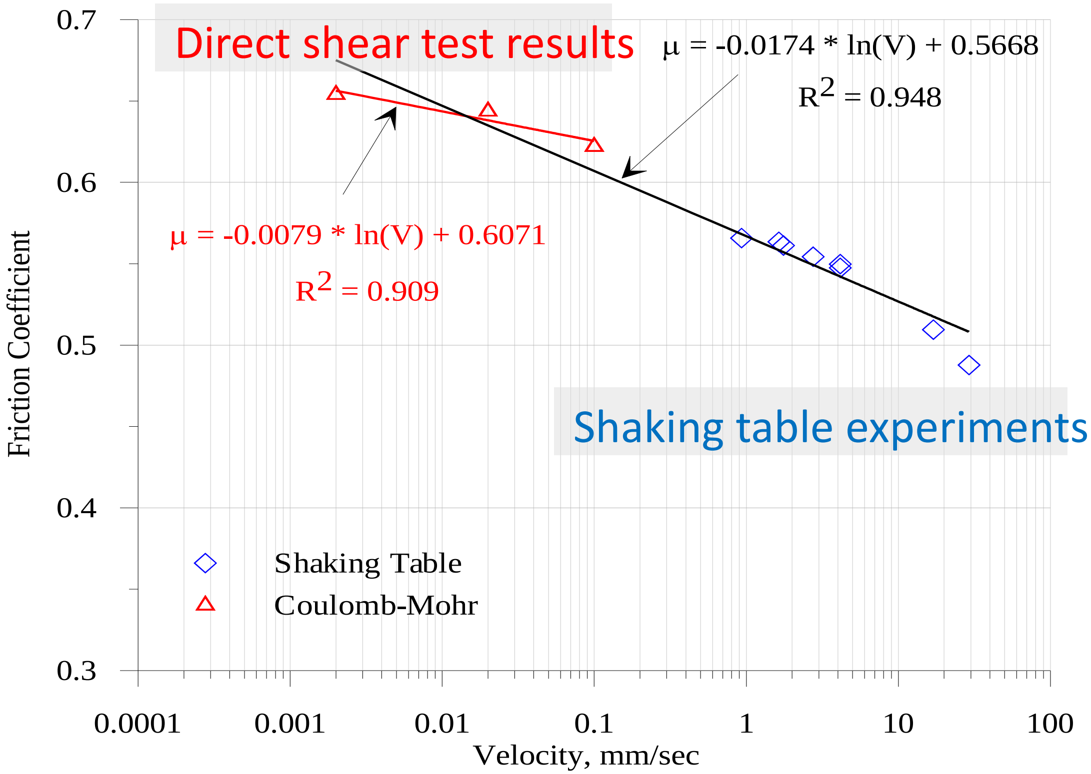


Observed Block “Run-out”



Friction Angle Degradation

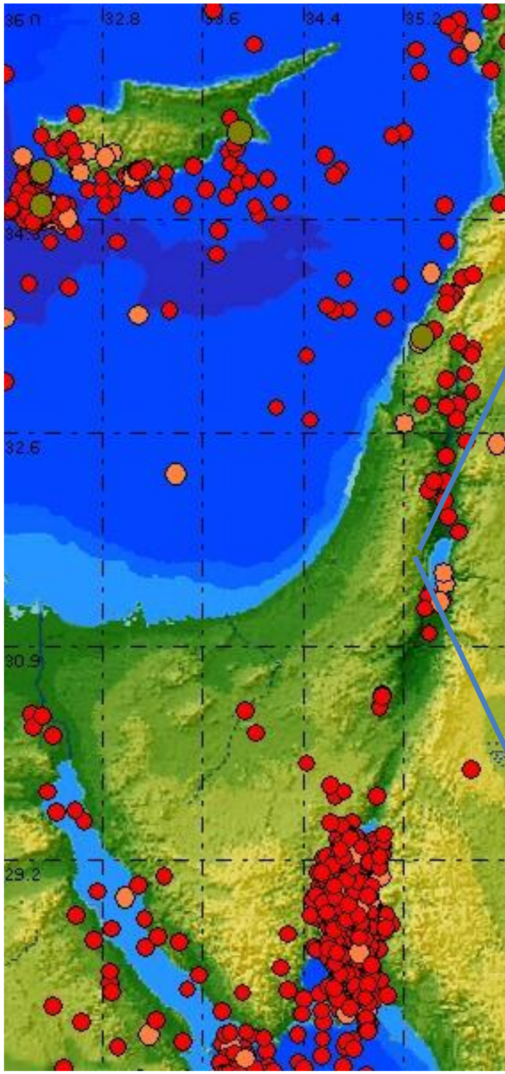


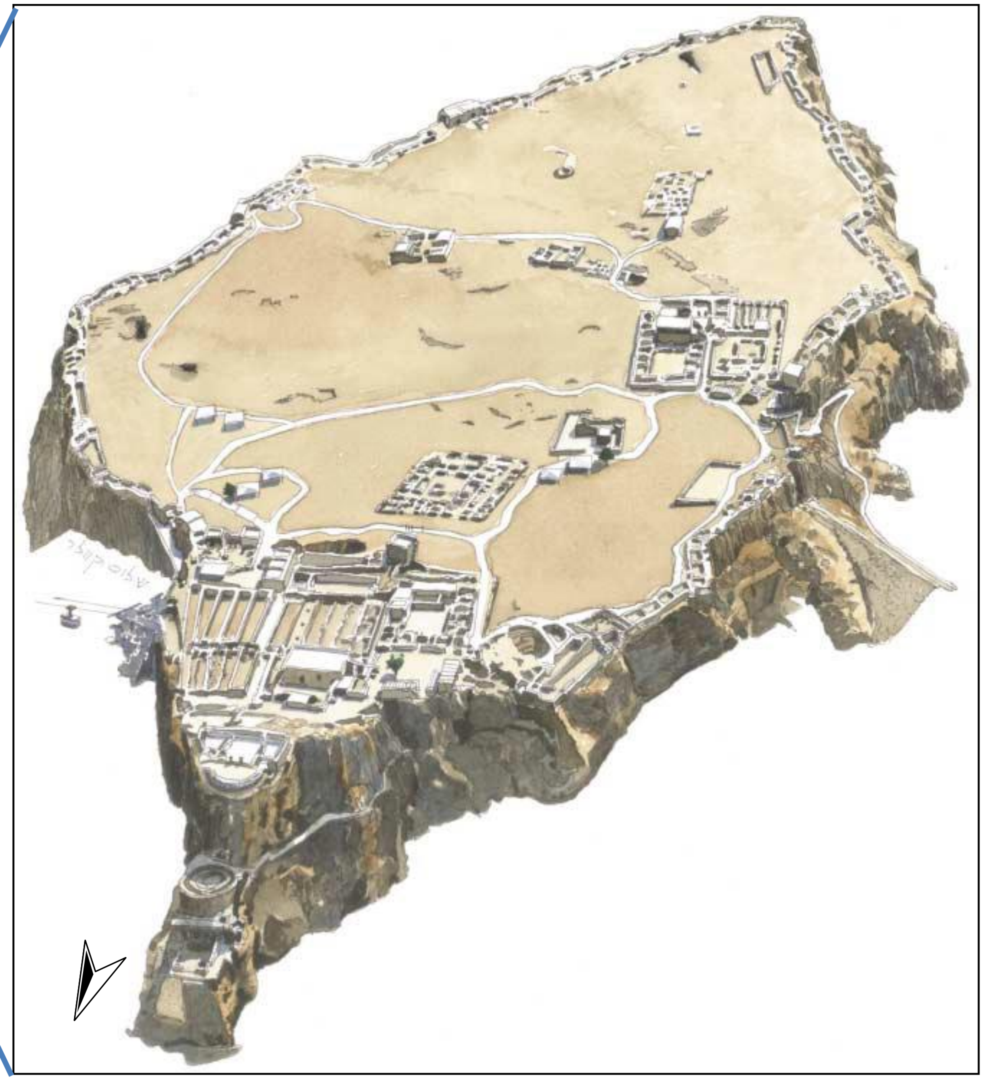


Conclusion: frictional resistance of geological sliding interfaces may exhibit both velocity dependence as well as degradation as a function of velocity and/or displacement. This is particularly relevant for dynamic analysis of landslides, where sliding is assumed to have taken place under high velocities. Therefore, a modification of DDA to account for friction angle degradation is called for. This has already been suggested by Sitar et al. (2005), *JGGE –ASCE;* a new approach has recently been proposed by LZ Wang et al. (in press), *COGE* (from Zhejiang University).

THERMAL VS. SEISMIC TRIGGERING

Masada World Heritage Site as Field Station

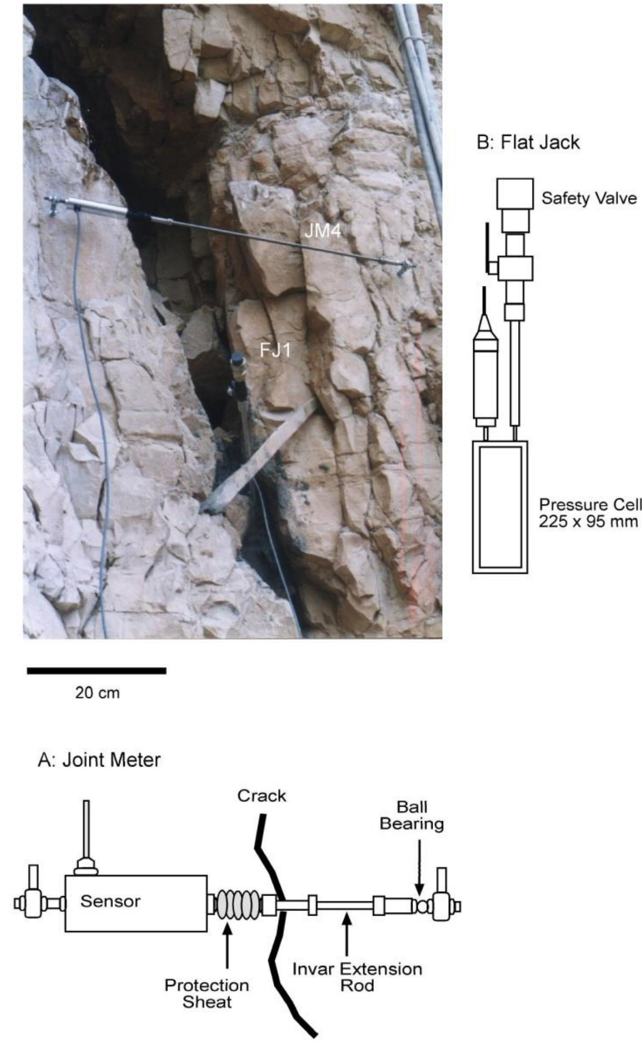




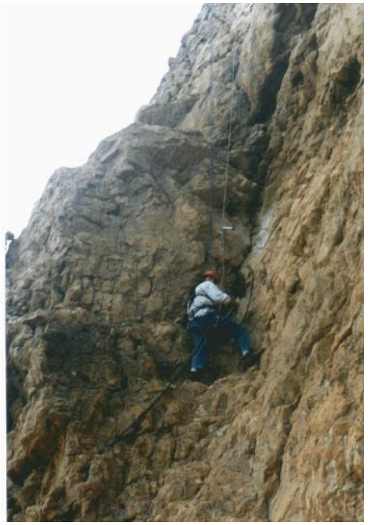
Six month monitoring in the East face: 1998

Hatzor (2003), *JGGE, ASCE*

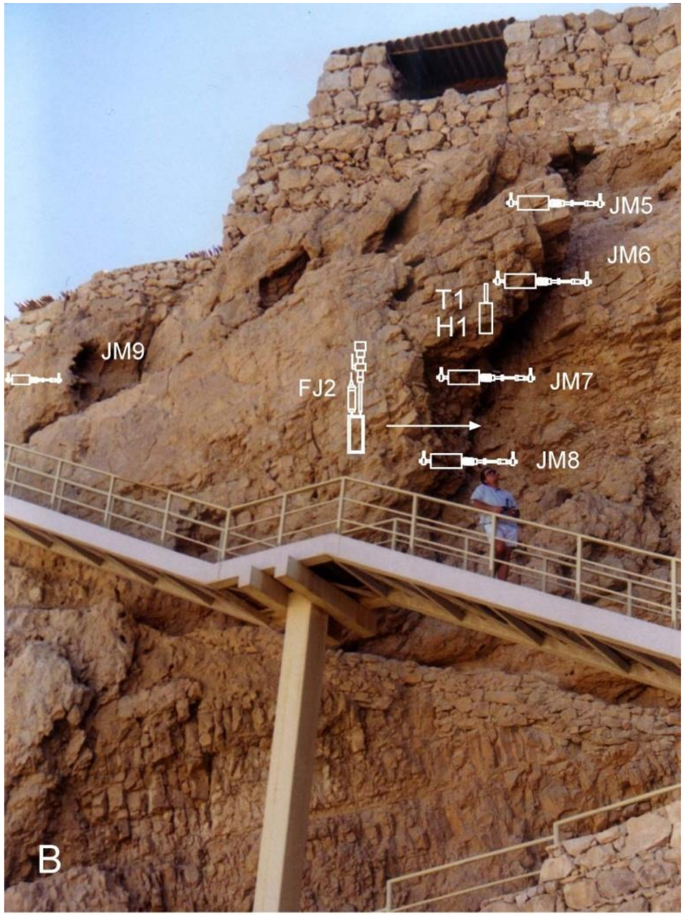
Joint meters and pressure transducers



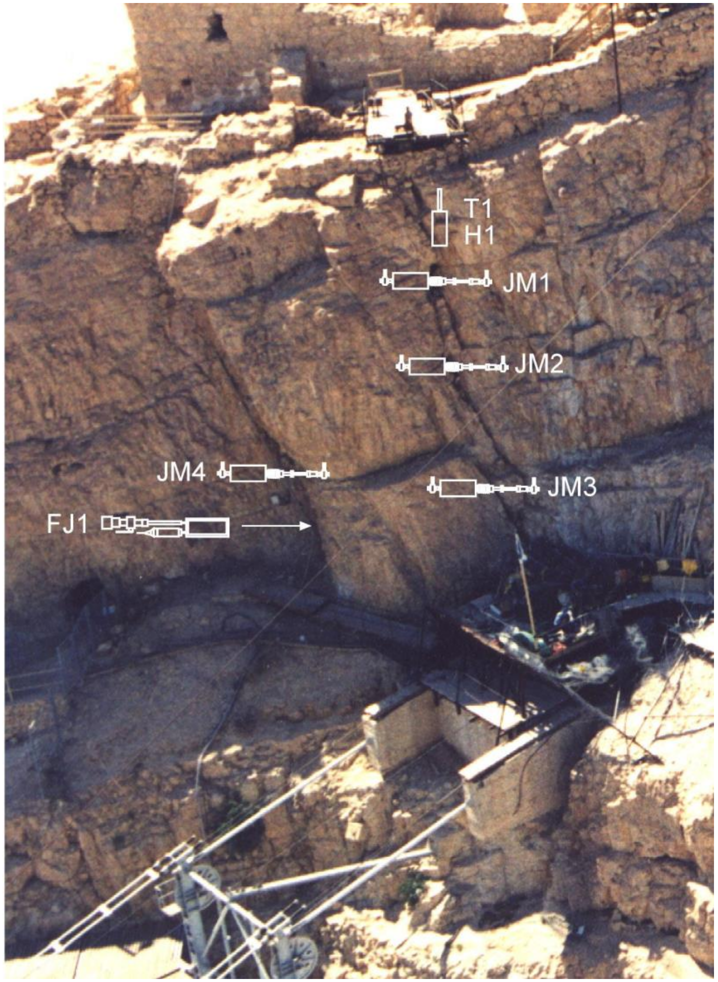
Monitoring Installation Program: East Face



Block 3

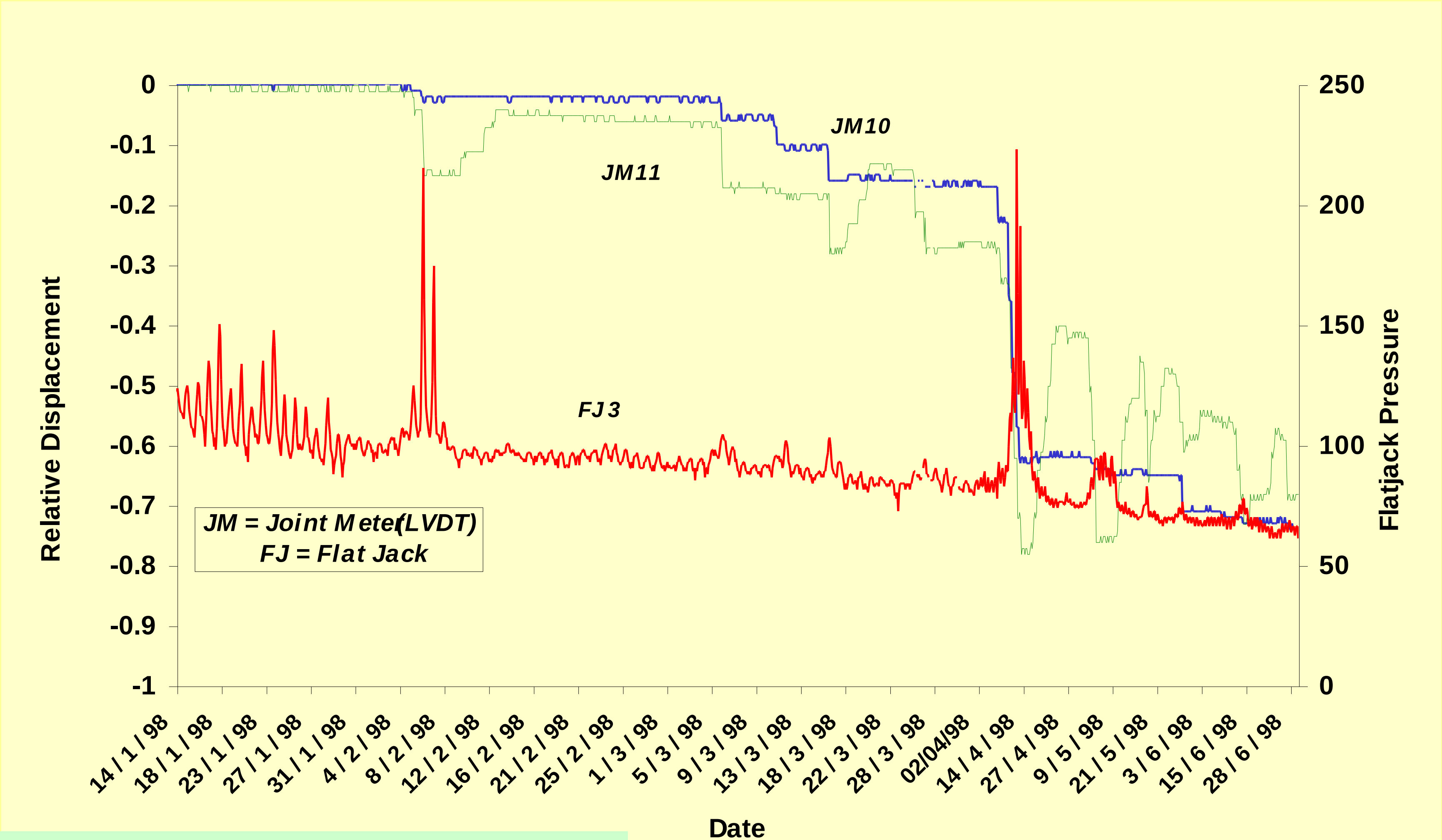


Block 2



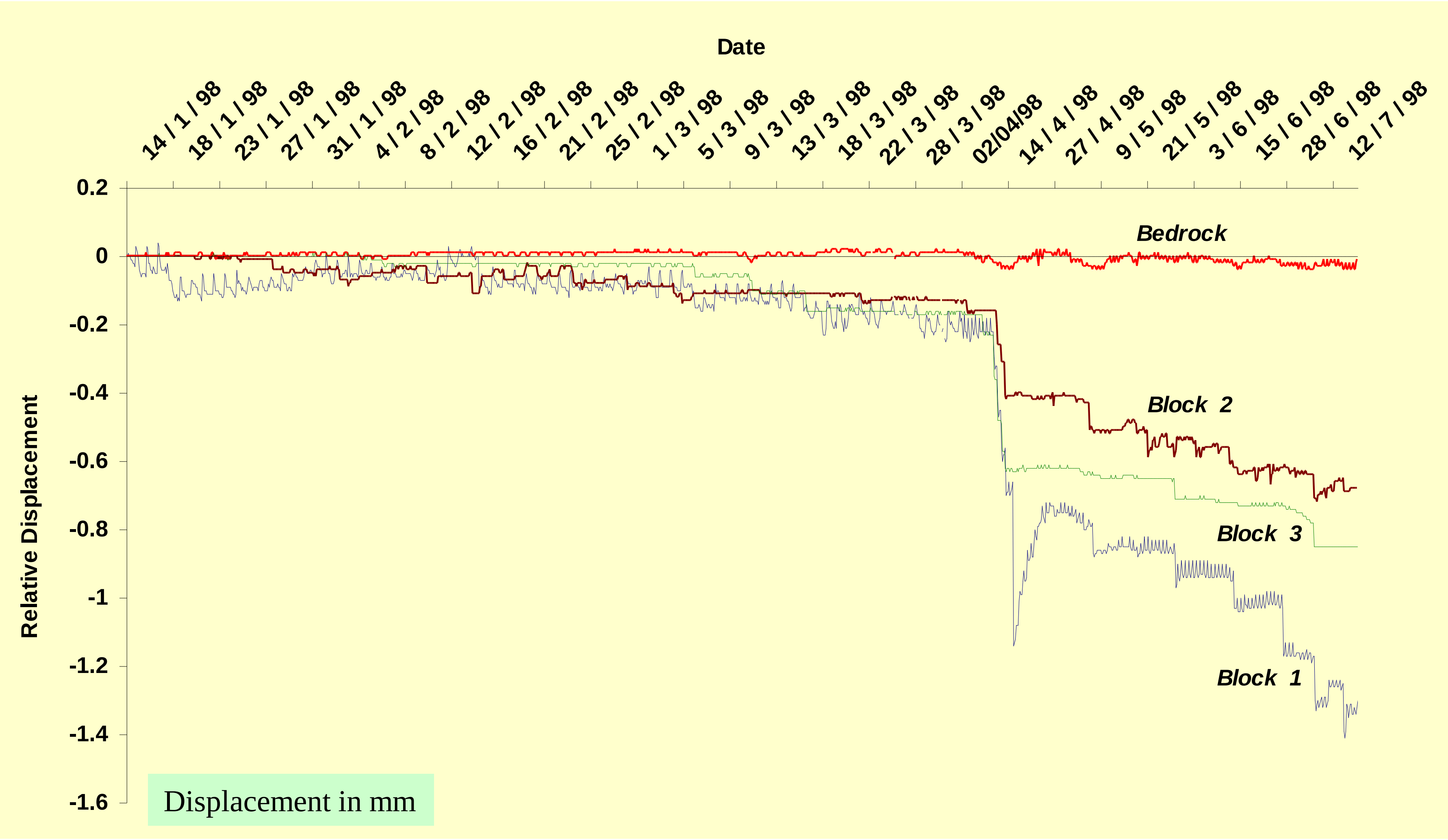
Block 1

Typical Displacement Output – Block 3

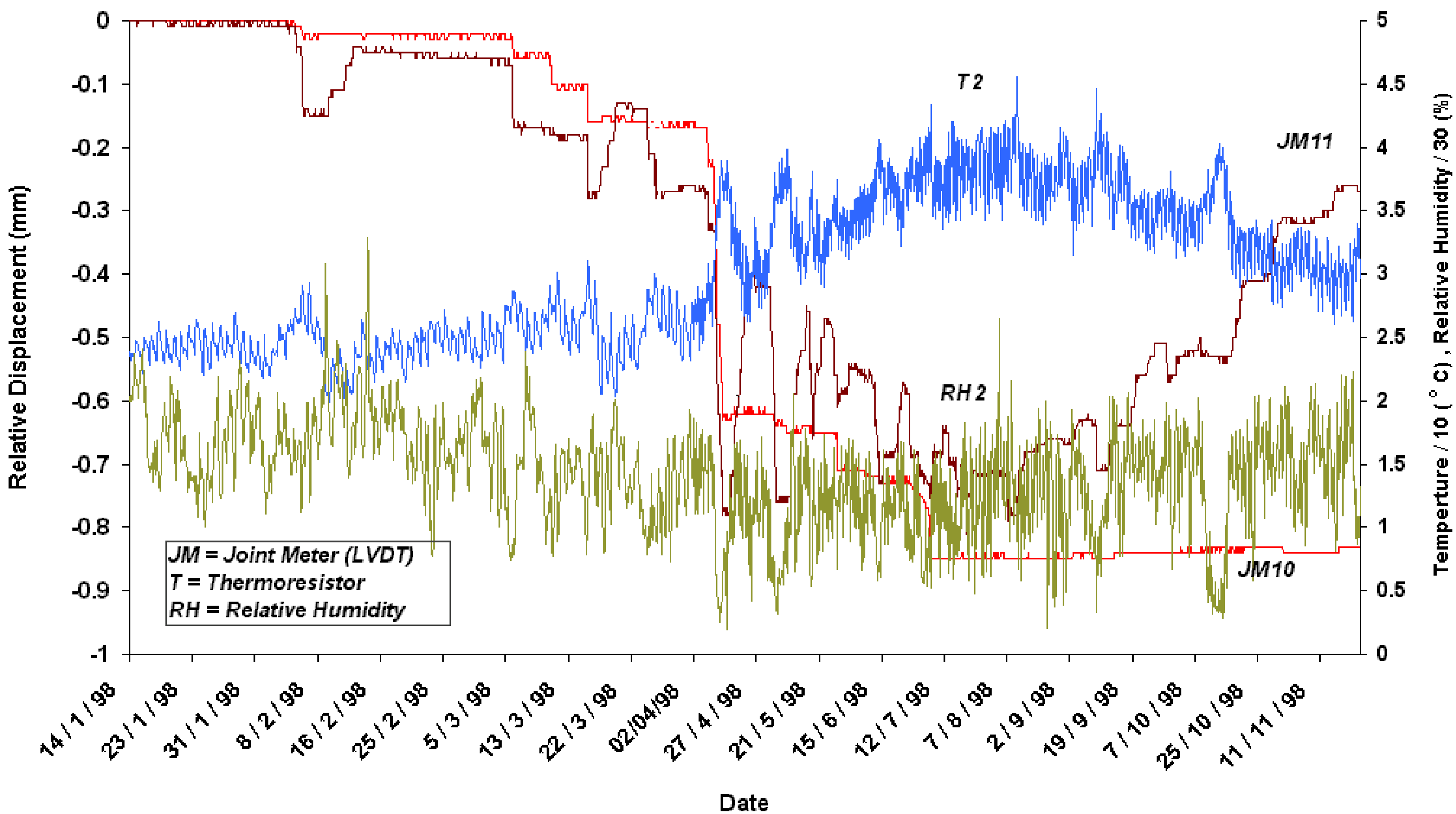


Displacement in mm, pressure in kPa

Superposition of outputs from 3 Blocks



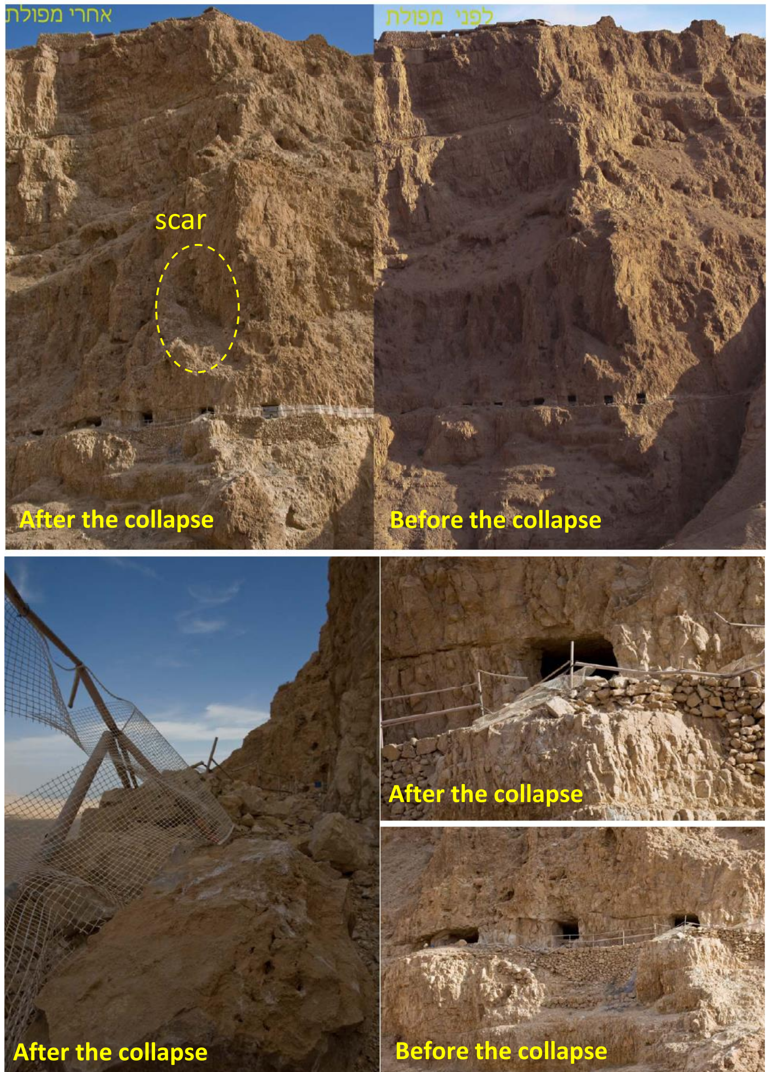
Influence of Climatic Changes on Block Displacement



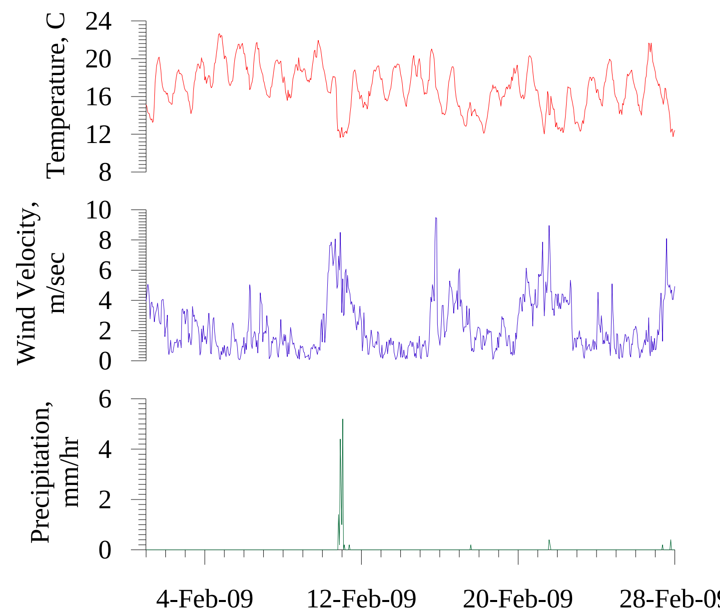
24 months of monitoring in West face: 2009 - 2011

Bakun-Mazor, Hatzor, Glaser, Santamarina (2012) *IJRMMS*

Motivation: A sudden block failure in 2009

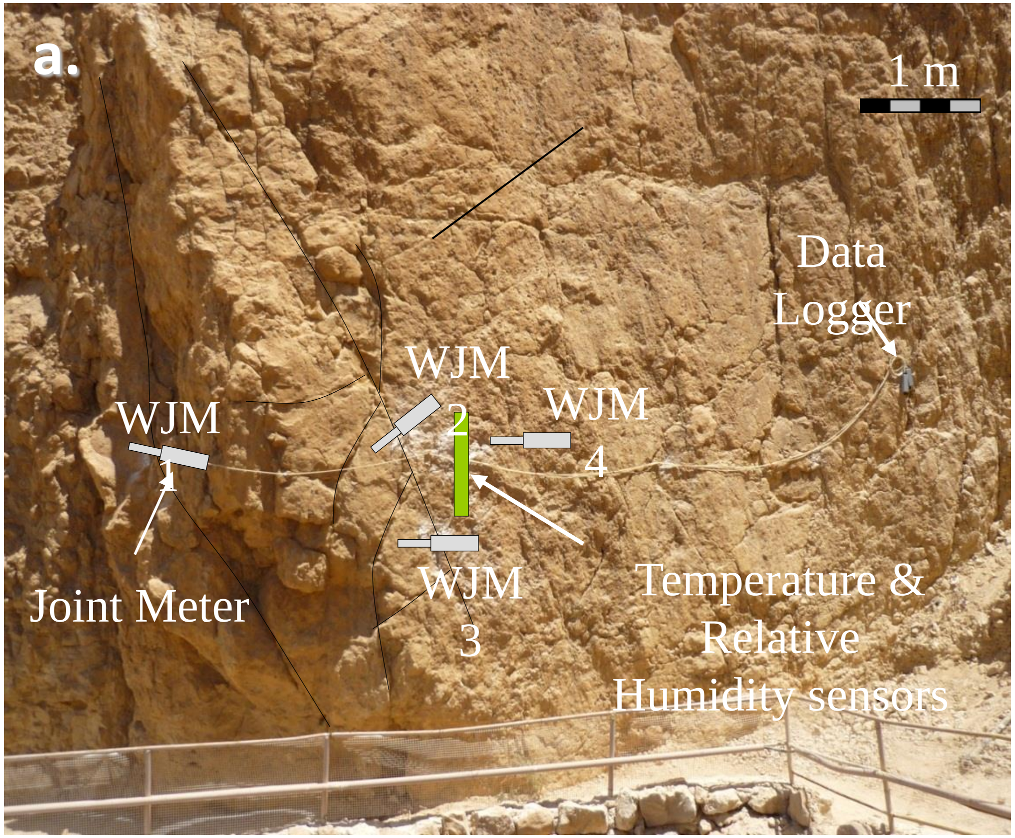


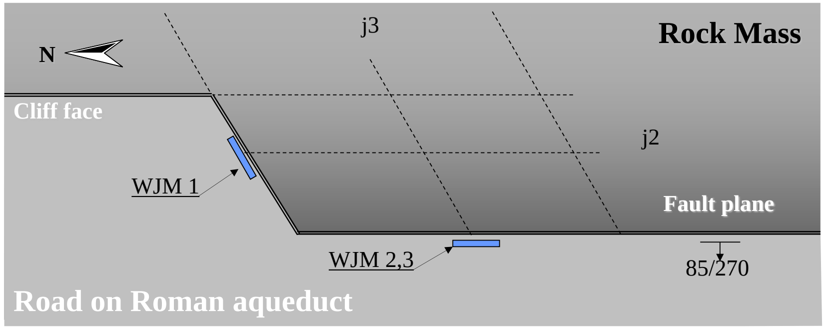
The west slope of Masada before and after the storm of February 10, 2009



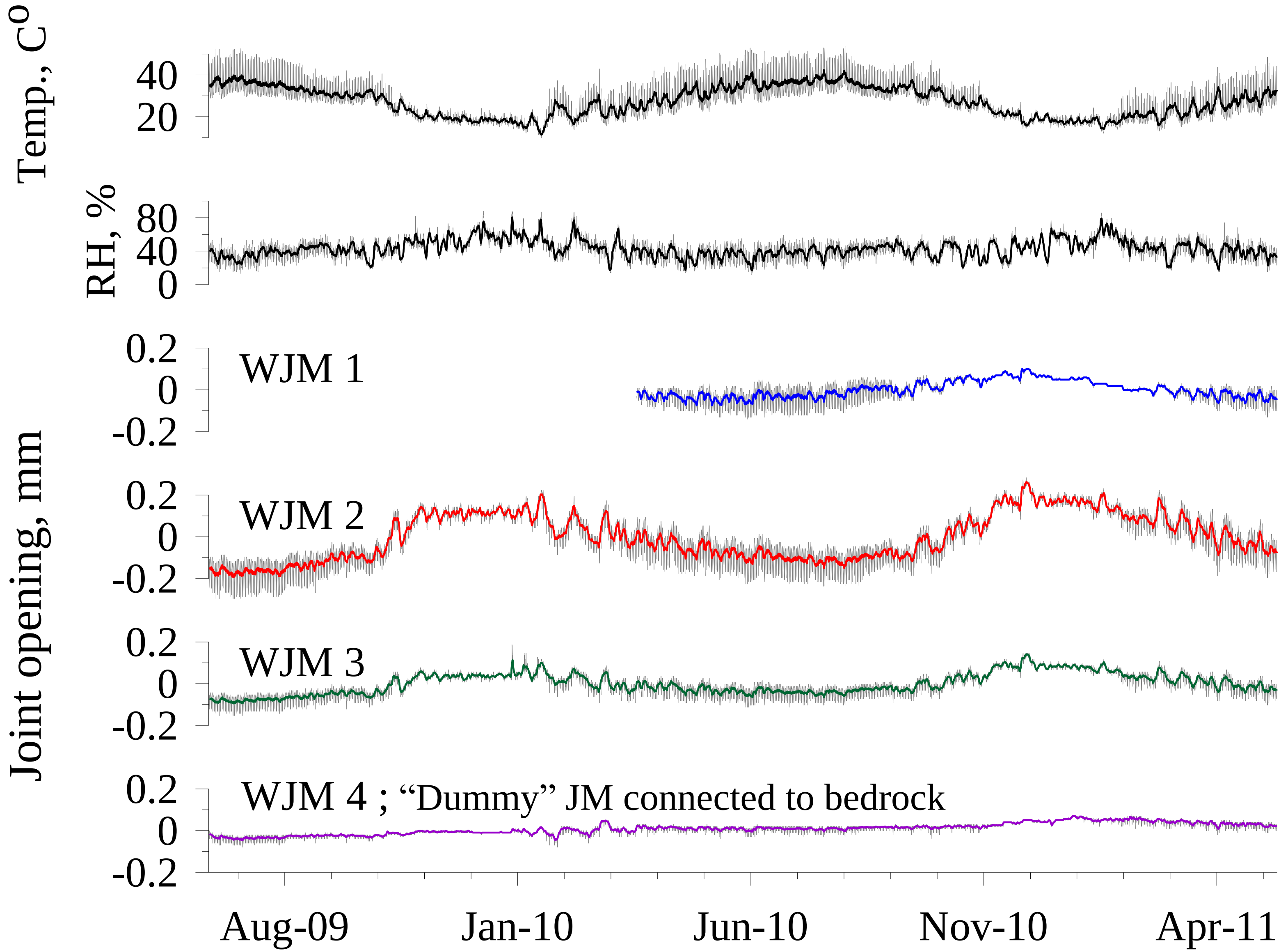
Temperature, wind velocity and precipitation, as recorded in the west slope of Masada, during February 2009.

Monitoring installation in west face

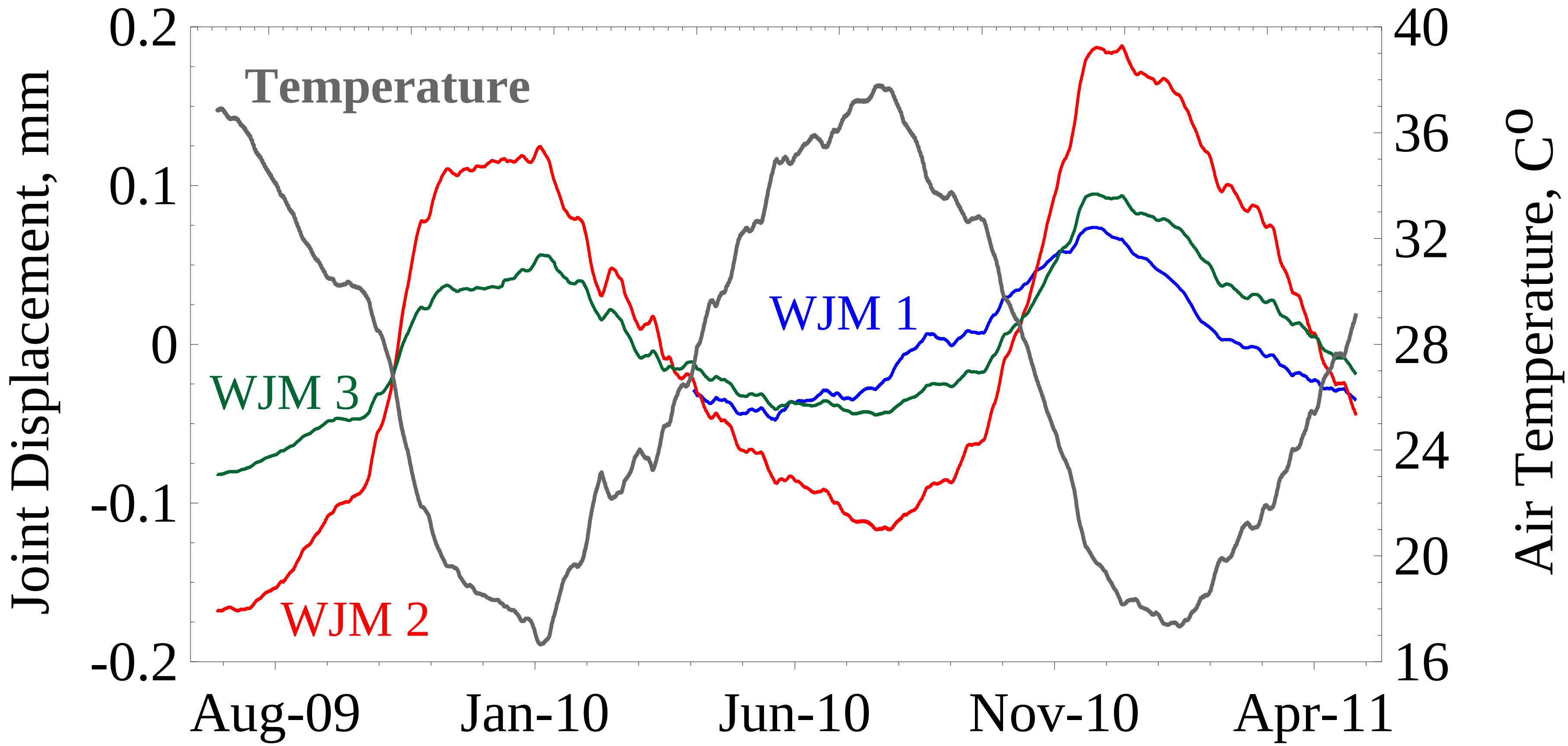




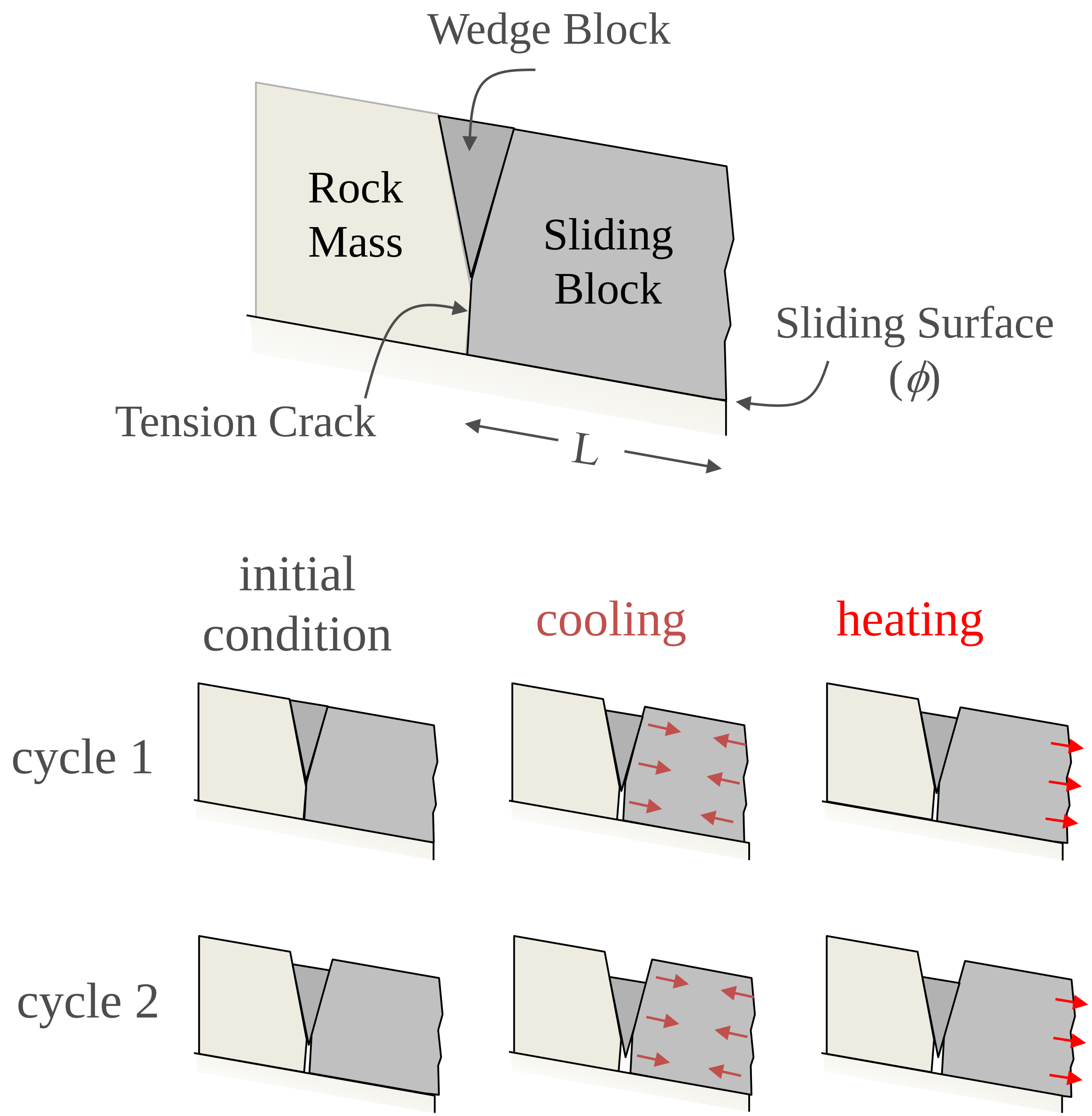
Temperature and displacement monitoring output



Temperature dependent cyclic opening/closure of joint aperture



Suggested Wedging - Ratcheting Mechanism



Theoretical model for thermally induced sliding

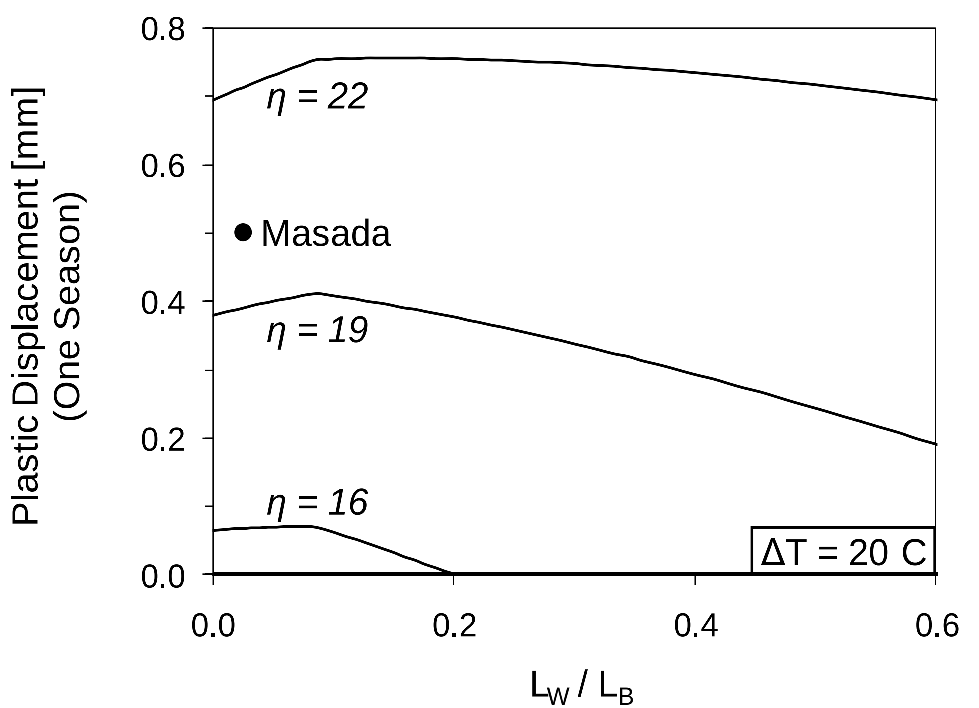
If the external temperature change ΔT exceeds the maximum temperature for elastic deformation ΔT_{max} the plastic displacement δ_j^p [m] that the block will experience is:

δ_T free thermal expansion

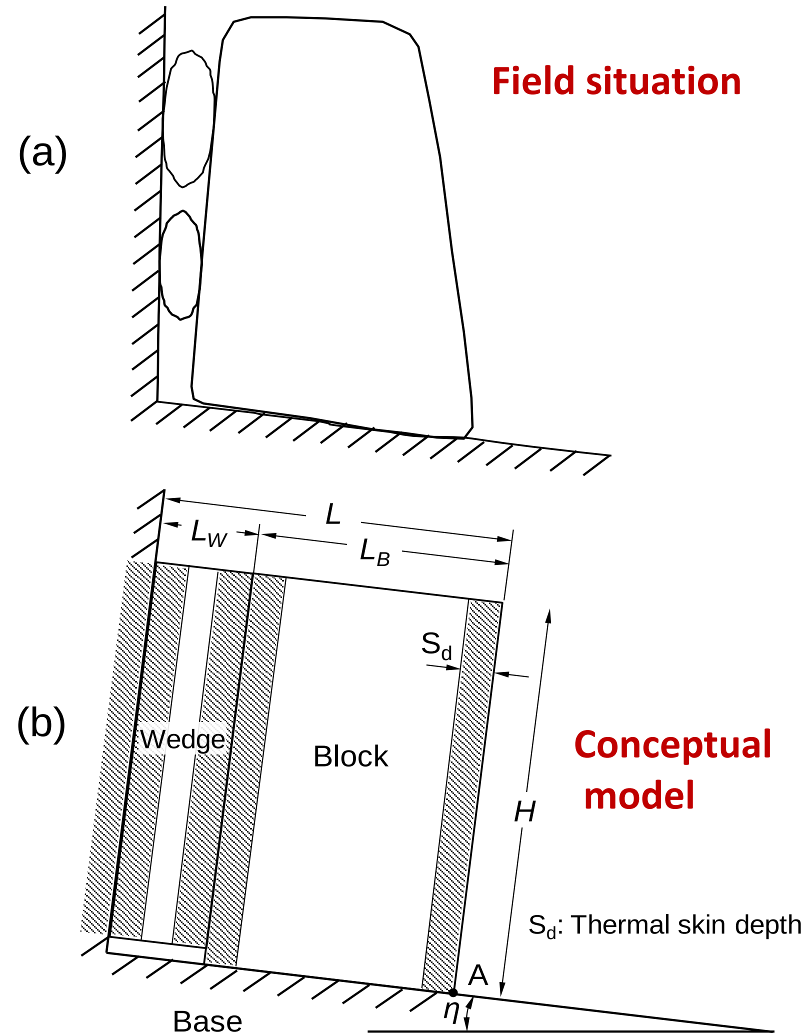
δ_σ elastic contraction

δ_j^* limiting joint elastic displacement

$$\boxed{\delta_j^p = \delta_T - \delta_\sigma - \delta_j^*}$$

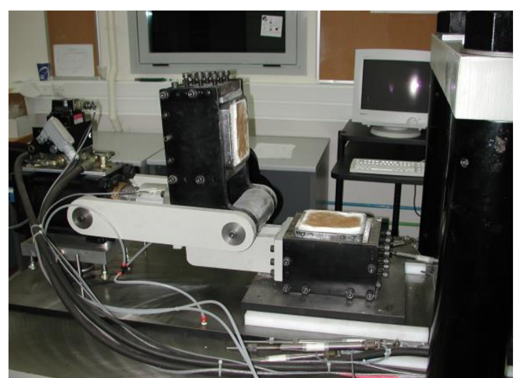


One-cycle plastic displacement for several plane inclinations. Dolomite block-wedge system subjected to a seasonal temperature change ΔT= 20°C.

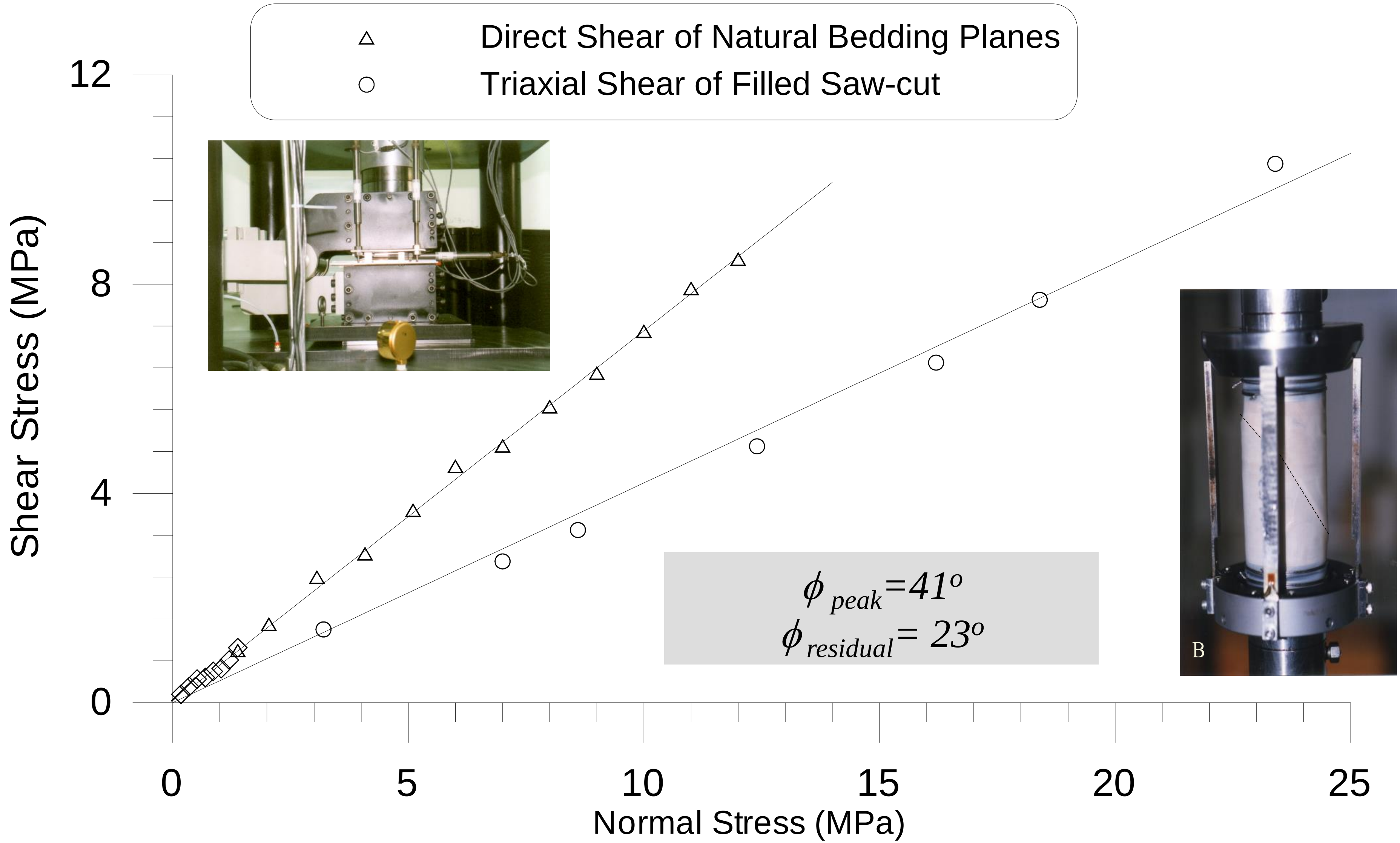


Pasten, Santamarina, and Hatzor (in prep.)

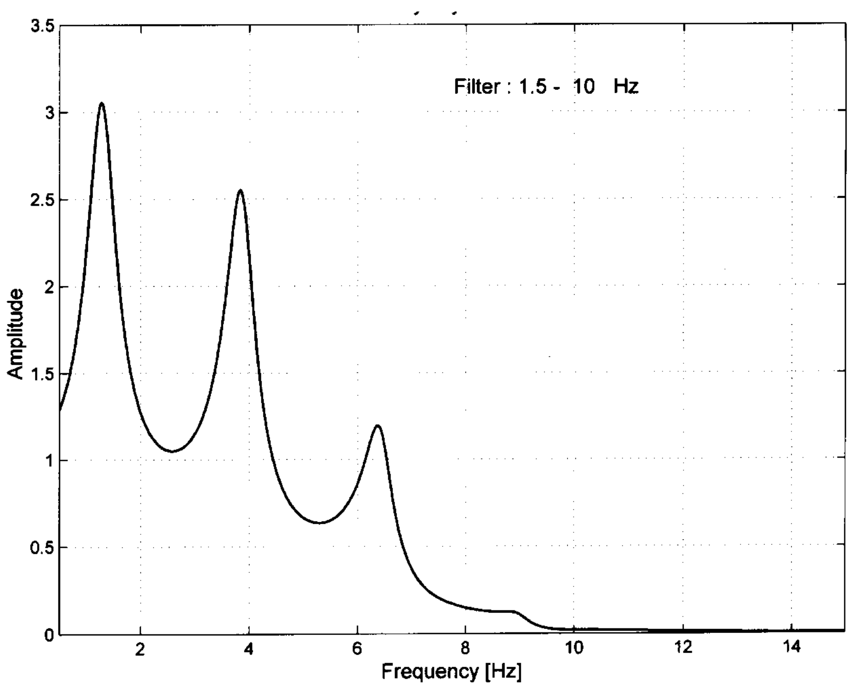
Shear strength of bedding planes in Masada



Failure envelope of smooth and rough surfaces



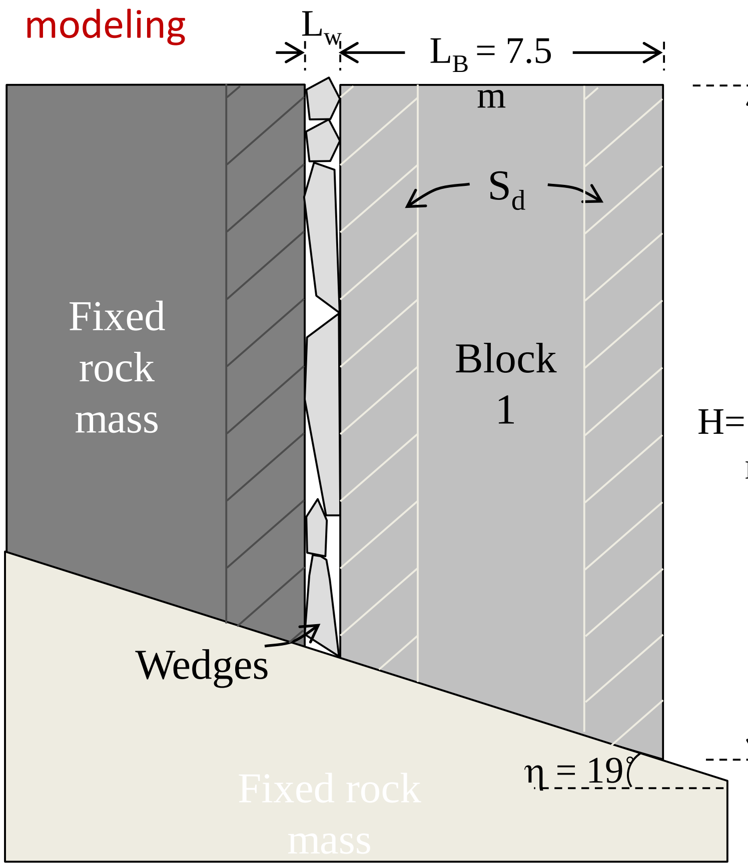
Input Motion: Consideration of Topographic Site Effect

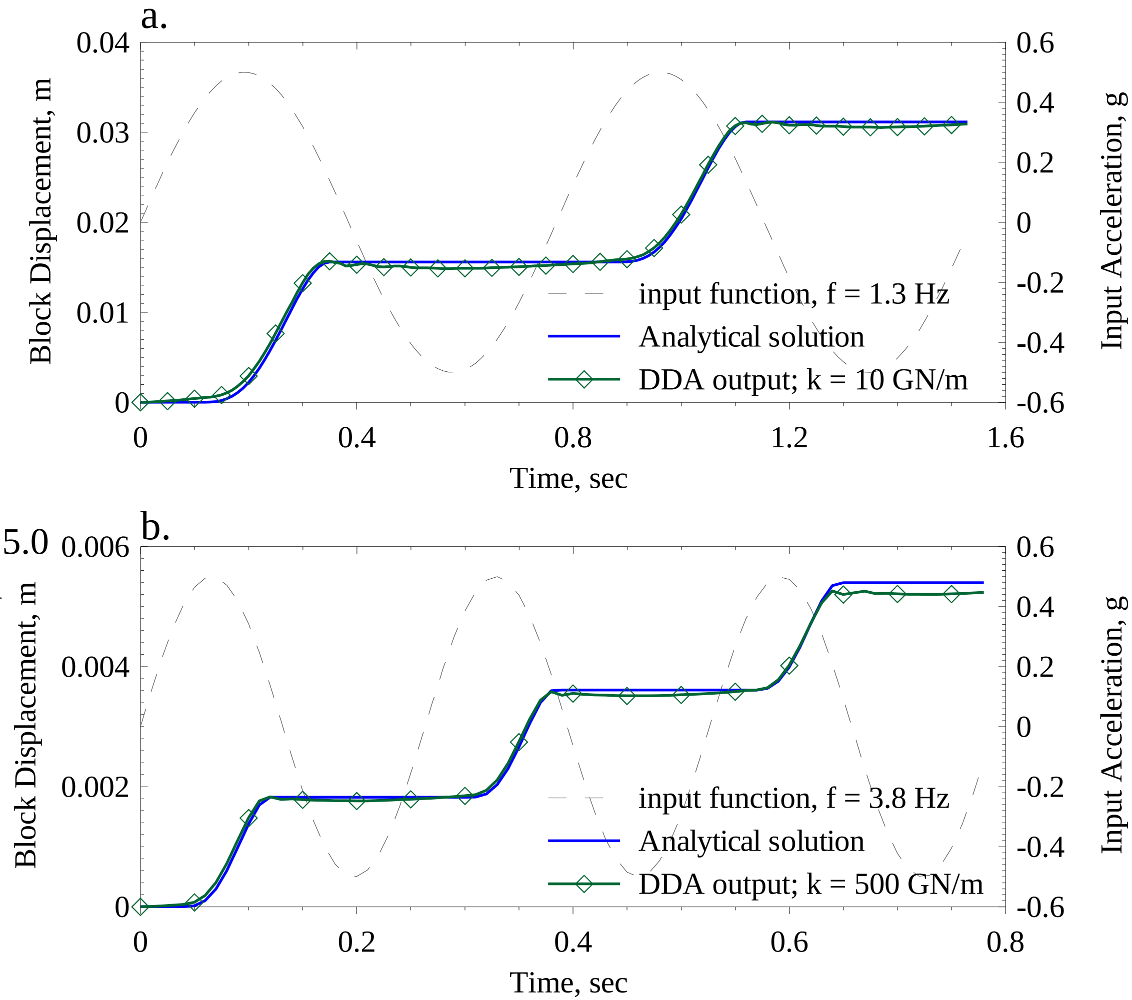


Empirical response function for the topographic site effect at Masada (Zaslavsky and Shapira, 2000).

Dynamic response to cyclic loading with DDA

The geometry of Block 1 in the East face of Masada is used for modeling

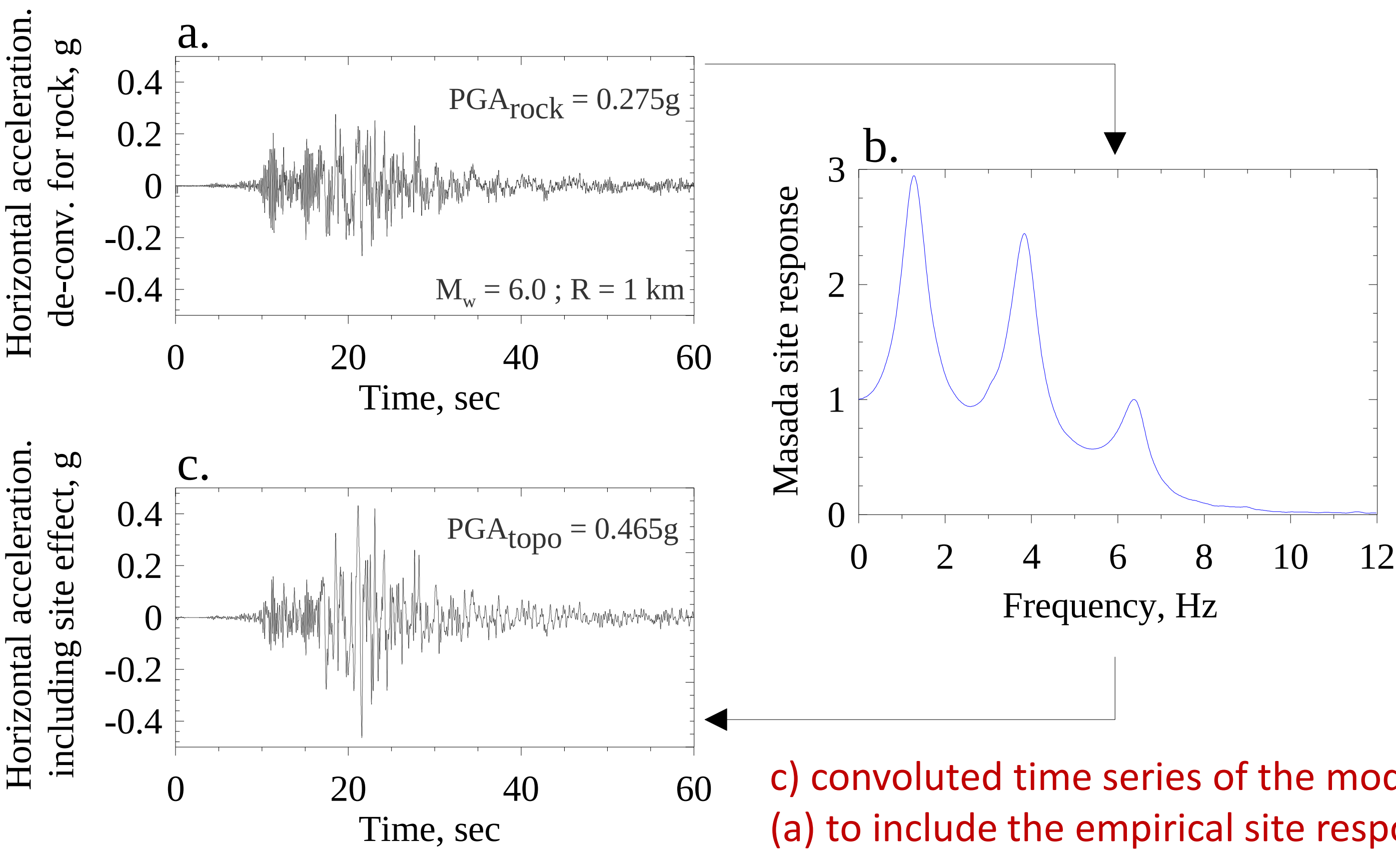




DDA results are strongly affected by the penalty, or contact spring stiffness, value, especially in dynamic simulations. We optimize the contact spring value using the analytical (Newmark) solution and the two measured resonance frequency modes of the mountain: 1.3 Hz and 3.8 Hz.

Scaling the input motion

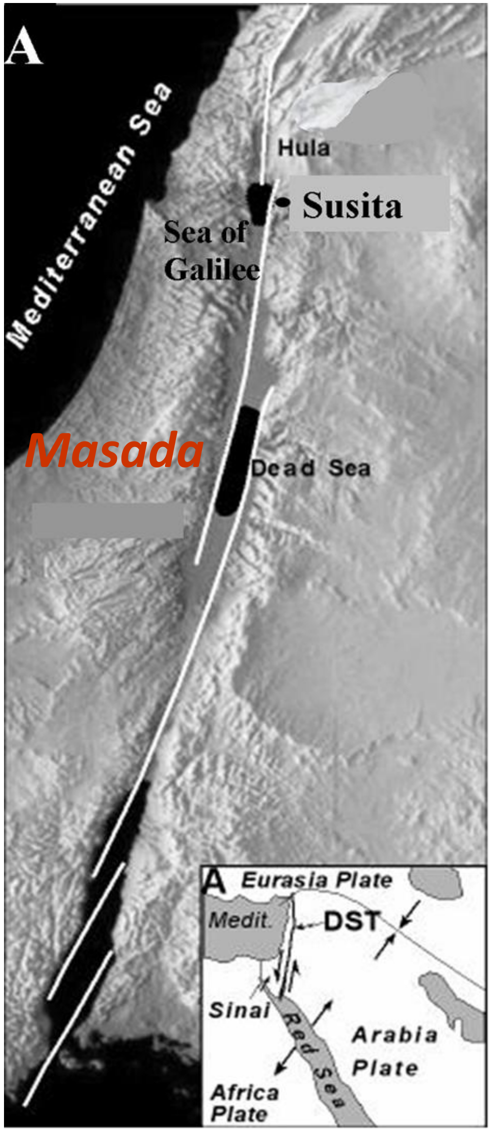
a) The Nuweiba earthquake as recorded in Eilat on a soil layer de-convoluted for bedrock response [*Zaslavsky and Shapira*, 2000] and scaled to PGA = 0.275*g*, corresponding to a M_w= 6.0 earthquake at a distance of 1 km from Masada

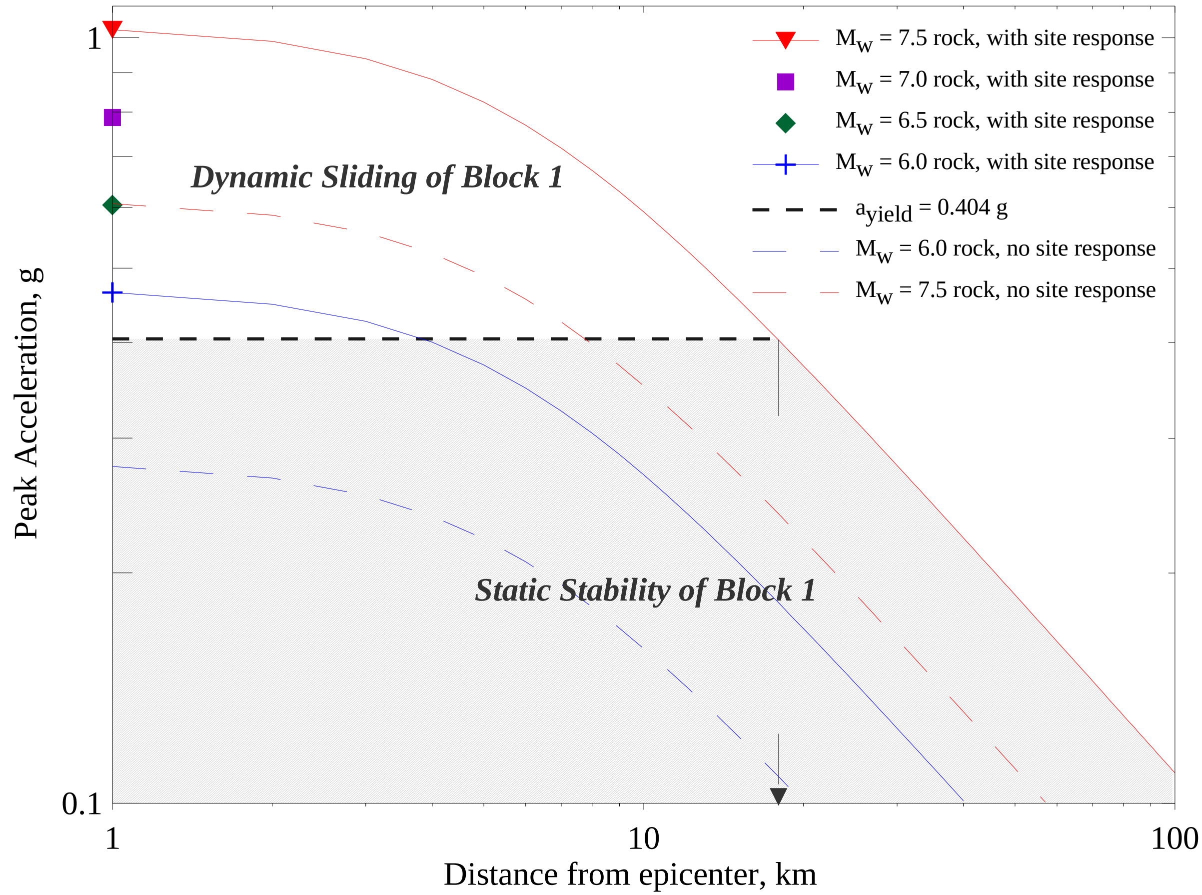


b) an empirical site response function for Masada [after *Zasalavsky et al.* 2002]

c) convoluted time series of the modified Nuweiba record (a) to include the empirical site response function for Masada (b)

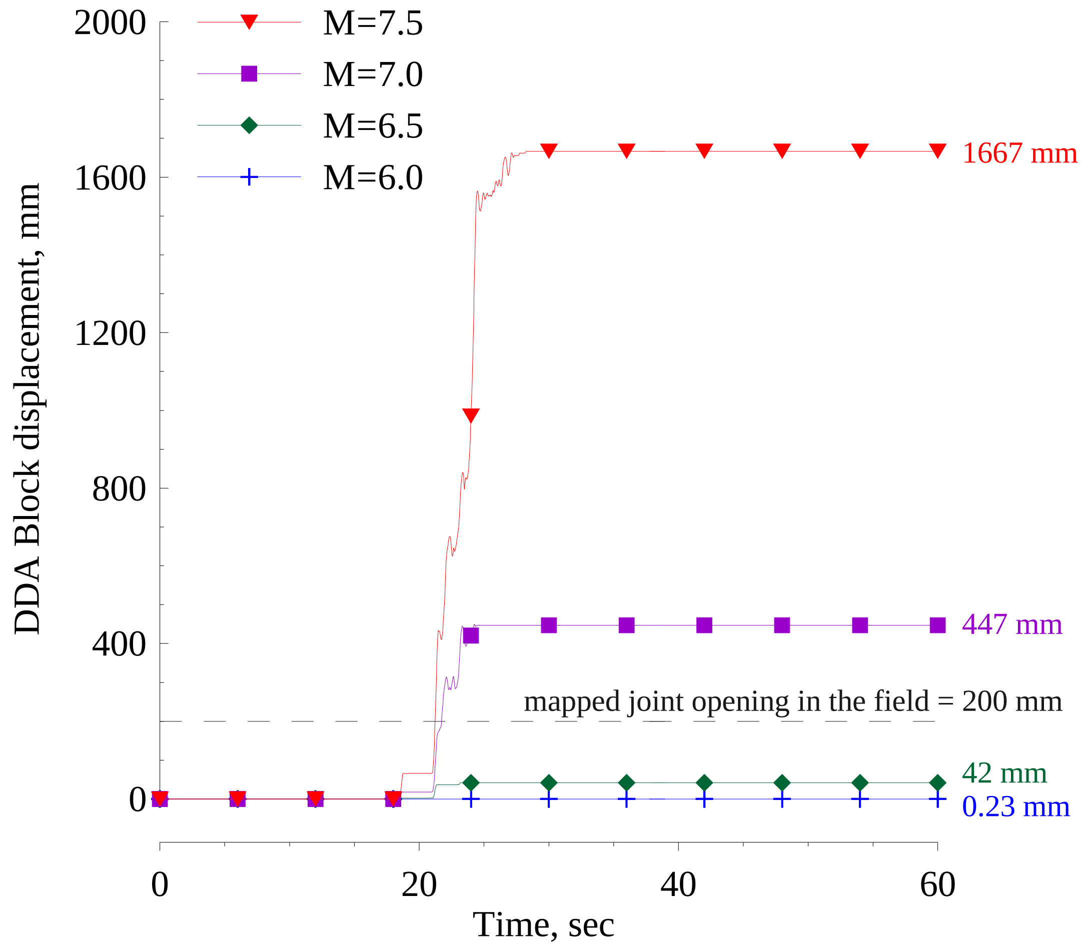
Response of Block 1 to regional earthquakes





Assumed attenuation curves for Dead Sea Rift earthquakes [after *Boore et al.*, 1997] (dashed lines) with amplification due to topographic site effect at Masada (solid lines and symbols). Shaded region delineates conditions at which seismically-induced sliding of Block 1 at Masada is not possible.

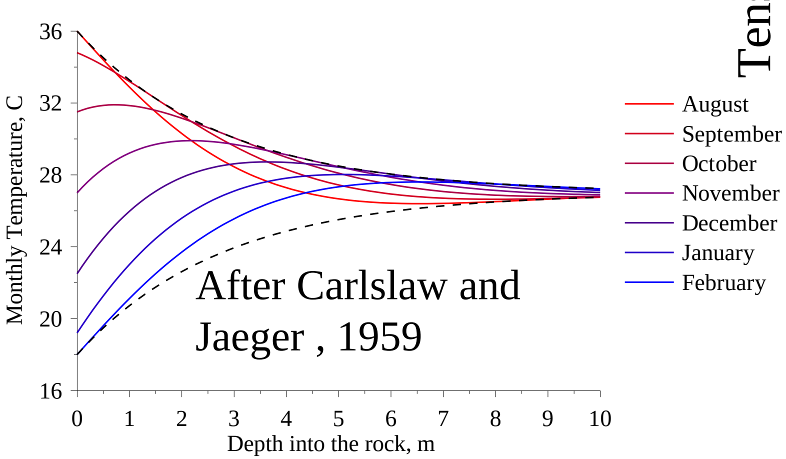
Maximum displacement of Block 1 in a single earthquake

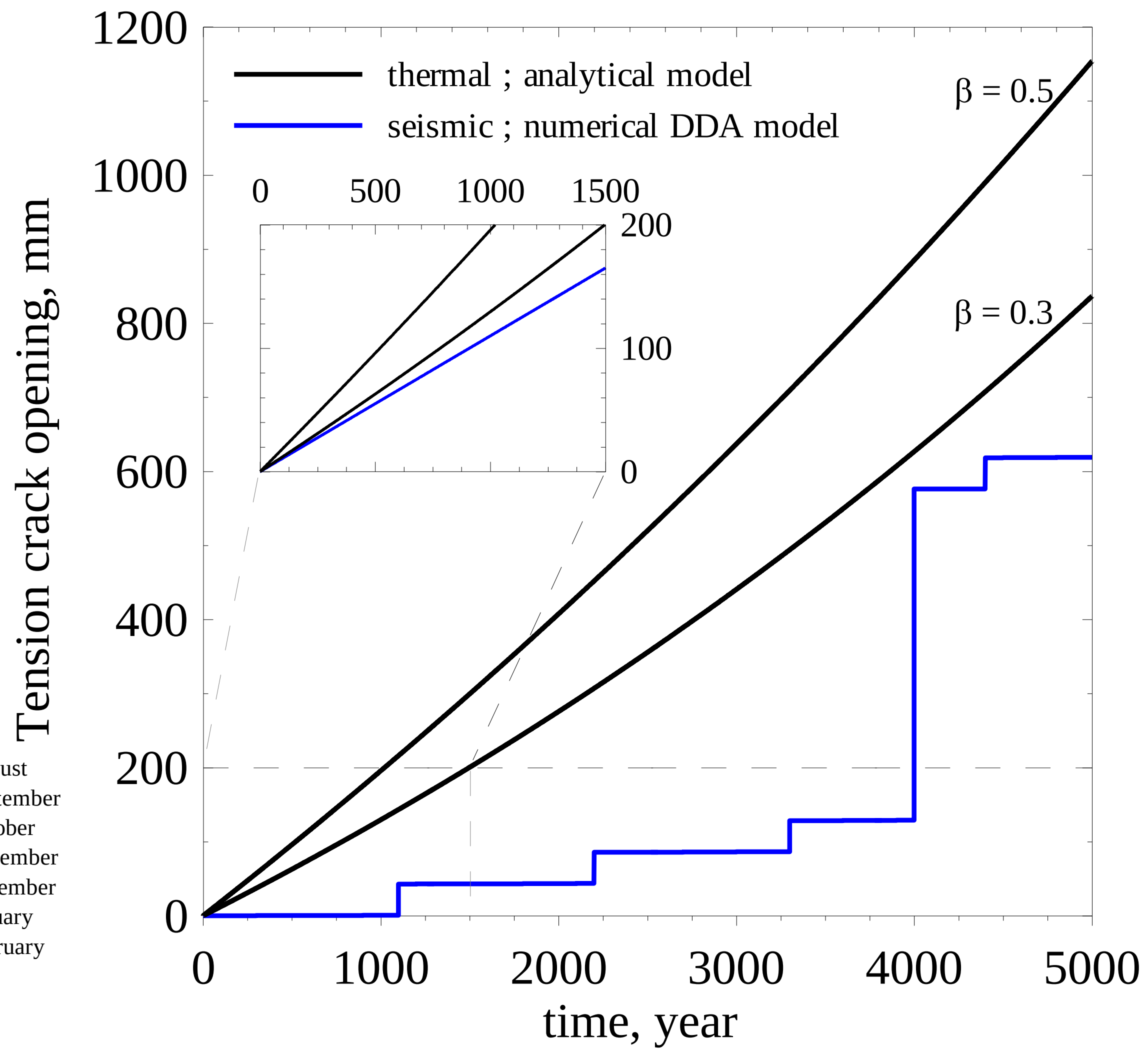


DDA results for dynamic displacement of Block 1 when subjected to amplified Nuweiba records corresponding to earthquakes with moment magnitude between 6.0 to 7.5 and epicenter distance of 1 km from Masada. Mapped joint opening in the field is plotted (dashed) for reference.

Comparison between thermal and seismic displacement rates for Block 1 in East Masada

Thermal displacement rate is calculated assuming β = 0.3 and 0.5. Seismic displacement rate is obtained by summation of earthquake magnitudes 6.0 to 7.0 with epicenter located 1 km from Masada based on the seismicity of the region. The seismic rates in the zoom-in box are for the long term seismicity (5000 years).





Summary and Conclusions

- The numerical, discrete element DDA method is shown to be suitable for performing accurate computation of dynamic interaction between blocks, making it an attractive tool for performing dynamic rock slope stability studies.
- In the DDA version used here a constant friction angle is assumed. It is shown here however that friction angle degradation should be considered depending on the interface properties and the sliding velocities. Therefore incorporating rate and state effects into DDA would be a significant enhancement.
- It has been shown through careful field measurements that rock joints are subjected to annual cyclic opening and closing motions due to thermal effects of climatic origin.
- Tension cracks filled with rock fragments subjected to seasonal temperature fluctuations may be prone to the described thermally induced ratcheting mechanism which could lead to irreversible annual plastic displacement of rock blocks.
- We show that when everything else is kept equal, thermally induced displacements may exceed seismically induced displacements over time in regions subjected to moderate seismicity and where the temperature amplitude is sufficiently high to induce thermal expansion.

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Thank you!