



Back Calculation of Earthquake-Rotated Objects (EROs)

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Outline

- Motivation
 - EROs in archaeoseismology
- Dynamic Response of Simple Structures
 - Monolithic Block
 - Rotation by translational GM
 - analytic
 - measured
- Outlook

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Earthquake-Rotated Objects EROs

Examples

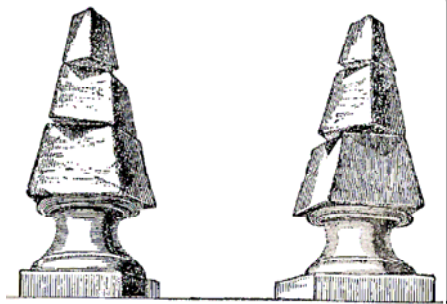
Bulletin of the Seismological Society of America, Vol. 91, No. 2B, pp. 998-1010, May 2000, doi: 10.1755/1.20000108
Tutorial on Earthquake Rotational Effects: Historical Examples
by Jan T. Kozák

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EROs Examples



Rotated obelisks, Claustro di St. Bruno
Calabria Earthquake, 1783

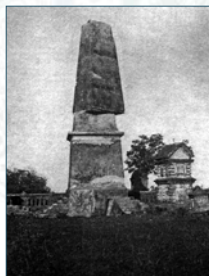
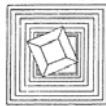
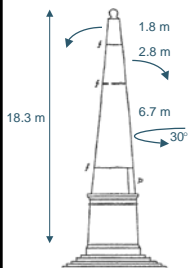
Lyell, 1830

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EROs Examples



Broken and rotated obelisk, Ingjis monument at Chihatak
Assam Earthquake, 1897-06-12

Davison / Oldham, 1899

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EROs Examples

- There is a thought-provoking chapter on rotation of pillars and monuments in which Oldham refutes all the more obvious explanations of what is undoubtedly a **complicated phenomenon** which may have a different mechanical basis in different instances.
- His conclusion, certainly acceptable, is that **waves must have arrived from many different directions** during the shaking

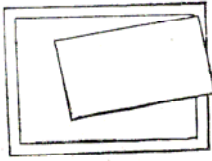
Richter, 1956

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EROS Examples



The monument faces south and north, and the statue on top of the column was moved six inches along the top of the shaft in easterly direction and towards the north;

FIG. 39. Displacement of Pulaski Monument at Savannah.

Rotated and shifted Pulaski Monument
Charleston Earthquake, 1886-08-31

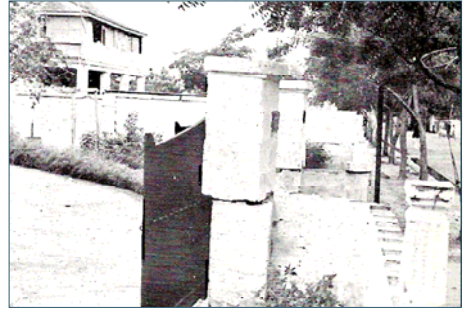
Dutton, 1987

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EROS Examples



Rotated upper part of gate pillars, Beach Avenue, Accra
Accra Earthquake, 1939-06-22

Junner et al., 1941

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EROS Examples



Rotated and toppled tombstones, Kushiro Cemetary
Tokachi-Oki Earthquake, 2003-09-26

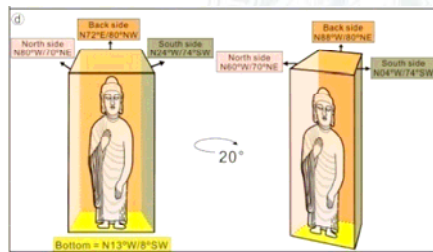
Photo curtsey R. Anoohepoor

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EROS Archaeo-Examples



Rotated Buddha Statue in Gyeongju Aream SE Korea

Jin et al, 2009

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EROS Archaeo-Examples



Rotated Blocks Great Theatre Larissa, Greece

Photo curtsey R. Caputo

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EROS Archaeo-Examples



Rotated south-eastern corner pier of the porticus, Ostia Antica

Photo curtsey Antonia Arnoldus

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EROS Archaeo-Examples



Rotated Lycien Sarcophagus, Pinara, SW Turkey

Hinzen et al, 2010 BSSA in press

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EROS Models

- Mallet, 1848
 - uneven distribution of contact forces with respect to CG
 - Rot1 Kozák (2006)
- Hoffmann, 1838; Mallet 1862; Reid, 1910
 - cross vibrations
 - combination of vibrations at right angles
 - Rot2 Kozák (2006)

H.F. Reid, 1910
T. Kozák, 2009

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EROS Questions

- Are pure translational GMs with the suitable frequency content and phase relation between the three components sufficient to explain all EROs?
- How significant are rotational GMs?
- Can observed rotations help to back calculate GM parameters?

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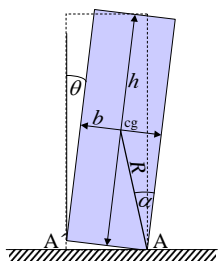


Discrete Element Model Code and Model Verification

Free Rocking
Forced Rocking

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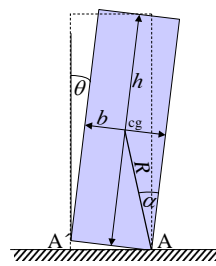


Rest

$$\dot{x}_0 = 0 \quad \theta = 0 \quad \dot{\theta} = 0$$

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Sliding $|f| \geq \mu_s F_N$

$$\dot{x}_0 \neq 0 \quad \theta = 0 \quad \dot{\theta} = 0$$

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Rocking $\frac{a}{g} \geq \frac{b}{h}$

$\dot{x}_0 = 0 \quad \theta < \frac{\pi}{2} \quad \dot{\theta} \neq 0$

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Slide-Rocking

$\dot{x}_0 \neq 0 \quad \theta < \frac{\pi}{2} \quad \dot{\theta} \neq 0$

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Translational Jump

$\dot{x}_0 \neq 0 \quad \theta = 0 \quad \dot{\theta} = 0$

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Rotational Jump

$\dot{x}_0 = 0 \quad \theta < \frac{\pi}{2} \quad \dot{\theta} \neq 0$

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Overtun

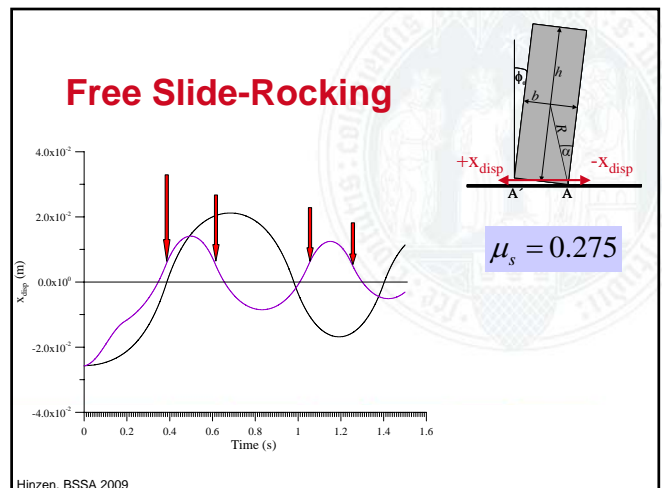
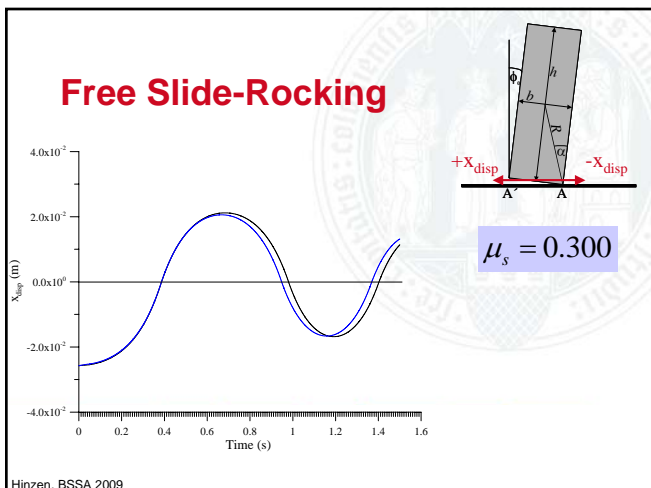
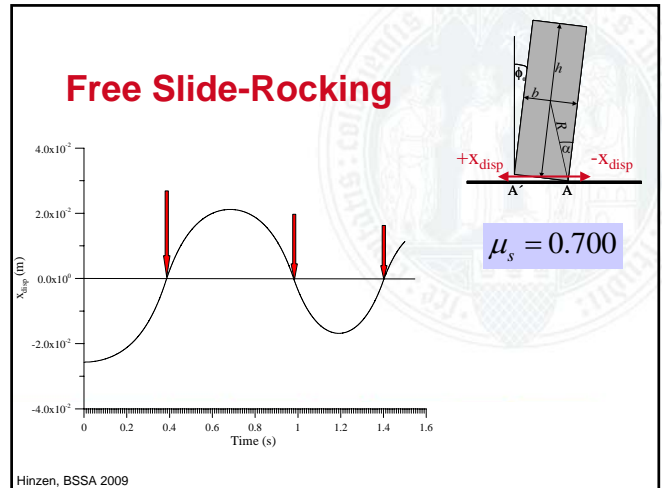
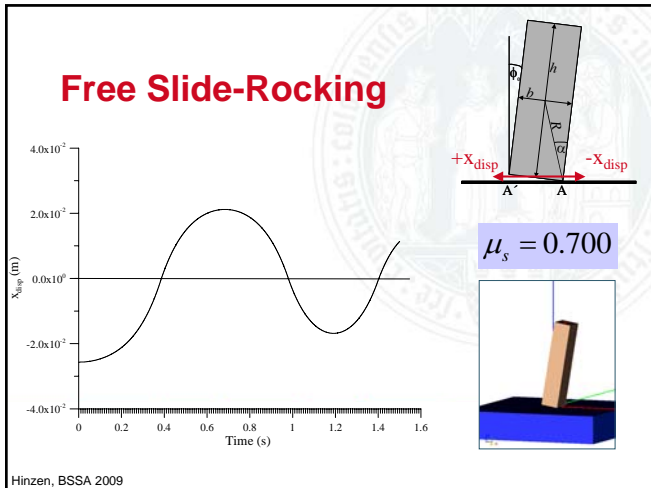
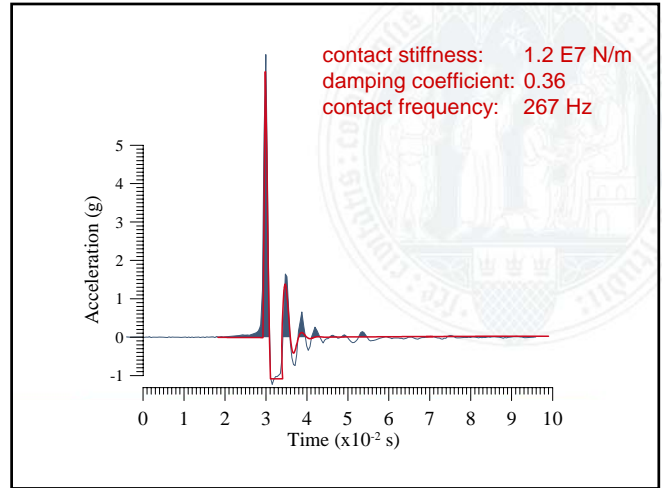
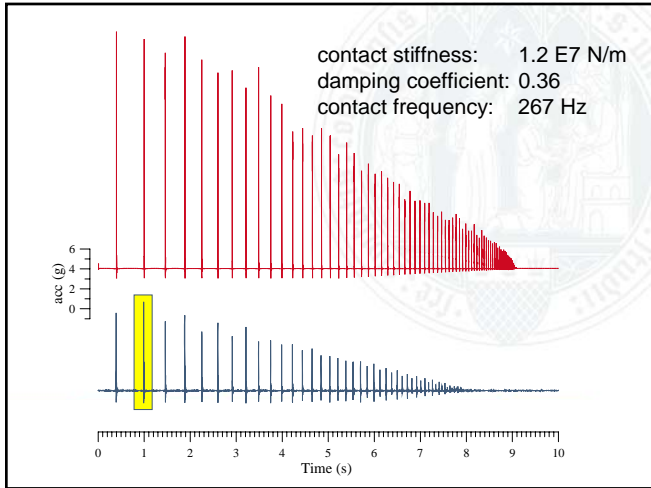
$\theta > \frac{\pi}{2}$

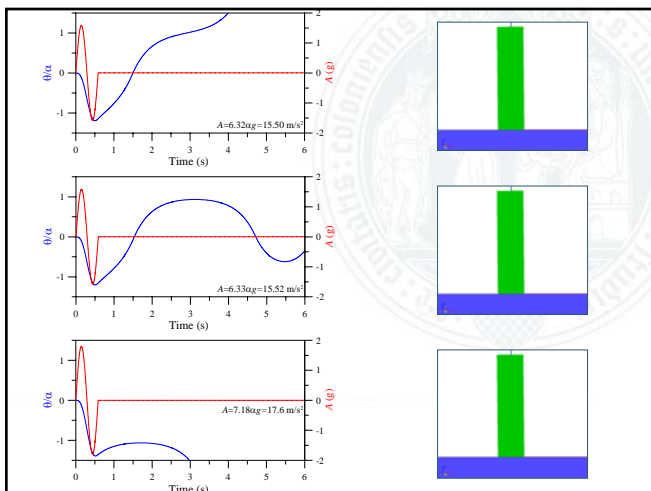
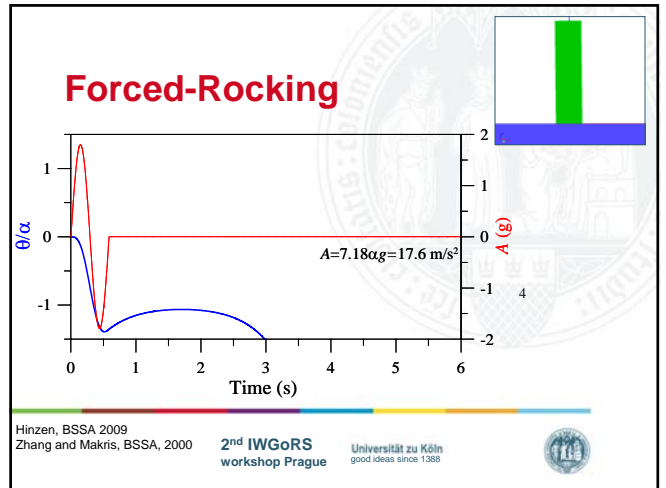
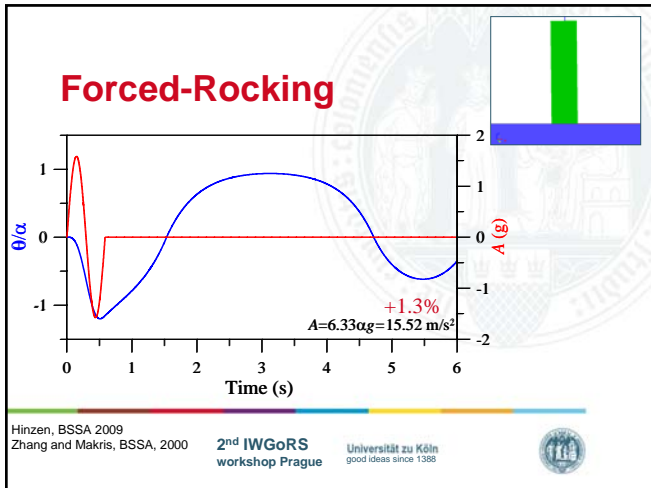
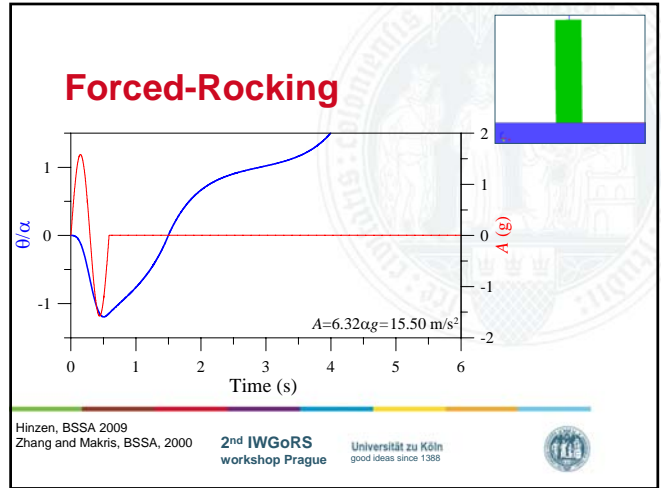
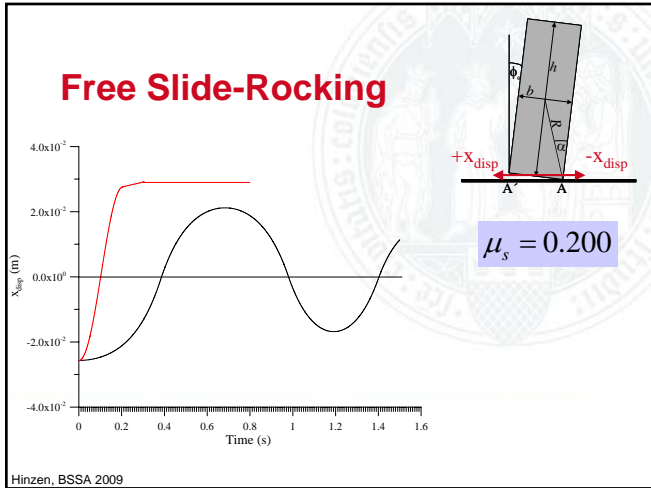
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Analog experiment Numerical experiment

accelerometer
 marble 6x8x30cm

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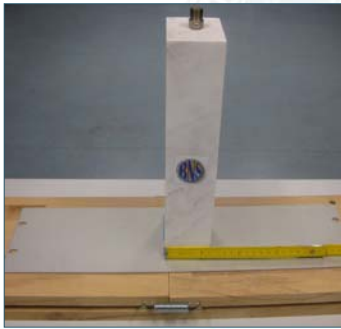
Translational GM

Analog Experiment

(free rocking with orthogonal translational motion)

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EROS Analog Experiment



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Translational GM

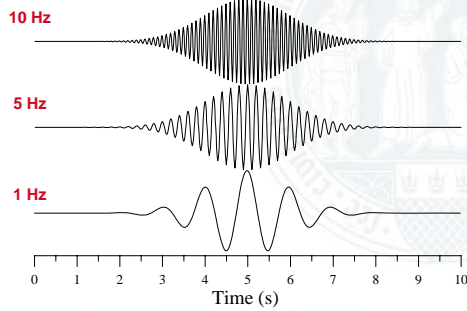
Morlet Wavelet
(two directions)

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Translational GM Morlet Wavelets

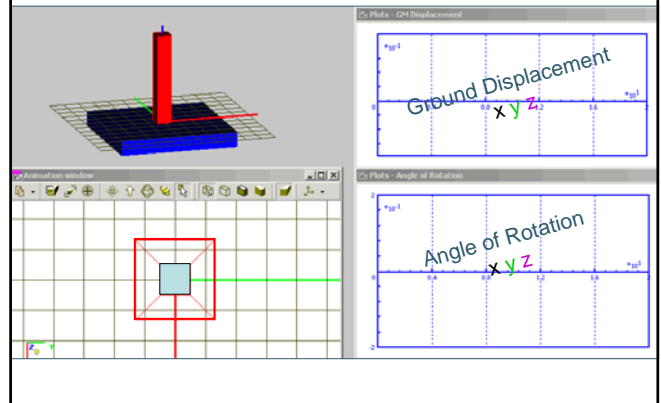


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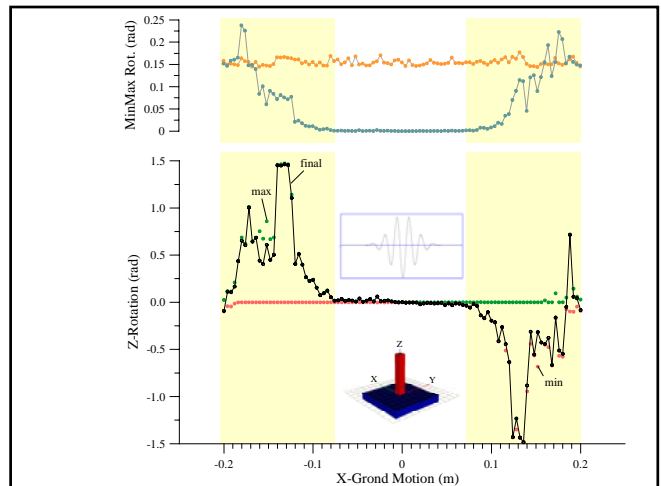
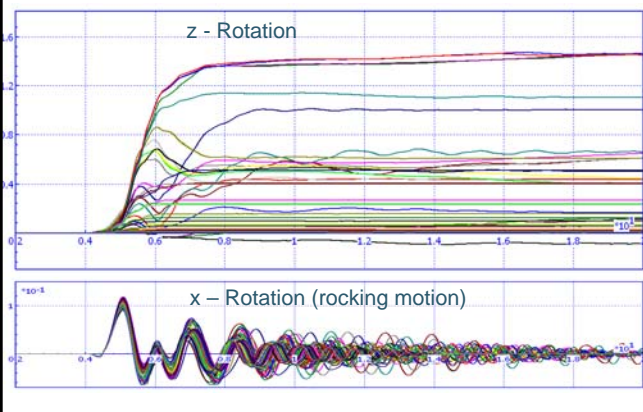
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EROS Translation x,y Morlet



EROS Translation x,y Morlet



Translational GM

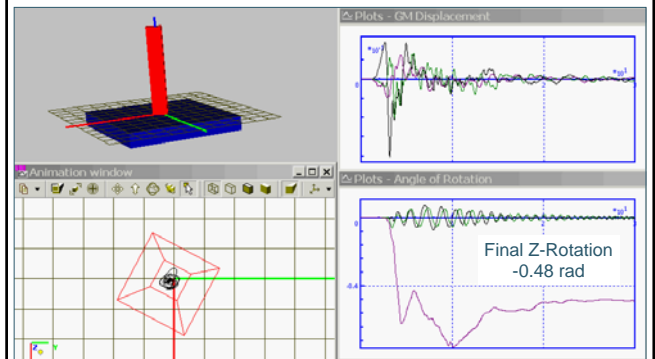
Measured SM
L'Aquila 2009
(three directions)

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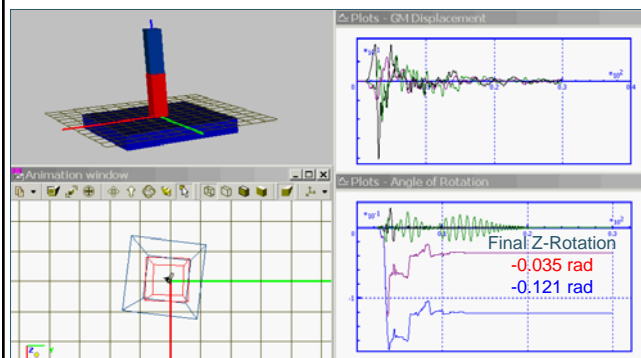
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EROS L'Aquila measured SGM



EROS L'Aquila measured SGM



EROS preliminar results of numeric test

- Translational GM rotate simple blocks
 - in case of even homogeneous contact
 - pure horizontal GM
- Once rocking starts, rotation around Z-axis occurs
 - amount of rotation depends on amplitude and duration of orthogonal GM component
- Structured blocks show smaller tendency to rotate
 - Numeric model tests confirm the crost vibration explanation from Hoffmann/Mallet/Reid (Rot2)

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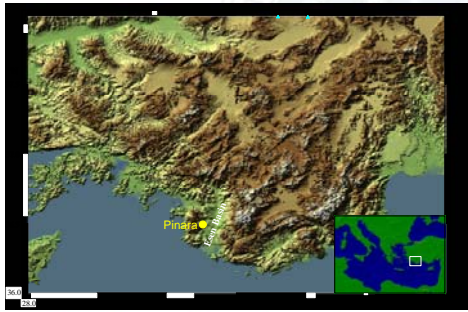
Field Case Pinara, SW Turkey

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Location



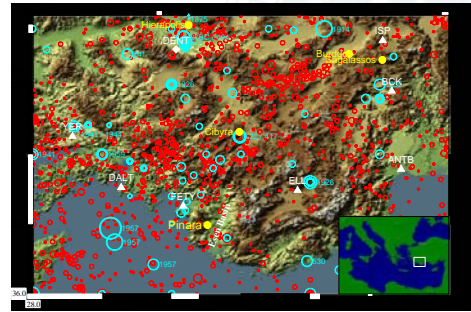
Seismicity

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Location



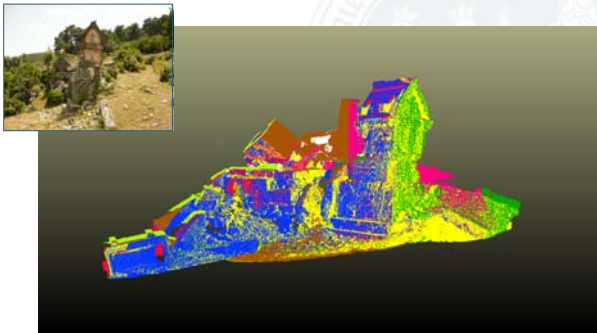
Seismicity

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Laserscanning (Lycien Tombs, Pinara)



Color Coded Scans

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Model Testing

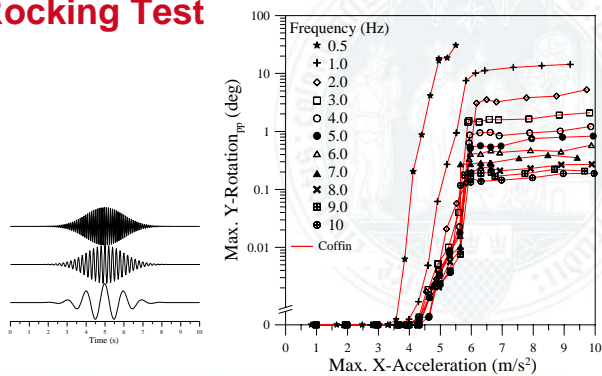
Free Motion
Rocking Tests

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Rocking Test



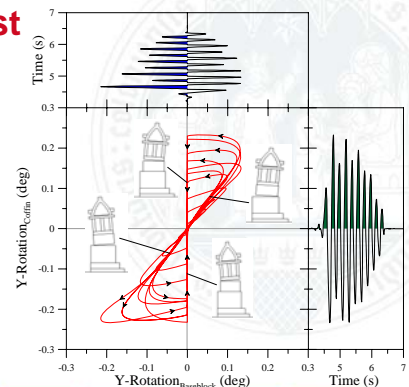
Morlet Wavelet

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Rocking Test



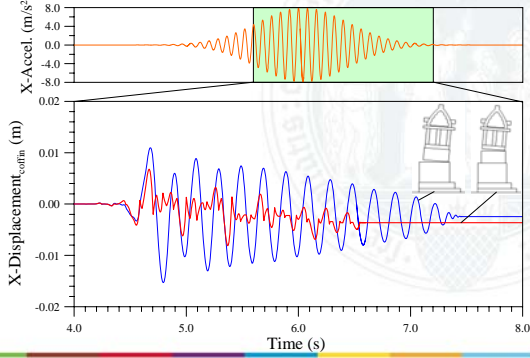
Morlet Wavelet
5 Hz / 7 m/s²

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Rocking Test



Fixed Model
vs
Sarcophagus

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Earthquake Loading

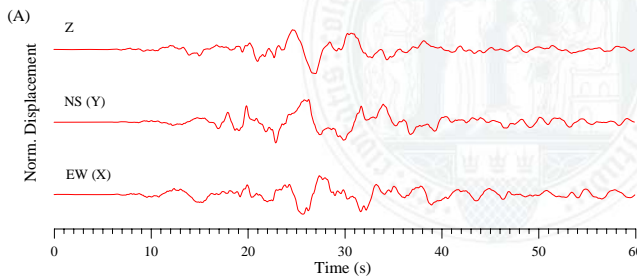
Scaled Ground Motions Fetye
Strong-Motion Record L'Aquila

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Earthquake Ground Motion

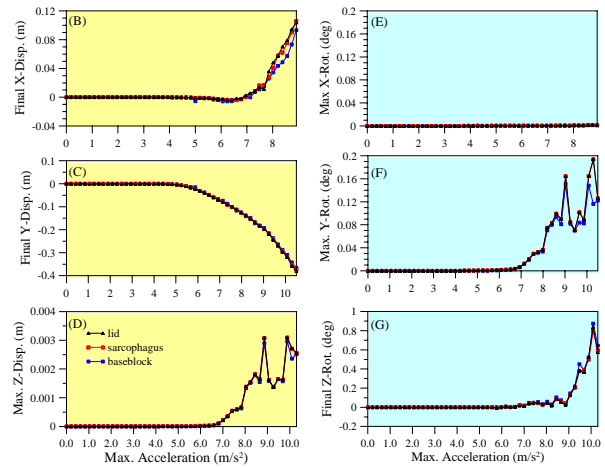


Hinzen et al., 2010 (BSSA)

FETY02

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Anthropogenic Action

Traces of Looting



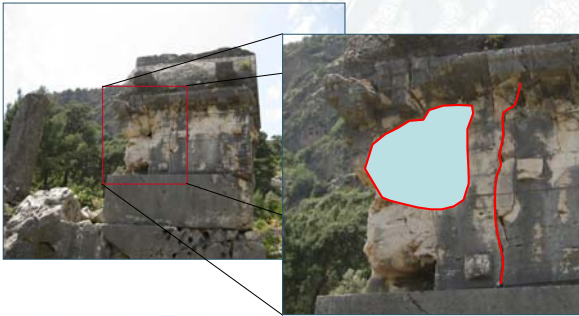
Lycian Sarcophagi

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Traces of Looting



Hinzen et al., 2010 (BSSA)

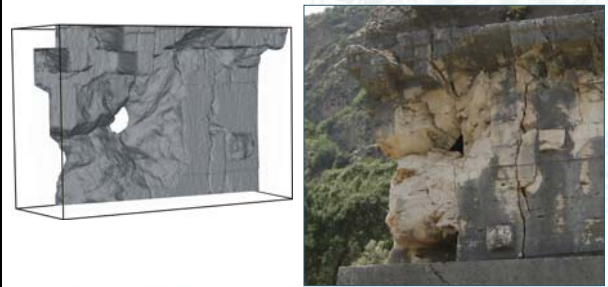
Explosion

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Traces of Looting



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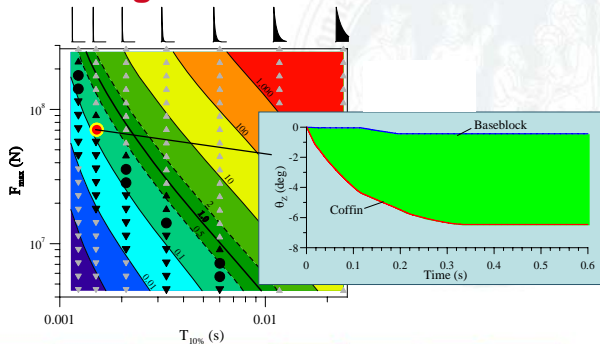
Explosion

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Modeling Results



Hinzen et al., 2010 (BSSA)

Rotation History

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Conclusion

Rotation of Arttumpara's
sarcophagus in Pınara has
anthropogenic causes

Hinzen et al., 2010 (BSSA)

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Conclusion & Outlook

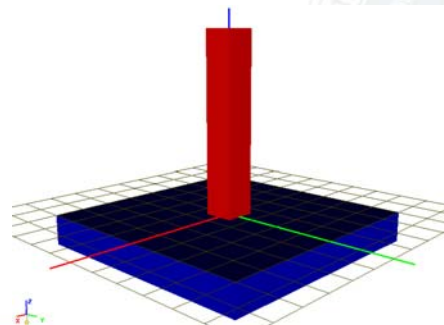
- Numeric models show that translational GMs are capable to rotate simple structures
- Rot2 model is supported
- Initiation of rocking is a key to subsequent rotation
- Systematic approach is needed
- The role of rotational GM components needs to be studied

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Thank you for your attention



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