

O.A.Σ.Π. SEMINAR

"The Protection of the Integrity of Monuments under Seismic Actions"

Thessaloniki 3-5, November 2011

# Seismic response of free-standing monolithic and multidrum columns of ancient Temples

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Nicos Makris

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University of Patras*

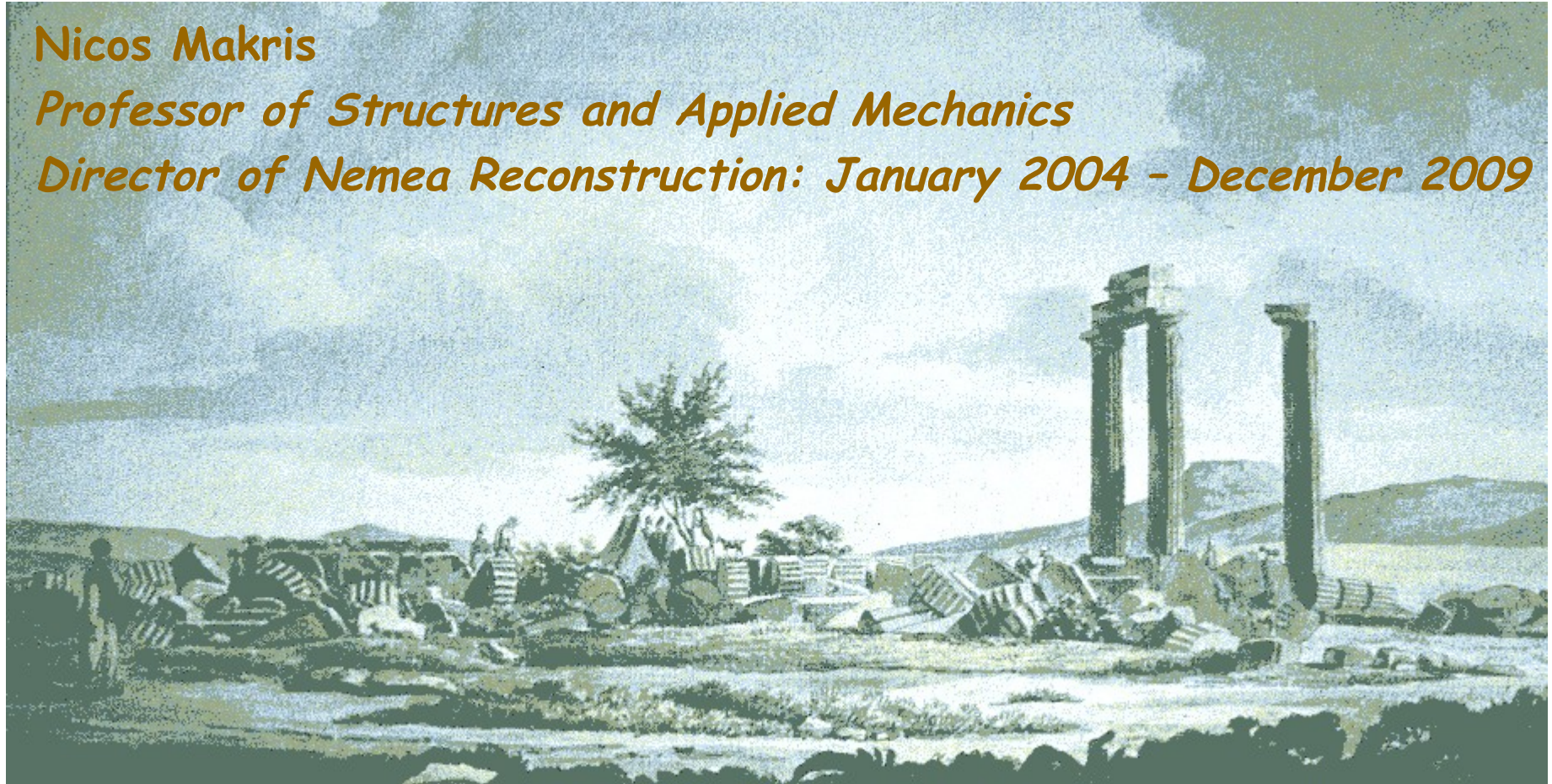
email: nmakris@upatras.gr

# The Reconstruction of the North-East Corner of the Temple of Zeus at Nemea

Nicos Makris

*Professor of Structures and Applied Mechanics*

*Director of Nemea Reconstruction: January 2004 - December 2009*

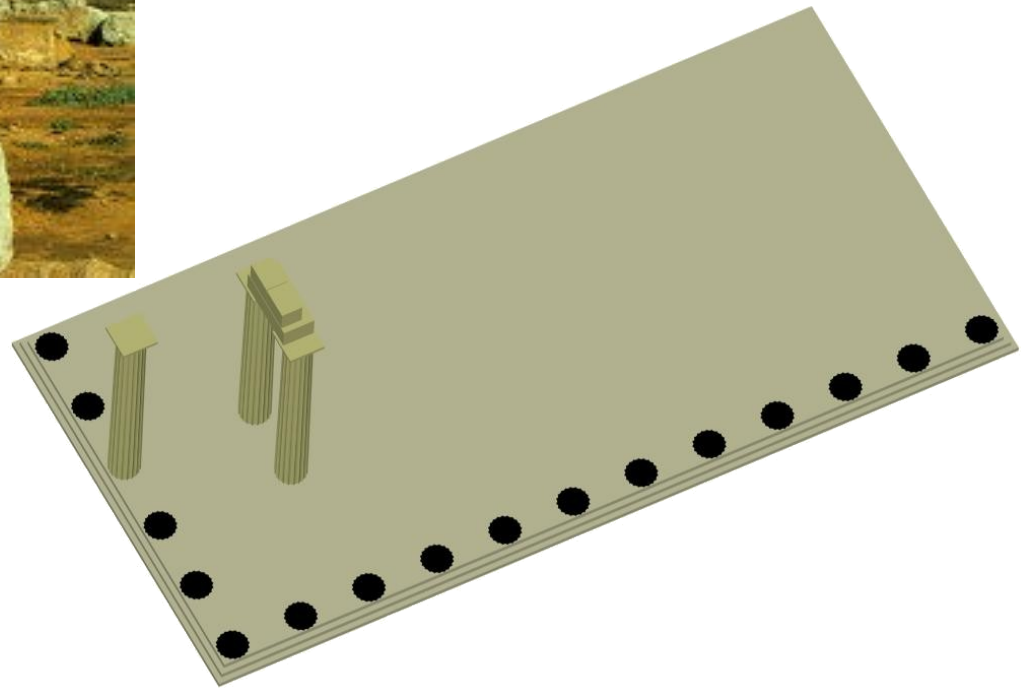


Nemea - Temple of Zeus, 1766





## View of the three columns standing from the ancient times





# The challenge of reconstruction. Why reconstructing ?

## Aerial View of the Temple (1977)



Columns have fallen to the outside

# Erroded column drums





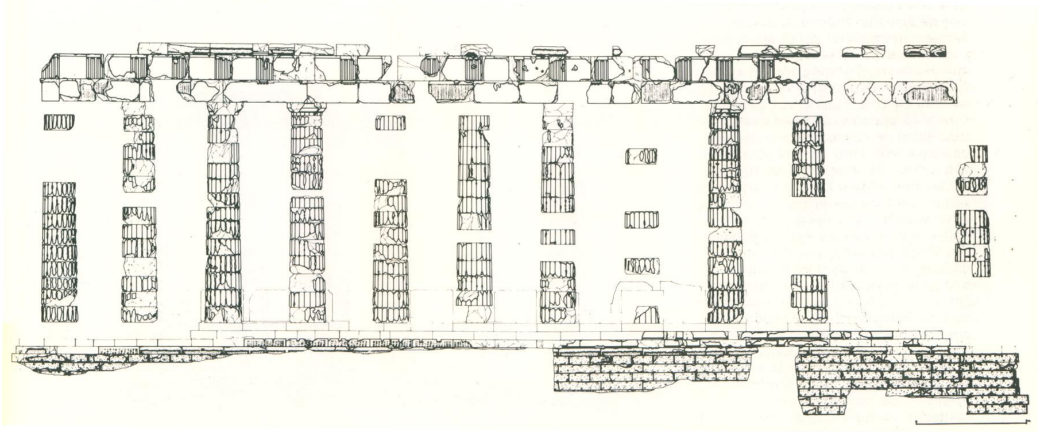
# View from the west of the 3 standing columns from ancient times



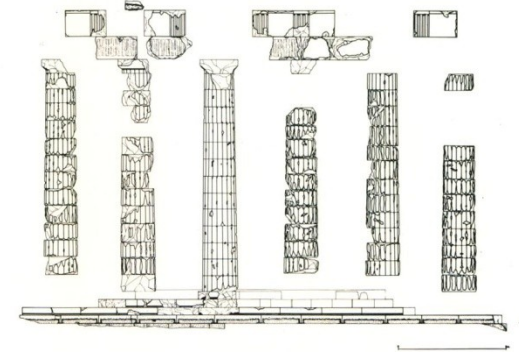


# Synthesis of the ancient stone blocks by Frederic Cooper (1980-1982), University of Minnesota

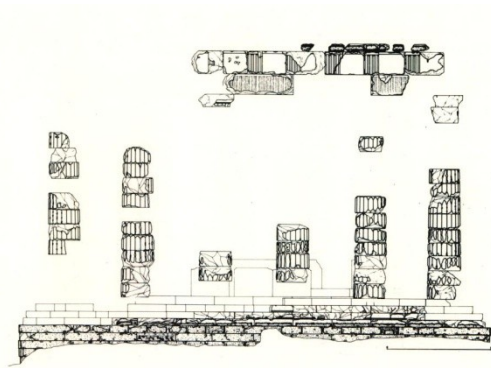
North view



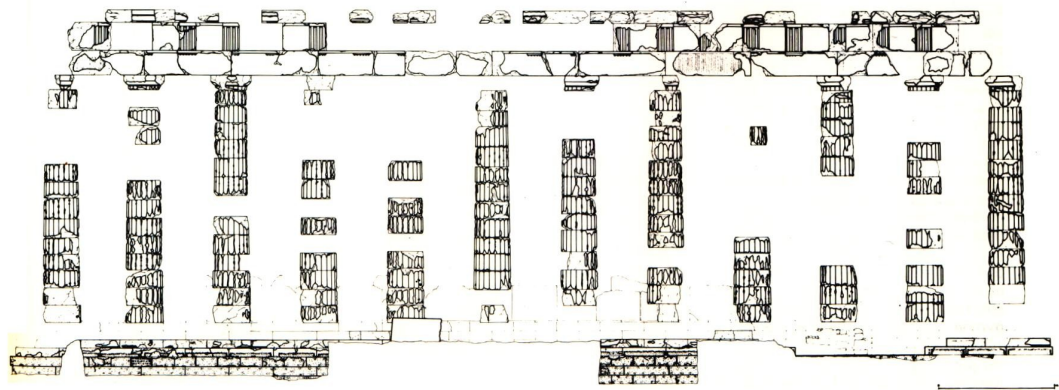
East view



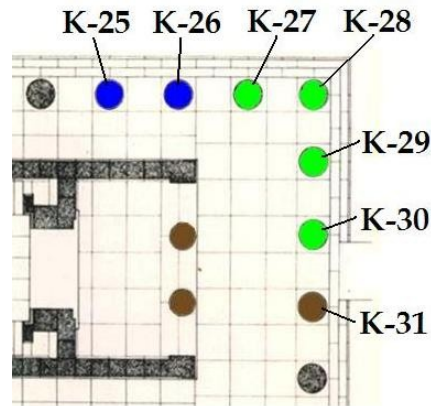
West view



South view



# Pilot Reconstruction: columns K-25 & K-26

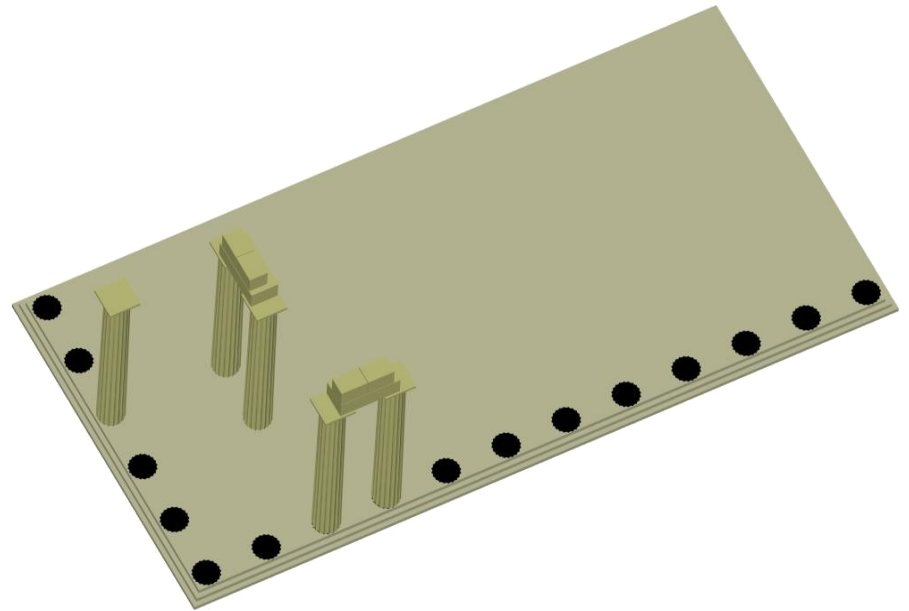


With the invaluable  
contribution of:

Dr. Kostas Zambas  
Prof. Manolis Korres  
Mr. Ioannis Arbiliias



# The pilot reconstruction: K-25 & K-26

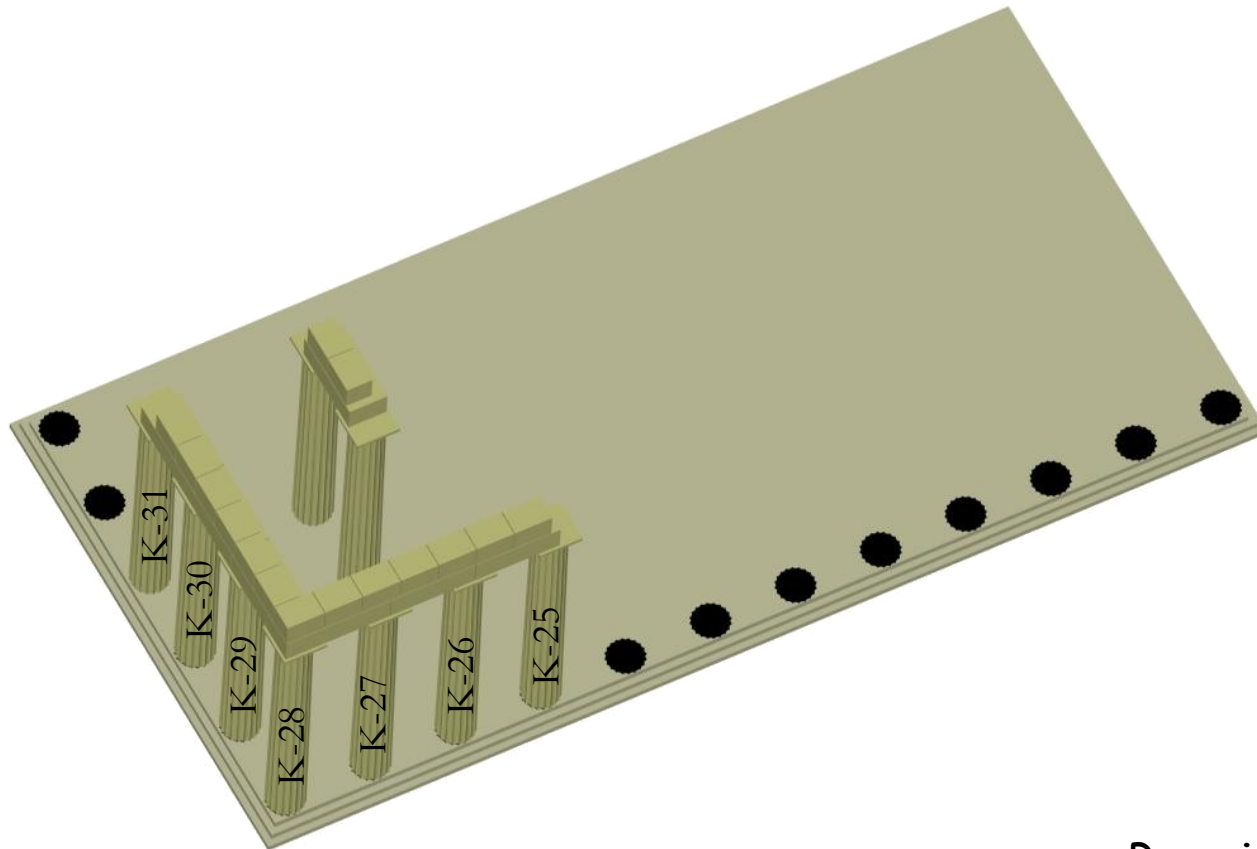


Completed: Summer 2002



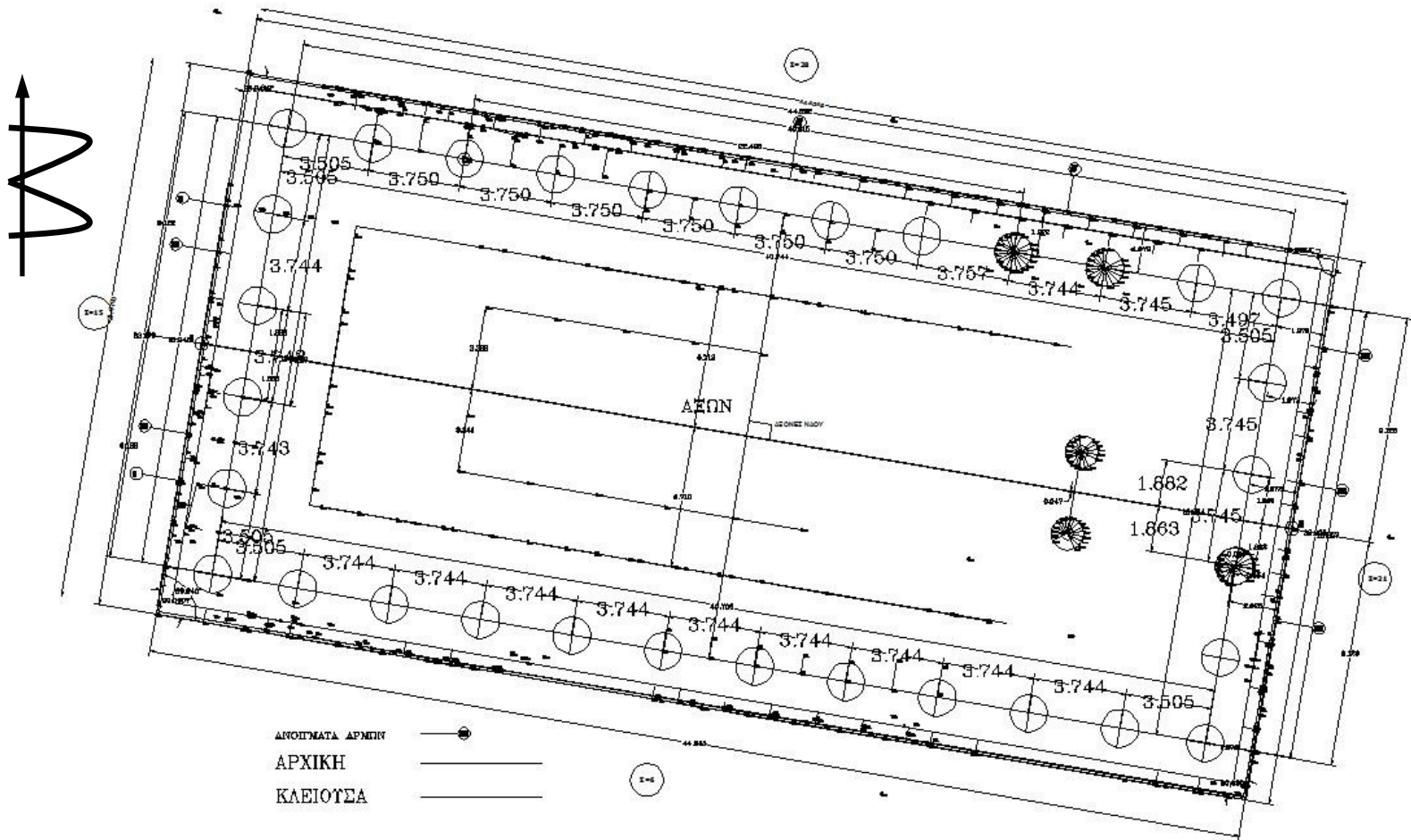
The shape of the temple after the completion  
of the second phase.

Reconstruction of K-27, K-28, K-29 & K-30



Permit issued on  
March 04 2004

# Detailed surveying of the current situation of the monument



Establishment of the centers of the columns based on a sophisticated optimization analysis

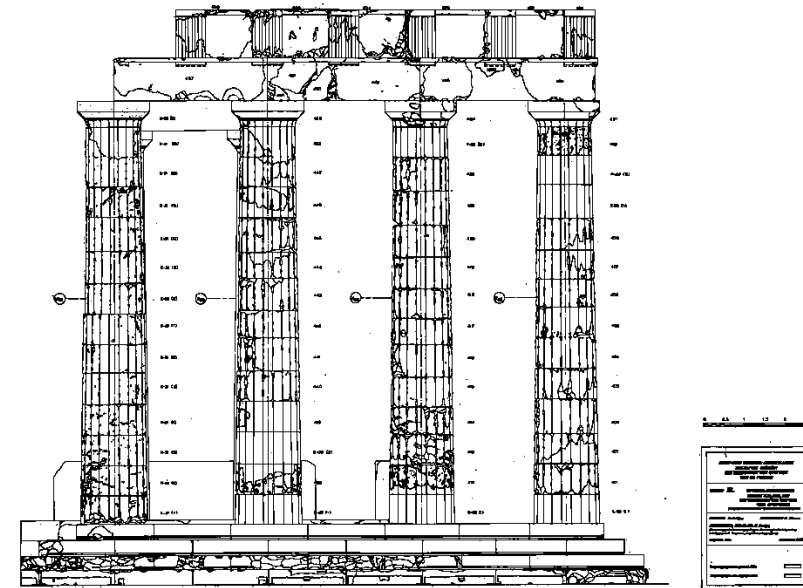
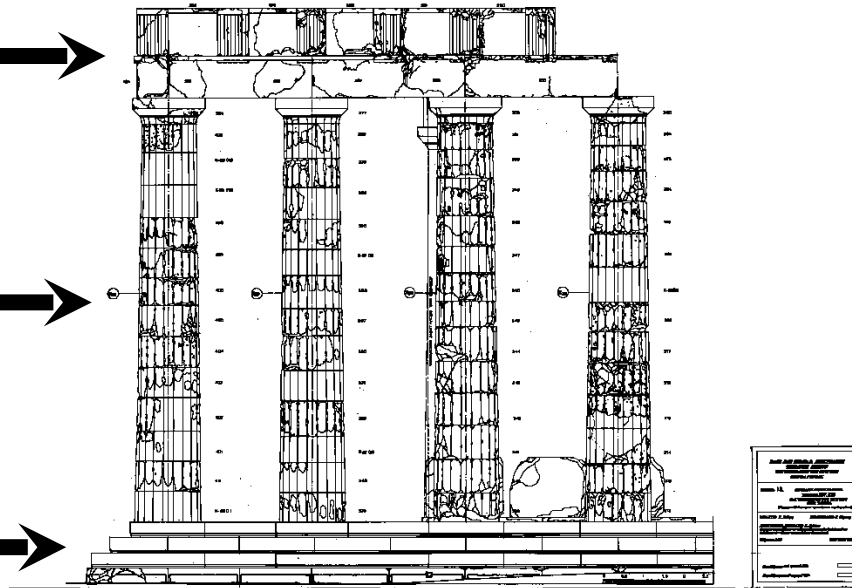
Epistyles and Frieze



Columns



Crepida





# Reconstruction of the crepida







## View of retrofitted ancient stones





# Wire-sawing and preparation of new material



## Retrofit of $\Delta$ -25: stylobate of ancient column K-31























έκορα και άνεργο.

ΤΕΤΑΡΤΗ 1/12/04

Το πρωί στείραμε με  
ζάιν τη θαλάσσι δίο  
ναό για το καθαίρι του σι-  
ρόβιου, και συνέχεια εδω-  
σαν τον οδηγό στη Δ-28  
και ξεκίνησα καινούριο και  
ζέλος βόιδομα το καρνα-  
ση στο ποταμίσιο του κα-  
ραίου του σιρόβιου και  
έφυγα λίγο τη Γ-12 μαζί  
με το Βακινάκη.

ΠΕΜΠΤΗ 2/12/04

Αυτίλεγα στη κίω έδρα  
της Δ-27 στην οποία  
συνέχεια τους οδηγούς  
Το κωστήρι έφτασε με  
τεχνικό κωστήρι για να  
πάρει τις επιφανείες της  
και για το ναό μαζί με  
καρναίση.

ΠΑΡΑΣΚΕΥΗ 3/12/04

Αυτίλεγα στην κίω έδρα  
της Δ-27 στην οποία συν-  
χία τους οδηγούς της επιφανείας

7 Δεκεμβρίου 2004

1<sup>ος</sup> οδηγός στο

κουτίλο της Γ8 και έφυγα

του 2<sup>ου</sup> Τέλος και του

2<sup>ου</sup> έφυγα του 1<sup>ου</sup> οδηγού

στο ένα κωστήρι.

S S

Τετάρτη 08 Δεκεμβρίου 2004

Τέλος του 1<sup>ου</sup> οδηγού στο

κουτίλο, κοψίλο ανιόχων

του 2<sup>ου</sup> οδηγού και έφυγα

του με πρέλιο. S S S

Πέμπτη 09 Δεκεμβρίου 2004

Συνέχεια και τέλος του 2<sup>ου</sup> οδηγού

στο κωστήρι, έφυγα του 1<sup>ου</sup> οδηγού

στο ανιόχων κωστήρι, τέλος.

Έφυγα στο 2<sup>ο</sup> οδηγό.

S S

Παρασκευή 10 Δεκεμβρίου 2004

Συνέχεια και τέλος του

2<sup>ου</sup> οδηγού στο κωστήρι της Γ8

Έφυγα του 1<sup>ου</sup> οδηγού

στο άλλο κωστήρι.

S S



# Need for retrofitting the column drums





## View of final result of retrofitted drums



# Works on existing and new column drums



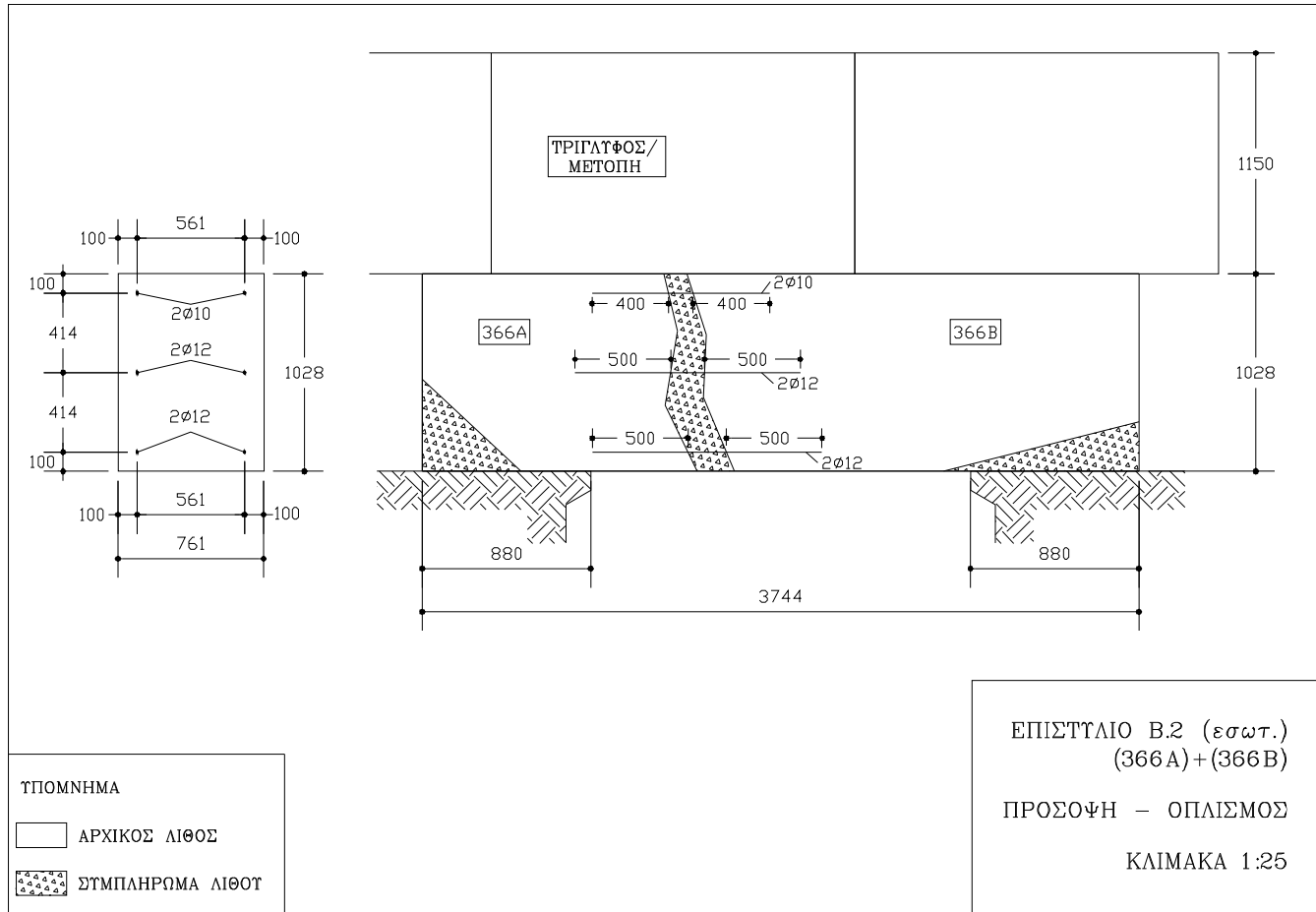


## View of fragmented epistyles

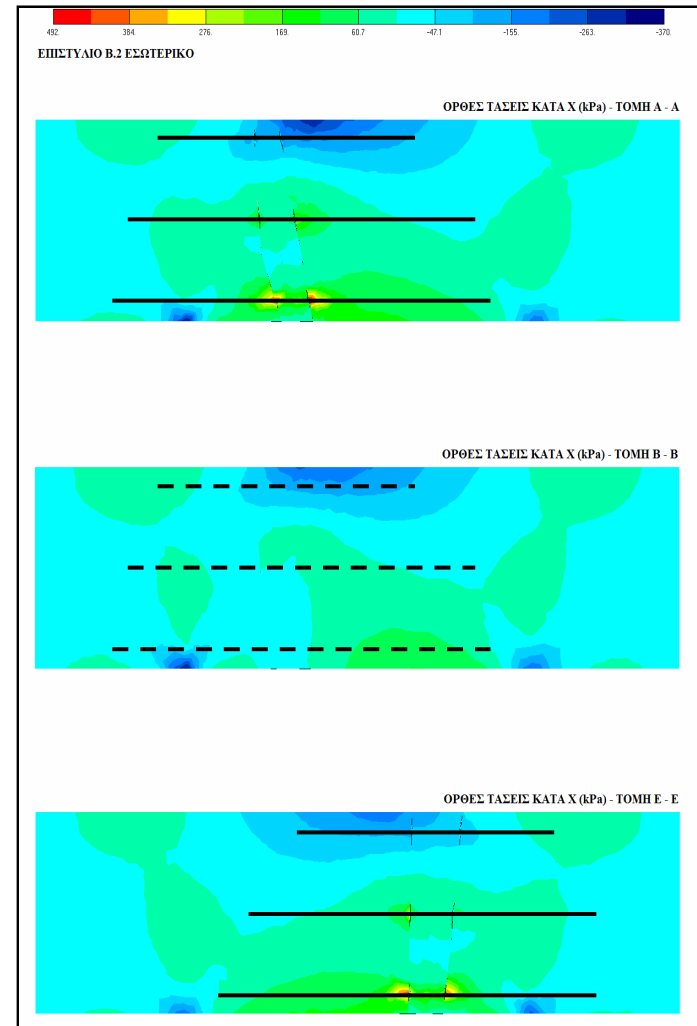
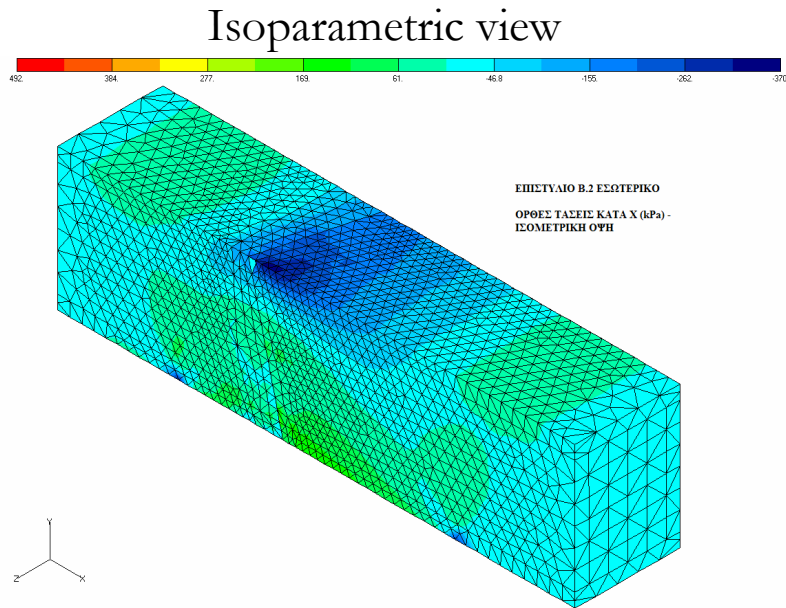




# Schematic of retrofitted epistyle



# Normal stresses in the epistyle





# Les grands oeuvres de l' homme

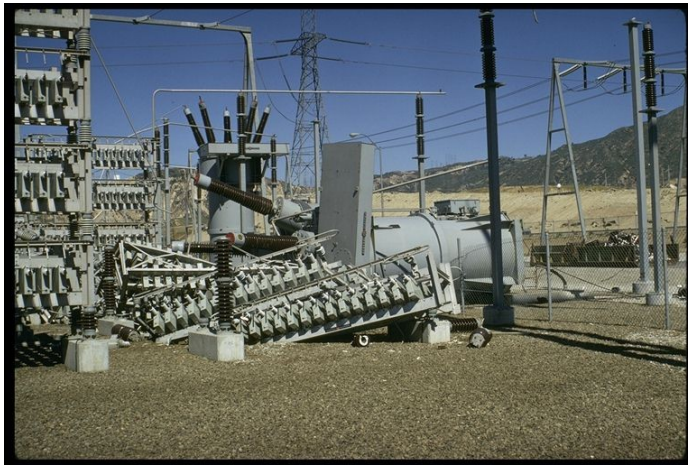




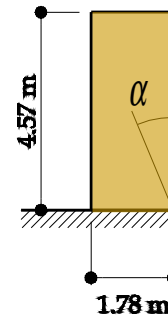




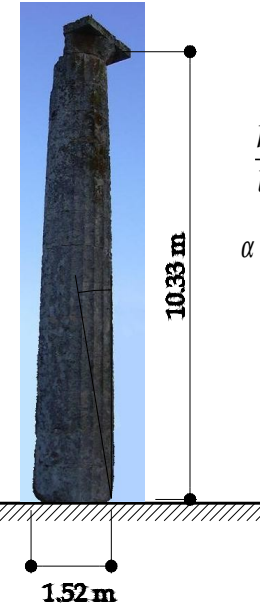
# Seismic Stability of free-standing slender structures



$$\frac{h}{b} = \frac{4.57}{1.78} = 2.57$$
$$\alpha = 0.371 \text{ rad (21.28}^\circ\text{)}$$

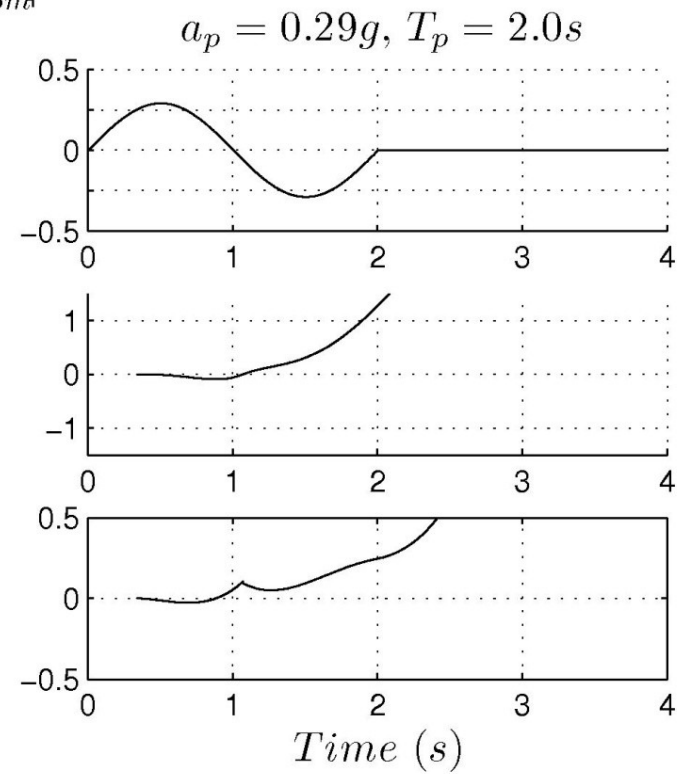
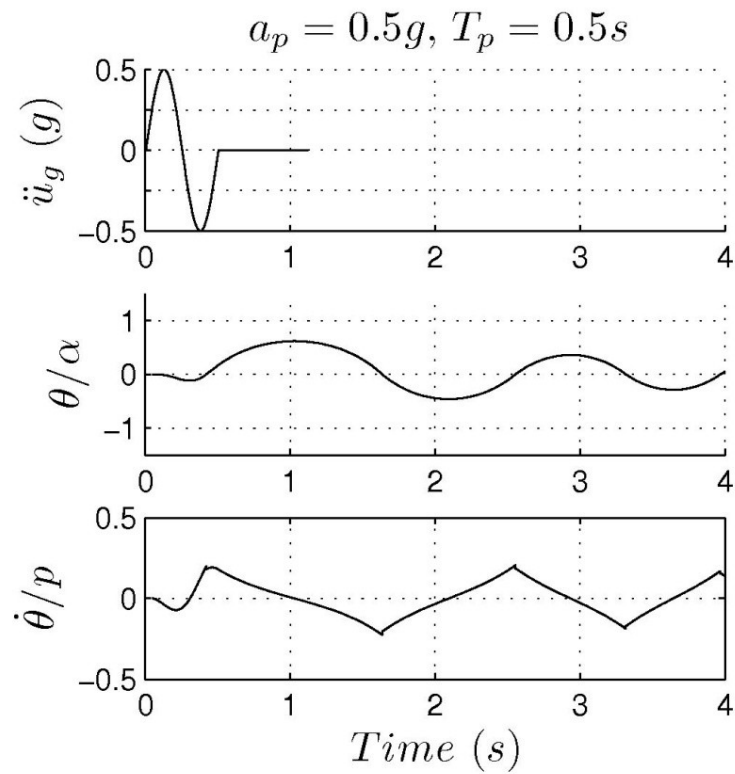
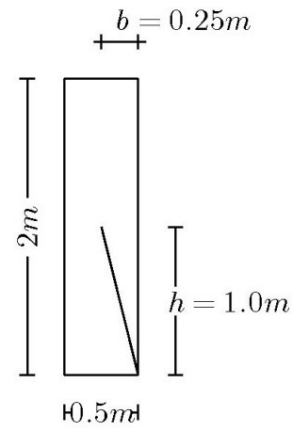


500 kV Electrical  
Transformer



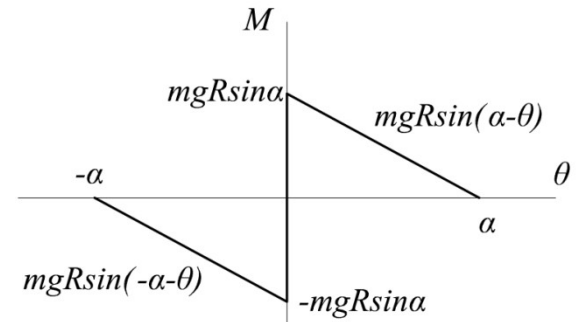
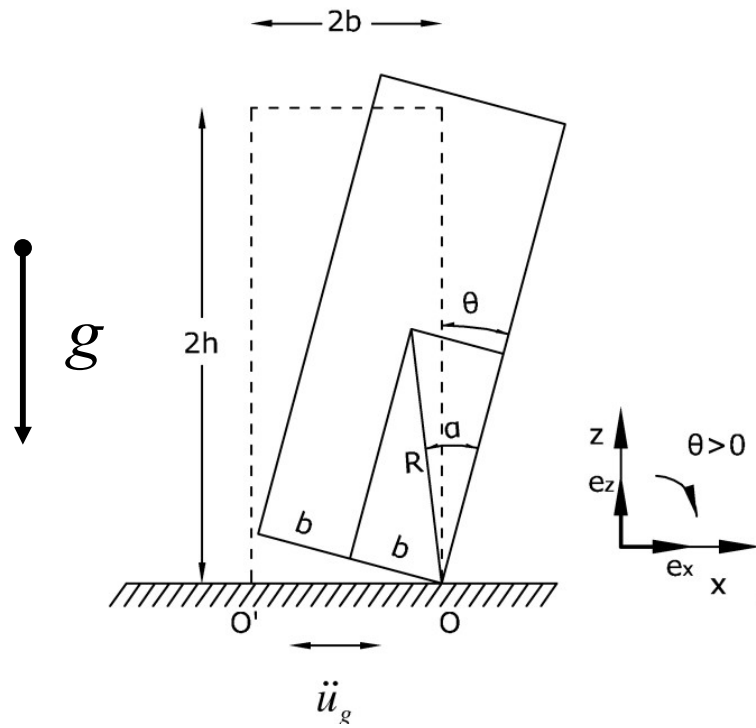
Column K-31

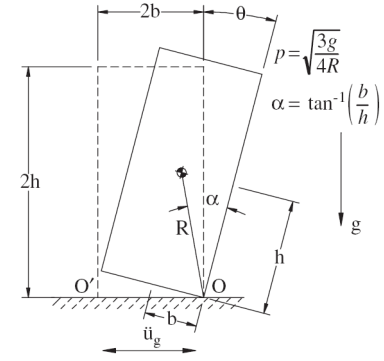
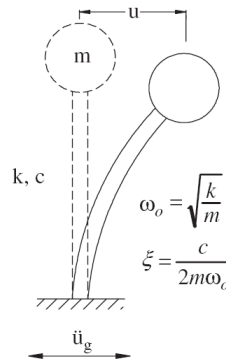
$$\frac{h}{b} = \frac{10.33}{1.52} = 6.80$$
$$\alpha = 0.147 \text{ rad (8.43}^\circ\text{)}$$





$$p = \sqrt{\frac{3g}{4R}}$$





Parameters/  
characteristics

Damped oscillator  
 $m, c, k$

Rocking rigid block  
 $b, h, g$

*Restoring mechanism*

Elasticity of the structure

Gravity

*Restoring force/moment*

$F = ku$   
(for linear springs)

$M = mgR \sin(\alpha - \theta)$   
 $R = \sqrt{b^2 + h^2}$

*Stiffness at stable  
equilibrium*

Finite

Infinite

*Restoring force/moment  
at stable equilibrium*

Zero

Finite:  $mgR \sin(\alpha)$

*Stiffness away  
from equilibrium*

Positive

Negative

*Frequency parameter*

Undamped natural frequency:

Frequency parameter:

$$\omega_0 = \frac{2\pi}{T_0} = \sqrt{\frac{k}{m}}$$

$p = \sqrt{\frac{3g}{4R}}$   
(for rectangular blocks)

*Damping parameter*

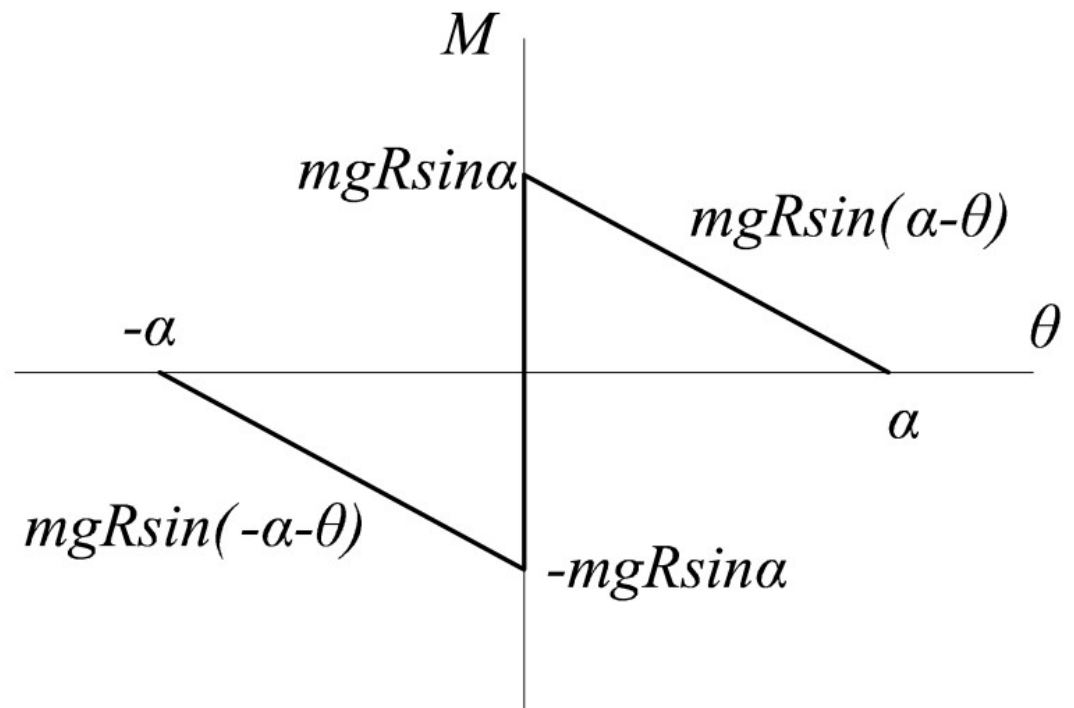
Viscous damping ratio:

Slenderness:

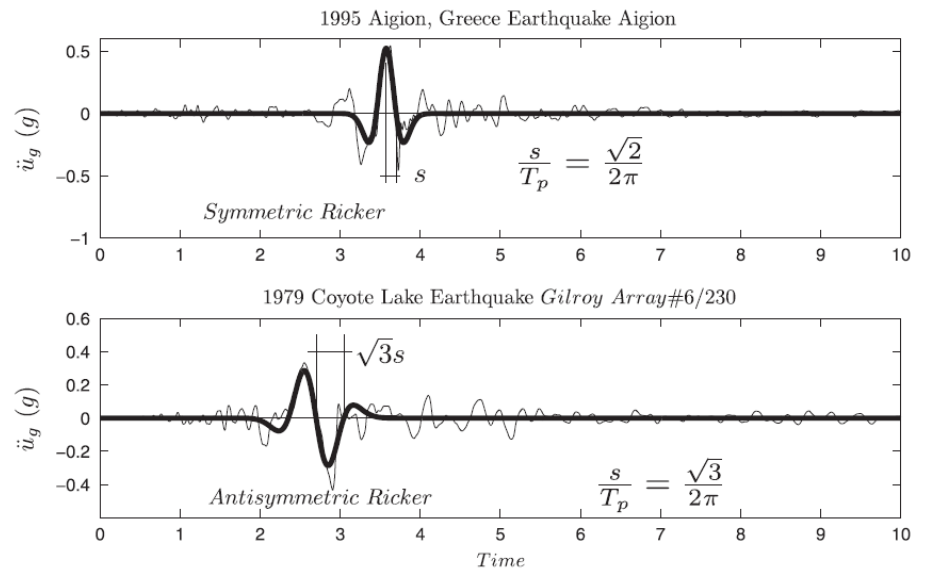
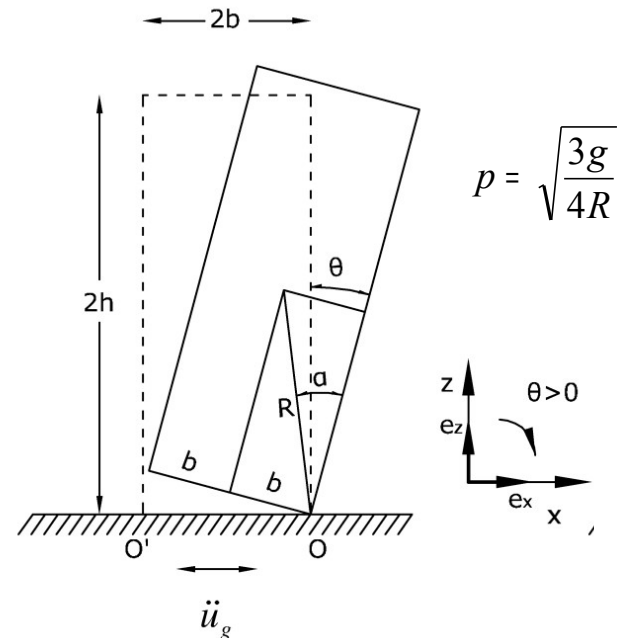
$$\xi = \frac{c}{2m\omega_0}$$

$$\alpha = \tan^{-1}(b/h)$$





# Dimensionless Products

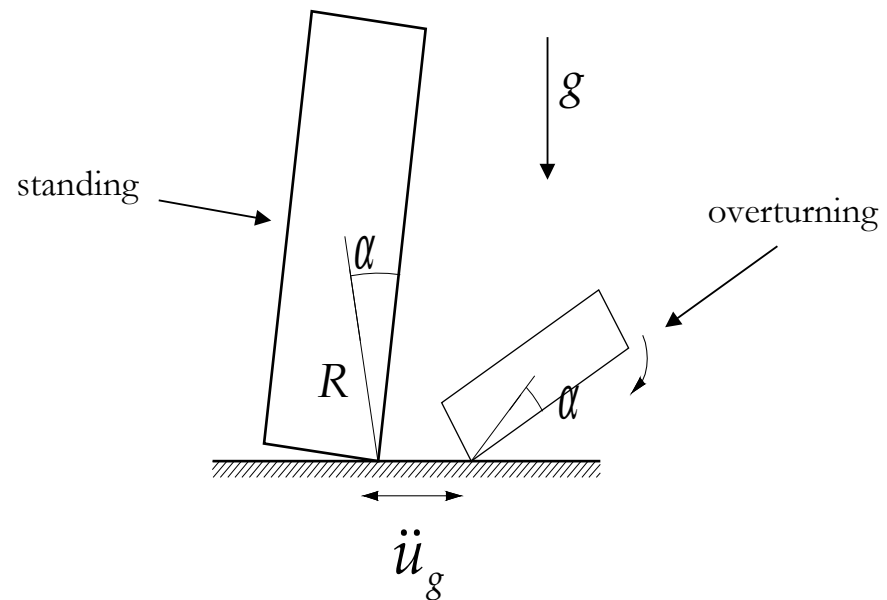




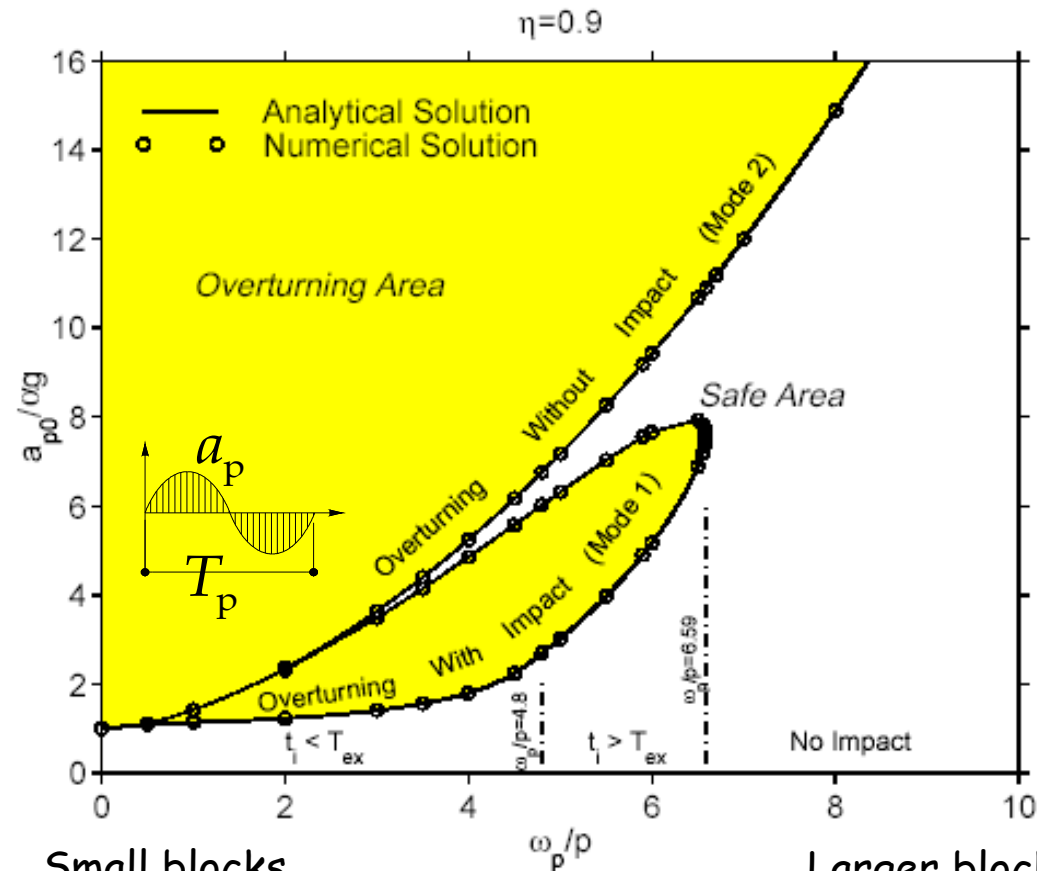
# Fundamental size-frequency effect: 1963 George W. Housner

(a) The larger of two geometrically similar blocks can survive the excitation that will topple the smaller block; and (b) out of two same acceleration-amplitude pulses the one with the longer duration is more capable to induce overturning

Conclusion reached from studies motivated from the destruction observed after the May 1960 earthquake in Chile.



# Zhang & Makris 2002

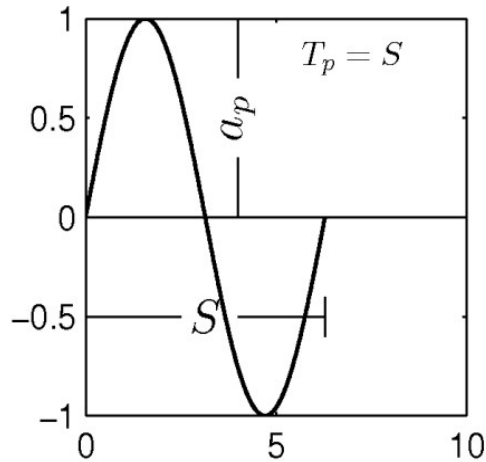


Small blocks  
or  
long period  
pulses

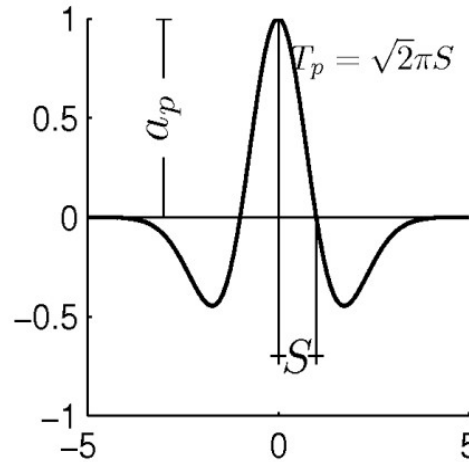
$$\omega_p = \frac{2\pi}{T_p}, \quad p = \sqrt{\frac{3g}{4R}}$$

Larger blocks  
or  
high frequency  
pulses

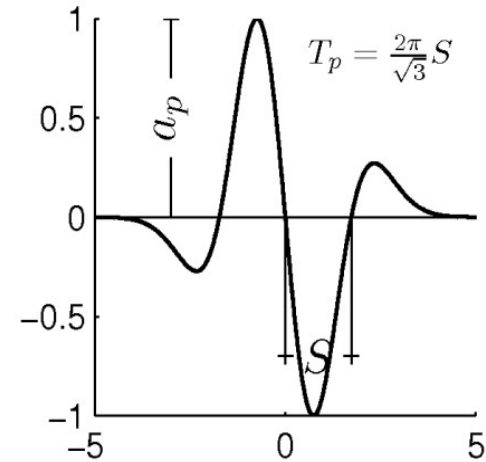
# Overtuning spectra of a rigid block standing free on a monolithic base



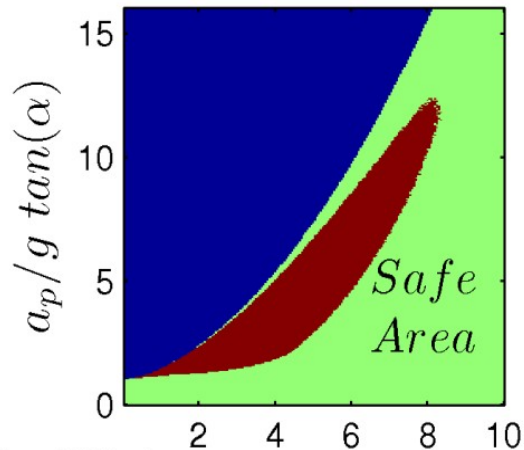
*One Sine*



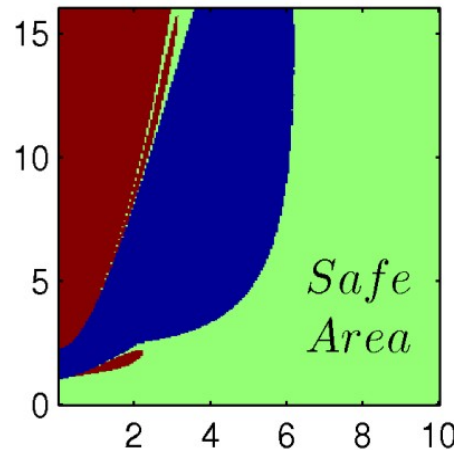
*Symmetric Ricker*



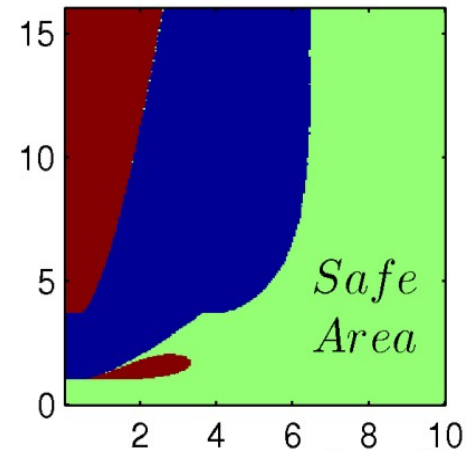
*Anti – Symmetric Ricker*



Small blocks or long period pulses



$\Pi_\omega = \omega_p/p$

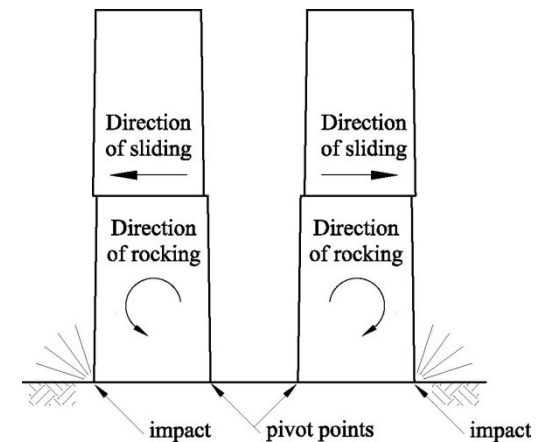
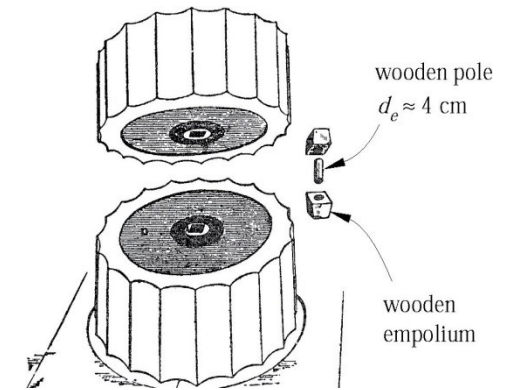
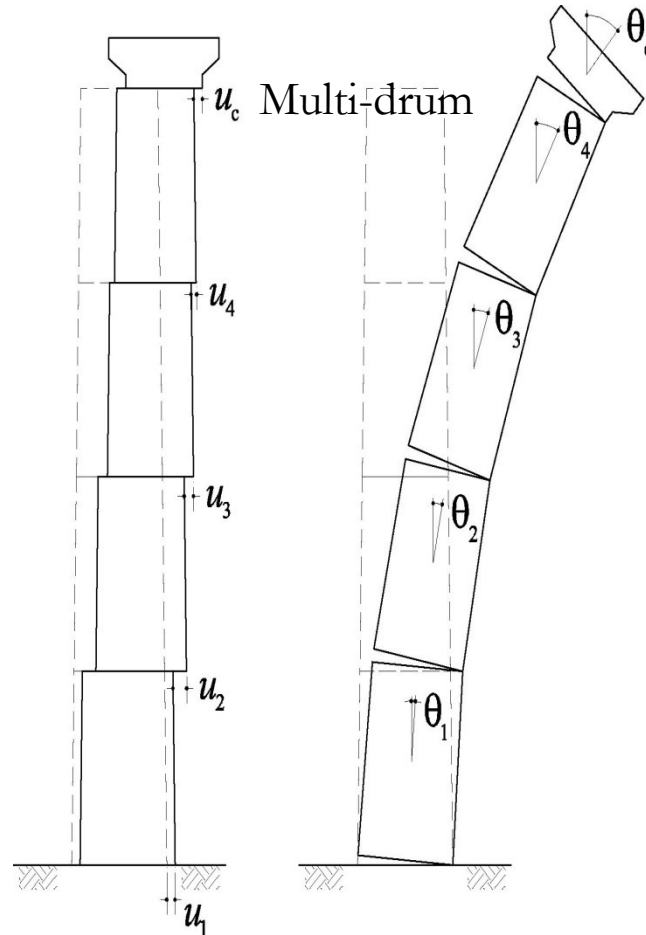
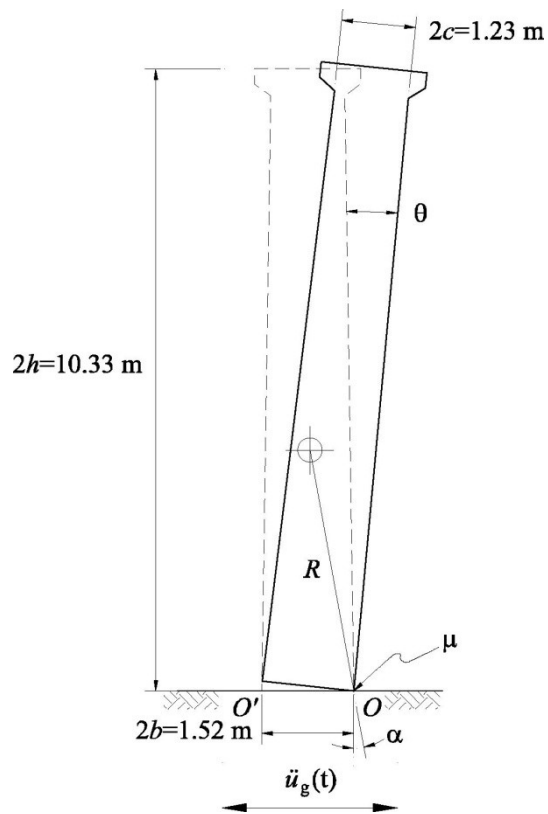


Large blocks or short period pulses

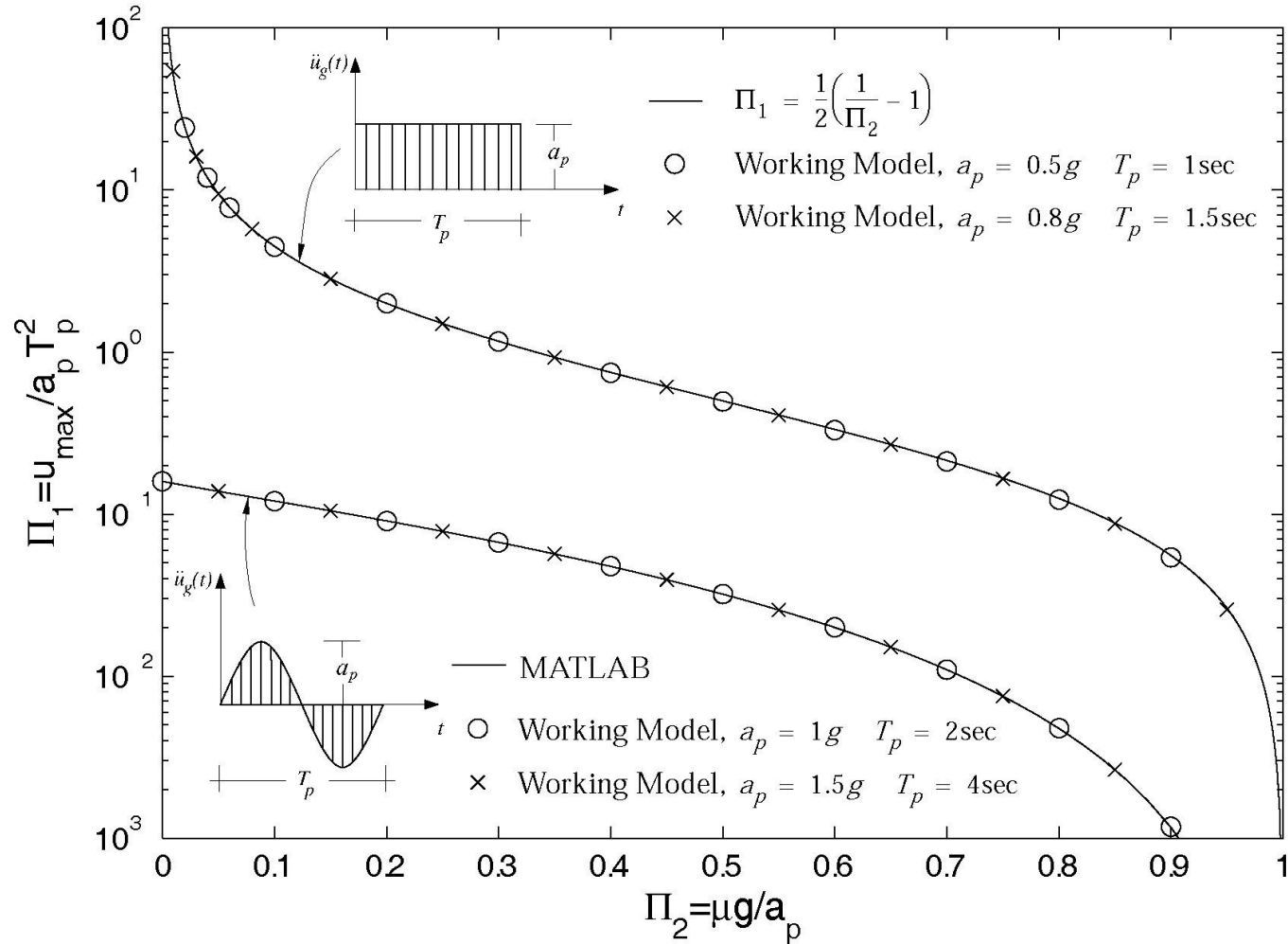


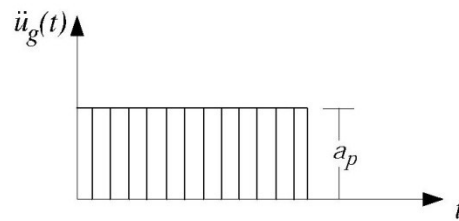
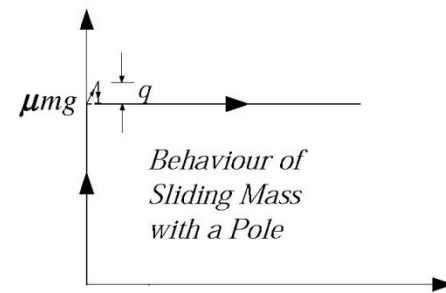
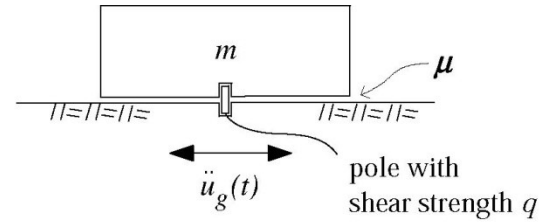
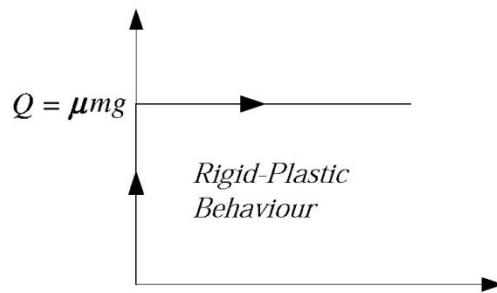
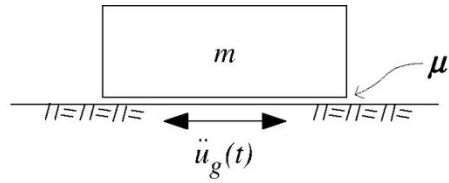
# Seismic response of monolithic and multi-drum column

Monolithic



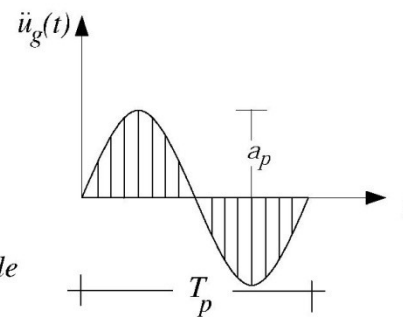
## Peak Displacement of a Sliding Block Subjected to Square and One-Sine Pulse Excitations



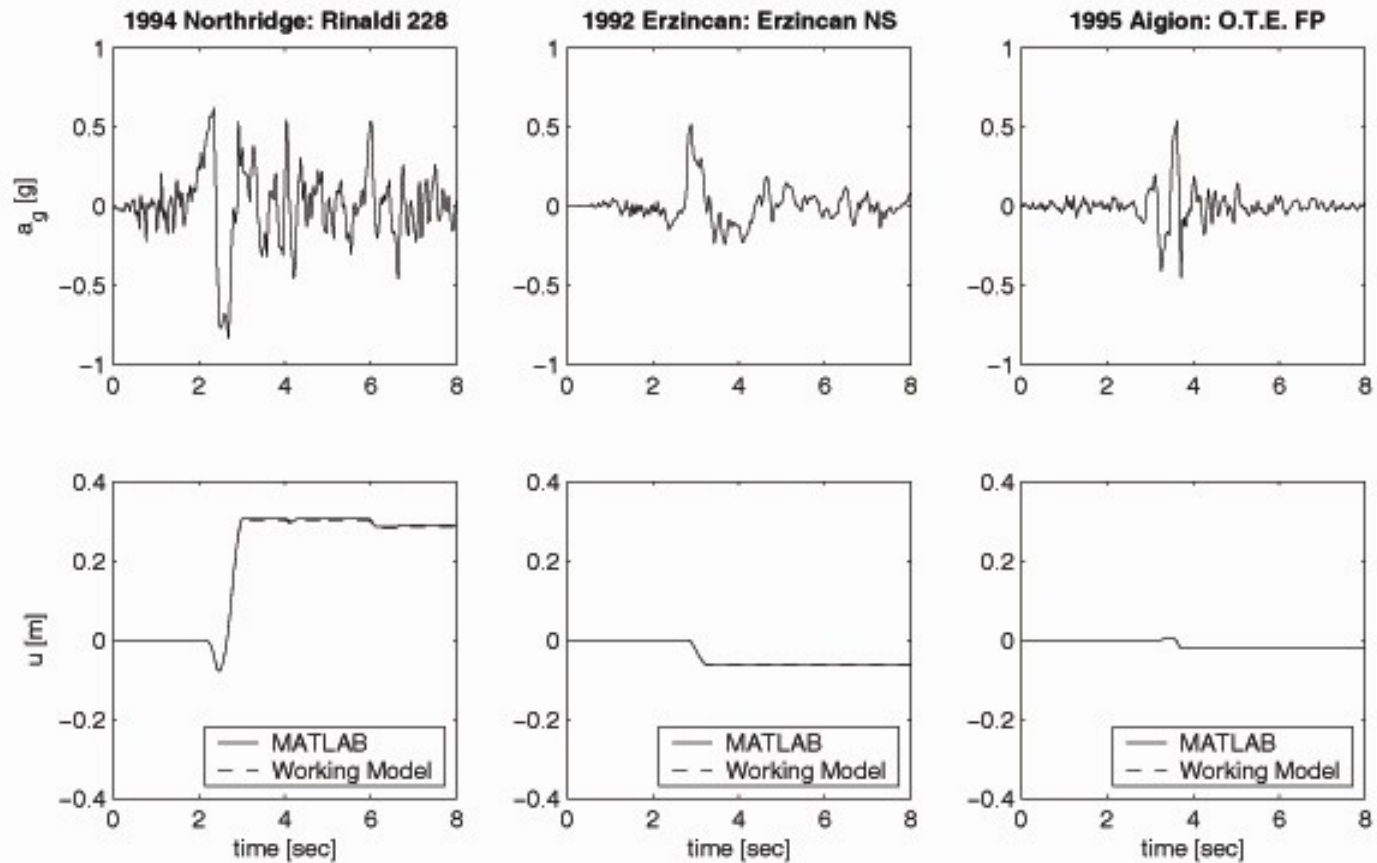


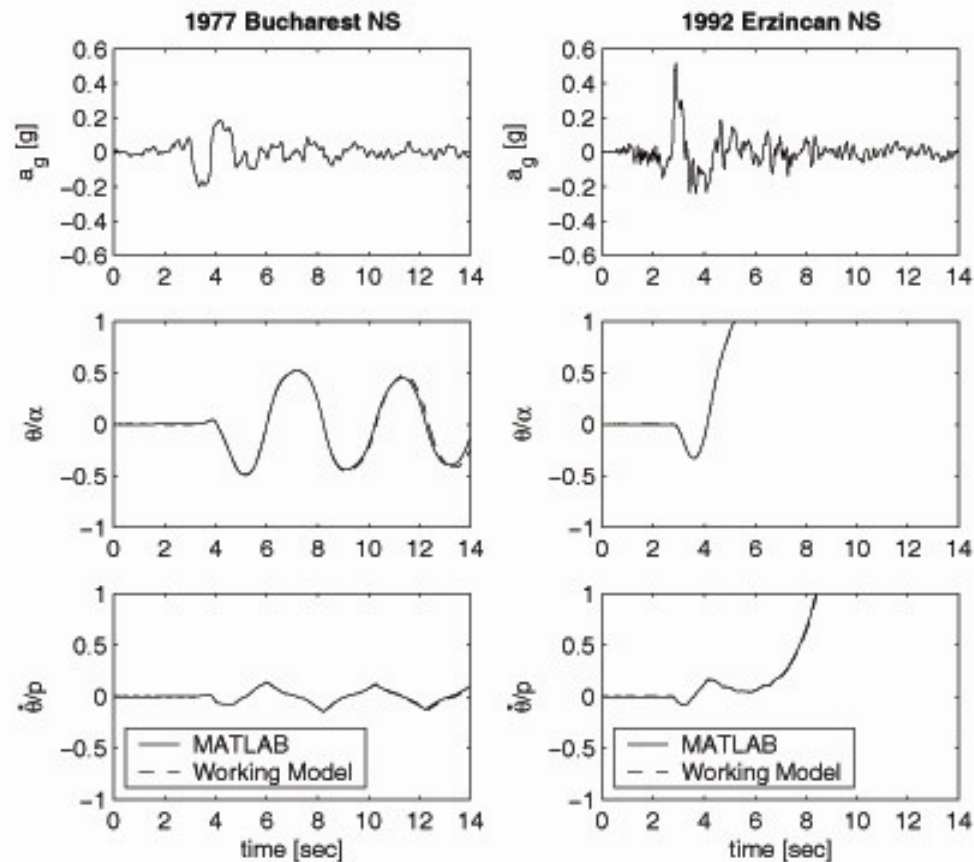
*Energetic Length Scale*

$$L_p \approx a_p T_p^2$$

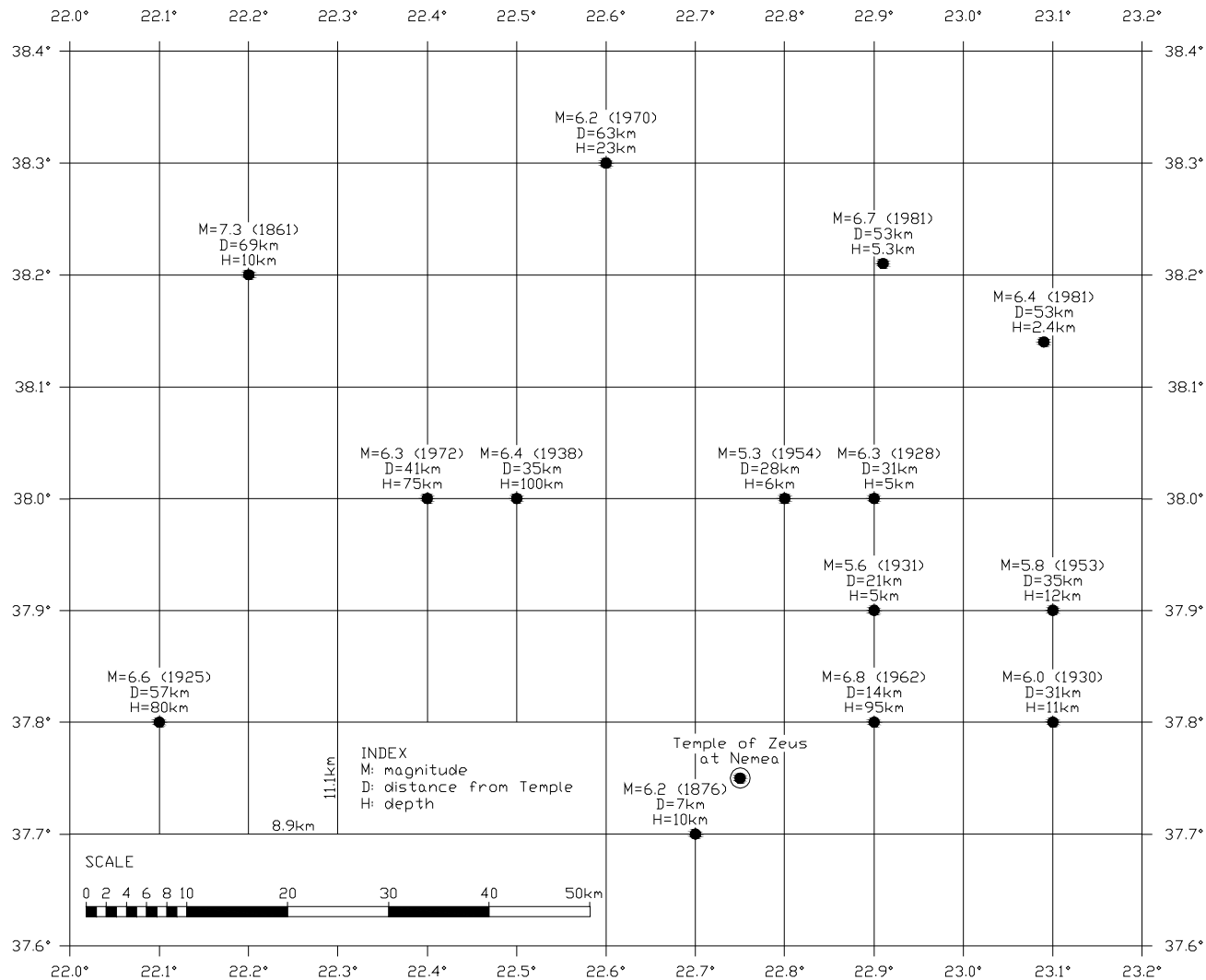








# Seismic Hazard

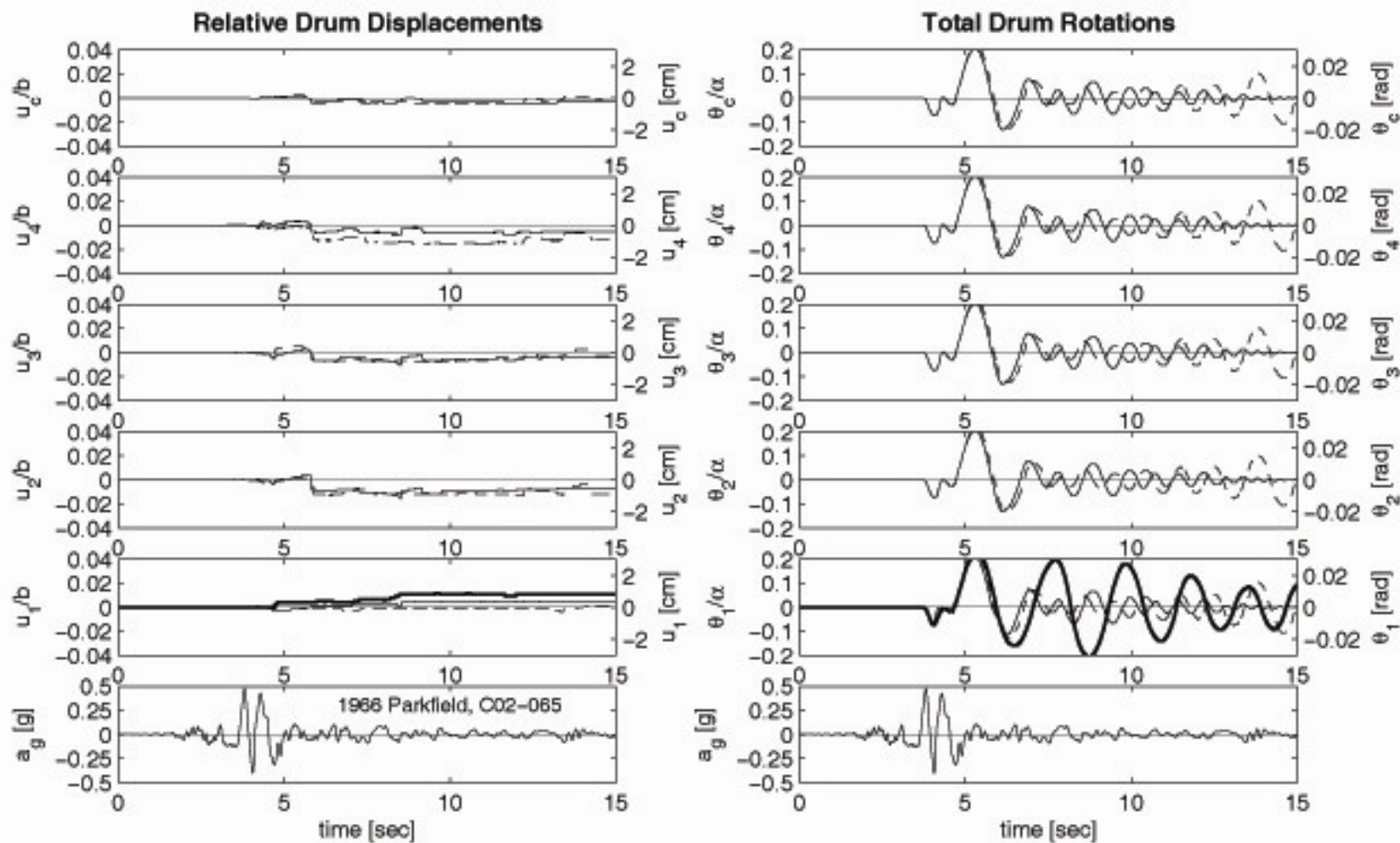


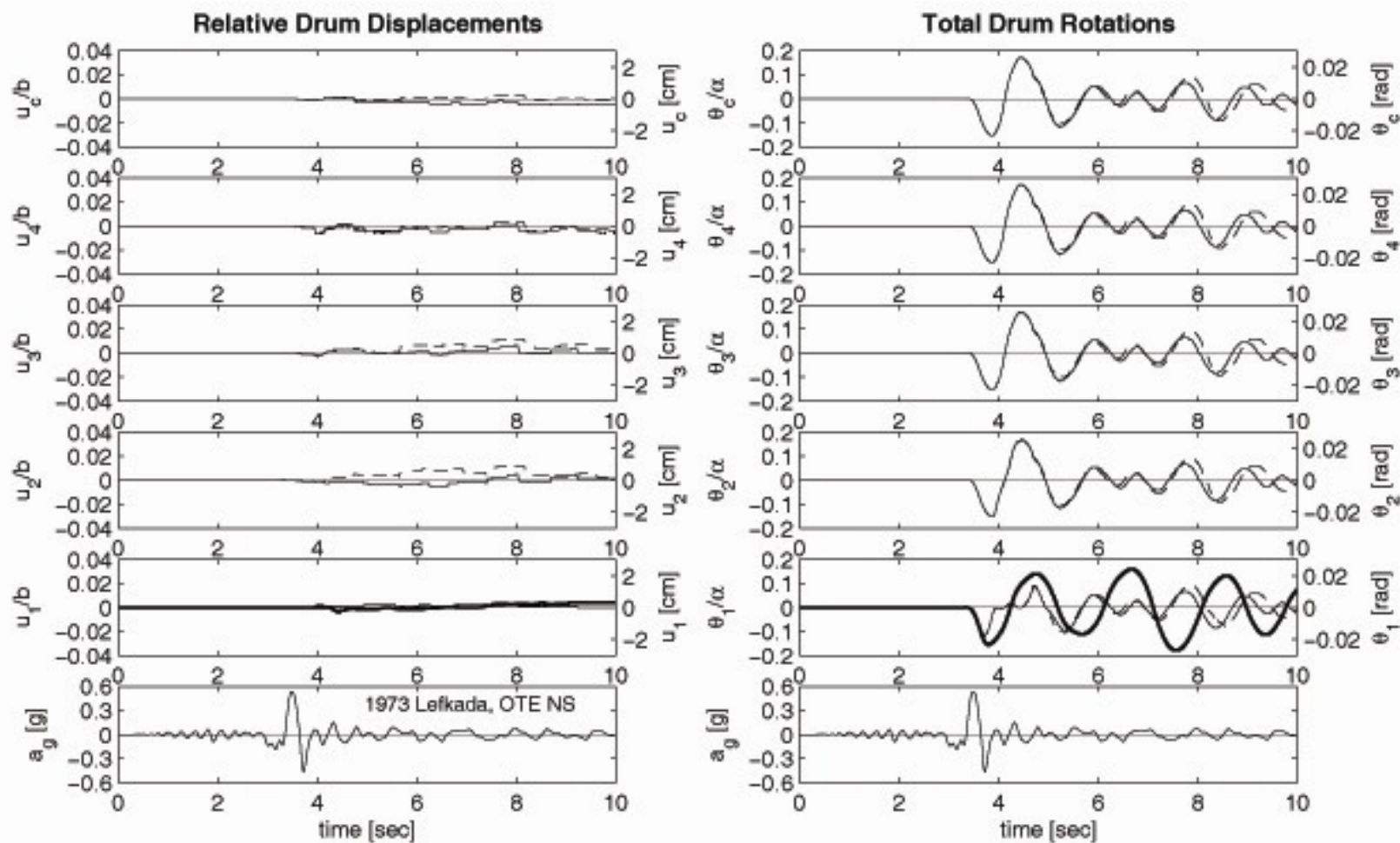
Location of selected historic earthquakes nearby the Temple of Zeus at Nemea.



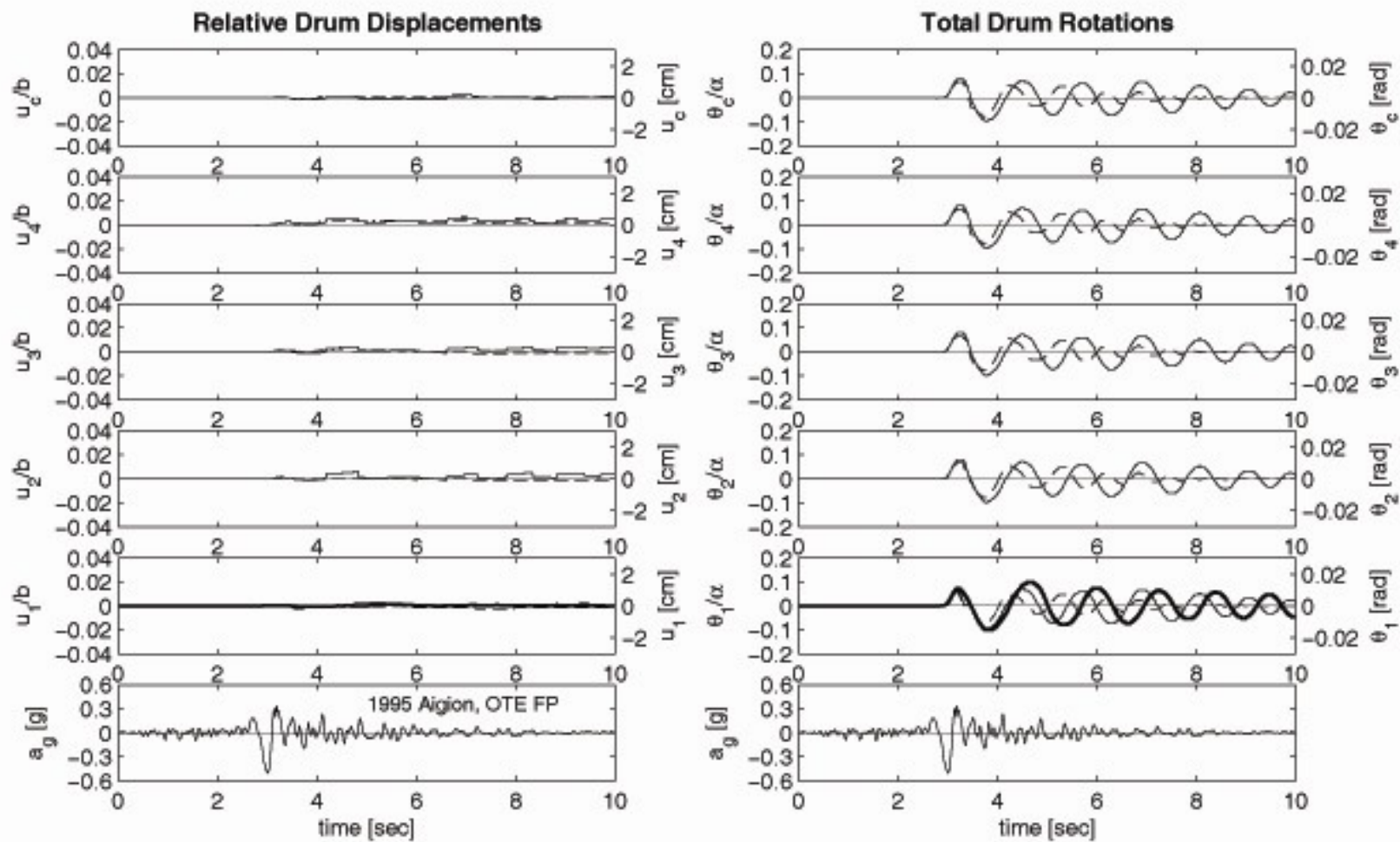
Table. Seismic Records that Represent to the Extent Possible the Seismic Hazard of the Area of the Temple of Zeus.

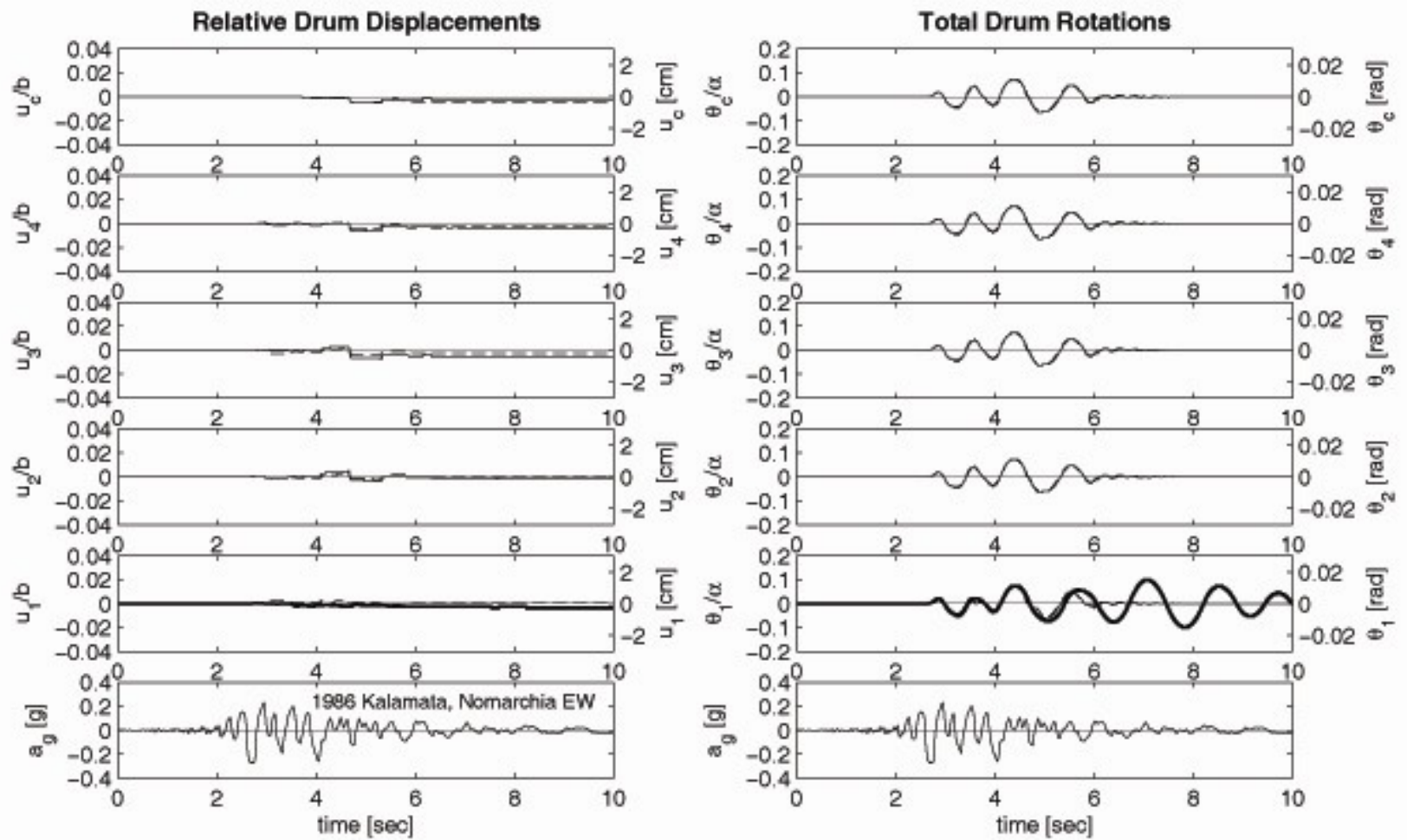
EARTHQUAKE	DATE		MAGN. M	RECORDING STATION	LOCAL SITE CONDITIONS	DIST. D (km)	PGA g	PGV cm/sec	PGD cm
Superstition Hills	1987	Nov. 24	6.7	El Centro Imperial Country	soil	13.9	0.36	46.4	16.0
				Westmoreland Fire Station	soil	13.3	0.21	31.0	20.1
Northridge	1994	Jan. 17	6.7	Simi Valley, Katherine Rd	soil	14.6	0.88	40.8	5.3
				Sun Valley, Roscoe Blvd	soil	12.3	0.44	38.3	10.0
Parkfield	1966	June 28	6.1	Temblor	rock	9.9	0.36	21.4	3.5
Leukada	1973	Nov. 04	6.0	OTE building	soil	20	0.53	55.0	11.6
Aigion	1995	June 15	6.2	OTE building	soft rock	18	0.50	43.3	7.1
Kalamata	1986	Sept. 13	6.0	Nomarhia building	hard soil	5.0	0.27	24.2	5.6
Parnitha	1999	Sept. 07	5.9	Sepolia B	13 m deposits of limestone	8.0	0.32	21.5	2.7
Bucharest	1977	March 04	7.2	Bucharest	soil	160	0.20	73.4	20.4
Kocaeli	1999	Aug. 17	7.4	Sakarya	soil	3.1	0.38	79.4	71.4

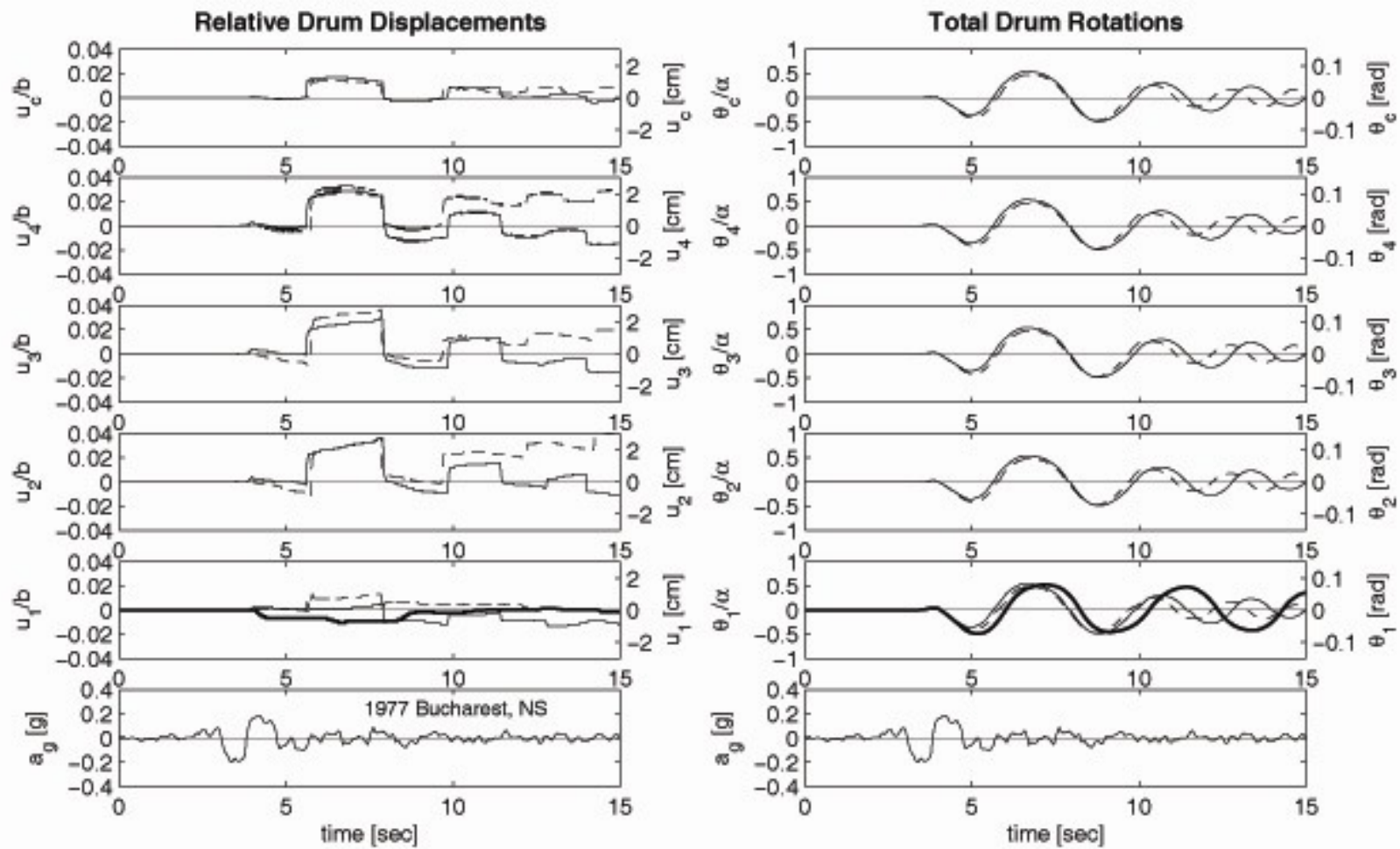




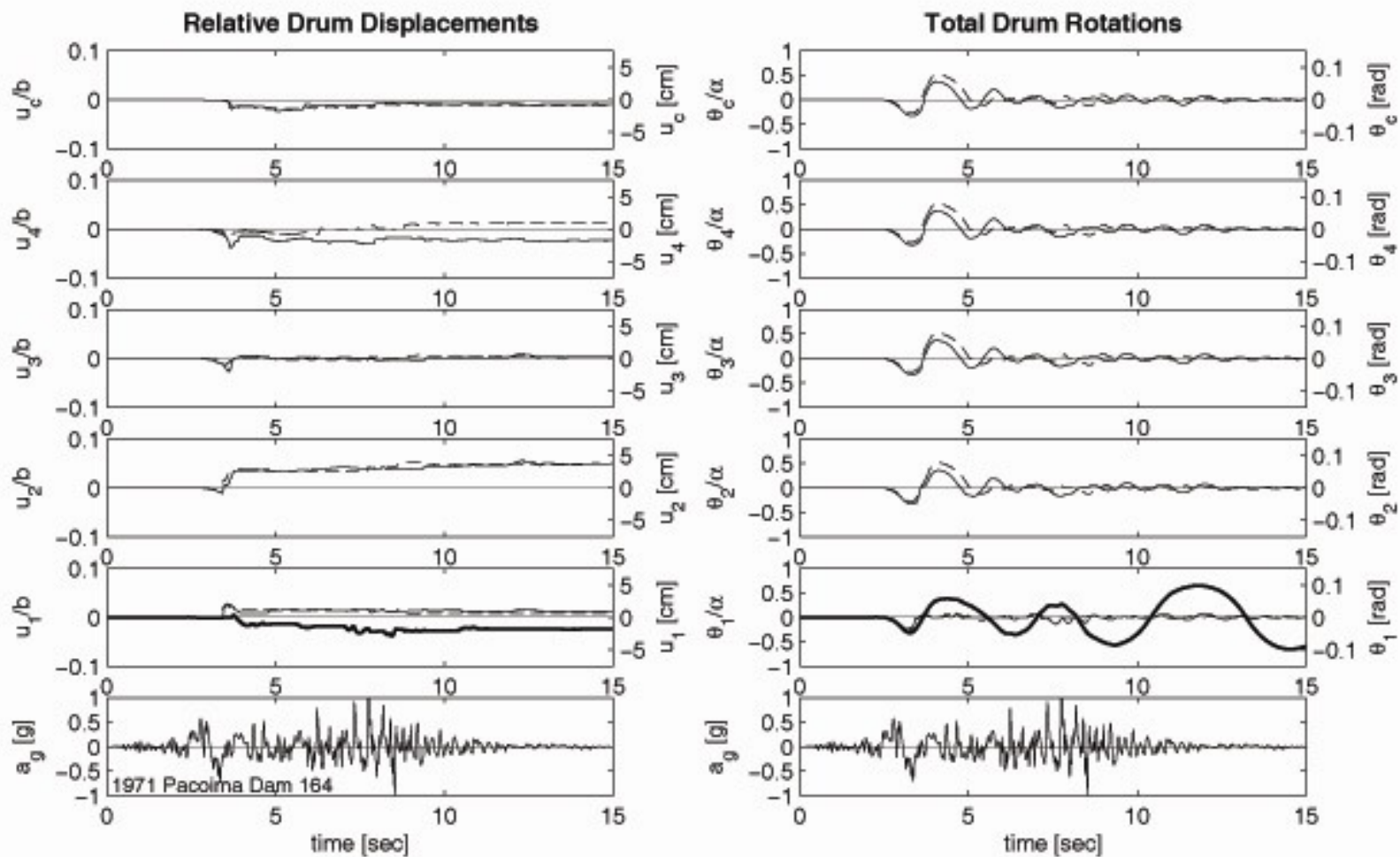


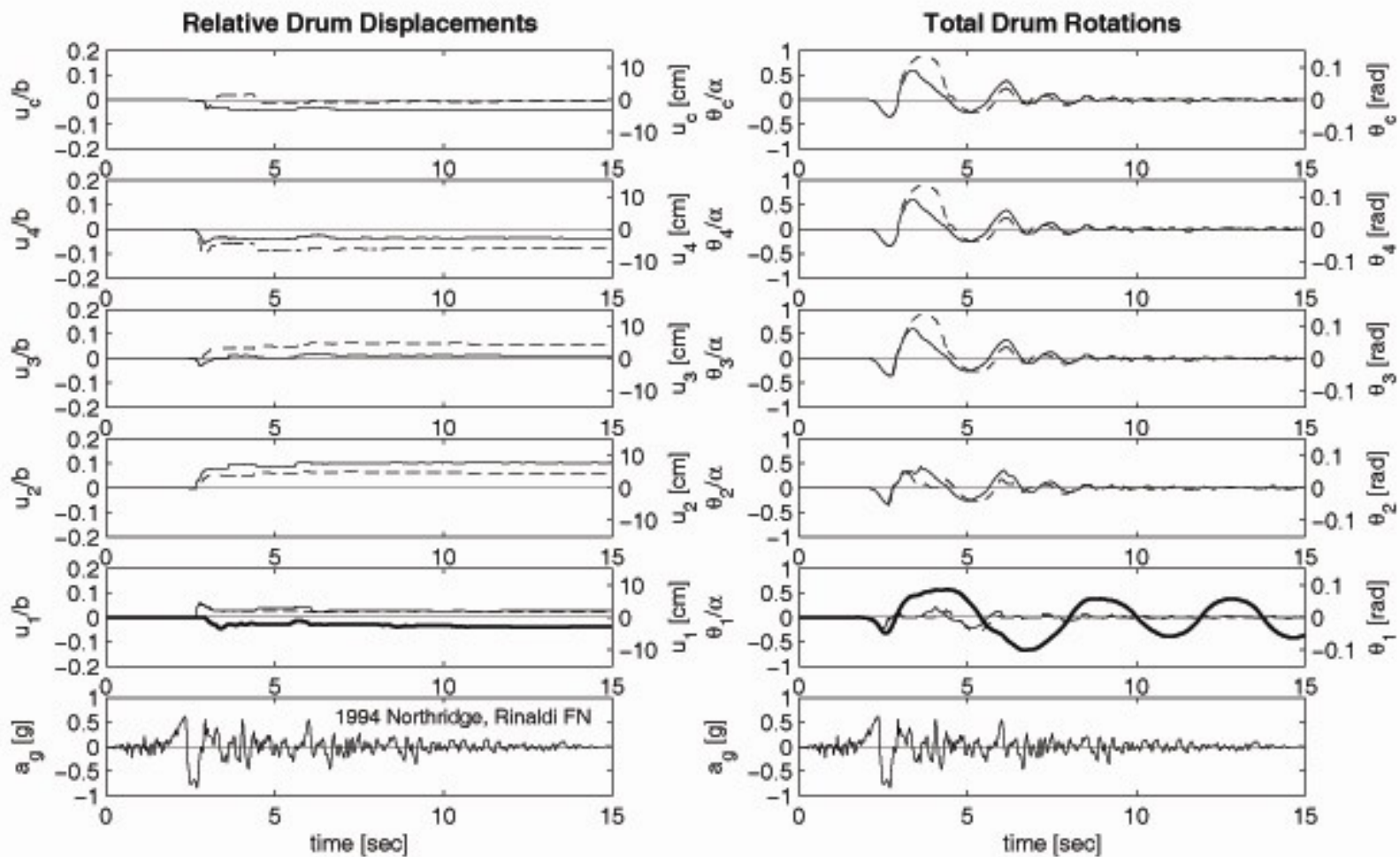


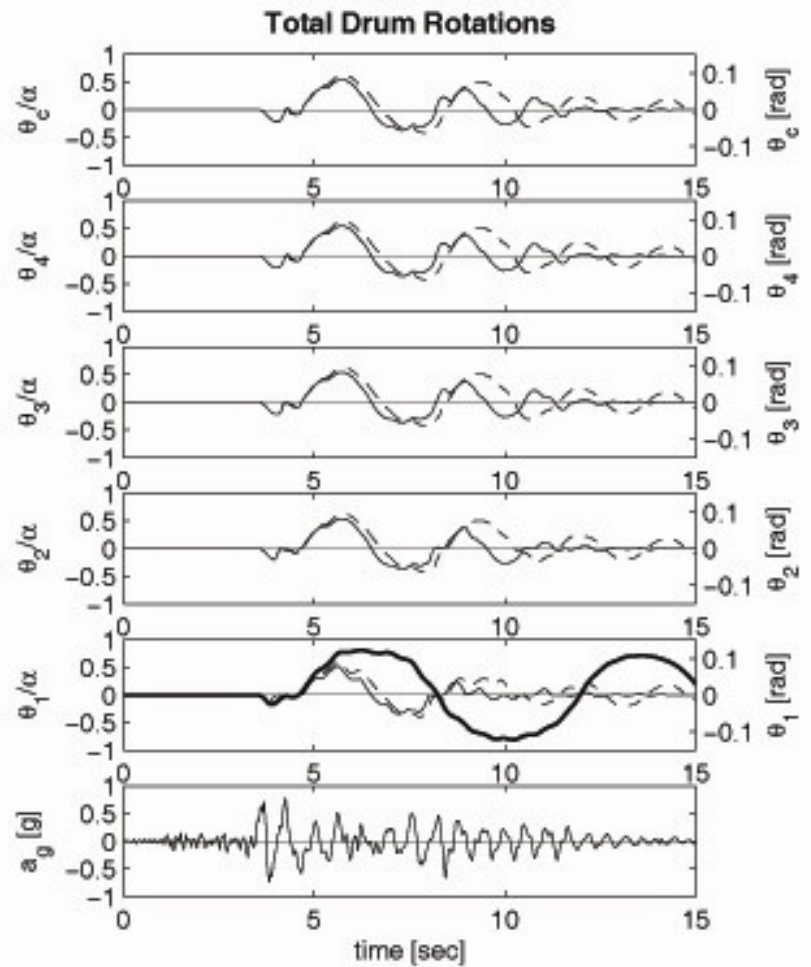
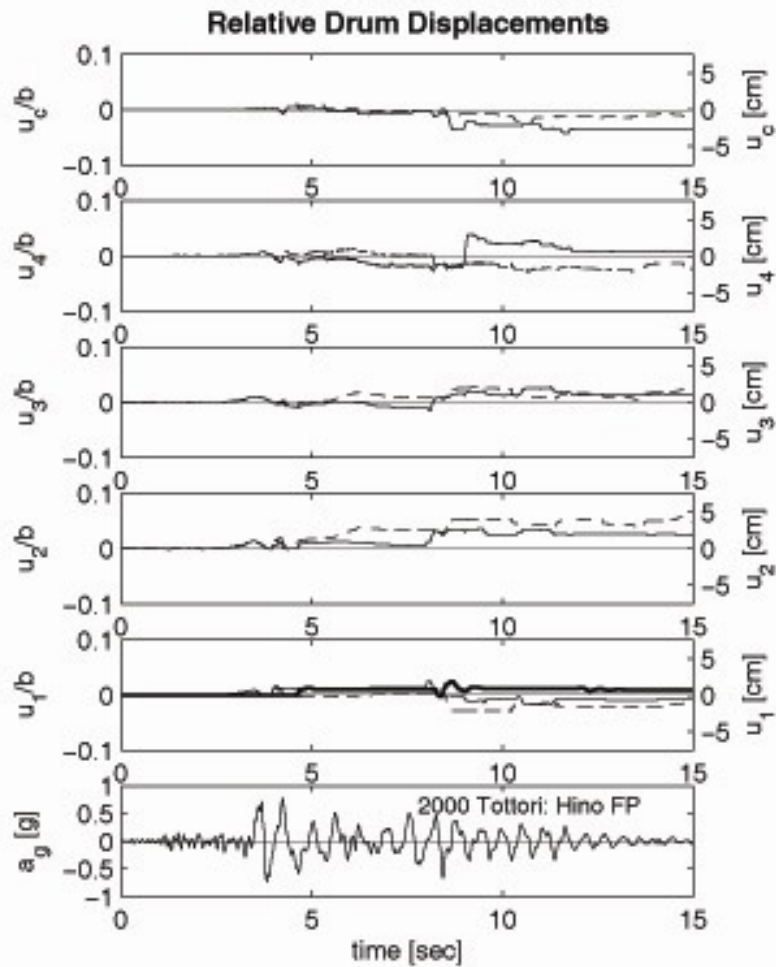




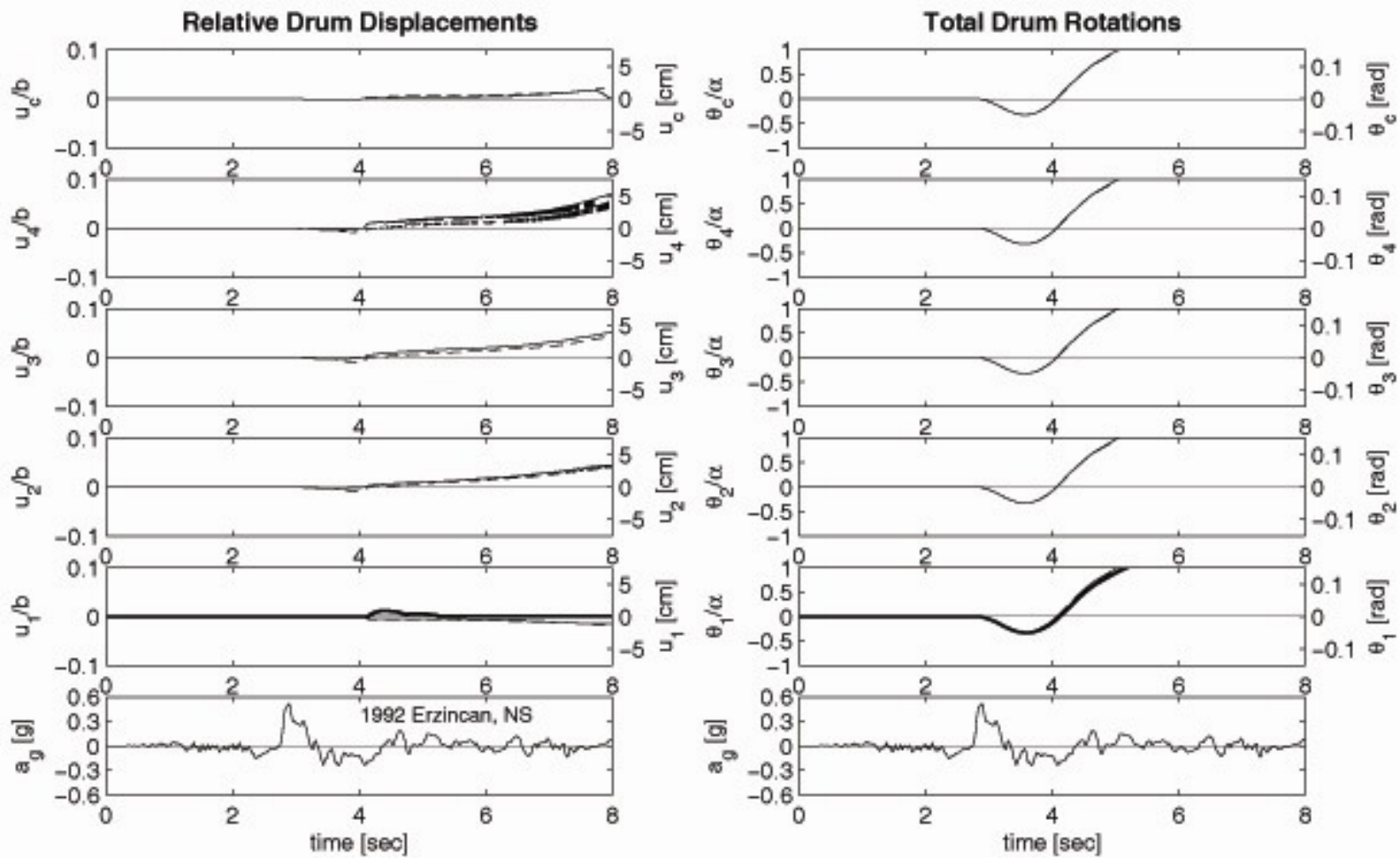


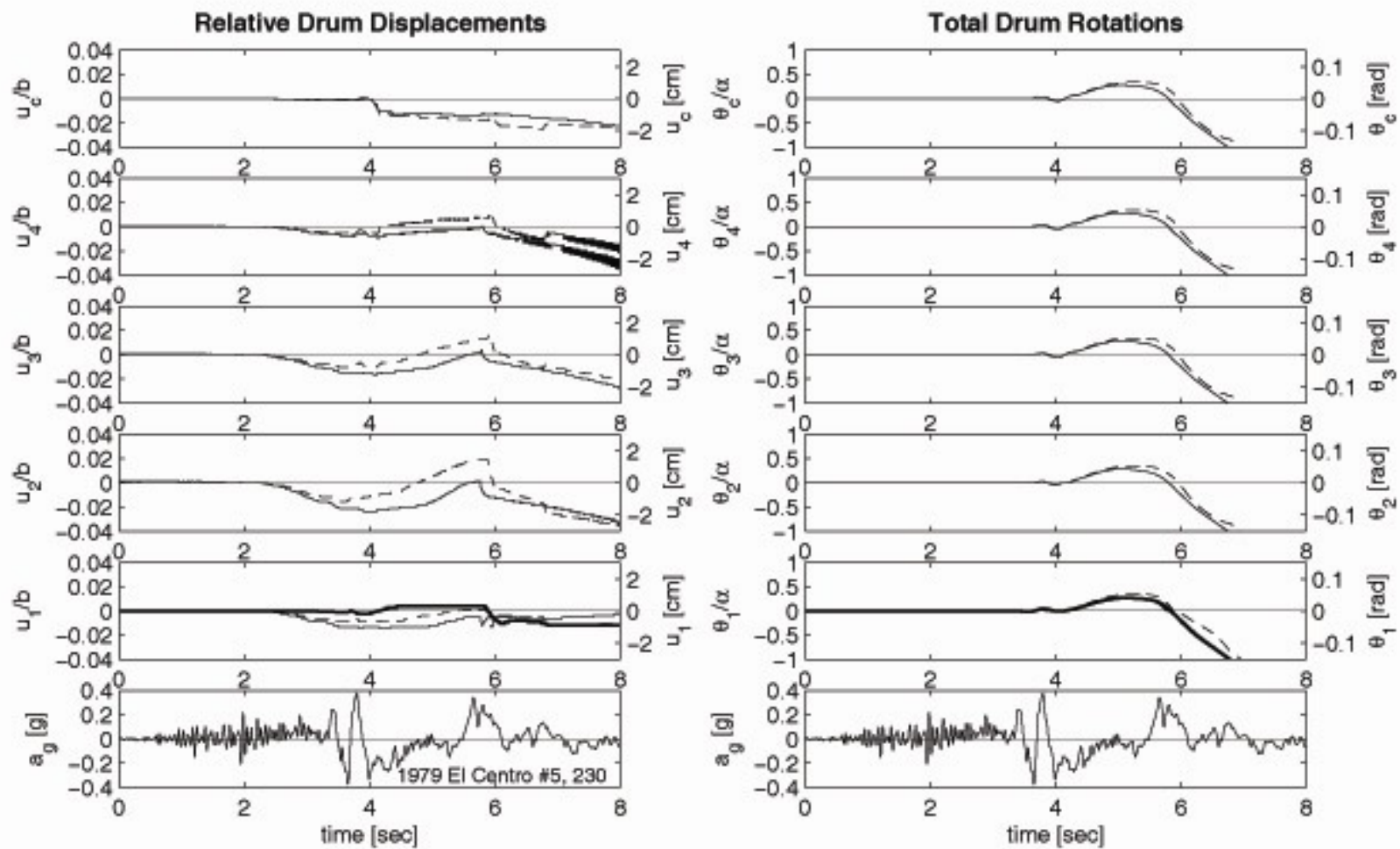


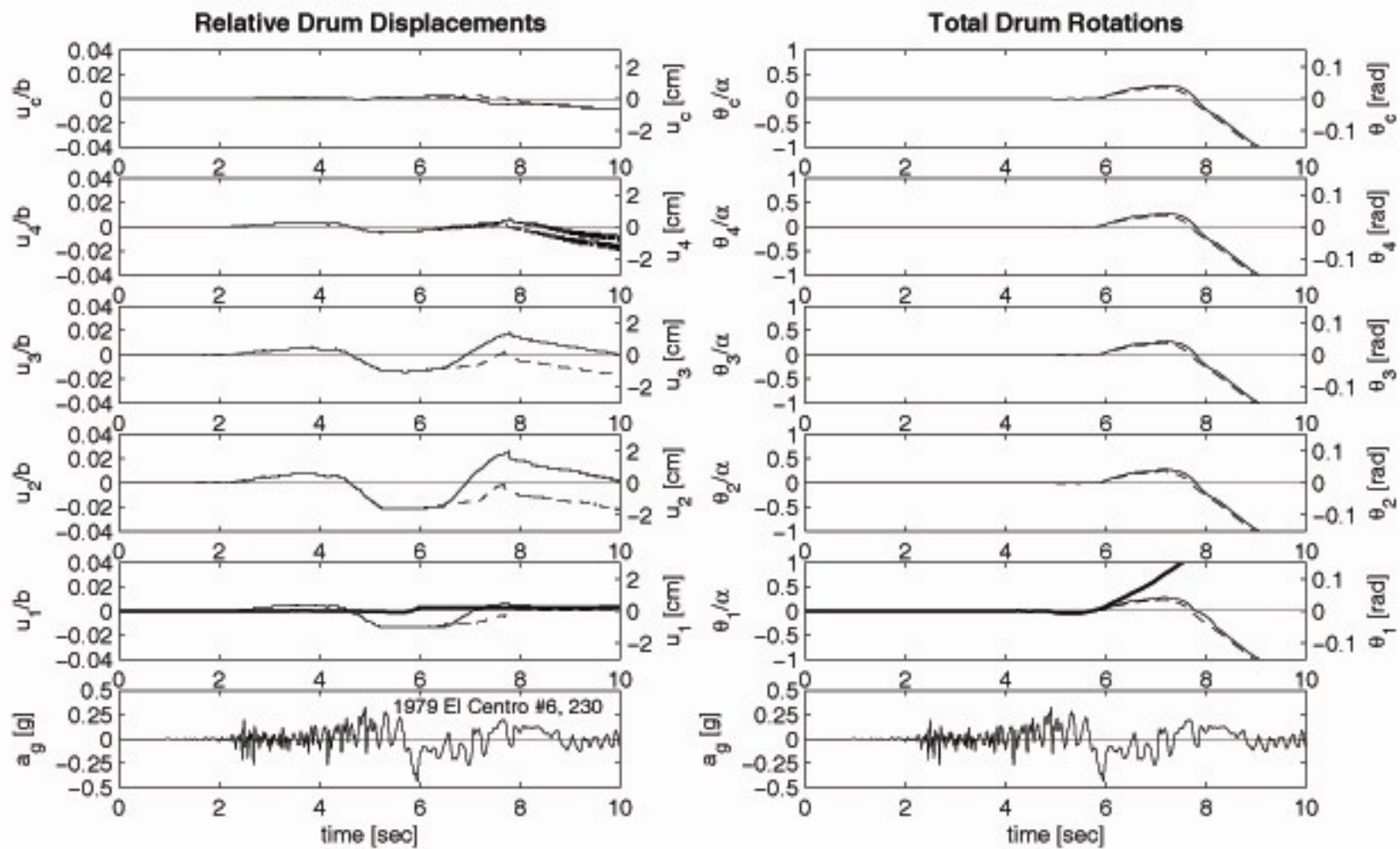




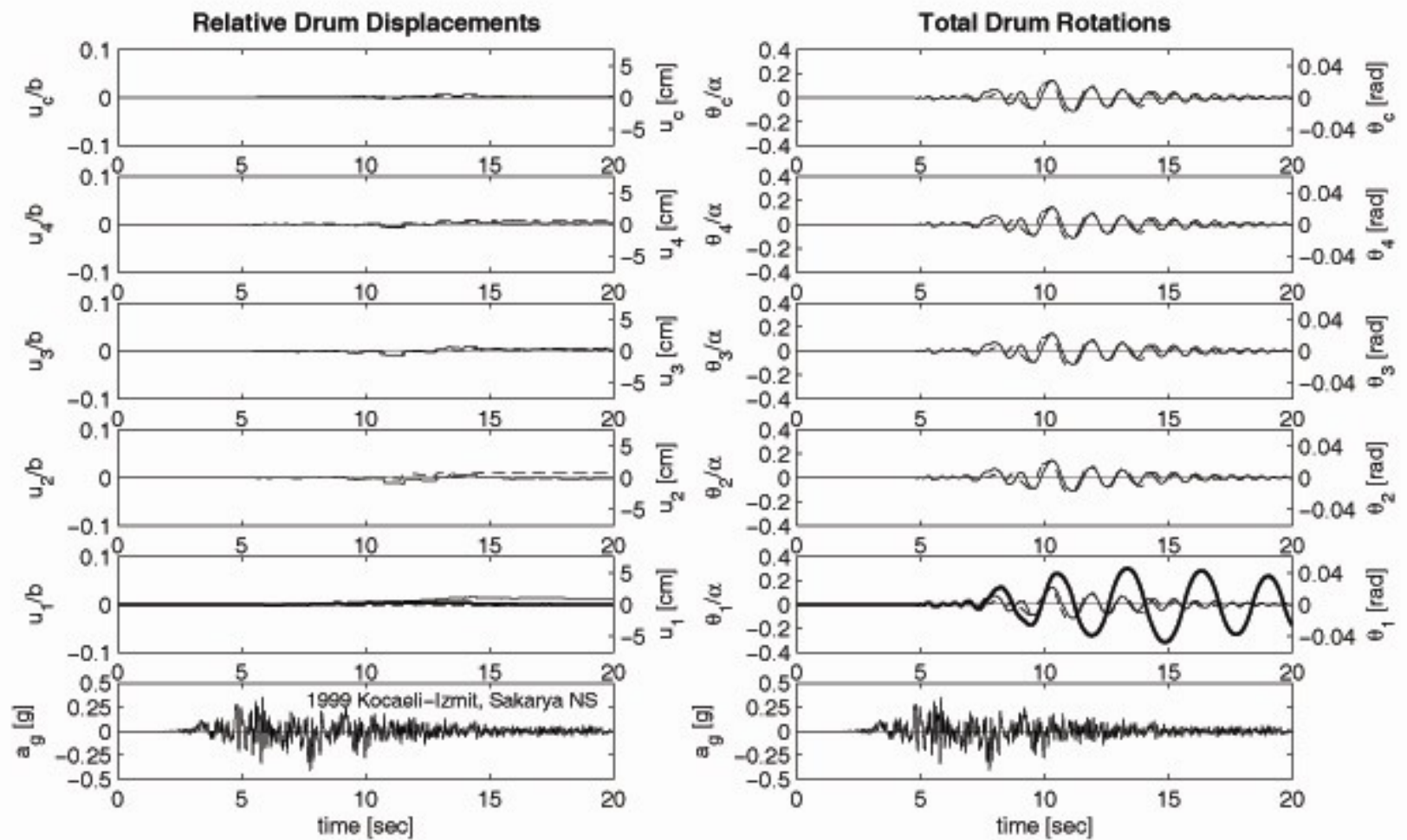












# Peak column rotations from various historic strong earthquake motions

