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3-Dimensional Rocking and Sliding Case Histories in the 2014 Cephalonia, Greece Earthquakes

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ABSTRACT

A twin event earthquake sequence of an M_w6.1 on January 26th and an M_w6.0 eight days later on February 3rd shook the island of Cephalonia, triggering damage in structural and harbor infrastructure. The strongest three recordings of the double event are analyzed in this paper: the Chavriata, Lixouri and Argostoli accelerograms. The Lixouri record bears the effects of near-fault directivity, containing acceleration pulses in its normal to the fault (EW) component. The most extensive damage occurred in the numerous cemeteries of the region, with tombstone topplings and large slippages being the most conspicuous. Some specific "rigid block" failure case histories, from the cemeteries of Lixouri and Chavriata, are explored in the paper. The systems are modeled in 3D, as rigid blocks resting through Coulomb friction on horizontal base. The latter is excited by three component accelerations: two in the horizontal directions and one in the vertical. The rocking, sliding, twisting and overturning of such rigid systems offer a strong indication of the 'destructiveness potential' of ground motions, which explain the cemeteries extensive damage. Unilateral and bilateral excitations are studied and the role of vertical acceleration is elucidated.

Introduction: Cephalonia's Earthquake History and the 2014 Earthquake Doublet

The Greek island of Cephalonia is located in the Ionian Sea, in a high seismicity region of complex tectonics, where the thrust belt along the Ionian and Adriatic sea is connected with the convex part of the Hellenic arc (Papazachos, 1990). Cephalonia has suffered numerous earthquakes of large magnitude, $6.0 < M_S < 7.5$ in the last 500 years (Papazachos & Papazachou, 1997). The seismic sequence of 1953 is the most catastrophic earthquake event ever in Greece, flattening 85 per cent of buildings on the island and killing 500. Thirty years after the destructive sequence of 1953, in 1983 another seismic succession was occurred. After thirty-one years from the sequence of 1983, in 2014, another earthquake-chain had struck in Cephalonia.

The first mainshock of $M_w = 6.1$ occurred on 26 January 2014, in the western part of Cephalonia island. The second mainshock of $M_w = 6.0$ followed on 3 February, just seven days after the first one. The epicenters of both events are shown in Figure 1. The seismic doublet inflict moderate damage in structural infrastructure, as well as several landslides, rock falls, ground and road crocking, severe liquefaction and quay-wall failures (GEER, 2014). Our team participated in the

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GEER reconnaissance mission to Cephalonia. In contrast with the overall satisfactory performance of domestic buildings (which were designed with the highest in Greece seismic acceleration of 0.36 g), all the eighteen cemeteries of the triggered region of Paliki (western Cephalonia peninsula) were extensively damaged. Toppling of headstones, breaking of covering tomb slabs, sliding and uplifting of heavy marble ornaments and vases were observed. Most notably, the cemetery in Lixouri (the second larger in the island after Argostoli's one) was totally damaged: almost every tomb was cracked with overturning headstones and ornaments.

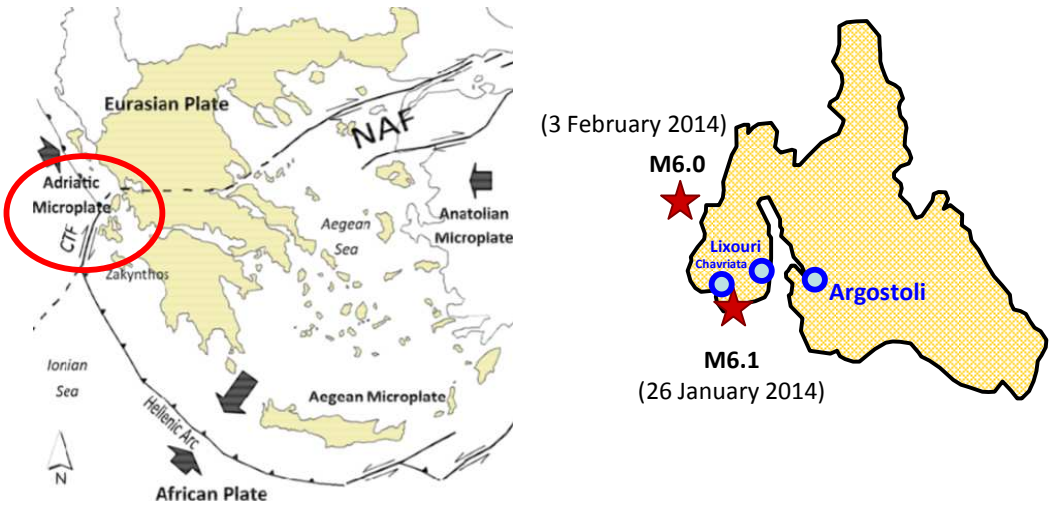

Figure 1. Map of Greece, with the location and the tectonic setting of Cephalonia. The EQ epicenters are pictured with the red stars, while the three recording sites are shown in blue.

The extent of the damage in the investigated cemeteries is an evidence of the ground motion severity. Our study focus on the rocking response of rigid bodies, either of a simple geometry (a rectangular block) or more complicated ones (a detailed headstone). The particular dimensions utilized in this study represent real cases observed and measured in detail in the field. A series of three dimensional finite element analyses are performed utilizing the ABAQUS finite element code. The parameters that are investigated include: (i) the simultaneous triggering by all three acceleration components (two horizontal and one vertical), and (ii) the influence of friction coefficient, μ, along the sliding/rocking interface. The need for a 3D modeling stems from the fact that only few results are available accounting for 3D rocking systems (and it will be described in detail at a next part). Therefore, a thorough insight into uplifting response in fully 3D conditions is of essential importance.

The Recorded Ground Motions

As base excitations are employed five real accelerograms recorded during the two earthquakes at three different sites on Cephalonia. In particular, the ground motions utilized herein are: (a) the Lixouri records from the January 26th event, and (b) Lixouri and Chavriata records from the February 3rd earthquake. All the three components of acceleration are illustrated in Figure 2 (with common acceleration and time scales). The digital data for both mainshocks were provided from the websites of NOA-IG (National Observatory of Athens Geodynamic Institute) and

ITSAK (Institute of Engineering Seismology and Earthquake Engineering).

Notice from Figure 2, that the accelerations recorded in Lixouri are quite strong: 0.54 to 0.64 g. The different levels of acceleration intensity are in full agreement with the damages reported at each site. For the Chavriata village, we present only the recordings of the second event because the station was installed after the first tremor. The horizontal peak ground acceleration at Chavriata, 0.72 g, was the highest recorded during the doublet.

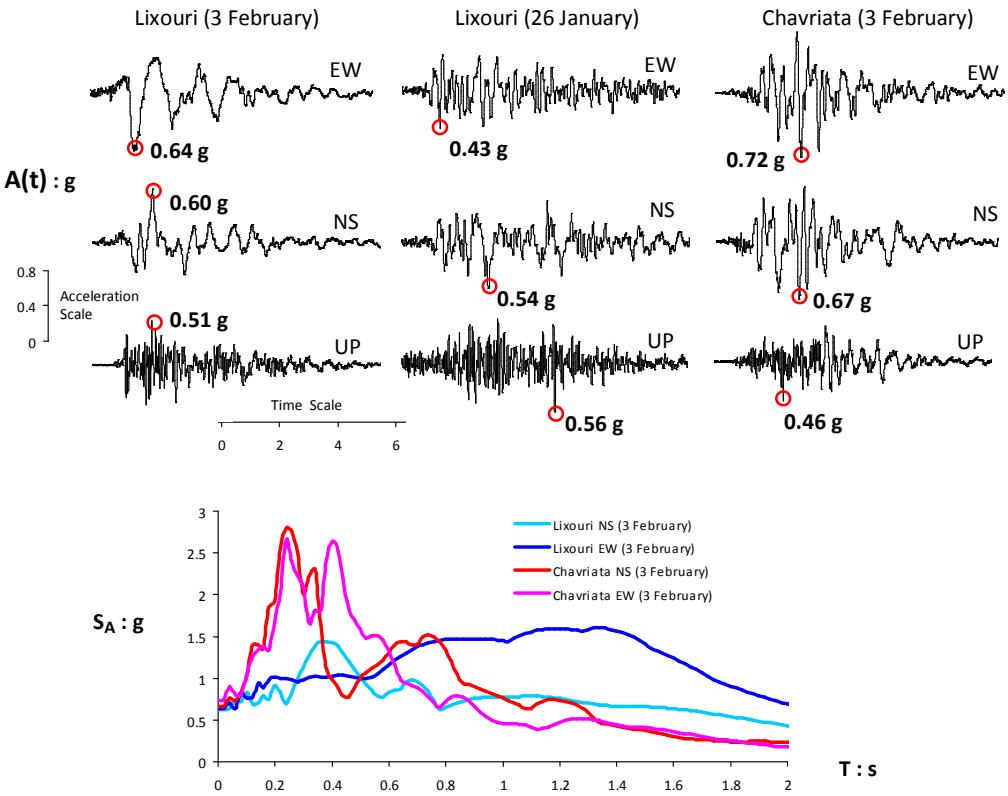

Figure 2. Acceleration time histories and elastic response spectra of the Lixouri and Chavriata records of the February event.

The Lixouri and Chavriata records from the earthquake of February, are by far the strongest ever recorded in Greece. They contain large amplitude as well as great period acceleration pulses, a possible indication of forward directivity effect. Their large period content become evident if we observe their elastic response spectra (bottom plot of Figure 2). Lixouri's spectra are plotted in bold blue and turquoise lines, and Chavriata's in red and pink respectively. It is evident that Lixouri EW spectrum presents a large period content, especially in the period range of 0.8 to 2 seconds.

3D Rocking of Rigid Body

It is a common practice to inspect the rocking response of slender objects in a seismic reconnaissance mission. Strong ground excitations can initiate rocking of a tall rigid body which

could end up in overturning. Numerous researchers studied this field, coping with the difficulties stemming from the chaotic nature of rocking and overturning phenomena. Milne and Perry in 1881 were the pioneers who first studied the uplifting response of rigid body. Housner in 1963 systematically examined the behavior of inverted pendulum structures during earthquakes. Classification of different rocking types of motion and overturning criteria were presented by Ishiyama (1982). Compliance of the supporting soil and the structural response of an uplifting system was taken into account by Apostolou et al. (2007), among others. Makris and his co-workers dealt with numerous aspects of overturning response, for instance the response under near-source ground shaking approximated by idealized wavelets, gaining invaluable insight into the physics of the problem (Makris & Zang, 1999; Makris & Roussos, 2000; Makris & Kostantinidis, 2003; Makris & Black, 2004). Frequently, systems that exhibit uplifting motion can also sustain slide-rock type of response. The criteria for initiation of sliding, rocking or sliding-and-rocking motion were presented by Shenton (1996) and later on by Taniguchi (2002). The vast majority of studies on uplifting systems refer to two-dimensional geometry. However, the phenomenon of a rocking body is a three-dimensional problem. A few results are available accounting for 3D geometry: Konstantinidis & Makris (2007), Chatzis & Smyth (2012), and Zulli et al. (2012). The need for further understanding and insight into uplifting response in fully 3D conditions is evident.

Figure 3. A marble vase observed in field (photos), modeled as rigid block on top of rigid base.

In the present study, a rectangular block with dimensions B (length) x B (width) x H (height) on top of a rigid base undergoing a three component seismic excitation is examined, as displayed in Figure 3. The block's dimensions are parametrically varied (Table 1). The contact between the rigid bodies and their base is simulated through a frictional interface governed by Coulomb's friction law. Hence, the frictional behavior is described by the coefficient of friction, μ.

Table 1. Dimension of rectangular rigid blocks studied herein and their characteristic parameters.

	Types of Rigid Blocks and Fundamental Rocking Parameters			
Block Dimensions **B** x **B** x **H** [in cm]	12x12x12	12x12x24	12x12x36	24x24x72
Size Parameter **R** [in m]	0.104	0.147	0.199	0.398
Overturning Acceleration $\mathbf{A_C}$ [in g]	1	0.5	0.33	0.33

A rigid rectangular block of mass, m, with aspect ratio B/H simply supported on a rigid base is subjected in earthquake acceleration, A(t). As long as the overturning moment, mA(t)gH, is smaller than the restoring moment, mgB, the block remains attached to its base. The instant the restoring moment is exceeded, uplifting starts. Therefore, the critical uplifting acceleration, A_C (in terms of g), required to statically overturn the block equals:

$$A_C = B/H \tag{1}$$

The size parameter, R, of the rocking block is determined as:

$$R = \sqrt{2\left(\frac{B}{2}\right)^2 + \left(\frac{H}{2}\right)^2} \tag{2}$$

The material of both structures is marble. The coefficient of friction, μ, at the block-base interface is parametrically investigated following in-situ measurement: μ = 0.7, 0.6, 0.5, 0.4. Excitation is applied at the bottom of the rigid base. The two horizontal and the vertical component of the Argostoli, Lixouri and Chavriata records (Figure 2) are imposed. The motions are imposed as recorded, with no modifications accounting for soil amplification or/and site effects, to study the destructiveness potential of the particular motions.

Results Discussion

The body has six degrees of freedom (DoF): the first three are the translational DoF, and the rest three DoF are the rotational. The rotation of the body is described with the angles of rotation (ϕ_{rx}, ϕ_{ry}, ϕ_{rz}) around the axes (x, y, z) respectively, and they are illustrated in Figure 4. We are interested in both rocking and sliding response of the bodies. For space limitation reasons, only few characteristic results will be discussed next.

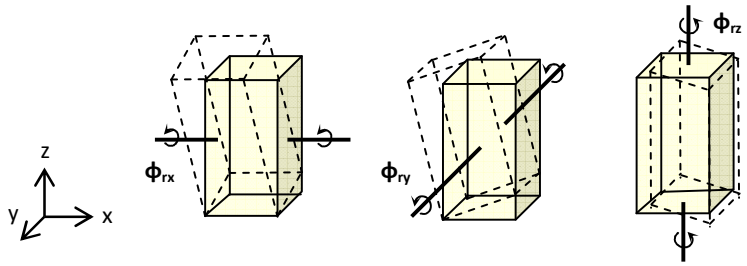

Figure 4. Rotational degrees of freedom.

The effect of the vertical acceleration component is shown in Figure 5. Blue solid line displays the rotational response induced only by the EW horizontal acceleration of the Lixouri record of February 3rd, for a coefficient of friction μ = 0.5. The red line corresponds to rotational angles triggered by the two horizontal components, whereas the black one shows the response due to all three acceleration components. In all cases, the block overturns around x-axis. However, torsional rotation occurs only when both horizontal components are applied as excitation. When only one of the two horizontal components acts alone, obviously there is no torsion, as no out-of-plane moments are induced. The presence of vertical acceleration results in earlier toppling of

the body. Observe in Figure 6 that for all three components overturning occurs at around 2.7 s, where with both horizontal components, failure takes place later, at 3.1 s.

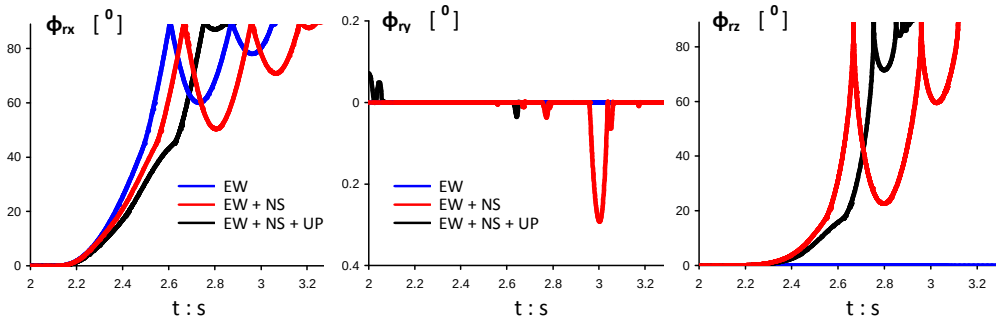

Figure 5. Rotational response of a 12x12x24 cm^3 vase, subjected to Lixouri (3 February) record.

Figure 6 illustrates the comparison between the permanent displacements of a 12x12x22 cm^3 marble vase measured in field at the Agios Dimitrios cemetery after the second earthquake (at left handside), and the corresponding numerical results for a friction coefficient of $\mu = 0.7$, with the three-components Chavriata excitation (at right). The results of the analysis are in fair agreement with the field observations. Just to mention that the photos of Figure 3 refer to this particular case.

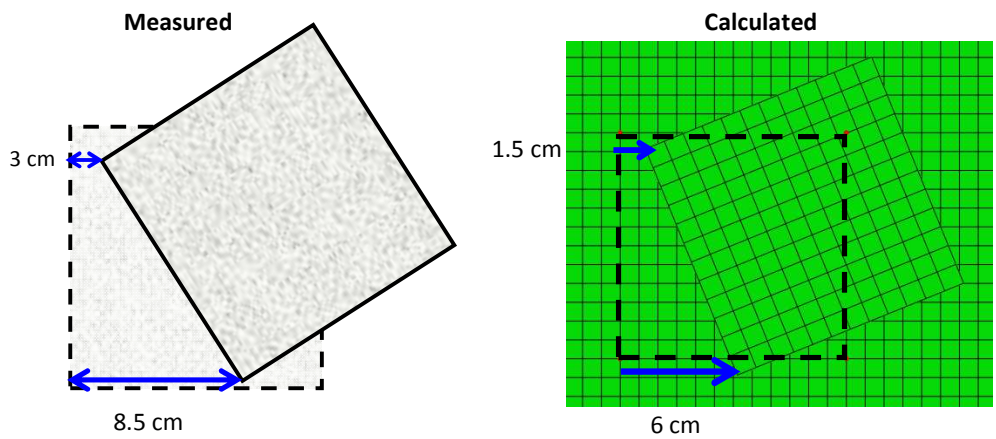

Figure 6. Comparison of final rotational response of a 12x12x22 cm^3 vase.

Figures 7 and 8 portray the effect of friction coefficient, μ. In Figure 7 are presented the three rotational angles along the x, y, and z axes for the Chavriata excitation. Notice in Figure 7, that as μ increases from 0.4 to 0.5 the rotational response ϕ_y and ϕ_z is increasing too. However, further increase of μ from 0.5 to 0.7 leads to a decrease of the rotational response. This is just a simple evidence of the chaotic nature of rocking response. Furthermore in Figure 8 are portrayed the sliding displacements along the x and y axes induced by the Lixouri record. The destructiveness of the recorded motions in Lixouri, which contain strong directivity pulses, is evident by the response of the slender blocks that are studied herein (compare the black solid line

that corresponds to slender block with the blue and pink lines).

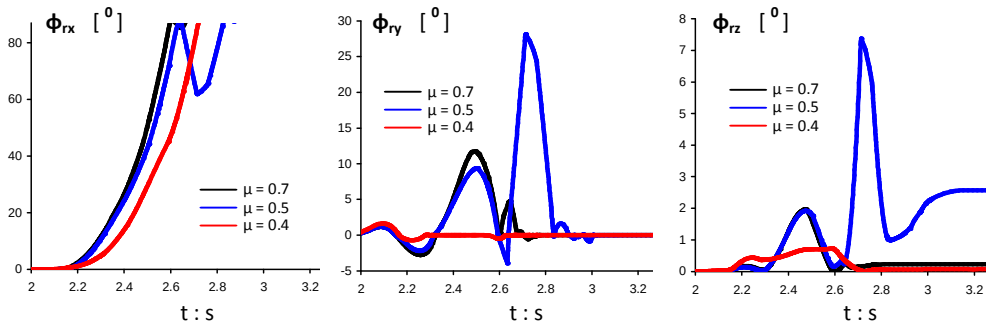

Figure 7. Rotational response of a 12x12x36 cm^3 vase subjected to Chavriata (3 February) record, for three different coefficients of friction.

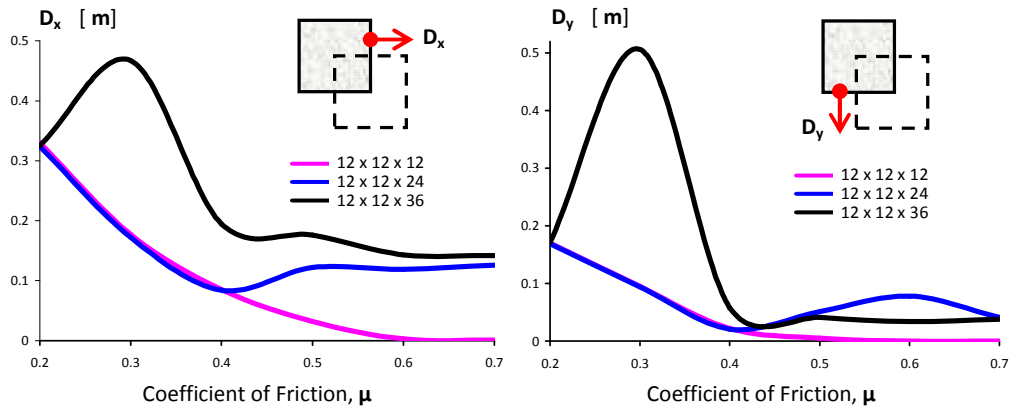

Figure 8. Sliding displacements, D_x and D_y along to horizontal axes -x and -y respectively, induced by the Lixoury (3 February) record.

Conclusions

The paper investigates the rocking and overturning response of rigid systems modeled in 3D. The base is excited by all three components of acceleration recorded during the Cephalonia 2014 EQ doublet. For the cases presented the vertical component of acceleration leads to earlier toppling of the block, and there is no definitive relation between rocking response and the friction coefficient, μ. An important conclusion of our study is that the recorded motion in Lixouri, with its strong long-period pulses (an obvious outcome of forward-rupture directivity), can explain the unprecedented extent of overturning failures observed in the cemeteries of the region.

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