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Rocking and Sliding Potential of the 2014 Cephalonia, Greece Earthquakes

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ABSTRACT

A twin event earthquake sequence of an Mw6.1 on January 26th and an Mw6.0 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. Symmetric and asymmetric sliding of a block resting through Coulomb friction on horizontal or inclined planes and rocking–overturning of rigid blocks, when excited at their base by these records, are studied in the paper. The rocking 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.

Keywords: 3D rocking, sliding, forward directivity, toppling

INTRODUCTION: THE CEPHALONIA DOUBLET EARTHQUAKE RECORDS

Cephalonia has suffered numerous earthquakes of large magnitude, 6.0 < MS < 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 Mw = 6.1 occurred on 26 January 2014, in the western part of Cephalonia island. The second mainshock of Mw = 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 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. The extent of the damage in the investigated cemeteries is an evidence of the ground motion severity.

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Our study focus on the sliding and rocking response of simple geometry rigid bodies, triggered by the recorded ground motions of the 2014 Cephalonia events. 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).

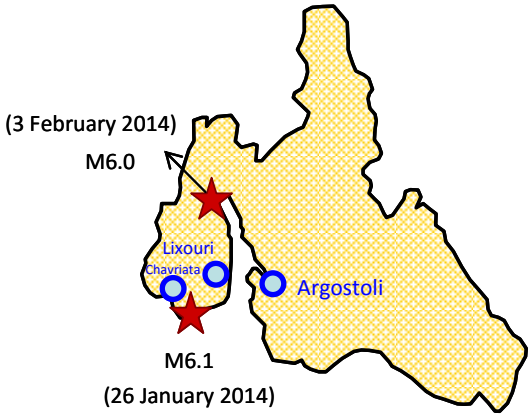

Figure 1. Map of Cephalonia with the EQ epicenters pictured with red stars, while the three recording sites are shown in blue.

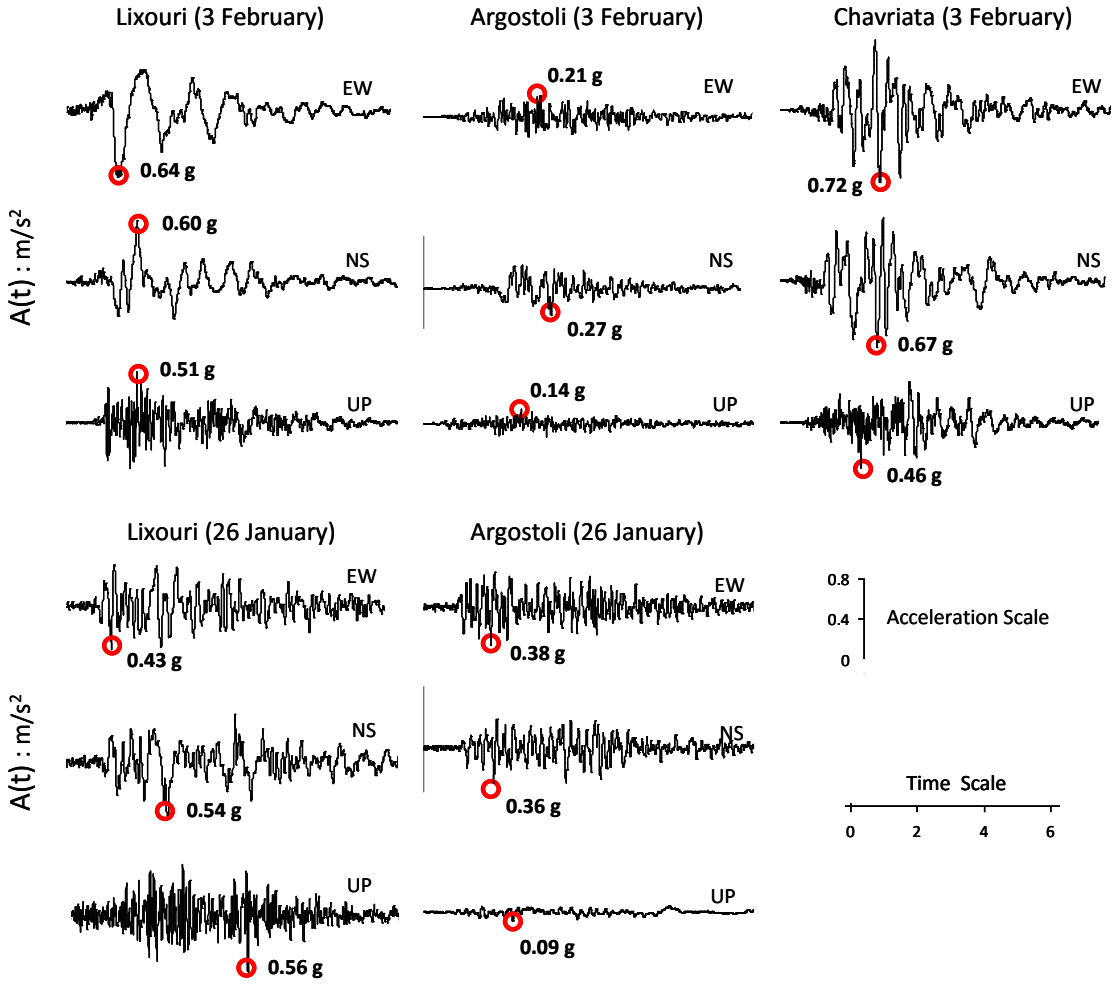

Figure 2. Acceleration time histories the Lixouri, Chavriata and Argostoli records of 2014 EQ events.

CHARACTERISTICS OF THE SELECTED MOTIONS AND THEIR ELASTIC RESPONSE SPECTRA

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 and Argostoli records from the January 26th event, and (b) Lixouri, Argostoli and Chavriata records from the February 3rd earthquake. Keep in mind that Chavriata station was put in service after the first earthquake, therefore available recordings exist only for the second event. All the three components of acceleration are illustrated in Figure 2 (with common acceleration and time scales). 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. The horizontal peak ground acceleration at Chavriata, 0.72 g, was the highest recorded during the doublet.

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. Figure 3 compares the 5%-damped response spectra of the Lixouri EW, and Chavriata NS ground motions with the spectra of two of the most destructive worldwide accelerograms: the Rinaldi and Takatori recordings from the 1994 Northridge and 1995 Kobe earthquakes, respectively.The damped elastic response spectra, in terms of spectral acceleration, S_A, offer a complete visual assessment of the potential of a ground motion to cause large response to (visco)elastic spring–mass systems. Lixouri's spectra are plotted in bold black line, and Chavriata's in red respectively. It is evident that Lixouri EW spectrum presents a large period content, especially in the period range of 0.8 to 2 seconds.

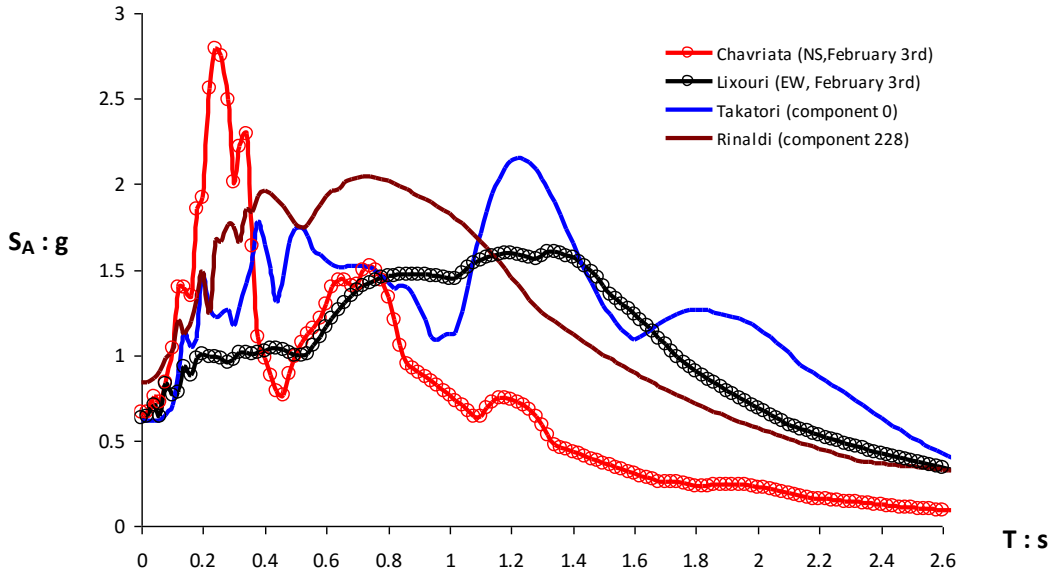

Figure 3. Elastic response spectra of the Lixouri and Chavriata ground motions of the February 3rd event and comparison with the Takatori (1995 Kobe) and Rinaldi (1994 Northridge) spectra.

Seismic behavior of three idealized systems is explored to calculate the potential of a record to inflict excess irrecoverable displacements. They are to be thought of as analogs of actual inelastic systems:

- the sliding of a rigid block on a horizontal base,
- the sliding of a rigid block on an inclined (= 30^o) base, and
- the rocking–uplifting–overturning of a rigid slender block on horizontal base.

The former two systems are characterized by a rigid-plastic symmetric or asymmetric restoring-force versus displacement relationships obeying Coulomb's friction law. The latter is characterized by a bilinear restoring–moment versus rotation relationship, comprising an initial rigid branch and a subsequent branch descending to zero at the angle of imminent overturning. In Figure 4 are illustrated the three systems and

their restoring force–displacement relation. The supporting base of each system is subjected to the particular ground motion under investigation, and the size of the resulting inelastic/nonlinear response serves as an index of the damage that this motion can inflict on the corresponding class of inelastic systems — the "destructiveness" potential of the motion.

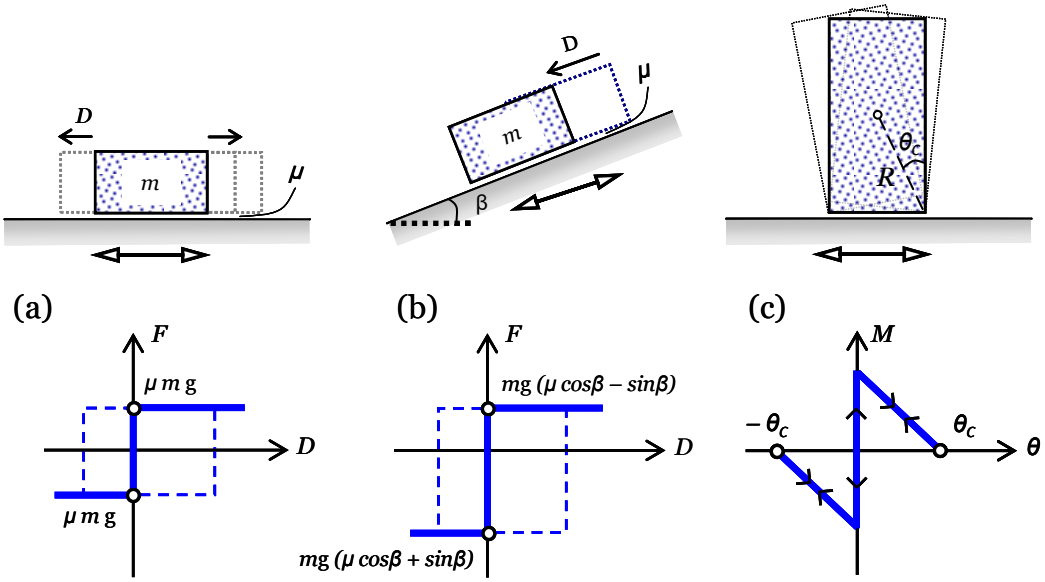

Figure 4. The fundamental systems studied herein: (a) ideally rigid-plastic sliding on horizontal plane, (b) ideally rigid-plastic sliding on inclined plane, and (c) rotational oscillation of a rocking block on rigid base.

SLIDING POTENTIAL OF THE SELECTED MOTIONS

The analysis of the behavior of a block on a horizontal or inclined base which is subjected to motion A(t) parallel to the plane is obtained from elementary rigid body kinematics along with Newton's second law of motion (Newmark, 1964). The critical acceleration which must be exceeded for slippage to be initiated are:

$$A_C = \mu g \quad (1)$$

$$A_{C1} = (\mu \cos\beta - \sin\beta)\, g \quad (2a)$$

$$A_{C2} = (\mu \cos\beta + \sin\beta)\, g \quad (2b)$$

in which A_C = the critical acceleration for sliding in either direction of the symmetric system; μ = the (constant) coefficient of friction; A_{C1} and A_{C2} = the critical accelerations for downhill and uphill sliding for the asymmetric system of a plane inclined at an angle β. Usually $A_{C1} << A_{C2}$ and as a result sliding takes place only downhill. Whenever the base acceleration exceeds A_C or A_{C1} (or, rarely, A_{C2}) slippage of the block takes place with respect to the base. This slippage lasts only momentarily, thanks to the transient nature of earthquake shaking; it terminates as soon as the velocities of the base and the block equalize. And the process continues until the motions of both the block and the base eventually terminate.

A detailed graphical presentation of the solution procedure is given in Figure 5, for the Lixouri EW motion of February. Yielding on an inclined base with A_C = 0.10 g, induced a total slippage of 1.18 m while symmetric sliding on horizontal plane results in 0.51 m of maximum displacement and only 0.26 m of final slippage. In asymmetric sliding, yielding displacement is building up at every acceleration cycle, leading to the final 1.18 m. On the contrary, in symmetric case, displacement on right at one cycle reverts at the next acceleration pulse and so on, resulting in an almost self-centered position of 0.26 m at the end of the motion.

Figures 6 and 7 illustrate the symmetric and asymmetric sliding spectra, respectively, of a set of Greek ground motions which consists of: the Chavriata and Lixouri records from the 2014 February event, the Lefkas records from the 2003 and 1973 earthquakes, the Aegion accelerogram from the 1995 Aegion event, the Monastiraki and Sepolia records from the 1999 Parnitha EQ, and Kalamata motion from the 1986 EQ.

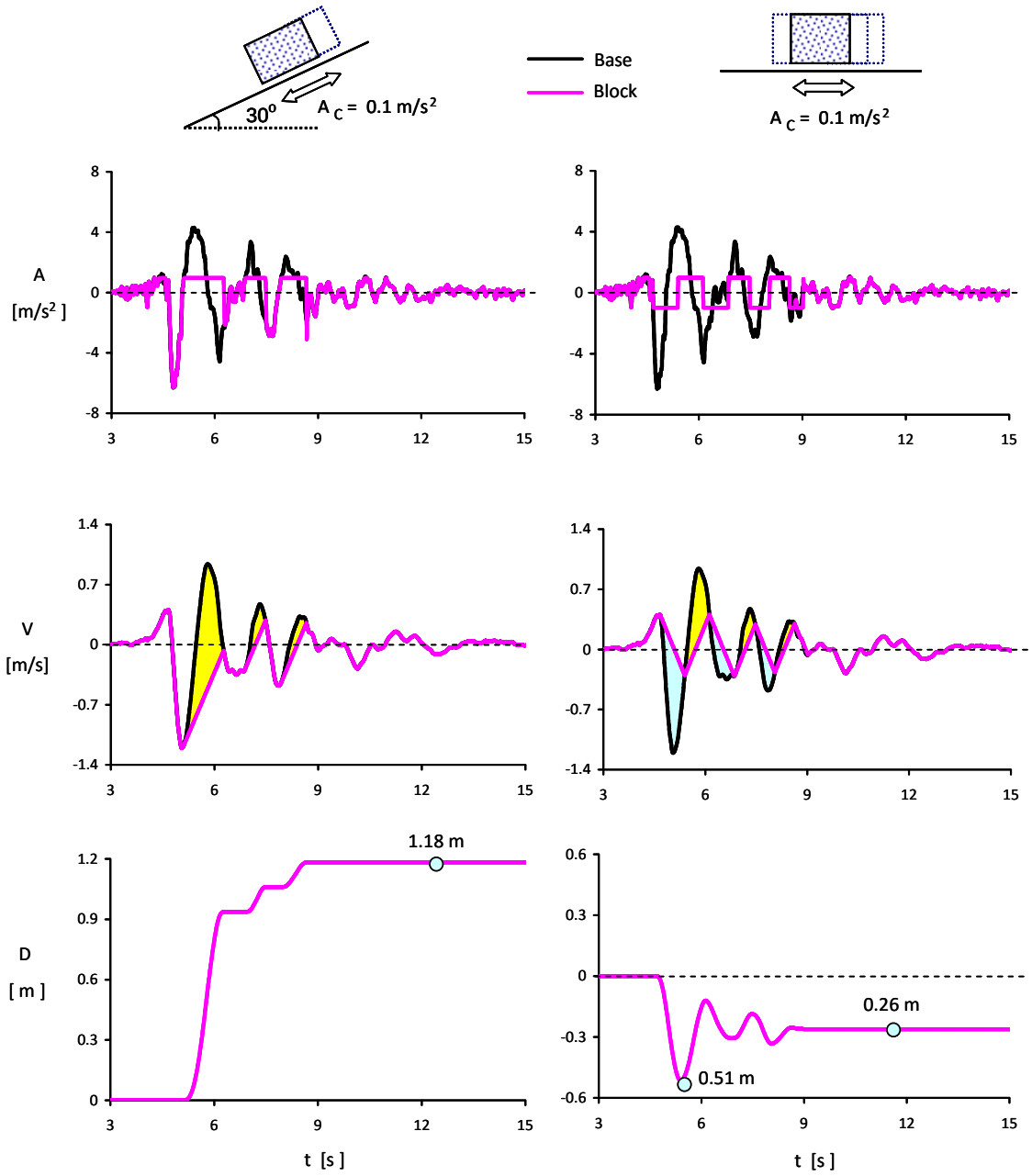

Figure 5. Influence of the symmetric (right) and asymmetric (left) nature of sliding on the response induced by the Lixouri EW ground motion of February 3rd, for critical acceleration A_C = 0.10 g.

OVERTURNING POTENTIAL OF THE SELECTED MOTIONS

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

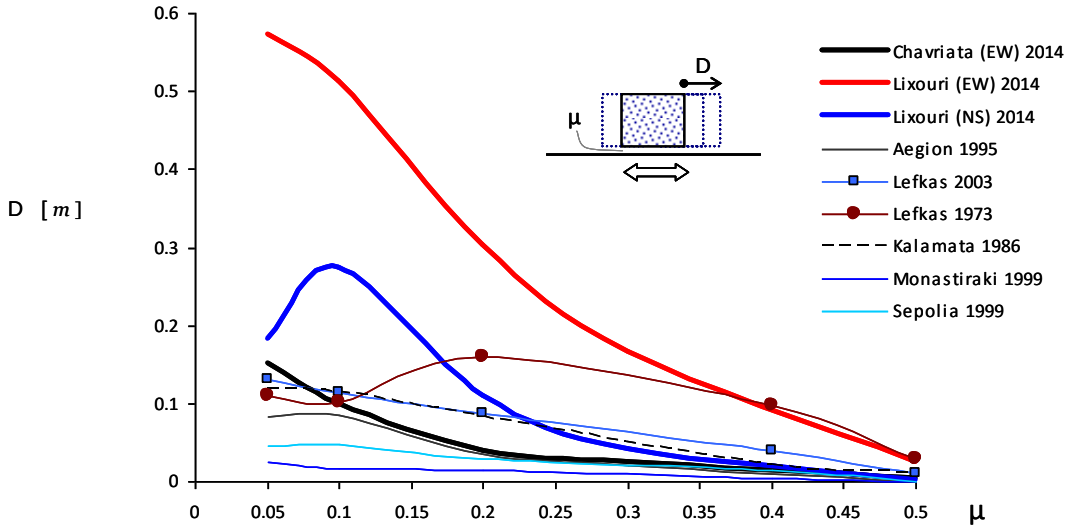

Figure 6. Symmetric sliding response in terms of yielding displacement, D, versus the coefficient of friction, μ, for several Greek records.

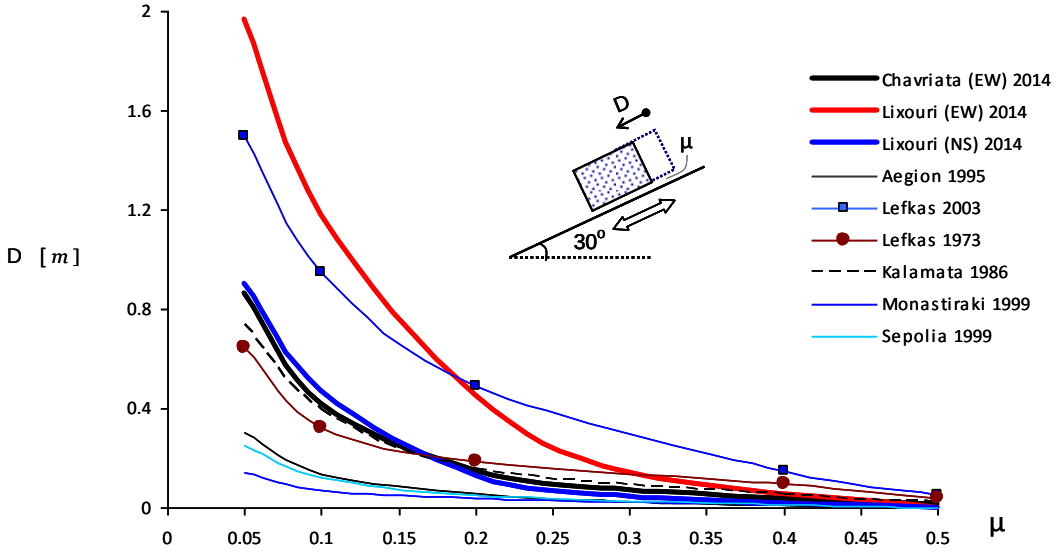

Figure 7. Asymmetric sliding response for an inclination of 30°, in terms of yielding displacement, D, versus the coefficient of friction, μ, for several Greek records.

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.

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 8. The block's dimensions are parametrically varied. The contact between the rigid bodies and their base is simulated through a frictional interface governed by Coulomb's friction law.

The rocking response of a slender solid block of mass m in non-sliding but tensionless contact with a rigid base which is subjected to motion A(t) is obtained numerically. The critical acceleration, which must be exceeded for uplifting of the block from its base to be initiated, is simply:

$$A_C = (B/H)\, g \qquad (3)$$

in which B = the width and H = the height of the solid block. Under a constant one–directional acceleration even barely exceeding Ac (i.e., under the action of a pseudostatic inertia force mA_C), the block will overturn. The response and overturning of a given block depend on the amplitude, frequency content, and the sequence of pulses of the ground motion. And for a given ground motion, the overturning is a function of the slenderness H/B and the absolute size of the block. It turns out that acceleration levels higher than A_C may be necessary to cause overturning of a block — in fact much higher, if the motion were dominated by high-frequency components.

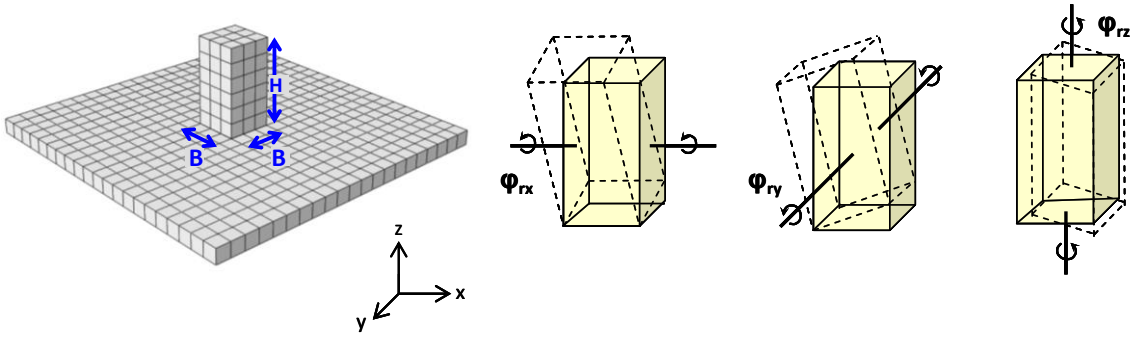

Figure 8. The F.E. model of rigid block on top of rigid base (left) and sketches of block's rotational degrees of freedom (right).

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 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.

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 8. For space limitation reasons, only few characteristic results will be discussed next.

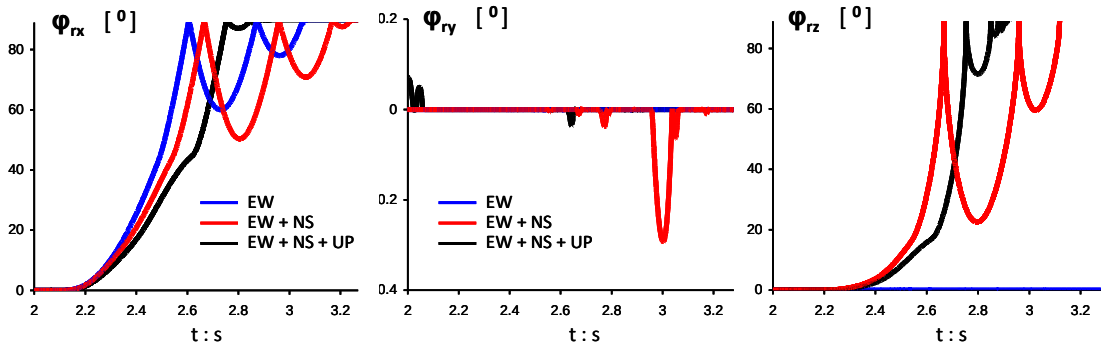

Figure 9. Rotational response of a 12x12x24 cm^3 vase, subjected to Lixouri (3 February) record.

The effect of the vertical acceleration component is shown in Figure 9. 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 9 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 10 portray the effect of friction coefficient, μ. The three rotational angles along the x, y, and z axes for the Chavriata excitation are presented in Figure 10. Notice, that as μ increases from 0.4 to 0.5 the rotational response φ_{ry} and φ_{rz} 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.

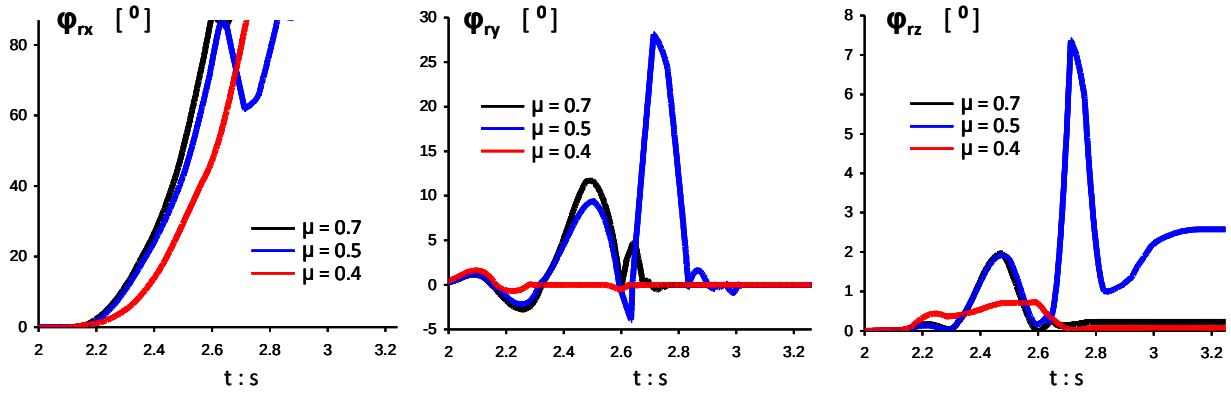

Figure 10. Rotational response of a 12x12x36 cm^3 vase subjected to Chavriata (3 February) record, for three different coefficients of friction.

CONCLUSIONS

The paper investigates the sliding and overturning response of rigid systems excited by ground motions recorded during the Cephalonia 2014 EQ doublet. Sliding spectra of the studied records give a more complete picture than the elastic response spectra alone. It was shown that the Lixouri and Chavriata motions of February event were of substantial damaging potential comparing with a representative set of records from Greek earthquakes of the last decades. As far as the rocking response is concerned, 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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