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3D ROCKING RESPONSE OF RIGID BLOCKS UNDER STRONG NEAR-FAULT SEISMIC SHAKING

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ABSTRACT

The dynamic rocking response of simple systems is studied in 3D accounting for: (a) the simultaneous action of the three seismic components of motion, and (b) the complex combination of sliding, twisting, uplifting, and jumping motion of such systems. A rectangular block with dimensions B (length) x B (width) x H (height) on top of a rigid base is examined, with block's dimensions varied parametrically. The contact between the rigid body and its base is simulated through a frictional interface governed by Coulomb's friction law, with coefficient of friction, μ. The influence of sliding and of vertical acceleration are elucidated. Excitations comprise records from recent catastrophic earthquakes in Greece, some of them bearing near-fault characteristics: the Lixouri and Chavriata records from the 2014 Cephalonia event. Specific "rigid block" failure case histories from selected cemeteries are also explored.

Keywords: Rocking; Sliding; Rigid Block; Strong Ground Motions

1. INTRODUCTION

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 overturning. Numerous researchers studied this phenomenon, 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). The rocking response due to harmonic motion were studied by Spanos & Koh (1984). 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 overturning instability of a three-rigid block system triggered by horizontal excitation was analytically examined by Kounadis & Papadopoulos (2016); whereas Kounadis (2015) presented the more general solution for the rocking response of multi-drum columns.
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

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for 3D geometry: Konstantinidis & Makris (2007), Chatzis & Smyth (2012), and Zulli et al. (2012). Recently, Mathey et al. (2016) had performed an experimental and numerical study on three dimentional response of rigid block systems when an geometrical defects are present. Therefore, the limiting knowledge on the 3D rocking response, makes the need for further understanding and insight into uplifting response in fully 3D conditions evident.

2. GEOMETRY OF THE STUDIED ROCKING SYSTEM

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 1. The block dimensions are parametrically varied (Table 1). The contact between the rigid bodies and their base is simulated through a Coulomb's friction law. Hence, the frictional behavior is described by the coefficient of friction, μ.

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

	Rigid block types & Rocking parameters			
Block Dimensions : cm B × B × H	12x12x12	12x12x24	12x12x36	24x24x72
Size Parameter R : m	0.104	0.147	0.199	0.398
Overturning acc. A_C: g	1	0.5	0.33	0.33

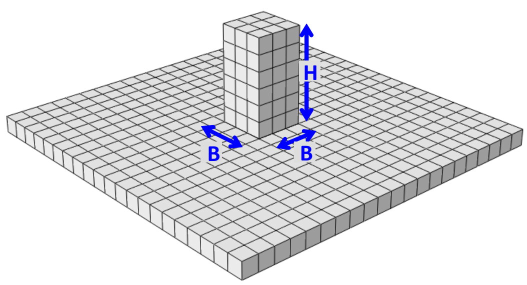

Figure 1. Finite element mesh of the studied rigid block on top of rigid base in 3D.

A rigid rectangular block of mass m with aspect ratio B/H on a rigid base is subjected to earthquake acceleration, A(t). As long as the overturning moment, mA(t)H/2, is smaller than the restoring moment, mgB/2, the block remains attached to its base. The instant the restoring moment is about to be exceeded, uplifting initiates. So, the critical uplifting acceleration, A_C , required to "statically" overturn the block is:

$$A_C = (B/H)g \tag{1}$$

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 coefficient of friction, μ, at the interface is parametrically investigated: μ = 0.7, 0.6, 0.5, 0.4. Excitation is applied at the bottom of the rigid base.

3. EXCITATION

As base excitations are employed real accelerograms recorded during several recent catastrophic earthquakes in Greece. In particular, the ground motions utilized herein are: Lixouri and Chavriata records from 2014 Cephalonia event, Aegion 1994, Lefkada 2003, and Monastiraki from 1999 Parnitha EQ. The digital data were provided from the websites of NOA-IG (National Observatory of Athens Geodynamic Institute) and ITSAK (Institute of Engineering Seismology and Earthquake Engineering).

Notice in Figure 2, that the accelerations recorded in Lixouri and Chavriata are quite strong: PGAs of 0.64 g and 0.72 g, respectively. These two records are by far the strongest ever recorded in Greece. They contain large amplitude as well as long period acceleration pulses, a possible indication of forward directivity effect. Their large period content becomes evident in their elastic response spectra (Figure 2). The Lixouri EW spectrum presents a long-period content, especially in the range of 0.8 to 2 seconds. Chavriata's spectrum is more high frequency. Comparing Lixouri's and Chavriata's elastic spectra with those of Aegion 1994, Lefkada 2003, and Monastiraki 1999 motions, the superiority of Lixouri's motion to inflict damage becomes evident. Field observations are in full agreement with the Lixouri recording: facing east, the tomb-stones (in Lixouri's cemetery) were disturbed mainly by the EW component of motion [Garini et al. (2017)].

For each seismic station, all three components are employed as base excitations: two horizontal and the vertical one.

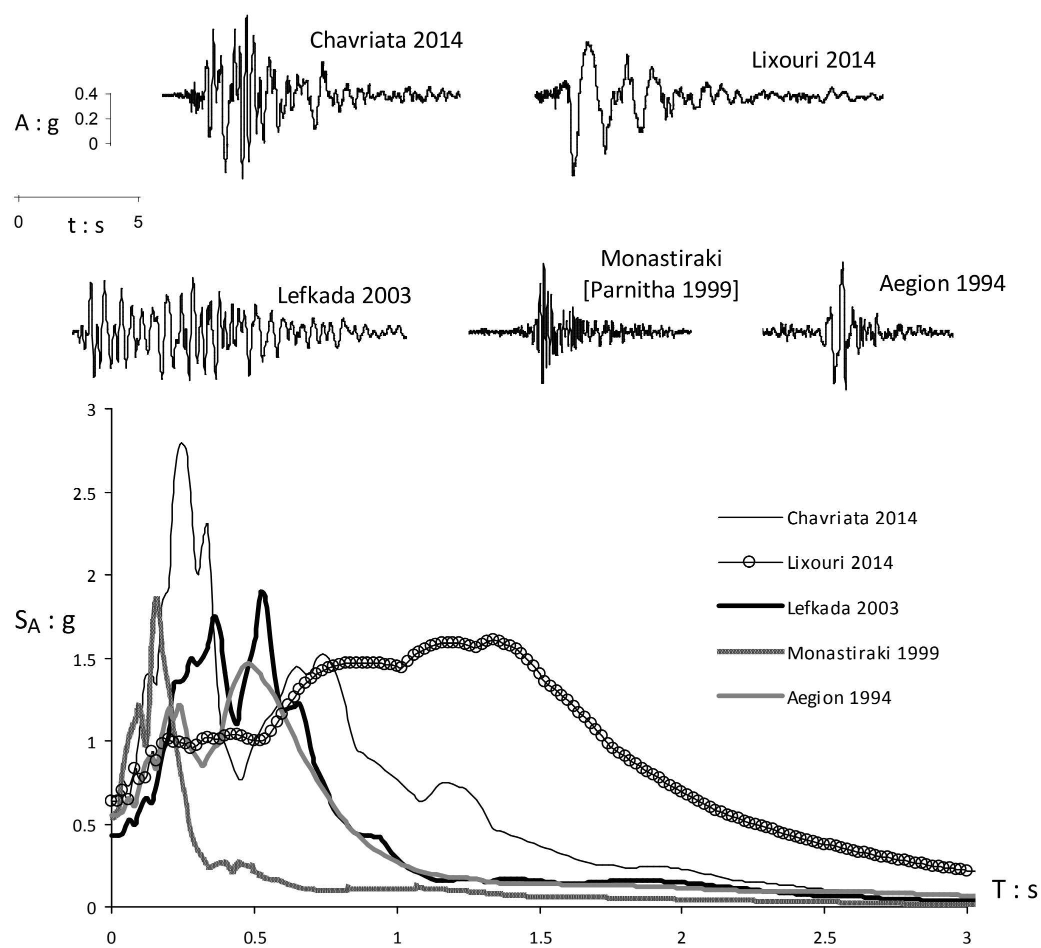

Figure 2. Acceleration time histories of the dominant horizontal component of each seismic station; and their corresponding elastic response spectra.

4. NUMERICAL RESULTS AND DISCUSSION

The body has six degrees of freedom (DoF): three translational and three 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, as illustrated in Figure 3.

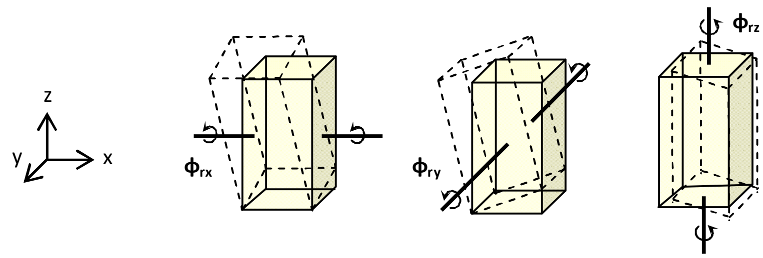

Figure 3. Rotational degrees of freedom of a rectangular rigid block.

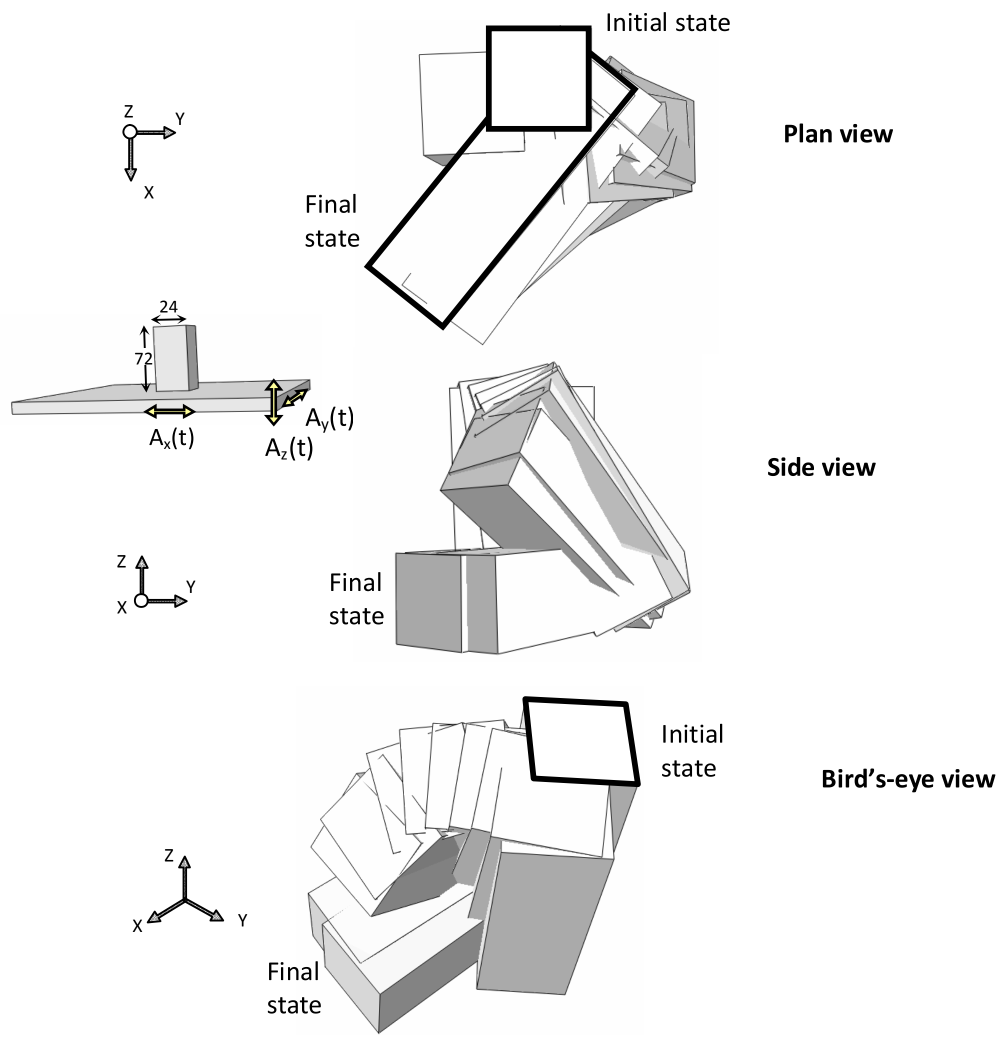

Figure 4. Snapshots of a 24×24×72 cm^3 rectangular block triggered by all three components of the Lixouri record of February 3 (in the y-direction by the EW, in the x-direction by NS, and in z-axis by the vertical component). The motion of the block is presented in three different angles of view. [$\mu = 0.7$].

We are interested in both rocking and sliding response of the bodies. For space limitations, only few characteristic results are discussed. Figure 4 portrays the snapshots of a 24 x 24 x 72 cm^3 marble block triggered with the three-component Lixouri motion. The coefficient of friction is 0.7. Overturning occurs in the very first seconds of the motion (at 2.2 sec) without many rocking cycles. The block topples immediately without even one impact. Out-of-plane moments are induced by the two horizontal components resulting in torsional rotation of the body.

The strongly non-linear nature of rocking can be proved by simple "sensitivity" type tests: by altering slightly the value of one controlling parameter, the uplifting response alters dramatically. This is confirmed in Figure 5. The geometry of the block and excitation remain the same, while the coefficient of friction, μ, is reduced from 0.7 to 0.5. As a consequence, the block performs in a completely different way: the orbit of the rocking block is deviating and the its final position alters substantially.

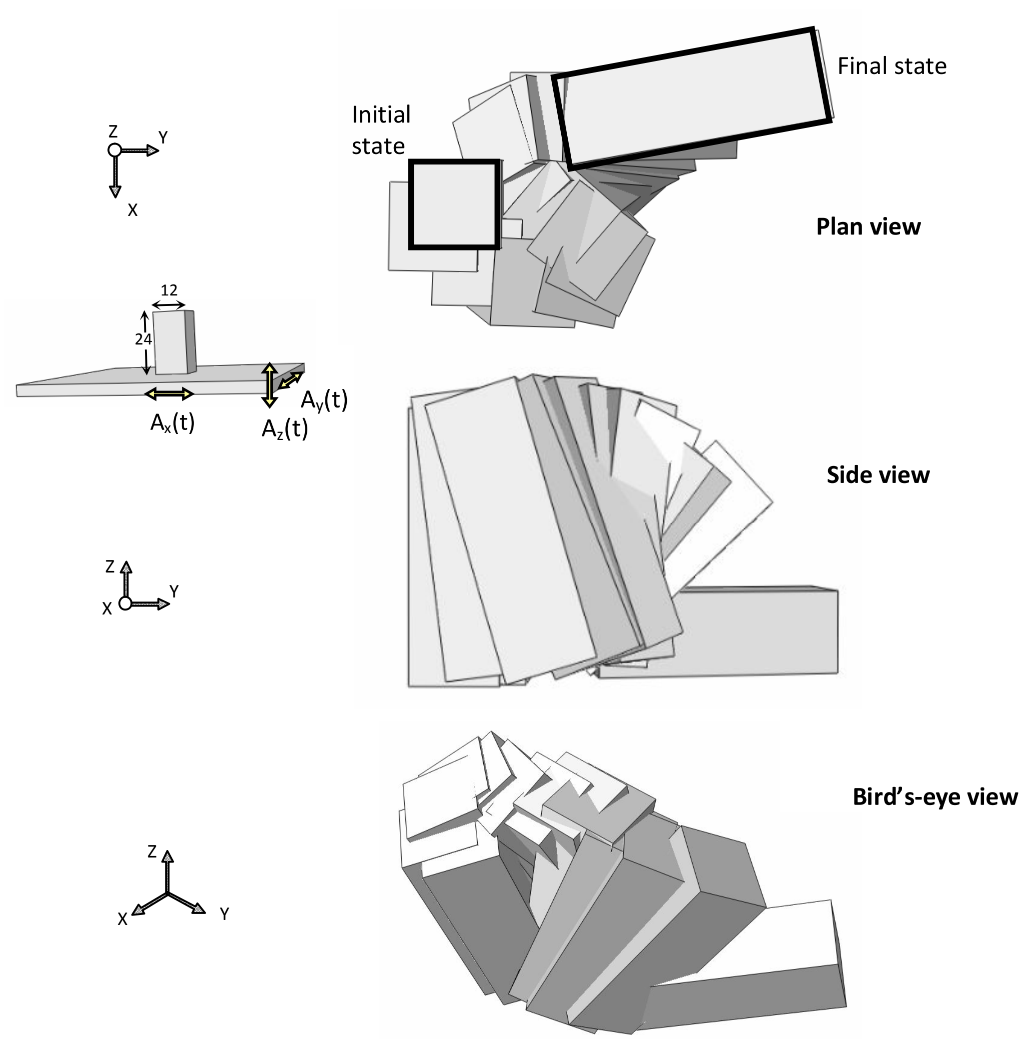

Figure 5. The coefficient of friction effect: snapshots of a 24×24×72 cm^3 rectangular block triggered by all three components of the Lixouri record of February 3 (in the y-direction by the EW, in the x-direction by NS, and in z-axis by the vertical component). [μ = 0.5]

For the same excitation, a smaller block of 12 x 12 x 22 cm^3 also topples along the x-axis as shown in Figure 6. In particular, Figure 6 presents the time histories of the three rotational angles along the x, y, and z axes (for a coefficient of friction 0.5). Notice, that while the block is uplifted along the x-axis, it also rotates along the y- and z- axes. The existence of φ_{rz} originates from the simultaneous act of the horizontal accelerations, as discussed earlier.

Figure 7 illustrates the comparison between the permanent displacements of a 12x12x22 cm^3 marble vase measured in the field (after the second earthquake), against the corresponding numerical results. The system is excited by the three-components Chavriata motion, and the friction coefficient μ is varied parametrically. The two Figures 9(f) correspond to the sliding displacement of the block along the two horizontal axis: on the left the slippage D_{x1} along x-axis, and on the right the slippage D_{x2} along the y-axis. For μ = 0.7, the results of the analysis are in fair agreement with the field observations [see Figures 9(e1) and (e2)]. Also, observe in Figure 9(f), that as μ increases from 0.2 to 0.7 the displacements D_{x1} and D_{x2} are not monotonically decreasing. This seemingly paradoxical behaviour is just a simple evidence of the chaotic nature of rocking response.

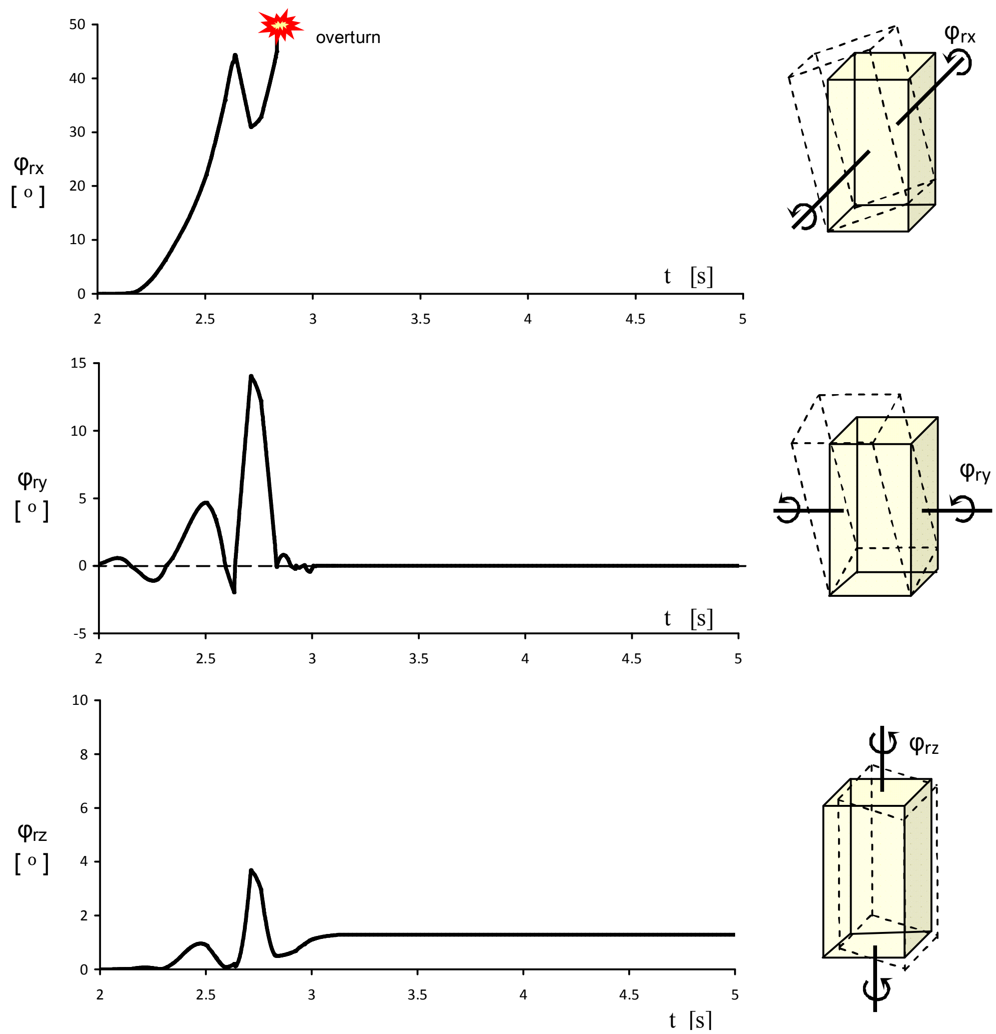

Figure 6. Rotation timehistories of the previous case of the 12×12×22 cm^3 rectangular block excited by the three-component Lixouri record of February 3rd [μ = 0.5].

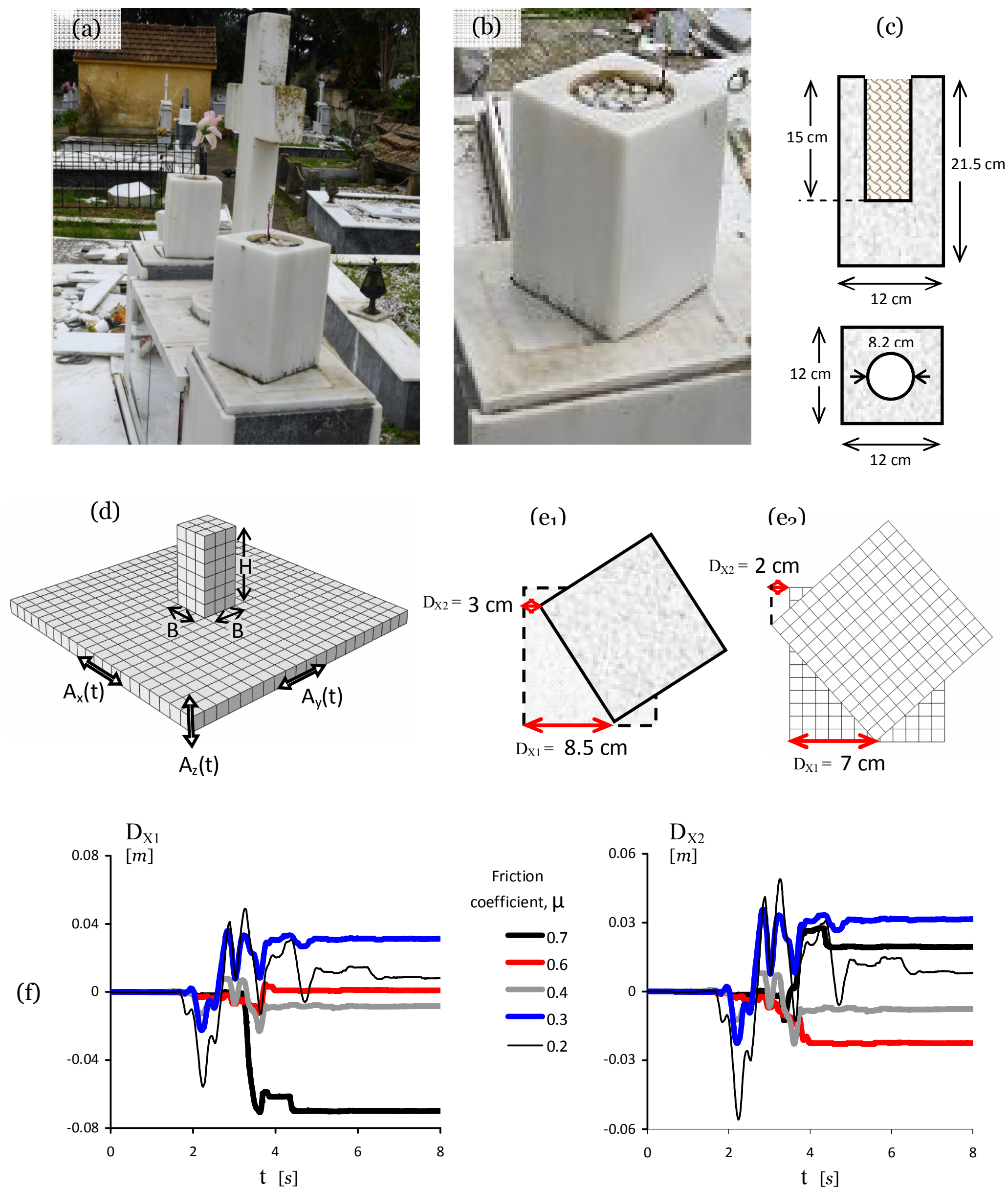

Figure 7. (a, b) Photos of the displaced marble vase after the second event; (c) geometry and dimensions [B×H = 12×22 cm^2] of the vase; (d) finite element model of the studied object; (e_1) sketch of the in-situ measured displacements of the vase; (e_2) calculated displacements for the "best approximation" of $\mu = 0.7$ and the Chavriata excitation; (f) sliding displacements, D_{X1} and D_{X2}, timehistories induced by three components Chavriata ground motion for different values of coefficient of friction, μ.

The effect of the vertical acceleration component is shown in Figure 8. Blue solid line displays the rotational response induced only by the EW horizontal acceleration of the 1994 Aegion record, for a coefficient of friction $\mu = 0.5$. 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 8 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.

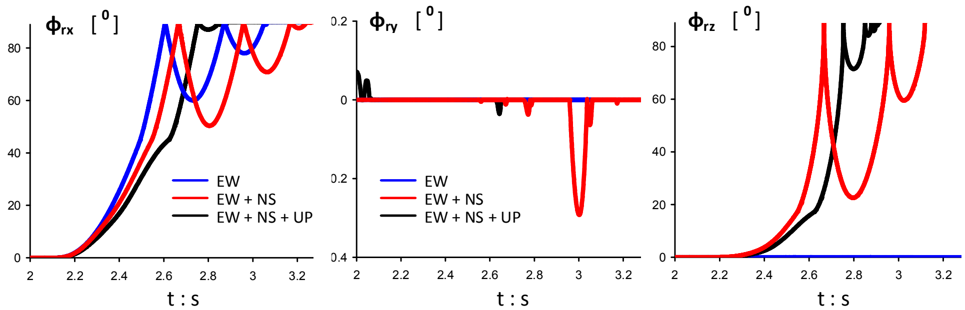

Figure 8. The effect of vertical acceleration: rotational response of a 12x12x24 cm^3 vase, subjected to 1994 Aegion record.

5. 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 recent Greek earthquakes. 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. Another important conclusion of our study is that the recorded motions in Cephalonia, with their 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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