Evidence of significant forward rupture directivity in an M_w6 earthquake, and its effect on monuments

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SUMMARY

While strong directivity effects have been mostly recognized in $M_w > 6.5$ earthquakes, the paper investigates the case of a strong such effect in a relatively small-magnitude event on 3 February 2014 in the island of Cephalonia in Greece. The second of two events (both of $M_w \approx 6$, and one week apart) produced a pernicious accelerogram in the main town, Lixouri, of the region. The paper provides evidence from geology, interferometry, and seismology to convince that the motion was the result of constructive interference in front of the direction of rupture of the obliquely-strike-slip fault. Moreover, the nature of the 2-component record itself is explored to demonstrate that its frequency content along with its strong fault-normal (FN) favorable polarity could only be an outcome or directivity. The T≈1.4 s broad spectral acceleration peak of 1.7 g (for 5% damping), totally unrelated to the estimated natural period (T ≈ 0.4 s) of the soil deposit, can explain much of the profound damage to monuments. In particular the toppling (as well as excessive rotation and sliding) of nearly-all the tombstones in the Lixouri cemetery is shown to correlate well with the characteristics of the FN component of the motion. By contrast, the excellent performance of the building stock can be persuasively attributed to the conservatively-robust construction practices of the past and the high base shear coefficient of the strict latest (1985, 2000) seismic codes.

1. INTRODUCTION: BRIEF OUTLINE OF THE EARTHQUAKES

In 2014, on January 26 and again on February 3, two earthquake events, both of M_w≈6, shook the westernmost peninsula of the island of Cephalonia. Their epicenters are shown on the map of Fig. 1(a) along, with the main tectonic features of the region [1]. The island's high seismicity originates in the so-called Cephalonia Transformation Fault (CFT), a major tectonic boundary connecting two subduction troughs (the Hellenic Arc in the south and the

Adriatic Fault Zone in the north), and passing close to the western edge of the island, as shown in Fig. 1(b).

The recent seismic history of the island attests to its very high seismicity. In August 1953, three, consequtive seismic events (on 9, 11 and 12 of August) with reported magnitudes 6.4, 6.6 and 7.2 [2] respectively, completely devastated the whole island (Fig. 2), as well as the islands of Zante and Ithaca. Nearly 500 deaths out of a population of about 20.000 and collapse of nearly a third of its mostly 2-story buildings prompted the development of the first Greek Seismic Code in 1959 and, perhaps more-importantly, the adoption of uniquely conservative and robust construction practices [3]. The recent seismic code, EAK-2000, imposed an effective ground acceleration A = 0.36 g - 0.45 g, in function of the structure's importance.

The two earthquakes of 2014 by contrast were truly "local" events: essentially only the western peninsula, Paliki, suffered any appreciable damage. There were no deaths. And with few exceptions, the building stock survived with only "cosmetic" damage. The history lesson of the 1953 disaster seems to have played its positive role. Geotechnical failures, on the other hand, were noticeable: landslides and rock falls, as well as some liquefaction and harbor quay-wall movements. See a detailed collective work as GEER Report [4].

But there was an exception to the arguably-excellent performance of the built environment: "failures" of all kind of monuments. Many sculptures in the peninsula, tomb-stones in cemeteries and churches, and even office standing equipment toppled or were severely displaced. In the cemetery of Lixouri, the main town of the peninsula, out of several hundred tomb-stones hardly any survived ! (Fig. 3). Facing east, the tomb-stones were disturbed by the EW component of motion. It turns out that for Lixouri this component (EW) was indeed not only the strongest of the two but also in absolute terms a most deleterious motion. We will present evidence that seismological (more than geotechnical) factors contributed to the broad peak of the response spectrum of this motion at $T \approx 1.4$ s. Extensive comparisons with records from other events will shed further light into the significance of this record. The performance of buildings will also be briefly addressed.

2. RECORDED MOTIONS OF THE TWO EARTHQUAKES

Three strong earthquake accelerograms were recorded in the most-heavily-shaken Palliki Peninsula : two in the town of Lixouri (in the January and February events), and one in the village of Chavriata (in the second event only). The three components of each of these records are portrayed in Fig. 4 (acceleration time histories) and in Fig. 5 (velocity time histories). The corresponding 5% damped acceleration response spectra are shown in Fig. 6. The following remarks are worthy of note:

- All the records exhibit high levels of acceleration, especially of the February event.
- Of all the records, the Lixouri (LXR) stands out for its large velocity (1.16 m/s), outcome of its richness in long-period components, as seen in its response spectrum.
- The Chavriata (CHV) motion has the strongest short-period components, resulting in the highest PGA, 0.73 g, and highest short-period spectral accelerations, exceeding 2.5 g.

We will concentrate mainly on the LXR record and the performance of structures and monuments in the town of Lixouri. The CHV record will be utilized for comparisons. But the seismological evidence first.

3. THE SEISMIC SOURCE

Before any other consideration, the geologic map of the peninsula, shown in Fig. 7, is quite revealing [5]. The epicenter of the February earthquake is located next to a fault, striking in exactly NS direction, and passing less than a kilometer away from the eastern coastline along which lies Lixouri. The alignment of the coastline with this fault is impressive. Hence, a first suspicion that this fault could be related to the generation of the February event.

The suspicion gets a push from the interferometry picture obtained from satellite. It is shown in Fig. 8, from Parcharides [6]. The strike-slip nature of the movement is evident; the boundary between left and right movement has a NS direction essentially coinciding with the aforementioned geologic fault. This constitutes significant evidence supporting the hypothesis that this may indeed be the generating fault.

A third piece of evidence comes from the seismological study of Sokos et al [7]. Using state-of-the-art wave— and fault-slip—inversion techniques they concluded the following : (i) the hypocenter of the February event is about 8 km north of Lixouri (indeed as shown in Fig. 1) at a shallow depth (z-5 km) ; (ii) the rupture was strike slip with a small thrust component; (iii) the main fault model is exactly NS, although a secondary fault segment trending N23E may have also ruptured; (iv) the rupture propagated predominantly southwards and upwards on both the main and the secondary fault segments.

The last conclusion of the Sokos et al (2015) study clearly shows that the region of Lixouri was in front of the rupturing fault, in addition to being very close to it. Fig. 9 is an artist's sketch of the main fault and its rupturing process.

All the above evidence combined supports the idea that Lixouri and its record LXR experienced forward rupture directivity effects in the February of Mw6 earthquake event. Subsequent analysis of the record will offer a further indisputable evidence (ultimate proof) that effect.

4. THE DIRECTIVITY AFFECTED LXR MOTION

It is well understood that at the propagation of the seismic rupture dislocation on the plane of the fault, at a speed only slightly smaller than the shear wave velocity of the surrounding rock, emits along the way seismic waves in all directions; but in the direction of propagation. Waves arrive at a particular site almost simultaneously (as the waves emitted later have a shorter distance to traverse). It is thus possible for these signals to "interfere constructively" and thereby produce large long-period pulse(s) of motion. The phenomenon, denoted as "directivity", describes the azimuthal change in wave energy due to a moving rupture. It has been recognized in near-fault records in numerous earthquakes: e.g., Kern County 1952, Parkfield 1966, San Fernando 1971, Imperial Valley 1979, Tabas 1978, Kalamata 1986, Aegion 1995 [8, 9, 10, 11, 12]. Somerville [13, 14, 15] studying the records of the Northridge 1994 and Kobe 1995 earthquakes showed that *"the radiation pattern of the shear dislocation on the fault causes this large pulse of motion to be oriented in the direction perpendicular to the fault, causing the strike-normal peak velocity to be larger than the strike-parallel peak velocity"* [13].

The two components of LXR (EW and NS) happened to be exactly in the fault-normal (FN) and fault–parallel (FP) directions. Hence: EW = FN and NS = FP. Their acceleration and velocity histories, as well as their response spectra, are compared in Fig. 10. The observed trends are quite clear:

- The peak FN velocity (≈1.2 m/s) is 2 times larger than the FP velocity.
- Despite its high-frequent spike of 0.61 the FP accelerogram does not exhibit any significant pulses, contrary to the FN component.
- The response spectra of the two components are vastly unequal and of different shape at periods above 0.5 seconds. Their differences are reminiscent of the Rinaldi (Northridge 1994) and the Takatori (Kobe 1995) records, the response spectra of which have been compared in Ref. 13 as well as in several subsequent publications, and hence are not shown here.

However, before concluding on the cause of the EW motion of LXR, there is one last consideration: soil effects. How do we know that they are not the key (if not the main) culprit of the large spectra values at T ≈1.4 s?,

The soil profile was obtained with a combination of a "Multichannel Analysis of Surface Waves" (MASW) and a Microtremors analysis by Zekkos et al (2015). It was found that there is a 20 m moderately-stiff alluvial stratum with an S-wave velocity of about 220 ± 30 m/s, underlain by a very stiff marl with a velocity of about 530 m/s near its top, and increasing with depth. The natural period of this profile is of the order of $T_1 \approx 0.4$ s. Thus, soil amplification cannot explain the shape and large amplitude of spectral values at periods around 1.4 seconds, although it undoubtedly must have had an effect in the low period range.

In addition, Fig. 11 compares the acceleration and velocity polar diagrams from the February and January records in Lixouri, along with the corresponding response spectra. Evidently: (i) only the February motion is substantially polarized in the EW direction; (ii) the peaks of the January motion are at T ≈ 0.75 s, unrelated to the 1.4 s of the studied motions - further evidence that the peak is not the exclusive product of soil resonance.

In conclusion, all the above provide incontrovertible evidence that the EW motion ín the town of Lixouri bears the seismological effects of forward rupture directivity.

5. CONSEQUENCES OF THE DIRECTIVITY–AFFECTED IN LIXOURI

5.1 The Excellent Performance of Buildings

The destructive potential of near-fault forward directivity-affected motions is known to be large. The Northridge 1994 and Kobe 1995 earthquakes offer vivid examples of such destructiveness. But the performance of the buildings in the town of Lixouri was exemplary. Fig. 12 shows a photograph of the typical two to three storey houses, invariably facing east (towards the sea!). They appear unscathed after the two earthquake events. How does this reconcile with the expected destructiveness of the EW=FN component of LXR?

Undoubtedly, the 1953 triple-earthquake disaster has much to do with this success. A very robust construction practice was initiated in the aftermath of those events, followed, years later, by a highly demanding seismic code. The latter specifies peak spectral values at low periods of about 1 g (in function of soil conditions) [16, 17]. A typical building under construction is photographed in Fig. 13. The thick reinforced concrete [RC] frame looks impressively (and certainly conservatively) robust. In addition, the infill masonry is well-confined (with RC beams around openings) and further reinforced with horizontal RC ties. Significant structural damage was only limited to older buildings that did not have this type of construction [4,17].

Thus, the large peak velocity (1.2 m/s), the even larger velocity step (2.1m/s), as well as the high spectral acceleration values (> 1 g) at large periods were of rather minor relevance and certainly not enough to damage the vast majority of the specific stiff building stock in the town of Lixouri.

5.2 Abundant Geotechnical Failures

The good performance of buildings did not extend to the natural environment. Numerous landslides littered the mountainous peninsula, along with distressing deformations of road embankments and (non-engineered) retaining walls [4]. The most significant damage of engineering facility was observed in the Lixouri harbor, located about 100 m from the LXR accelerograph station: liquefaction on the free field, lateral displacements in excess of 1 m of the merely 5-meters deep quay-wall, as seen in the photo of Fig. 14.

Such failures are compatible with the severity of the LXR EW record, and reminiscent of the failures in the port of Kobe (although at a much smaller scale).

5.3 The non-survival of monuments

The high destructive potential of the EW component of LXR can explain the unprecedentedly poor performance of all kinds of monuments, such as sculptures and tombstones. By poor performance we mean substantial displacement and rotation of squatty items, and overturning of slender ones, as shown in the photos of Fig. 15. A few specific analyses of actual observations will demonstrate the compatibility of the ground motion and with that performance.

As an introduction, however, to such analyses let us note that whereas the response spectra examined so far in the paper provide information on the potential of a motion to cause unacceptable deformation in more-or-less elastic systems, the monuments studied here respond with strongly nonlinear and/or inelastic restoring mechanisms: Coulomb sliding, geometric change by uplifting, or combinations of the two.

Symmetric and asymmetric sliding of a rigid block on horizontal and inclined base planes, respectively, have been used as analogs of actual inelastic systems in many geotechnical applications [18, 19]. The slippage of a block due to base excitation with a particular ground motion is indicative of the destructive potential of that excitation.

To examine the sliding potential of the Fault Normal (FN) and Fault Parallel (FP) components of LXR, we obtain their spectra

$$D = D(A_c;\beta)$$

in which D = slippage in m; A_c = the critical (or yield) acceleration of the system; β = the angle of the base from the horizontal. For β=0°, $A_c = \mu g$, where μ = coefficient of friction. For β # 0, $A_c = (\mu \cos\beta - \sin\beta) g$ for base motion parallel to its inclined plane.

The obtained spectra (for β=0° and 30°) are compared in Fig. 16 with the corresponding spectra of three other records: the Takatori record of the Kobe 1995 earthquake (one of the most deleterious motions ever recorded) ; the CCCC record of the Christchurch 2011 earthquake (associated with the damage of the historical Catholic Cathedral of the city); and the FKS-017 motion recorded in Fukushima in the M_w9 2011 Tohoku earthquake (chosen for its similar peak, 0.65 g, with LXR). Notice that :

- On level ground the sliding potential of the FN component of Lixouri is of the same level as Takatori, exceeding the sliding potential of both the CCCC and FKS (in addition, of course, to that of the FP component);
- On the inclined plane the asymmetric sliding potential is sensitive to the number of significant cycles. Takatori gives again the highest slippage, but the FN component has roughly similar potential with the much-much longer FKS motion (120 rather than 10 seconds).

No doubt the studied motion could inflict substantial damage to inelastic systems characterized with small yield acceleration.

Now let us proceed with the specific analysis of a sliding and a toppling observation in the Lixouri cemetery.

Analysis of the response of a squatty block

Among the numerous toppling observations in the cemetery we chose for analysis with the Lixouri record the square prismatic block of Fig. 17. Most other tombstones where much more slender, as also were all the sculptures, and thus their overturning even with a less pernicious ground excitation than that of Lixouri EW is easily explained.

The analysis is performed in a 2-dimensional space, with the EW component acting parallel to two sides of the block. The block has dimensions 12 x 12 cm^2 in plan and 22 cm in height. It is made of fairly porous marble having mass density of about 2.5 t/m^3. This was one of the most common decorative blocks in all cemeteries, utilized for flower pots or other ornaments.

In the Lixouri cemetery the vast majority of them toppled ; in other cemeteries (which presumably have suffered a less destructive shaking) they survived after substantial sliding and rotation in plan (about their vertical axis). Exceptionally, a few of these blocks that did not displace at all were found to be perfectly glued to their base (probably with cementatious mortar). A key issue of our analysis was therefore the selection of the pertinent coefficient of Coulomb friction. Originally these blocks were barely “glued” to their base with a simple adhesive stuck. Evidently, however, the first earthquake of 26th January whose peak ground acceleration in Lixouri was a high-frequency 0.54 g had probably destroyed whatever gluing was there available. In fact, some sliding was reported of a number of tombstones following the first event. Therefore, a marble-to-marble coefficient of friction μ, varying between 0.5 and 0.7, as measured in situ, was varied parametrically in our analysis.

A numerical analysis of the geometrically-nonlinear response due to uplifting as well as frictional sliding of the rigid block on a rigid base subjected to the LXR EW=FN motion was obtained using ABAQUS. The result : overturning even with the smallest coefficient of friction, 0.50, despite an initial slippage of 5 cm. Fig. 17 shows a sequence of snapshots of the block's positions as it travels from its original position (a), to slippage (b), then to a first temporary overturning (c), the impact of which helps the block to lift up but not enough to stand on its base, and avoid toppling again (d). This time the excitation has essentially stopped and the overturning is the final state.

Therefore, the Lixouri EW = FN component can reproduce the collapse of even stout monuments. On the contrary the FP = NS component alone would not have led to overturning, as illustrated in Fig. 18. It is seen that several sliding and uplifting episodes take place, but no collapse. The destructive power of only the FN motion is clear.

A further support of the realism of our analysis is given in Fig. 19. All three components of the Lixouri record excite the base, and the block performs a 3-dimensional rocking-sliding-twisting motion until it finally overturns. No doubt the FN component is the main driver of rocking and sliding, while the FP component acting at a moment when the block has uplifted causes the torsional response. The vertical component has a more limited effect, although admittedly this cannot be discerned in the figure.

Comparison of the effects of Lixouri and Chavriata motions

To further demonstrate the high destructive potential of the Lixouri motion we compare its effects on a particular type of tombstone against the effects of the Chavriata motion.

The specific tombstone, fairly common in all cemeteries, is pictured in Fig. 9. In the Chavriata cemetery one such tombstone was displaced and rotated about a vertical axis (Fig. 9 (b))-not a small "feat", given that the block was much heavier near its bottom and hence difficult to uplift and overturn. Yet, overturning is what happened (abundantly) in the Lixouri cemetery as (barely) seen on the lower left corner of Fig. 9 (c).

An analysis is presented similar to the one described above with the strongest horizontal component of each of the two motions as excitation. The results are compared in the plots of Fig. 9(d) and 9(e) for Charviata and Lixouri, respectively. In Fig. 9(d) despite substantial rocking reaching an angle of 10^o the monument does not fall down, but experiences substantial sliding and “torsional” rotation. This is in good qualitative agreement with the measured displacements. By contrast, the large acceleration pulse of the Lixouri motion leads to toppling before the block had any chance to slide. Again this is exactly what was observed in the respective cemetery.

6. CONCLUSIONS

(1) There is ample evidence supporting the claim that forward-rupture directivity strongly influenced the recorded accelerogram in Lixouri, during the $M_w 6$ earthquake of February 2014 in Cephalonia. Geological, interferometric, and seismological data concur that the seismogenic fault run in NS direction parallel to the coast line about 1 km west of Lixouri, and that the rupture originated 7 km north of Lixouri and propagated towards it.

(2) The nature of the record offers the ultimate support to the directivity claim:

- The FN component is much stronger than the FP for $T > 0.5$ seconds, as seen in their acceleration response spectra.
- The FN component has a strong velocity pulse with PGV ≈ 1.16 m/s and a devastating velocity step a $\Delta V \approx 2.1$ m/s.
- The shape of acceleration response spectrum with a very broad peak in the period range 0.8 s < T < 1.5 s is reminiscent of the corresponding spectra of several notorious motions bearing directivity effects, such as Rinaldi (1994) and Takatori (1995).
- The potential of the FN component to inflict severe sliding of a block on a horizontal or inclined base is very high, comparable to that of Takatori and Rinaldi (both of $M_w > 6.7$), as expected from such near-fault motions [18, 20].

(3) The devastation of sculptures and other monuments in Lixouri, and expecially in its cemetery, where slender and even most of the squatty tombstones overturned is convincingly attributed to the directivity-modulated nature of the FN component of motion: strong long-duration velocity pulse, high PGA, high spectral accelerations over a wide period range. The “failure” of the harbor quay-wall which displaced laterally in excess of 1 m, and the numerous landslides, further attest to the destructiveness potential of the motion.

(4) As a fortunate exception to the above observations, the buildings of the town had had an excellent performance. Being mostly only 2-story high, they were certainly below the high spectral amplitude range of the motion; but the main cause of the success originated in the disastrous earthquake triplet of August 1953. Robustly conservative construction practices in the aftermath of those events, followed by severe seismic design regulations in recent years have led to seismically sound buildings. Hence their excellent performance is not irreconcilable with the potential destructiveness of the particular Lixouri ground motion.

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