Rotation of Objects during the 2009 L’Aquila Earthquake Analyzed with 3D Laser Scans and Discrete-Element Models

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INTRODUCTION

Earthquake-rotated objects (EROs) have been observed and described for centuries (e.g., Hoffmann, 1838; Mallet, 1862; Reid, 1910). Several theories about the rotating mechanisms have been developed. Kozák (2006) classified rotating effects as those caused by a deviation between the projection of the center of gravity into the contact plane and the point of strongest adhesion (Rot1) and those due to subsequent arrival of ground-motion phases from different directions (Rot2).

The EROs found in the literature include parts of buildings, such as chimneys, monuments, tombstones, and columns, often described with great care and in detail by early earthquake reports (Mallet, 1862) or still accessible (Boschi et al., 1994). In most cases rotational effects are observed on vertically oriented objects such as gravestones, tall monuments, and single columns (Kozák, 2009). Although earthquake-toppled objects (ETOs) allow the determination of minimum ground-motion thresholds which caused the toppling (Kamai and Hazor 2008; Hinzen, 2010, 2012), EROs and earthquake-deformed objects (EDOs) present the chance to make a more detailed back calculation of the causative ground motion (Yegian et al., 1994; Lee et al., 2009; Hinzen et al., 2010; Hough et al., 2012).

Numerous EROs were observed and documented during the 2009 L’Aquila earthquake in central Italy. Cucci and Tertulliani (2011) and Castellano et al. (2012) showed a correlation between the occurrence of EROs in the mesoseismic zone, the fault orientation, and the site conditions. Some of the simply structured and vertically oriented objects mapped by Cucci et al. (2011) and Cucci and Tertulliani (2011) offer the opportunity to use local strong-motion records to test different hypotheses about the mechanisms that caused the rotation. A main question in this context is whether near-field rotational components of ground motion are necessary to rotate the studied objects or whether 3D purely translational ground motions are sufficient to explain the observations. In this study, we use discrete-element models of EROs that are based on laser scans to study the dynamic behavior of the EROs and rotations induced by translation ground motions and uneven foundations.

OBJECTS ROTATED DURING THE L’AQUILA EARTHQUAKE

In a 2011 field campaign, selected EROs in the mesoseismic zone of the 2009 L’Aquila earthquake, still in the original rotated position, were surveyed by 3D laser scanning, resulting in a set of virtual models (Fig. 1). The scanning technique and instrumentation used in this study has been described in detail by Schreiber et al. (2012). Location accuracy of the points in the 3D point cloud at the distance range used in this study (1–15 m) is better than ±2 mm. These models provided detailed measures of displacements and rotations and served as a basis for the construction of discrete-element models (DEMs). Included are several gravestones and monuments in L’Aquila and a war memorial in the village of Paganica.

Paganica War Memorial

The Village of Paganica suffered heavy damage of intensity VIII, particularly in the village center with several medieval buildings. The Paganica war memorial in front of the church is located less than 350 m from the surface rupture of the causative fault (Fig. 1). It is of special interest because the 14.7° (0.26 rad) counterclockwise (ccw) rotated monument is a simple block with a height to width ratio of 1.52. That means it rotated, although it cannot be regarded as a vertically oriented object (Kozák, 2006). Whereas the earthquake ground motion was sufficiently large to rotate the monument block, it did not significantly harm the rather delicate-looking column-baldachin structure (Fig. 2). The columns are 2.2 m high and only small cracks were visible on the baldachin structure.

A virtual model of the monument was combined from four laser scans and contains $3.5 \times 10^6$ 3D points (Fig. 2). Computer-aided design (CAD) software was used to measure the dimensions necessary to construct a DEM. The resulting DEM is composed of 17 elements (Fig. 3). The monument is made from a local limestone and a density of 2.8 Mg/m$^3$ was used. The viscoelastic friction forces were modeled with a static and dynamic coefficient of friction of 0.6 and 0.5, respectively. For the calculations, the base of the columns was fixed to the foundation, assuming the builders used reinforcement in this connection. The four elements forming the baldachin were coupled with fixed joints; however, the baldachin itself has a full six degrees of freedom in the joints connected to the
column tops. Discrete-element simulations were made with Universal Mechanism version 6.0 (Pogorelov, 1995, 1997). In contrast to finite-element models, the discrete-element method allows a separation between individual blocks and to trace their movement when they topple or fall by means of Newtonian mechanics (Williams et al., 1985). The software code used in this study has been tested and applied in several previous studies on object rotation (Hinzen, 2012), archaeoseismology (Hinzen, 2009; Hinzen et al., 2013), and simulation of a seismoscope (Hinzen and Kovalev, 2010).

The general behavior of the monument was first tested with analytic signals, such as Morlet wavelets and tapered sinusoidal signals. These were sequentially applied in one, two, and three orthogonal translational directions. Figure 4 shows an example of such a simulation using a cosine-tapered harmonic signal of 5 Hz and peak accelerations from 1.0 to 5.0 m/s². With a flat base underneath the monument block and a coefficient of static friction of 0.6, the translational ground motions induce only minor rotations smaller than 0.01 rad (Fig. 4).

As shown in Figure 3, the base directly underneath the monument block is made from two separate pieces of limestone. Therefore, we tested the effect of an uneven base by incrementally increasing a height difference between the two blocks from 0.5 to 5 mm. Figure 4 shows the increasing cumulative rotations that occur when a 2 mm step between the base blocks is assumed. Using the 5 Hz harmonic signal, the observed rotation of 0.25 rad is reached when the peak acceleration is about 4.5 m/s². Figure 5 shows the effect of changing frequency of the harmonic signal. Again, no rotation is induced when the base is flat; however, with a 2 mm step and 5 m/s² maximum acceleration, rotations of up to 0.46 rad occur. The high variability of the rotational behavior with small changes in frequency of the ground motion stresses the nonlinearity of the problem. However, ground motions with amplitudes well in the range of the observations during the mainshock are capable of causing the observed rotation by pure translational excitation.

During the aftershock sequence a temporary station (ITalian ACCELEROMETRIC Archive, ITACA, 2010) was set up...
in Paganica 530 m south-southeast of the monument (Fig. 1). In addition to other stations, this instrument recorded a $M_w$ 5.1 aftershock (Fig. 6). We scaled the observed ground motion with factors between 1.0 and 8.0 to study its effect on the DEM. The Z-axis rotation in Figure 7 during the 3D ground motion from the measured aftershock clearly

Figure 2. (a) and (b) show a photo and the laser-scan model of a war memorial in Paganica (Fig. 1), respectively. The center block of the memorial measures 0.75 m at its base and is 1.14 m high; (c) and (d) show a photo and the laser-scan detail of the monument, which rotated 14.7° in a counterclockwise direction.

Figure 3. The discrete-element model (a) is composed of 17 elements: (1) ground, (2) base, (3–6) pedestals underneath the (7–10) columns, (11, 12) gables, (13–15) sides and base of the baldachin, (16) split base block, (17) the monument. The total height is 4.2 m. (b) shows in detail the split base of the monument; during the computer simulations of the rotational behavior, a height difference between the two base plates has been considered; (c) shows a photo of this detail.

Figure 4. Comparison of calculated Z-axis-rotation history between the model of the Paganica memorial with a flat base plate and a split base plate with a 2 mm step. The ground-motion signal was a tapered sinusoidal signal of 5 Hz and 10 s duration with maximum accelerations as indicated at the right side of the diagrams. The five curves assuming a flat base all plot on top of each other.

Figure 5. (a) and (b) show a photo and the laser-scan model of a war memorial in Paganica (Fig. 1), respectively. The center block of the memorial measures 0.75 m at its base and is 1.14 m high; (c) and (d) show a photo and the laser-scan detail of the monument, which rotated 14.7° in a counterclockwise direction.

Figure 6. The discrete-element model (a) is composed of 17 elements: (1) ground, (2) base, (3–6) pedestals underneath the (7–10) columns, (11, 12) gables, (13–15) sides and base of the baldachin, (16) split base block, (17) the monument. The total height is 4.2 m. (b) shows in detail the split base of the monument; during the computer simulations of the rotational behavior, a height difference between the two base plates has been considered; (c) shows a photo of this detail.
increases with larger scale factors of the ground displacement and with an increase of the step of the base underneath the rotating block. With a 5 mm step and a scale factor of 8.0, the final rotation reaches 80% of the observed value. The non-linearity and sensitivity to small changes in the input parameters is documented by the change of the sense of rotation.

L’Aquila Cemetery
Several tombstones and other grave decorations rotated in the L’Aquila mesoseismal zone as a direct result of the earthquake (Cucci et al., 2011). During our survey of the L’Aquila Central Cemetery, three objects, including a 3.4 m obelisk, a decorative single column of 1.23 m height and 0.13 m radius and a tombstone topped with a sculpture in form of an angel, were selected for further studies (Fig. 8). The obelisk is located at a distance of 55 m from the other two objects that are directly adjacent to each other. The obelisk shows a rotation of 5.0° clockwise (cw) of the top block, the decorative columns toppled toward south and the neighboring tombstone rotated 7.15° cw as deduced from the laser-scan model (Fig. 8).

Construction of the DEMs of the obelisk (Fig. 9) and the decorative column from the laser-scan models was straightforward. The angel on top of the tombstone had to be simplified; however, dimensions were chosen so that the main mass distribution resembled the original object. We used the same material and model parameters as were applied to the Paganica monument. Of special interest was the response of these closely
neighboring objects to similar ground motions. The three objects of rather different form and size essentially comprise architectural seismoscopes sensitive to different frequency and phase relations of the three components of ground motion.

Several ground-motion signals were used to simulate the response of the three objects from the L’Aquila cemetery. Figure 10 summarizes the results obtained from model calculations using the seismogram measured at station AQV (Fig. 1). Under the load of the original record, the obelisk rotates to roughly 20% of the observed value; however, in a cw sense, opposite to the observed rotation. Scaling-up of the ground motion in steps of 5% once more indicates the high nonlinearity of the reaction of the obelisk. At the 105% level, the rotation switches to cw and the final angle is 4.3° (86% of the observed value). At the 115% level of the measured ground motion, the rotation is cw again; however, the angel reaches a maximum rotation three times the observed value.

The simulated movements of the column and the tombstone (Fig. 11) when driven by the original record of AQV (ITACA, 2010) are close to the observed response: (1) the sense or the tombstone rotation is cw, the same sense as observed; (2) the simulated rotation is 6.49° compared to the observed 7.15°; (3) the column topples, and (4) the toppling direction points toward south. Figure 11 shows six snapshots from the motion of the tombstone/column model during the excitation with the original record of station AQV (Fig. 10). At 2.0 s, the first significant movement of the column and the tombstone is initiated. At 4.0 s a clear rocking of both objects occurs resulting in the toppling of the column, which impacts on the ground 5.5 s after the start. The decaying ground-motion amplitudes beyond 5.5 s are still large enough to further rotate the still-rocking tombstone, which comes to a rest after ~7 s.

**DISCUSSION AND CONCLUSION**

The laser-scanning technique has been applied to construct virtual models of several EROs in the L’Aquila 2009 mesoseismal zone. These models have been used to construct discrete-element models of a stocky monument in Paganica and three vertically oriented objects on a L’Aquila cemetery for testing their dynamic behavior and reaction to pure lateral ground motion. The Paganica memorial with a height-to-width ratio of 1.52 does not rotate significantly in the computer simulations when pure translational 3D-ground motions are applied and the base is kept perfectly flat. This behavior is observed during shaking with harmonic signals and also when scaled measured strong ground motions are used. For an uneven base block the monument significantly rotates under the load of the same ground motions. Assuming a 2 mm step at the base, which is made of two materially-distinct blocks, harmonic
motions of 3 and 5 Hz and 5 m/s\(^2\) peak ground acceleration (PGA) of 10 s duration rotate the monument by the same amount as observed (14.7°).

The amount of rotation which occurs when scaled seismograms of an M 5.1 aftershock are used indicates that uneven height of the base is a plausible cause of the rotation of the monument. The graph labeled Column shows the angle of rotation of the decorative single column; arrow, the impact of the fallen column to the ground. The graph labeled Obelisk shows the angle of rotation around the Z-axis of the obelisk; numbers at the end of each trace, the scaling factor of the ground motion; dashed line, the observed angle of rotation; vertical gray lines, the times of the snapshots shown; ccw, positive rotation; cw, negative rotation.

Whereas the 3.4 m high obelisk of the L’Aquila cemetery requires a 5% increase of the maximum amplitude of a measured strong-motion seismogram from station AQV to provoke the observed rotation, the neighboring angel-topped tombstone and the decorative column rotate and topple in the simulation in a manner similar to the observation. Considering the uncertainty of input parameters, the nonlinearity of the problem, and the different site conditions at AQV and the cemetery, this result can best be explained by chance. However, the movement of these three objects can be readily explained by pure lateral ground motions with reasonable amplitudes and without the need for rotational ground-motion components. This indicates that the rotation mechanism Rot1, defined by Kozák (2006), fully explains the selected ERO examples from the L’Aquila 2009 mesoseismal zone.

ACKNOWLEDGMENTS

We thank C. Fleischer, S. Rosellen, and H. Kehmeier for the help with the laser scanning fieldwork. The latter two also worked on the processing of the point clouds and the construction of the discrete-element models, respectively. We are grateful to S. K. Reamer for discussions and comments, which helped to improve the draft of the manuscript. We thank ITalian ACcelerometric Archive (ITACA) working group for making available the strong-motion records used in this study. Comments from an anonymous reviewer and Editor J. Lees are appreciated.

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