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ANALYSIS OF ROTATION SENSOR DATA FROM THE SINAPS@ KEFALONIA POST-SEISMIC EXPERIMENT

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ABSTRACT

The complete description of the ground motion during an earthquake is not specified by only three translation components. Indeed, it also needs the description of three rotation components. The earthquake sequence that began in January 2014 in the Ionian Sea with two M6+ in Kefalonia Island gave the opportunity to record an extensive set of data within the framework of the SINAPS@ program post-seismic campaign that took place over a period of 18 months. In this context, a rotation sensor was installed in co-location first with the center of a dense array of seismometers on a rock outcrop and second with an accelerometer in the sedimentary basin. This data set leads to a database of several thousands of well recorded events. Even if the noise characterizing rotation data is higher than for accelerometers (and a fortiori higher than for seismometers), this data set allowed:

- the comparison of rotation data with accelerometer data, up to 0.33 g, in order to investigate the relation between the Peak Ground Acceleration (PGA) and Rotation (PGR) at this particular site,
- the comparison between the rotational wavefield assessed from the rotatiometer and from spatial derivative on the dense area of velocimeters (that should provide rotation value).

This work provides an important contribution, from both qualitative and quantitative viewpoints, to the assessment of the usefulness of rotation data.

Keywords: six components analysis, rotation sensors, spatial derivative, dense array.

INTRODUCTION

Earthquake waves had rotational effects on historical monuments that have been observed for many years. One of the earliest and most notorious ones is the rotation of the monument to George Inglis (1850 Chatak, India) after the 1897 Great Shillong earthquake (Fig. 1). A summary of all rotation related macroseismic observations can be found in Lombardi et al., 2016.

However, during an earthquake, seismologists usually record the translational ground motions along the X, Y and Z axis. This is not enough to fully characterize the ground motions. The rotational ground motions, though poorly known presently, could be significant and may be as important as the translational ones in some cases. They have been left out since their measurement has long been very uneasy, and also because they seemed unimportant. Richter (1958) said: “Theory indicates, and observation confirms, that such rotations are negligible”. But he didn’t justify it and didn’t have the right instruments for the rotation. Over the past decades, rotational seismology caught the attention of many earthquake scientists and researchers. At first, Teisseyre (1974) derived rotation seismograms from an array of horizontal seismographs. Then others developed new methods to calculate the rotation rate and interpret it, like Spudich et al. (1995) and Spudich and Flecher (2008). Nigbor (1994) and Takeo (1998) tried measuring the rotation rate directly from a gyro sensor in near-field regions. And Igel et al (2005) used a ring laser gyro to record rotational motions for large, long distance events. Now, less expensive rotation sensors allow to measure and observe the rotational ground motions with good sensitivity.

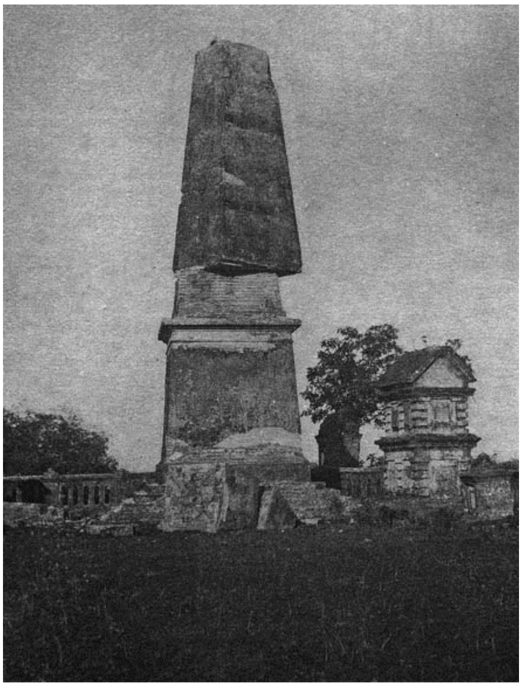

Figure 1. Rotation of the monument to George Inglis (1850 Chatak, India) after the 1897 Great Shillong earthquake, observed by Oldham (1899) (from Lee et al. ,2011).

From a theoretical viewpoint, the linear elasticity states that, under the hypothesis of infinitesimal deformation (Cochard et al., 2006), the displacement u of a point x is linked to a neighboring point x + δx by: (Aki and Richards, 2002)

$$u(x+\delta x) = u(x) + \varepsilon\,\delta x + \omega \times \delta x \tag{1}$$

where ε is the strain tensor and:

$$\omega = \frac{1}{2}\nabla \times u(x) \tag{2}$$

is the infinitesimal angle of rigid rotation (a pseudo-vector) created by the disturbance. So, to completely define a medium behavior around point x, the three translation and rotation components are needed.

It is interesting to record the rotational ground motions with the translational ground motions using collocated rotation and translation seismometers. They can give more reliable information about the wavefield properties as well as new information. For example it’s useful to separate the shear wavefield from the compressional one.

In this paper, we study the rotational ground motions observed from a rotation sensor collocated with the center of a dense array of 21 broadband seismometers on one hand and with an accelerometer on the other hand near the town of Argostoli, in Kefalonia Island, Greece. This data was recorded during a post-seismic survey, launched after the two magnitude 6+ earthquakes that occurred in early 2014, within the framework of the SINAPS@ project.

PRESENTATION OF THE TWO ARGOSTOLI DATA SETS

The site of interest is located near the town of Argostoli, in the Kefalonia Island in the Ionian Sea. This site has been chosen by the SINAPS@ project, funded by ANR (French National Research Agency), ("Earthquake & Nuclear Plant: Ensure and Sustain Safety") (http://www.institut-seism.fr/projets/sinaps/) to install a vertical array to validate non-linear 3D simulation codes.

In January 2014, a seismic sequence started in Kefalonia with two magnitudes 6+ earthquakes (26/01/2014 and 3/02/2014, see Theodoulidis et al., 2016) and was reactivated with the magnitude 6.5 Lefkada Island earthquake (27/11/2015). It enabled a post-seismic survey of the SINAPS@ project. Many events were detected using 3 types of sensors: broadband seismometers, accelerometers and a rotation sensor.

This survey had three goals. First, the installation of a dense array of 21 broadband seismometers to study the spatial variability of the seismic motions with small wavelengths in a “Rock” site. Then, the installation of some accelerometers in the Koutavos park to record strong motions on soft soils. Finally, the installation of the rotation sensor, which was collocated first with the center of the dense array, and then with an accelerometer in the Koutavos park.

The dense array geometry is a 5 branches star with a seismometer in the center and seismometers forming circles of radiuses varying from 10 to 180 m. It recorded almost 2000 good quality events that correspond to the seismic sequence of the two Cephalonia earthquakes and some earthquakes with larger epicentral distances and coming from more various azimuths (Fig. 2).

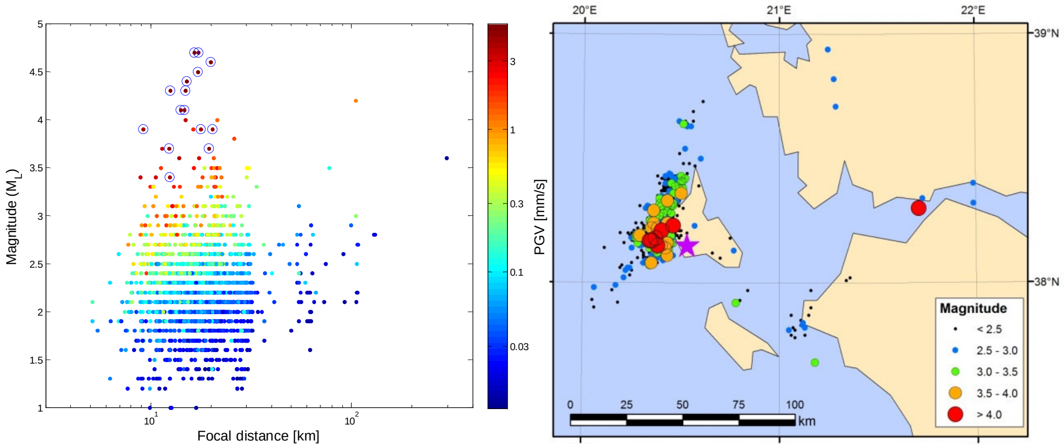

Figure 2. On the left: Events from the “Dense Array” database presented in a diagram Magnitude / Focal distance. The highest magnitudes created the seismometers saturation (blue circles). On the right: Map of the epicenters (Earthquakes from 6 February to 10 March 2014). (From Hollender et al., 2015). The purple star indicates the location of the rotation sensor.

Argostoli- Rock site

The dense array has been set up in massive Cretaceous limestone at about 2 km South-East of the Koutavos park on “rock” with a V_{S30} of 830 m/s. The rotation sensor was collocated with a broadband seismometer at the center of the dense array for 3 weeks from February 19, 2014 to March 10, 2014. As a result, 833 events were recorded. We applied a criterion to retain only signals with a signal-to-noise ratio greater than 10 and we eliminated all the saturated events, which finally left us with a total of 118 good quality recordings. The magnitudes range from 1.9 to 3.6 and the hypocentral distances range from 12 km to 50 km.

Argostoli- Soft soil site

The rotation sensor was collocated with an accelerometer for 16 months from March 11, 2014 to July 2, 2015 in the Koutavos park with a V_{S30} of 250 m/s. As a result, 4016 events were recorded. After applying the "signal-to-noise ratio > 10" criterion, we retained 803 events. The magnitudes range from 1.6 to 5.7 and the hypocentral distances range from 5.3 km to 660 km.

CORRELATION BETWEEN THE THREE COMPONENTS

Argostoli- Soft soil site

To study the rotation sensor behavior, we applied to the signals a cosine taper at the borders and a bandpass filter between 1 and 10 Hz. Then the sensor has been corrected from its instrumental response. Fig. 3 (top) shows the correlation of the maximum absolute value of the rotational rate between the three components. We observe here that the three rotation components have the same order of magnitude.

Argostoli- Rock site

The same analysis has been done for the rock site (Fig. 3, bottom). Here, we notice that the scatterplot is above the x=y line for both the Nrot versus Erot and the Zrot versus Nrot plots. This means that the vertical component (I.e., torsional motion) is most often the largest, and the East component (rocking) is most often the smallest. We will comment this observation in the section “array-derived rotation rate”.

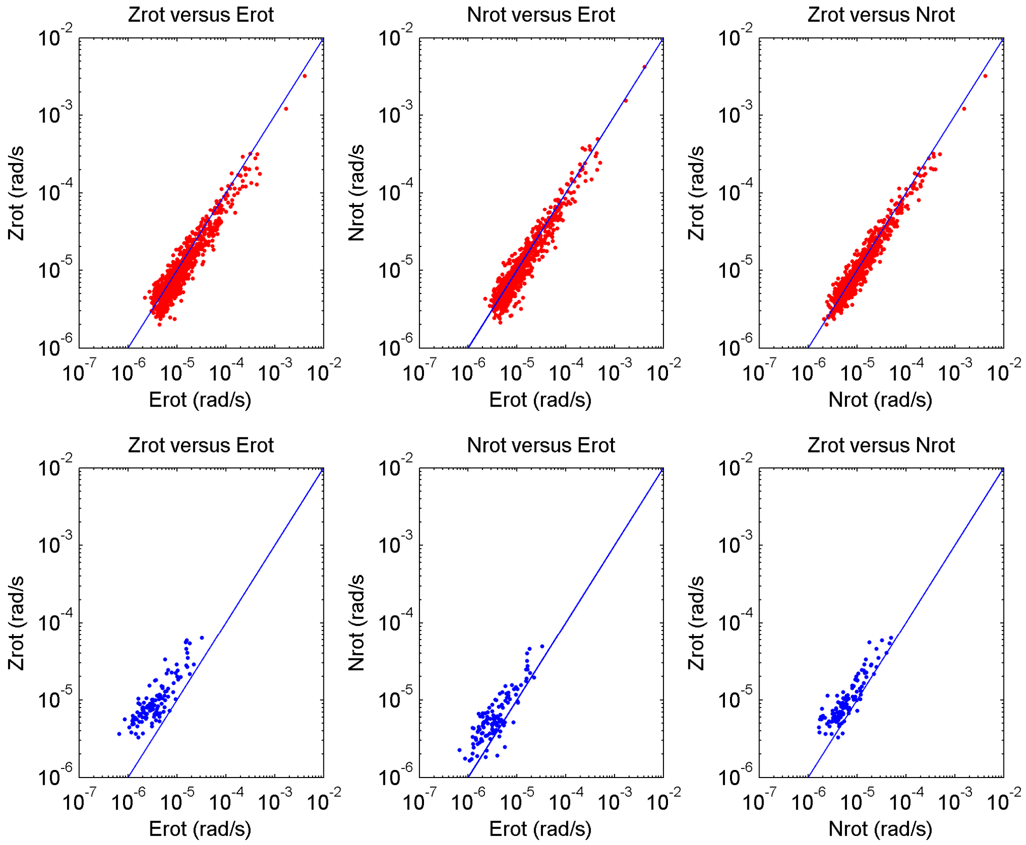

Figure 3. Correlation of the maximum absolute value of the rotational rate between each pair of components for the soft site (top) and the rock site (bottom)

PGA / PGR CORRELATION

Argostoli- Rock site

The peak ground acceleration (PGA) represents the maximum absolute value of the translational acceleration along the three components (horizontal: E, N; and vertical: Z). For the rock site, the translational acceleration is calculated from the derivative of translational velocity time histories which were processed with a cosine taper and bandpass filtered between 1 and 10 Hz.

As usual, the PGA is higher for the horizontal components than the vertical one. The highest value is 0.008 g, and corresponds to an event of magnitude 3.4 and a hypocentral distance of 18.5 km (Fig. 4). This value is rather low due to the fact that we excluded events for which saturation was suspected for the high-sensitivity broad-band seismometers. The peak ground rotation (PGR) is the maximum absolute value of the rotational rate time history along the three components (horizontal: E, N; and vertical: Z). On the opposite of the PGA, the PGR is higher around the vertical axis (“torsion”), than around the horizontal axis (“rocking” or “tilt”).

Argostoli- Soft soil site

For the soft site, the PGA is again higher for the horizontal components axis than the vertical one. The maximum value is 0.33 g for an event of magnitude 5 and a hypocentral distance of 20 km in the 8th of November 2014 (Fig. 4).

Comparison with database from bibliography

We compared our two Argostoli data sets with three other data sets from the bibliography: Liu et al. (2009) (data from Taiwan); Takeo et al. (2009) (data from Japan) and Yin et al. (2016) (data from California). The main features of these data sets as well as those from the Argostoli subsets are listed in Table 1. The Fig. 4 shows the plot of PGR values versus PGA values for each event of each data set. The Fig. 5 shows the same data adding information concerning the magnitude through a color scale. We notice that the overall results are comparable in terms of order of magnitude.

To go further, we computed a linear regression between the logarithm (log10) of PGR (expressed in rad/s) and logarithm (log10) of PGA (expressed in g):

$$Log(PGR) = a + b\, log(PGA) \tag{3}$$

The obtained lines are shown in Fig. 6. The values of the slope as well as the standard deviation are given in Table 1. It is interesting to notice that there is no evidence of differences between rock or soil sites. The overall standard deviation is also comparable, except for the GVDA database from Yin et al., 2016, for which the value is more than the double of the other database.

RESIDUAL ANALYSIS OF THE SOFT SOIL SITE DATABASE

We also plotted the residuals (difference between points and the regression line) of the linear regression of log10(PGR) versus log10(PGA) in the soft soil site from Argostoli in order to investigate whether additional parameters should be introduced in the correlation between PGA and PGR (Fig. 7). We tested the effect of magnitude, back-azimuth, hypocentral distance and duration.

Actually, the data set is strongly biased by the aftershock sequence which affects mainly the distribution in terms of back-azimuth and distances. Despite these limitations, there is no obvious effect of back-azimuth. By contrast, there might be a slight effect of magnitude (in average, the higher the magnitude, the higher the ratio between PGR and PGA), as well as of the hypocentral distance. Nevertheless, there is probably a strong link between magnitude and hypocentral distance in our database since higher magnitudes are globally associated to more distant events. The results on duration could also be linked to magnitude.

Table 1. Information about the Argostoli data and the bibliographic data.

	Argostoli- Rock site	Argostoli- Soft soil site	HGSD Taiwan- Liu et al. 2009	Ito, Japan- Takeo et al. 2009	GVDA- Yin et al. 2016
Number of events	118	803	52	216	74
Dates	19 February 2014 to 10 March 2014	11 March 2014 to 2 July 2015	8 May 2007 to 17 February 2008	20 April 1998 to 30 April 1998	Since 2008
Site conditions	Vs30~830 m/s	Vs30~250 m/s	Unknown	Unknown	Vs30~280m/s
Maximum PGA	0.008 g	0.327 g	0.047 g	0.341 g	0.12 g
Magnitude of the maximum PGA	3.4	5	5.77	5	5.4
Maximum Magnitude	3.6	5.7	6.63	5	7.2
Slope: b	0.96	0.95	0.97	1.09	0.90
Intercept: a	-2.12	-2.14	-1.95	-1.81	-2.09
Standard deviation	0.1031	0.1282	0.1154	0.108	0.2552

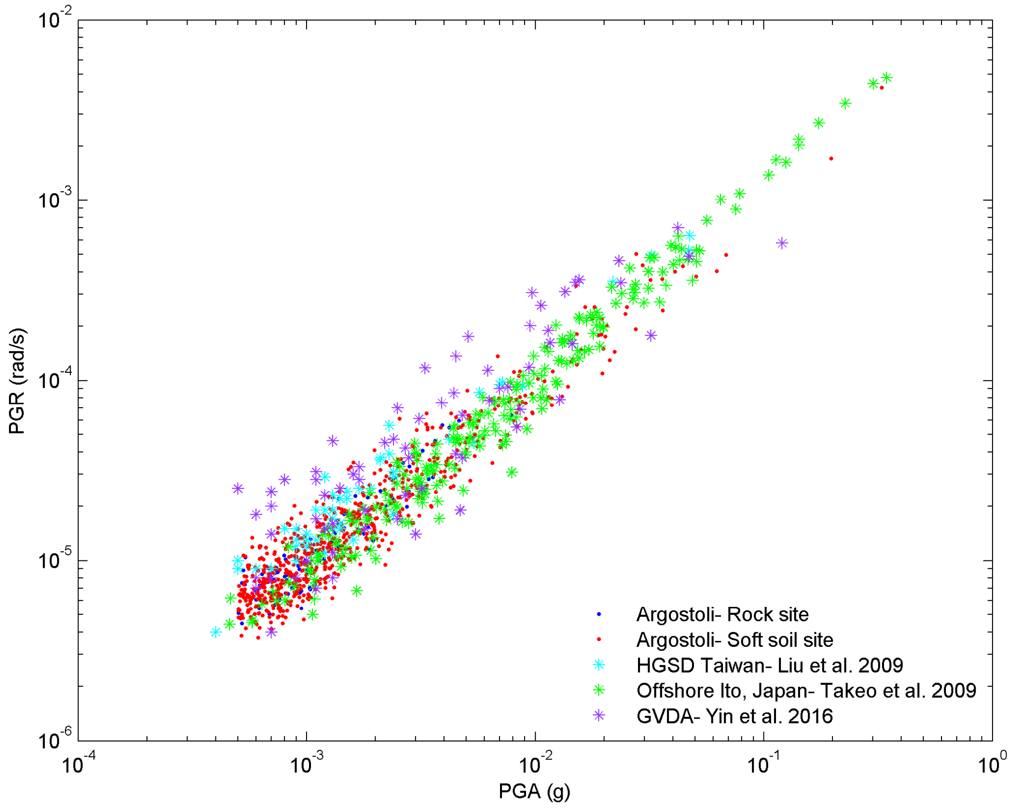

Figure 4. Comparison of all the Argostoli data with the bibliographic data in terms of relationship between PGR and PGA.

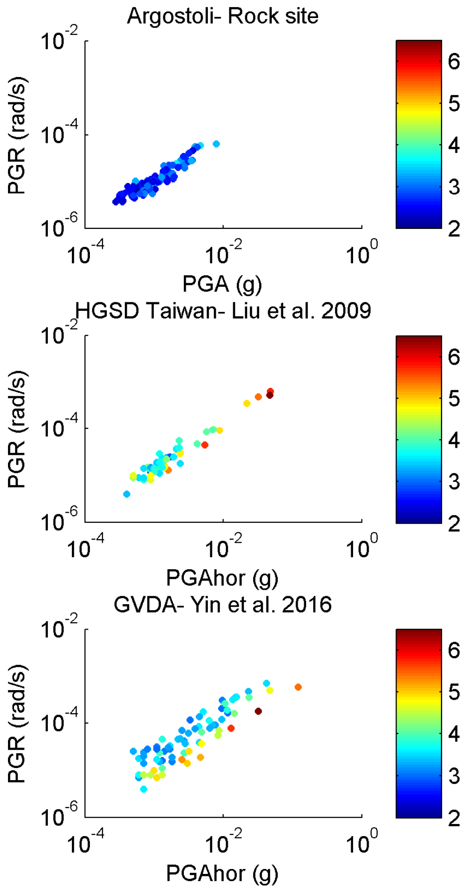

Figure 5. Comparison of the Argostoli PGR-PGA relation with the bibliographic one using a magnitude colorscale.

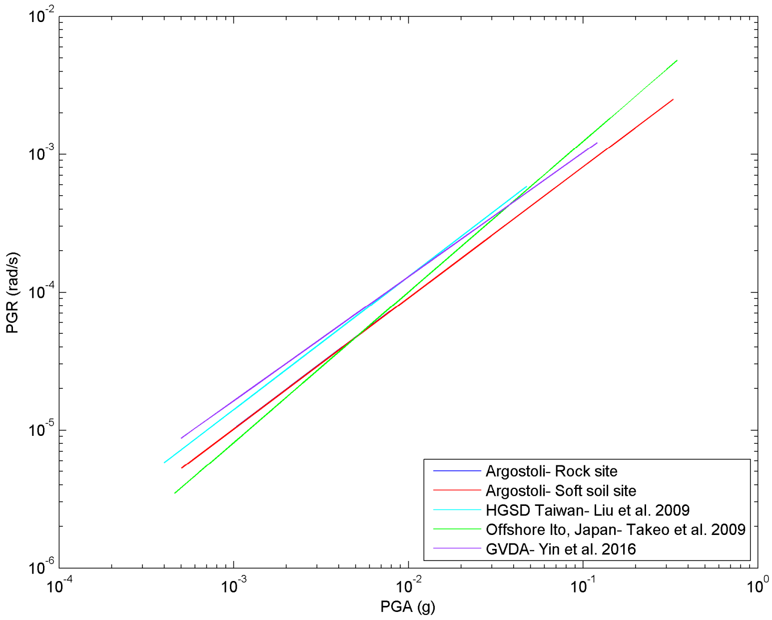

Figure 6. Comparison of the linear regression of the Argostoli data and the bibliographic data.

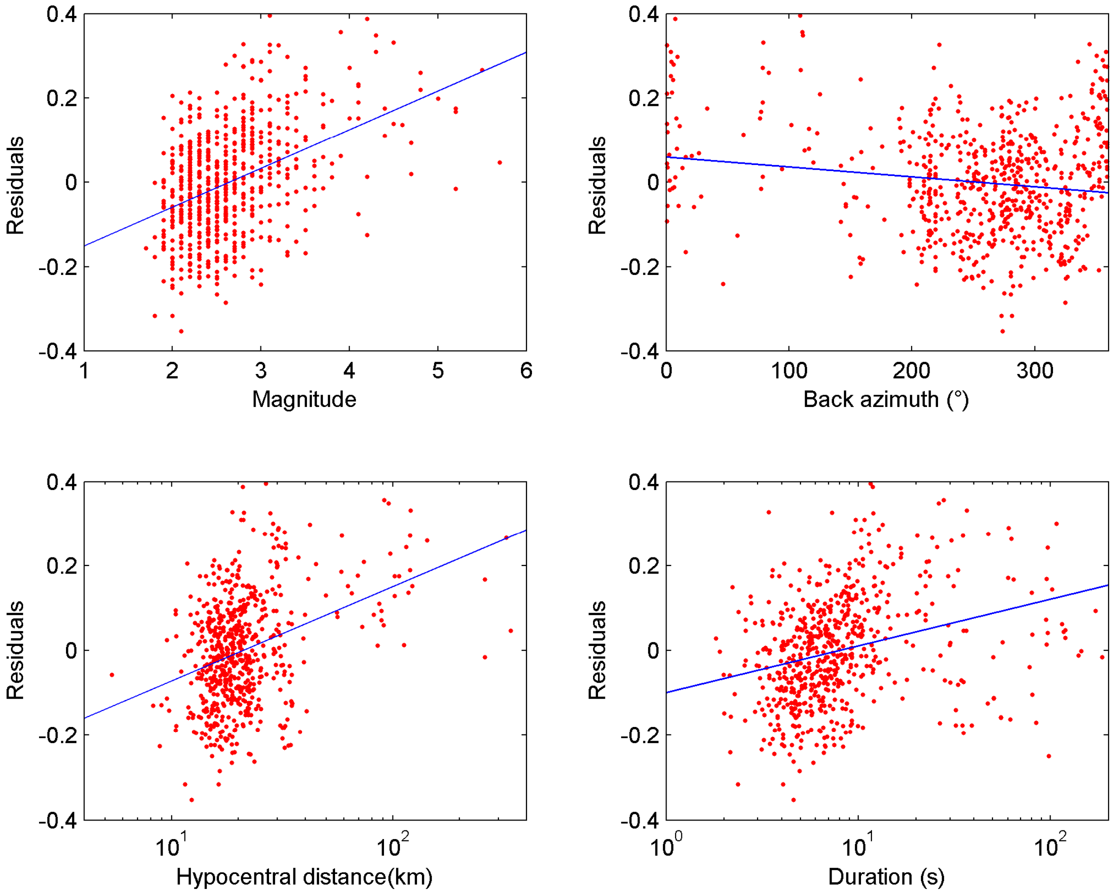

Figure 7. Residuals of PGR-PGA relationship for the soft soil site versus the magnitude (top left), the back azimuth (top right), the hypocentral distance (bottom left) and the duration (bottom right).

ARRAY-DERIVED ROTATION RATE

The spatial derivatives of displacements from a seismic array can also be used to estimate the rotations. Spudich et al. (1995) and Spudich and Fletcher (2008) proposed a seismo-geodetic method to derive the rotation rate, by inverting the measured displacements to get strains and stresses. The main assumption is that the strain tensor is spatially uniform in the material under the array.

The same authors actually developed a Matlab software to perform the inversion and calculate the rotation, the strain and their errors. It is named strainz17 and can be downloaded from the USGS website: http://earthquake.usgs.gov/research/software/strainz17/. This is the code we used to calculate the rotation rate from the data of our dense seismometer array, and then compare the so-obtained results with the records from the rotation sensor. The whole array is composed by 4 circles of 5 sensors with increasing radius (10, 30, 90 and 180 m) (Fig. 8).

We used a subset of 6 stations with the seismometer in the center and the 5 others forming the “smallest” radius circle (R=10 m). The rotation sensor was located in the center of the circle. To get the rotation rate, we used the velocity time histories as an input. The frequency band where the signal/noise ratio is higher than 10 is 3-30 Hz. Fig. 9 compares rotation records and rotation estimate derived from translation array for one given event. The time histories match quite well for the East component with a small difference of amplitude, the recorded rotation rate being slightly larger than the array derived one. However, for the North component, the recorded rotation rate is two times larger than the array-derived one, and for the vertical component the recorded rotation rate is three times larger than the array derived one (Fig. 9). This is consistent with the mentioned above, rather high differences of amplitudes between the three components of the rotation measurements (Fig. 3). These differences are not present on the rotation values derived from the "translation array", which provide similar values for the three components. This feature is not only observed in the event shown in Fig. 9, but is linked to most of the events.

We tested the derivation with all the radiuses (10, 30, 90 and 180 m). We noticed that the best fitted data corresponds to the radius 10. For the larger circles, the array derived data doesn't match well the rotation records. In fact, the larger the circle radius, the less the amplitude of calculated rotation.

In order to propose one possible explanation for this difference, we can mention that the geology of the rock site is rather heterogeneous within the first few meters beneath surface due to alteration process (weathered zone). In this area, one can find massive limestone blocks as well as red decalcification clay zones, with a typical metric to plurimetric scale. We suggest that this heterogeneity can have an influence on punctual rotation measurement, whereas a rotation value derived from a larger device (here, 20 m of diameter) is smoother, with less sensitivity to metric scale heterogeneities, and induces fewer differences between components.

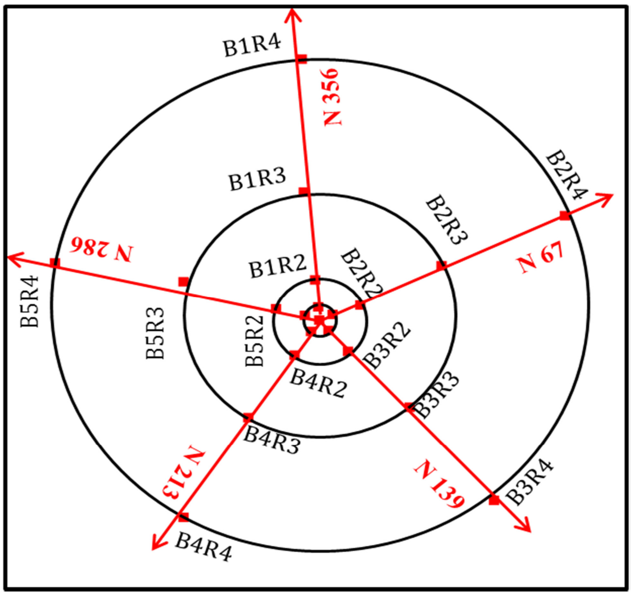

Figure 8. Geometry of the array.

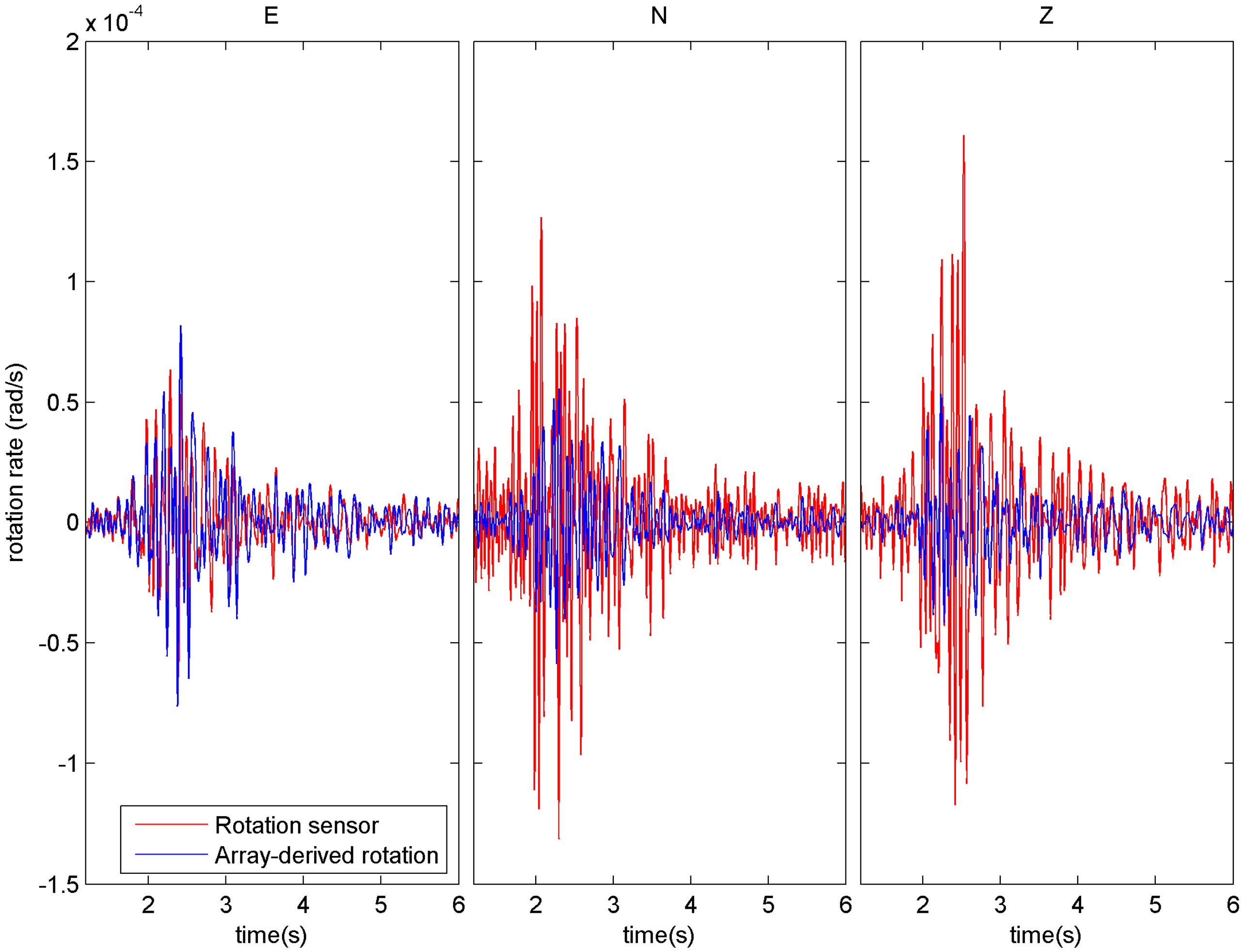

Figure 9. Comparison of the array-derived rotation rate with the one recorded from the rotation sensor for the 3 components.

CONCLUSIONS

The interest in rotational seismology is growing more and more nowadays because of all the additional information it can bring in different domains like seismology, geodesy and earthquake engineering. Indeed, the rotational sensor experiment in Argostoli provided many results. First of all, in terms of PGA/PGR correlation, there is no large difference in the rotation behavior in the two types of soil in Argostoli: rock and soft soil. Then, the comparison between the rotation derived from array data and the measured one indicates the possibility for a significant effect of small scale (I.e., a few meters) heterogeneities in the soil. This could suggest that rotations evaluated at different distance scales could be significantly different. This may be important for buildings since the effect of rotation may be different depending on the size of the basements. Our further work will be focused on the spectral analysis of the Argostoli databases.

ACKNOWLEDGMENTS

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