

Review: Progress in Rotational Ground-Motion Observations from Explosions and Local Earthquakes in Taiwan

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Abstract Rotational motions generated by large earthquakes in the far field have been successfully measured, and observations agree well with the classical elasticity theory. However, recent rotational measurements in the near field of earthquakes in Japan and in Taiwan indicate that rotational ground motions are 10 to 100 times larger than expected from the classical elasticity theory. The near-field strong-motion records of the 1999 M_w 7.6 Chi-Chi, Taiwan, earthquake suggest that the ground motions along the 100 km rupture are complex. Some rather arbitrary baseline corrections are necessary in order to obtain reasonable displacement values from double integration of the acceleration data. Because rotational motions can contaminate acceleration observations due to the induced perturbation of the Earth's gravitational field, we started a modest program to observe rotational ground motions in Taiwan.

Three papers have reported the rotational observations in Taiwan: (1) at the HGSD station (Liu *et al.*, 2009), (2) at the N3 site from two TAIwan Integrated GEodynamics Research (TAIGER) explosions (Lin *et al.*, 2009), and (3) at the Taiwan campus of the National Chung-Cheng University (NCCU) (Wu *et al.*, 2009). In addition, Langston *et al.* (2009) reported the results of analyzing the TAIGER explosion data. As noted by several authors before, we found a linear relationship between peak rotational rate (PRR in mrad/sec) and peak ground acceleration (PGA in m/sec²) from local earthquakes in Taiwan, $PRR = 0.002 + 1.301 \text{ PGA}$, with a correlation coefficient of 0.988.

Introduction

Linear or translational motions (T_x , T_y , and T_z) along the X -, Y -, and Z -axis and angular or rotational motions (θ_x , θ_y , and θ_z) about the X -, Y -, and Z -axis are required to completely describe the motions of a rigid body (Evans *et al.*, 2009). In addition, 6-component strains are also required for a deforming body (Bath, 1979). Observational seismology is based mainly on measuring translational motions due to difficulties involved in measuring rotational motions and strains and a widespread belief that rotational motions are insignificant. For example, the footnote in Richter (1958), "Theory indicates, and observation confirms, that such rotations are negligible," is misleading. Richter did not provide any references, and there were no instruments sensitive enough to measure rotation motions at the level of microradian per second ($\mu\text{rad/sec}$) at that time. Aki and Richards (1980) stated, "The state-of-the-art sensitivity of the general rotation-sensor is not yet enough for a useful geophysical application," and in the second edition, Aki and Richards (2002) remarked, "...seismology still awaits a suitable instrument for making such measurements."

In the past decade, rotational motions generated by large earthquakes in the far field have been successfully measured at sites in Germany, New Zealand, and southern California (e.g., Igel, 2007), and observations agree well with the classical elasticity theory (Suryanto *et al.*, 2006). However, recent rotational measurements in the near field of earthquakes in Japan (Takeo, 1998, 2009) and in Taiwan (Huang *et al.*, 2006; Liu *et al.*, 2009) indicate that rotational ground motions are 10 to 100 times larger than expected from the classical elasticity theory. Two papers by Teisseyre (1973, 1974) are among the first to consider rotational motions beyond the classical elasticity theory. Two recent monographs contain many chapters on theoretical and observational aspects of rotational motions (Teisseyre *et al.*, 2006, 2008).

The more than 50 near-field strong-motion records of the 1999 M_w 7.6 Chi-Chi (Taiwan) earthquake suggest that the ground motions along the 100 km rupture are complex (Lee *et al.*, 2001). Without some rather arbitrary baseline corrections or high-pass filtering (e.g., Boore, 2001), it is difficult to double integrate the acceleration data to obtain com-

parable values of displacements that were observed independently by geodesy. Because rotational motions can contaminate our observations due to the induced perturbation of the Earth's gravitational field, we wonder if rotational motion is a contributing factor. Consequently, we started a modest program to observe rotational ground motions in Taiwan.

Three papers have reported the rotational observations in Taiwan: (1) at the HGSD station (Liu *et al.*, 2009), (2) at the N3 site from two TAIGER explosions (Lin *et al.*, 2009), and (3) at the NCCU campus (Wu *et al.*, 2009). All the relevant data obtained so far will be accessible from the Web site of the International Working Group on Rotational Seismology (see the Data and Resources section). In addition, Langston *et al.* (2009) present the results of an analysis of the TAIGER explosion data using the gradiometry method (Langston, 2007a,b,c).

The purpose of this article is to present a brief review of the progress made in observing rotational ground motions in Taiwan by introducing the aforementioned papers, highlighting some of the results, and discussing the ongoing monitoring program. We encourage other researchers to use these data for further studies, and we welcome comments and suggestions on our current program in observing rotational ground motions in Taiwan.

Methods for Observing Rotational Ground Motions

Rotational ground motions can be measured directly by gyroscopic sensors or inferred indirectly from an array of translational sensors. According to Cochard *et al.* (2006), displacement \mathbf{u} of a point \mathbf{x} is related to a neighboring point $\mathbf{x} + \delta\mathbf{x}$ by

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

where $\boldsymbol{\varepsilon}$ is the strain tensor, and

$$\boldsymbol{\omega} = \frac{1}{2} \nabla \times \mathbf{u}(\mathbf{x}) \quad (2)$$

is a pseudovector representing the angle of the rigid rotation generated by the disturbance. The three components of rotation about the X -axis, Y -axis, and Z -axis at the Earth's surface are given by the following equations (e.g., Cochard *et al.*, 2006):

$$\begin{aligned} \omega_x &= \partial u_z / \partial y, & \omega_y &= -\partial u_z / \partial x, \\ \omega_z &= \frac{1}{2} (\partial u_x / \partial y - \partial u_y / \partial x) \end{aligned} \quad (3)$$

Therefore, rotational ground motions can be observed by: (1) an array of translational accelerometers indirectly by assuming that contamination from rotational motions is small in the measured acceleration and that the classical elasticity theory is valid (e.g., Spudich *et al.*, 1995; Huang, 2003; Spudich and Fletcher, 2008) or (2) rotational sensors directly (e.g., Nigbor, 1994; Takeo, 1998; Huang *et al.*, 2006; 2009).

There are several earlier experiments to measure rotational ground motions; for example, Droste and Teisseyre (1976) were the first to record rotational waves successfully in Poland. However, it is beyond the scope of this review to discuss these pioneering papers, and we will concentrate only on the recent measurements of local earthquakes and explosions using small and not too expensive rotational sensors.

Using a GyroChip rotational sensor, Nigbor (1994) succeeded in recording rotational ground motions at a distance of 1 km from a large explosion at the Nevada Test Site (NTS). Using similar instruments, Takeo (1998, 2009) recorded rotational ground motions excited by nearby earthquakes offshore of the Izu Peninsula of Japan during an earthquake swarm in 1997 and in 1998, respectively. However, after Nigbor (personal comm., 2006) moved his equipment to a recording site in Borrego Mountain, southern California, he did not record significant rotational ground motions, even with more than a decade of observations.

Translational acceleration is often called linear acceleration or simply acceleration. Because velocity is commonly used in strong-motion seismology in conjunction with acceleration and displacement, we prefer (following Takeo, 2009) to use rotational rate for angular or rotational velocity. We could use spin rate as suggested by Majewski (2008) as well. Following the International System of Units (Lide, 2002), the unit for acceleration is m/s^2 , and the unit for angular velocity is radians/s (rad/s). However, to avoid too many decimal places, it is more convenient to use milliradians/s (mrad/s) for rotational rates. [To conform to journal style, this paper uses the abbreviation sec instead of s.] Earthquake engineers often use the acceleration due to gravity, g , as the unit for ground acceleration. Because $g \approx 9.80 \text{ m/sec}^2$, 1 m/sec^2 is approximately $0.1 g$.

Previous Rotational Ground-Motion Studies in Taiwan

To study near-field strong motions on nuclear power plant structures, the SMART-1 array was set up in Lotung, Taiwan, in 1980, and it was closed at the end of 1990 (Shin *et al.*, 2003). It consisted of a central site and accelerographs in three concentric circles with radii of 200 m, 1 km, and 2 km, respectively, and each circle had 12 evenly spaced sensors. All 43 accelerographs were tied to a common time base with timing to better than ± 0.01 sec. Each accelerograph consisted of a triaxial force-balance accelerometer capable of recording $\pm 2 g$ connected to a digital event recorder that uses a magnetic tape cassette for recording. The accelerographs were triggered on either vertical or horizontal acceleration at an adjustable preset threshold. Signals were digitized with a 13 bit resolution at 100 samples/sec. Using the SMART-1 data, Oliveira and Bolt (1989) estimated the rotational components of surface strong motion for five earthquakes ranging from M_S 5.7 to 7.8 at epicentral distances from 6 to 84 km. Their computation method involved using station pairs of the array and averaging over the array by

stacking. Their results indicate peak vertical-component rotational values on the order of $40 \mu\text{rad}$. However, the SMART-1 array was established at the dawn of the digital era, and its recorded acceleration data are probably of too low a resolution (at 13 bit) to yield accurate spatial derivatives of displacement for computing rotational motions according to equation (3).

Huang (2003) inferred ground rotational motions of the 1999 Chi-Chi, Taiwan, earthquake using the records from an acceleration array on the Li-Yu-Tan dam, located 6 km north of the northern end of the Chi-Chi earthquake fault rupture. This 7-element array was designed to monitor the seismic response of the dam and consists of four stations installed on the surface: one inside the dam, one near the base of the dam, and one at the dam crest. A PRR of about 0.4 mrad/sec was obtained using the computational method of Oliveira and Bolt (1989).

Inspired by Nigbor (1994) and Takeo (1998), C.C. Liu and B.S. Huang began recording earthquakes with triaxial rotation sensors at Station HRLT near Hualien in eastern Taiwan on 12 December 2000. The sensors used were a PVC-5 rotation transducer (sensitivity: 0.2 V/rad/sec) and a GyroChip rotation transducer (1.43 V/rad/sec). A 12-channel, 19 bit datalogger by Kinemetrics was used to record the output of the rotation sensors as well as a Force Balance Accelerometer (FBA) under trigger mode at 200 samples/sec. Unfortunately, no useful rotational ground-motion data were obtained after about 5 yr of continuous observations. They concluded that the rotation transducers used were not sensitive enough.

Observing Rotational Ground Motions at Station HGSD

In July 2004, C.C. Liu and B.S. Huang deployed a high-resolution, triaxial rotational seismometer (Model R-1 made by eentec/PMD) at station HGSD in eastern Taiwan. The sensitivity of the R-1 is 50 V/rad/sec , 35 times higher than that of the GyroChip and 250 times higher than that of the PVC-5. The HGSD station was established as a plate boundary observatory with geodetic, seismic, and strain instruments. They chose this station to observe rotational ground motions because this site was already well instrumented. From 7 December 2004 to 12 November 2006, several hundred earthquakes were recorded with the R-1 at the surface and the Guralp CMG-3TB broadband seismometer at a depth of 100 m in a borehole. However, it was a learning lesson for them during this time period, and their operation ended in November 2006 when both R-1 sensors ceased to operate.

Realizing that the R-1 rotational seismometer had not been tested independently, the first author (W.H.K. Lee) persuaded the Central Bureau of Taiwan (CWB) in early 2006 to contract Kinemetrics for upgrading two of the CWB 6-channel K2 digital accelerographs to take on an R-1 rotational sensor as an external input. We call this instrument

K2 + R1. The K2 is a well known accelerograph made by Kinemetrics (see the Data and Resources section). These upgraded units were tested in southern California in the fall of 2006 (Nigbor and Lee, 2006) and also in Taiwan.

Very recently, Nigbor *et al.* (2009) carried out extensive tests on commercial rotational sensors and concluded that the R-1 sensor generally meets the specifications given by the manufacturer, but that clip level and frequency response vary enough that more detailed calibrations are warranted for individual units. (See the Data and Resources section for the transfer function of the R-1 sensor.) The instrument response is nearly flat from 0.1 to 20 Hz, and its self noise is $< 10^{-6} \text{ rad/sec rms}$ in the same frequency band as confirmed by Nigbor *et al.* (2009). Therefore, we concluded that the R-1 is capable of measuring rotational velocity expected from small (magnitude ~ 4 to ~ 5) local earthquakes that frequently occur near the HGSD station in a distance range of up to about 100 km.

One K2 + R1 instrument was borrowed from CWB by C.C. Liu for deploying at the HGSD station in April 2007 to start the phase 2 operation. A new vault was constructed at the HGSD station to house the K2 + R1 instrument and a 6-channel, 24 bit Quanterra Q330 datalogger with a Kinemetrics EpiSensor and a Mark Product short-period seismometer (Model L-4A; 2 Hz natural frequency). From 8 May 2007 to 17 February 2008, more than 50 local earthquakes were recorded by the K2 + R1 instrument. Locations of earthquakes with good rotational motions recorded at the HGSD station are shown in Figure 1 (earthquake parameters from Central Weather Bureau, 2007, 2008). Successful operation of this system was interrupted due to flooding of the HGSD station site in mid February 2008 and resumed in May 2008.

Liu *et al.* (2009) obtained some interesting records of rotational ground motions from more than 50 local earthquakes during a 9 month period. The local magnitude of these earthquakes ranged from 2.6 to 6.6 at hypocentral distance from 14 to 260 km. The largest PRR (0.63 mrad/sec) was recorded from an M_w 5.1 earthquake at a hypocentral distance of 51 km from the HGSD station at 13:40, 23 July 2007. Previously, Takeo (1998) observed an even larger than expected rotational rate in the source vicinity (at $\sim 3 \text{ km}$ distance) of magnitude ~ 5 earthquakes. The highest PRR was 26 mrad/sec around the east–west axis from an magnitude 5.2 earthquake at 14:09, 3 March 1997. Readers are referred to Liu *et al.* (2009) for discussions of the rotational motion observations made at station HGSD.

Observing Rotational Ground Motions from Explosions

Because we do not know when earthquakes will occur near a given station even in a highly seismically active region like Taiwan, a convenient way to collect seismic waveform data is from explosions. Lin *et al.* (2009) took advantage of

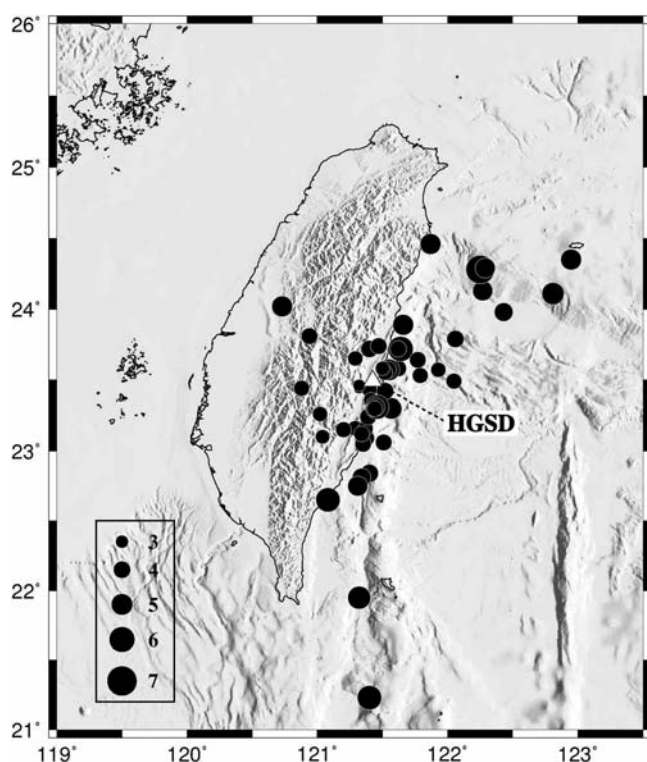


Figure 1. Location of earthquakes with good rotational motions recorded at the HGSD Station in eastern Taiwan from 8 May 2007 to 17 February 2008. The size of the dot is proportional to the earthquake magnitude (M); sample dot sizes are shown in the legend.

two explosions (3000 kg of explosives for the N3P shot and 750 kg of explosives for the N3 shot) that were set off on 4 March 2008 at the N3 explosion site in northeastern Taiwan, part of an active refraction experiment for the TAIwan Integrated GEodynamics Research (TAIGER) project for testing models of Taiwan orogeny (see the Data and Resources section). To record these two explosions, eight triaxial rotational sensors, 13 triaxial accelerometers, and 12 six-channel, 24-bit dataloggers with Global Positioning System (GPS) receivers were deployed to record continuously several hours before and after the explosions. These instruments were installed at about 250 m (1 station), 500 m (11 stations), and 600 m (1 station) from the explosions. The 11 stations form a center array with station spacing of about 5 m.

Except for the GyroChip rotational sensor, onscale records were obtained for all the deployed sensors. Although the N3P shot used four times more explosives than the N3 shot used, the peak ground translational acceleration and rotational rates at the 13 station sites from the N3P shot are about 1.6 times larger than those for the N3 shot. Large variations (by tens of percents) of translational accelerations and rotational rate were observed at the center array with station spacing of about 5 m. The largest PRR was observed for the X component: 2.74 and 1.75 mrad/sec at a distance of 254 m from the N3P and N3 shots, respectively. Nigbor (1994) observed PRR of 38 mrad/sec at 1 km distance from a very large (1 kiloton) chemical explosion at the NTS.

Lin *et al.* (2009) designed their instrument deployment for observing rotational ground motions directly and indirectly. The collected translational acceleration and rotational rate data offer many subarray station configurations to compare measured point rotational motions with areal rotational motions inferred from data recorded by an array of accelerometers. Spudich *et al.* (1995) and Spudich and Fletcher (2008) developed a powerful method to infer rotational ground motions from translational acceleration data of an array. Applying their software (Spudich and Fletcher, 2009) for an area defined by a 5-element subarray, we obtained a computed rotational rate that is about 3 times larger than that directly measured at the array center. Because the R-1 instrument response is from 0.1 to 20 Hz (Nigbor *et al.*, 2009), a plausible explanation for this discrepancy is that the R-1 sensor did not record the high-frequency contents (> 20 Hz) of these two explosions, and thus yielded a much lower value. Another plausible explanation is the complex wave propagation noted by Langston *et al.* (2009).

Data collected by the instruments available to Lin *et al.* (2009) were not optimal for recording explosions because (1) the Q330 dataloggers can only sample at 200 samples/sec, whereas 1000 samples/sec may be needed, and (2) the response of the R-1 rotational sensor is limited to about 20 Hz, whereas 200 Hz may be needed.

Rotational ground motion in addition to contemporaneous dynamic strain observations theoretically unify the understanding of translational wave motions in continuum mechanics. Langston *et al.* (2009) used the TAIGER explosion data recorded at the N3 array to determine the composition of the strong-motion seismograms from the 3000 kg and 750 kg explosions using recently developed techniques in seismic wave gradiometry. Solutions of the wave equation require specific relationships between the spatial and temporal derivatives of the wave field. Generally, a spatial gradient in the wave field is linearly related to the wave field itself and its time derivative through coefficients that are functions of the geometrical spreading and wave apparent velocity, respectively (Langston, 2007a,b,c; Langston and Liang, 2008). In fact, as equation (3) shows, the horizontal spatial gradients of the vertical component of the wave field are the horizontal tilts, or rotations, about a horizontal axis. Seismic wave gradiometry incorporates rotations in their pure forms as a basis for wave field decomposition.

The strong-motion wave field from the N3 array was used to derive spatial gradients using geodetic array methods (e.g., Spudich *et al.*, 1995; Langston and Liang, 2008) and then was related to the wave field through gradiometry methods to determine wave apparent velocities, wave type, and azimuths of propagation as well as radial and azimuthal amplitude behavior. Results show that body and surface wave propagation was complex, showing the effects of scattering from velocity and topographic heterogeneity in the near-source region. Direct P waves arrived at the array 35° clockwise off-azimuth, suggesting refraction from a dipping interface. Initial high-frequency Rayleigh waves were

seen to propagate 45° in the counterclockwise direction from the radial azimuthal direction and may have been reflected from the valley side. Later arriving Rayleigh waves were seen to propagate in all azimuths, even back toward the source, indicating significant scattering in this mountainous region of Taiwan. Rotation about the vertical axis was comparable in amplitude to the areal strain, suggesting that the explosion sources were not axisymmetric or that wave scattering effectively coupled P -, SV -, and SH -wave fields.

This kind of information is invaluable for understanding seismic wave fields of all types and frequency bands because it places significant constraints on the kinds of models that may be used to understand the data. The use of seismic rotations and strains in conjunction with the translational wave field should allow a deeper understanding of seismic data before more involved modeling. The determination of wave attributes directly from the rotation, strain, and translation data also suggests new kinds of empirical studies of structure and source parameters from dense arrays of seismometers.

Observing Rotational Ground Motions along an Active Fault

Because the data obtained at the HGSD station indicate that rotational motions from local earthquakes have similar values to those observed by Takeo (1998), we started to investigate rotational ground motions more thoroughly in 2007. Wu *et al.* (2009) deployed four sets of instruments at the National Chung-Cheng University, Chiayi, Taiwan, in order to study earthquakes in detail in the near-field for both seismology and earthquake engineering. In this study, both rotational and translational ground motions are being monitored along the active Meishan fault where a major earthquake that occurred on 17 March 1906 (magnitude 7.1) may reoccur. The deployed instruments include: (1) a 32-element seismic array in free field, (2) a colocated six-channel unit comprising a three-component broadband seismometer and a three-component accelerometer, (3) a colocated six-channel unit with an accelerometer and an external rotational sensor, and (4) a 32-element accelerometer and rotational sensor array in a building about 300 m away. This deployment is the first to record 6-degrees-of-freedom ground motions in free field and in a building nearby. Within seven months of the initial deployment, 24 local earthquakes were recorded by one or more of the four instrumentation sets. As usual in any new deployment of instruments, Wu *et al.* (2009) encountered many operational difficulties in the field that are being corrected step-by-step.

Some Practical Issues in Observing Rotational Ground Motions

It is difficult to establish a field program for observing rotational ground motions because of the prevailing belief that rotational motions are insignificant. Also, sensitive rotational sensors are expensive. However, the prevailing belief

is based on the linear elasticity theory that is adequate in the far field, but there is no confirmation of its validity based on observations in the near field of local earthquakes. Indeed, the pioneering work of Takeo (1998) indicates that the rotational motions are 10 to 100 times larger than expected theoretically.

From numerical modeling, Bouchon and Aki (1982) obtained a maximum rotational rate about the vertical axis of 1.5 mrad/sec at 1 km distance from a magnitude ~ 6.5 earthquake. This implies that we need a rotational sensor capable of measuring $\mu\text{rad/sec}$ if we have any chance of observing rotational ground motions from local earthquakes. Although highly sensitive rotational sensors have been available for aeronautical and space applications for decades, they are too expensive for seismologists. In fact, a typical American-made rotational sensor capable of measuring at the $\mu\text{rad/sec}$ level costs about \$50,000. The ring laser gyro that detected the rotational motions of teleseismic events in Germany is a multimillion dollar instrument for astronomical work to study the variations of the Earth's rotation.

When the R-1 rotational sensors became available in 2004 at about \$6000 each (ten times less expensive than comparable sensors), it was still difficult to find funding to purchase them. Nevertheless, they are within reach using discretionary funds. We started a program in Taiwan by making use of available resources (including manpower and instruments). This approach is obviously not optimal, but the difficulties we encountered in the past four years provided some valuable lessons. We will now discuss a few practical issues.

Reliability of the R-1 Sensors

There is now enough evidence (from three different groups of users) that (1) colocated and nearly colocated R-1 sensors produced similar records; (2) very similar records were obtained from an explosion by an R-1 sensor and a GyroChip sensor that were colocated; and (3) excellent agreement was obtained (Wassermann *et al.*, 2009) between the recorded R-1 waveforms and those computed from an accelerometer array deployed around the R-1 from a building collapse in Munich, Germany. However, our calibration of 8 R-1 sensors indicated that their sensitivities differed from the manufacturer's values by as much as a few tens of percents.

The first two R-1 sensors deployed in Taiwan in late 2004 ceased to operate after about one year in the field and were sent back to Russia for repair. Therefore, seismology is still waiting for reliable and affordable rotational sensors that can measure rotational ground motions at the $\mu\text{rad/sec}$ level. In the meantime, we push forward with the 13 R-1 rotational sensors in Taiwan including five new ones that arrived in September 2008. We have requested funding for 20 more rotational sensors, and hopefully by the time funding is available, there will be a greater selection of rotational sensors available for purchase.

Array Deployment of Translational and Rotational Sensors

Given questions regarding the reliability of the R-1 sensors and whether rotational ground motions from classical elasticity theory (i.e., equation 3) are valid in the near field of local earthquakes, we need to deploy an array of translational and rotational sensors side by side to study the nature of ground motions. Our current deployment at the National Chung-Cheng University (see Wu *et al.*, 2009) is an attempt to deal with these two issues. In addition, we also address a key question of engineering interest by deploying both translational and rotational sensors in a nearby building. In partic-

ular, what are the rotational motions in a building and their implications for building designs?

An Efficient Way to Deploy Instruments

Lin *et al.* (2009) demonstrated the advantages of collecting rotational ground motions data from explosions using a portable array of translational and rotational sensors. However, equipment for their portable array was assembled by borrowing existing instruments for a temporary field deployment limited to about two weeks. It is therefore desirable to have a dedicated portable array so that we can deploy it quickly to record aftershocks and explosions. An array simi-

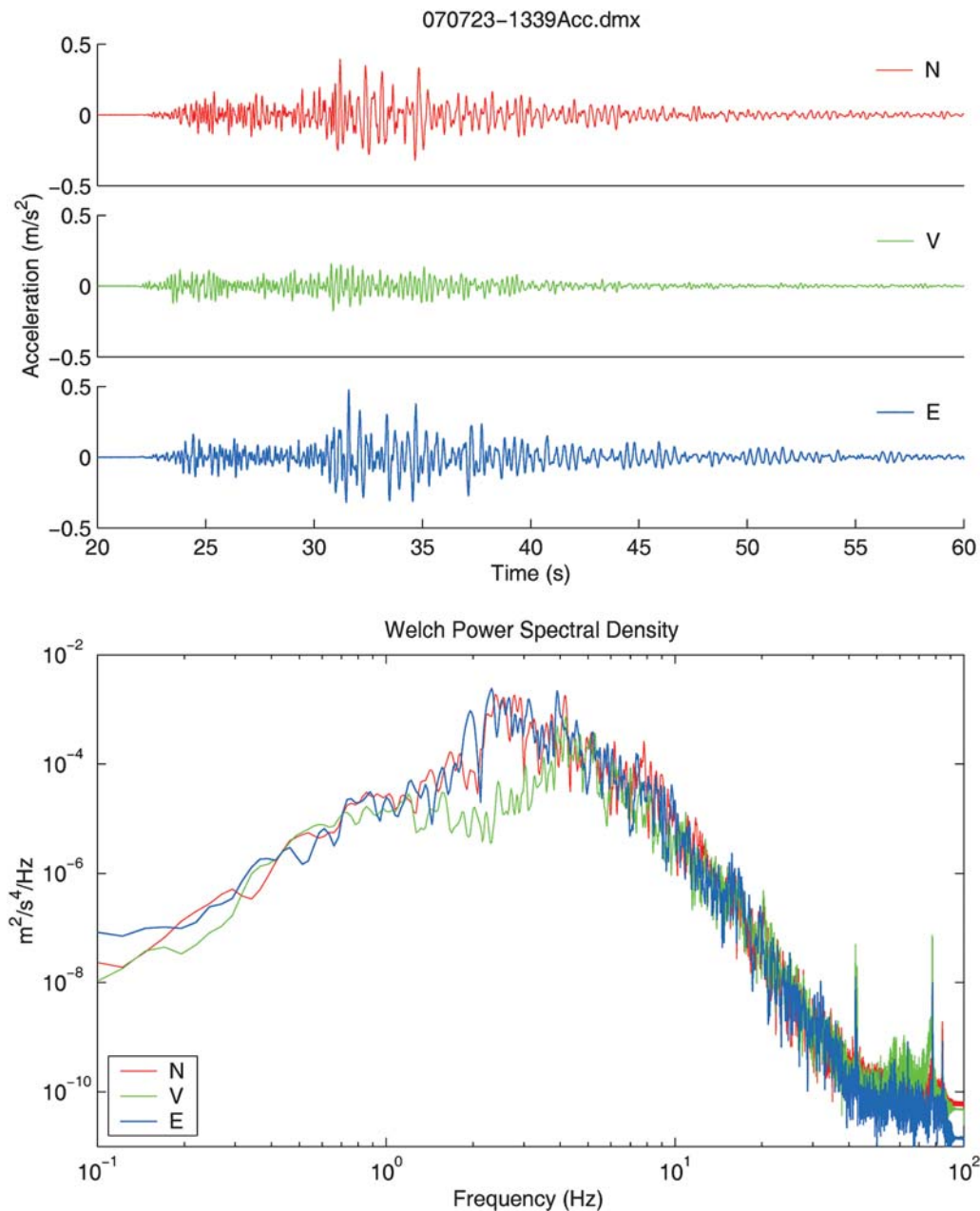


Figure 2. Amplitudes and spectra of translational acceleration recorded by the K2 + R1 instrument at the HGSD station from its internal three-component accelerometer for the earthquake on 23 July 2007 (see the Discussion section).

lar to what Lin *et al.* (2009) deployed would cost \$0.5 million in 2008. The authors plan to submit a proposal for funding such a portable array for rotational seismology in the near future. Such portable arrays will be very useful in chasing aftershocks of large earthquakes in the near field.

Discussion

It is instructive to present an example of translational and rotation data from a local earthquake. The largest PRR recorded by us so far is from an M_w 5.1 earthquake at a hypocentral distance of 51 km from the HGSD station at 13:40

on 23 July 2007 (UTC). Figure 2 shows the amplitudes and spectra of translational acceleration recorded by the K2 + R1 instrument at the HGSD station from its internal three-component accelerometer (Model FBA-23 by Kinemetrics) for this earthquake. The plotted data have not been corrected for instrument response. Please note that the accelerometer response is flat from 0 to 50 Hz. The PGA recorded is 0.47 m/sec^2 with much higher amplitudes for the two horizontal components than those for the vertical component. Figure 3 shows the amplitudes and spectra of rotational rate from its external three-component rotational sensor (Model R-1 by eentec) for the same earthquake. The plotted data

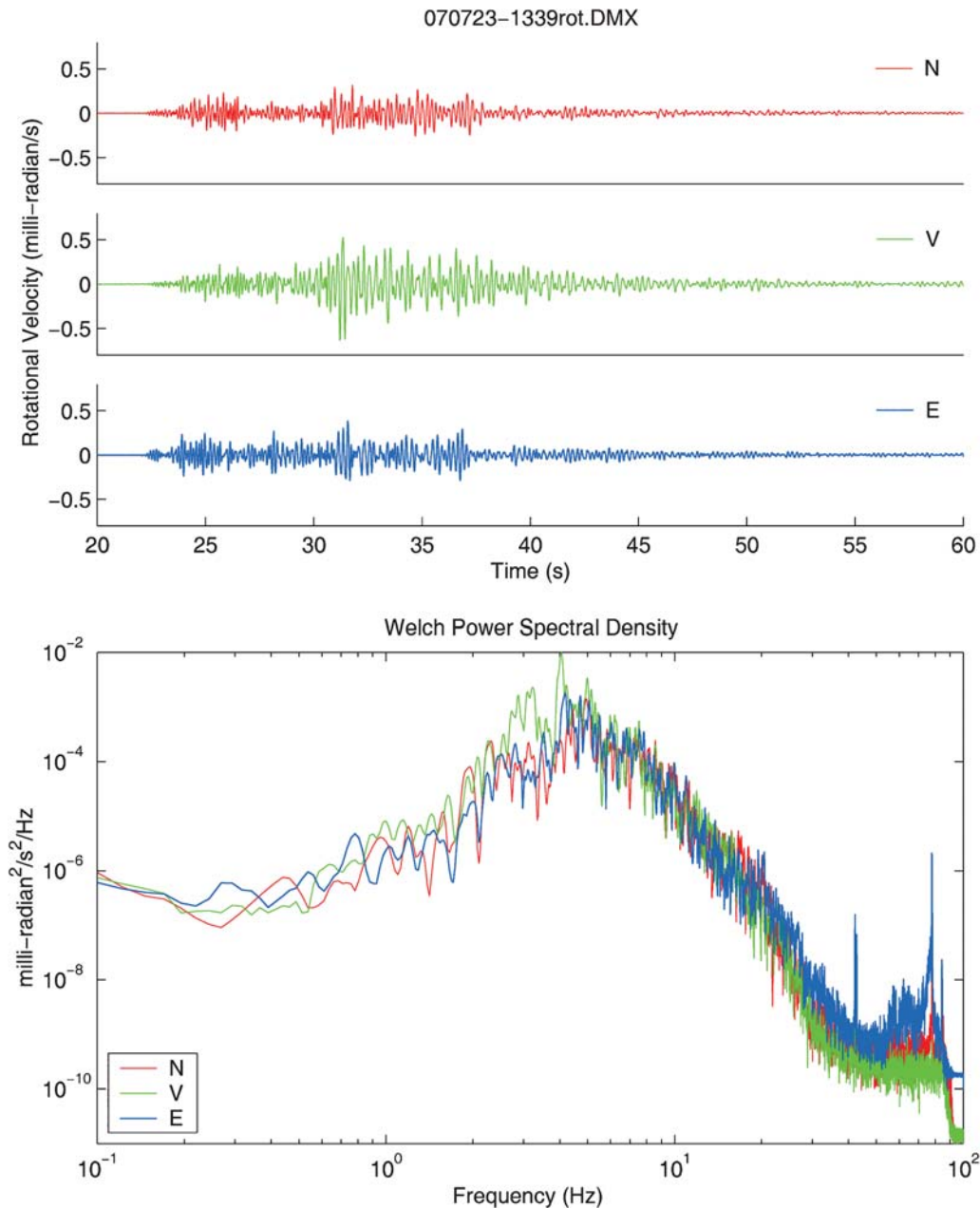


Figure 3. Amplitudes and spectra of rotational rate recorded by the K2 + R1 instrument at the HGSD station from its external three-component rotational sensor for the earthquake on 23 July 2007 (see the Discussion section).

have not been corrected for instrument response. Please note that the rotational sensor is a more narrowband instrument than the accelerometer, and its response is nearly flat from 0.1 to 20 Hz. The PRR recorded is 0.63 mrad/sec for the vertical component with much higher amplitudes for the vertical component than those for the two horizontal components. This makes sense according to equation (3), as the vertical component of rotational motion is governed by the horizontal gradients of the horizontal displacements.

The spectra in Figure 2 show that the dominant frequency band in ground acceleration is from about 2 to 5 Hz for the two horizontal components, whereas the spectra in Figure 3 show that the dominant frequency band in ground rotational rate is from about 2.5 to 5.5 Hz for the vertical component. Thus, the R-1 sensor with frequency response from 0.05 to 20 Hz is adequate for monitoring rotational motions from local earthquakes.

So far, the rotational ground-motion data obtained from local earthquakes are from a single station. Although we started deploying rotational sensors at several stations, we are waiting for data from multiple stations for individual earthquakes. The current available data in Taiwan are not adequate for investigating attenuation of rotational motions with distance from the source. However, we can try to study the relationship (if any) between the rotational and translational ground motions. Figure 4 shows the PRR in mrad/sec versus PGA in m/sec^2 for the earthquake data set from Liu *et al.* (2009, top frame) and from Takeo (2009, bottom frame). The first data set has 52 earthquakes, and a straight line can be fitted quite nicely using the polyfit function of MATLAB (2000),

$$\text{PRR} = 0.002 + 1.301 \text{ PGA}. \quad (4)$$

For comparison, we show the data set from Takeo (2009), which has 216 earthquakes with much larger PGA range. Again, a straight line can be fitted

$$\text{PRR} = -0.0036 + 1.454 \text{ PGA}. \quad (5)$$

The error bounds are then computed using the polyval function of MATLAB (2000) as shown in Figure 4. The dashed lines are plotted with an interval of $\pm 2\sigma$ corresponding to a 95% confidence interval.

In order to study this linear relationship in more detail, a program was written to fit a straight line,

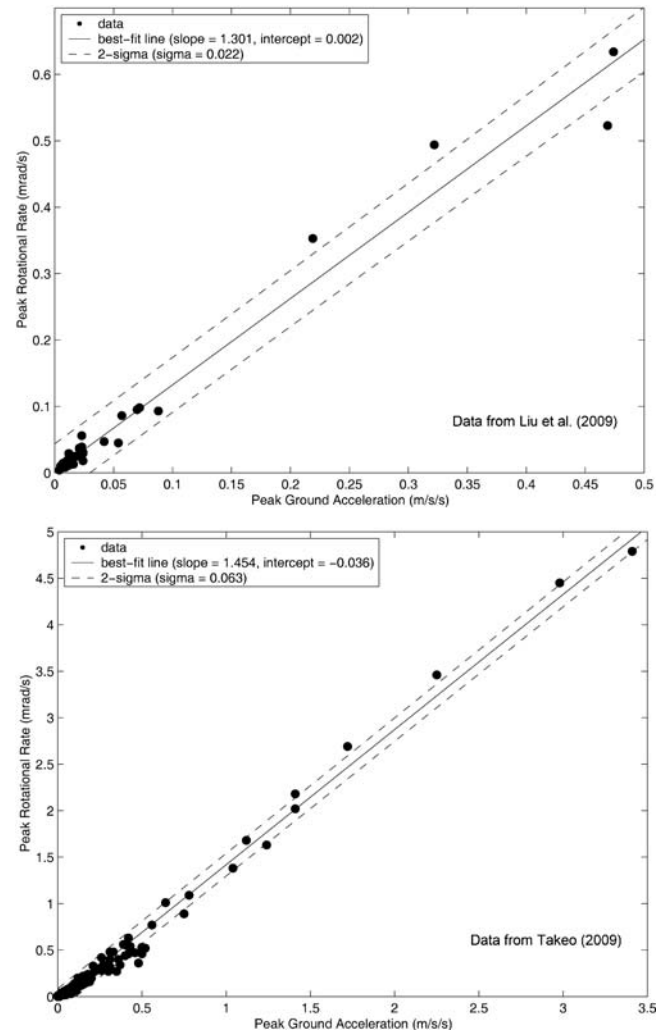


Figure 4. PRR versus PGA for the earthquake data set from Liu *et al.* (2009, top frame) and from Takeo (2009, bottom frame). See text for explanations.

$$y = a + bx, \quad (6)$$

to a set of observations (x_i, y_i) , $i = 1, \dots, n$, using the least squares algorithm of Gauss (Gellert *et al.*, 1977) and assuming each observation has weight = 1. Our results can be summarized in Table 1 where ε_a and ε_b are the standard error of a and of b , respectively; ε is the standard error of the fit; r_{xy} is the correlation coefficient.

Obviously, we will need far more data to establish a definitive relationship between PRR and PGA. Several authors

Table 1
Least Squares Fit to a Straight Line with Error Estimates for the Rotational Observations*

| Data Set | Data Samples | $b \pm \varepsilon_b$ (sec/km) | $a \pm \varepsilon_a$ (mrad/sec) | ε (mrad/sec) | r_{xy} |
|--------------------------|--------------|--------------------------------|----------------------------------|--------------------------|----------|
| Liu <i>et al.</i> (2009) | 52 | 1.301 ± 0.028 | 0.002 ± 0.003 | 0.028 | 0.988 |
| Takeo (2009) | 216 | 1.454 ± 0.010 | -0.036 ± 0.004 | 0.060 | 0.995 |

*Of Liu *et al.* (2009) and Takeo (2009).

have noted similar linear relationships (e.g., Spudich and Fletcher, 2008; Stupazzini *et al.*, 2009; Takeo, 2009; Wang *et al.*, 2009). In particular, Takeo (2009) showed a linear correlation between the maximum rotational displacements around vertical axis and the maximum (ground) velocities. Our two plots in Figure 4 are equivalent to Takeo's linear relationship without performing the integration for the measured rotational rate and ground acceleration to obtain rotational displacements and ground velocities. The b slope in equations (4) and (5) has the dimension unit of sec/km, or the dimension unit for slowness (the inverse of velocity). Spudich and Fletcher (2008) interpreted this slowness as the inverse of an apparent velocity characterizing the seismic wavefield. We would also like to draw attention to the physics of rotational motions beyond the classical elasticity (e.g., Teisseyre *et al.*, 2006, 2008).

Data and Resources

All translational and rotational seismograms described in this article were collected by the authors. Free online access to observational data is available at the Web site of the International Working Group on Rotational Seismology (<http://www.rotational-seismology.org/>, last accessed January 2009). A detailed description and technical specifications for the K-2 accelerograph can be found at the manufacturer's Web site (<http://www.kinometrics.com/>, last accessed January 2009). Transfer function of the R-1 sensor can be found at the manufacturer's Web site (<http://www.eentec.com/>, last accessed January 2009). Information from TAIwan Integrated GEodynamics Research (TAIGER) project for testing models of Taiwan orogeny is available at <http://taiger.binghamton.edu/> (last accessed January 2009).

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