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Observing Rotational and Translational Ground Motions at the HGSD Station in Taiwan from 2007 to 2008

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Abstract Because of a lack of suitable instruments, rotational ground motions have not been observed until the last decade. Rotational measurements in the near field of earthquakes in Japan (Takeo, 1998) indicate that rotational ground motions are many times larger than expected from the classical elasticity theory. After failing to obtain useful rotational ground motions (using similar rotational sensors as Takeo did), we deployed a far more sensitive rotational velocity sensor (R-1) at the HGSD station in eastern Taiwan. From 7 December 2004 to 12 November 2006, several hundreds of earthquakes were recorded during our Phase 1 operation. This was mostly a learning exercise to solve field operation problems; Phase 1 operations ended when our two R-1 sensors ceased to operate. A K2 + R1 instrument was deployed in the spring of 2007 to start our Phase 2 operation. From 8 May 2007 to 17 February 2008, we observed 52 local earthquakes with good rotational velocity signals (with signal-to-noise ratio >~5), together with excellent translational acceleration signals (with signal-to-noise ratio >~10). Unfortunately, field operation was interrupted due to flooding of the HGSD station site in mid-February 2008; we just resumed normal operation in June 2008.

This article reports our observations of rotational and translational ground motions made at the HGSD station so far. We concentrate on describing our instrumentation and the data obtained from 52 local earthquakes during our Phase 2 operation and present some very preliminary results.

Introduction

Richter (1958) stated that "perfectly general motion would also involve rotations about three perpendicular axes, and three more instruments for these. Theory indicates, and observation confirms, that such rotations are negligible." However, Richter did not provide any references, and there were no instruments sensitive enough to measure rotation motions at the level of microradians per second (μrad/sec) at that time. Aki and Richards (1980) stated that "the state-of-the-art sensitivity of the general rotation-sensor is not yet enough for a useful geophysical application." In the second edition, Aki and Richards (2002) remarked: "… note the utility of measuring rotation near a rupturing fault plane (…), but as of this writing seismology still awaits a suitable instrument for making such measurements."

In the 1990s, using a GyroChip rotational sensor, Nigbor (1994) succeeded in recording rotational ground motions at 1 km distance from a large explosion at the Nevada Test Site; in addition, Takeo (1998), using similar instruments, recorded rotational ground motions excited by nearby earthquakes offshore of the Izu Peninsula of Japan during an earthquake swarm in March 1997. However, R. L. Nigbor (personal comm., 2006) did not record significant rotational ground motions after he moved his equipment to a recording site in southern California for over a decade of observations.

The 50+ near-field strong-motion records of the 1999 Chi-Chi, Taiwan, earthquake indicate 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, it is difficult to double integrate the acceleration data to obtain similar values of displacements that were independently observed by geodesy. Because all translational sensors are disturbed by tilt signals because of the Earth's gravitational effect, we wonder if rotational motion (i.e., tilting around the horizontal axes and spinning around the vertical axis) is a contributing factor. Huang (2003) inferred ground rotational motions of the 1999 Chi-Chi, Taiwan, earthquake using the records from a dense acceleration array on the Li-Yu-Tan Dam, located 6 km north of the northern end of the Chi-Chi earthquake fault rupture, and obtained a peak rotation velocity of about 0.4 mrad/sec.

Because of limited funding, C. C. Liu and B. S. Huang began recording earthquakes with triaxial rotational sensors (similar to those used by Nigbor [1994] and Takeo [1998]) at the HRLT station near Hualien in eastern Taiwan on 12 December 2000. Unfortunately, no useful rotational ground-motion data were obtained after about five years of continuous observations. They then concluded that the rotation transducers that were used were not sensitive enough. Liu and Huang then deployed a high-resolution triaxial rotational velocity sensor (Model R-1 made by eentec/PMD) at the HGSD station in eastern Taiwan in July 2004.

During the Phase I operation (from 7 December 2004 to 12 November 2006), several hundreds of earthquakes were recorded with the R-1 at the surface, along with the Guralp CMG-3TB broadband seismometer at a depth of 100 m in a borehole. Our Phase 1 operation ended in November 2006 when both R-1 sensors were sent back to Russia for repair. The Phase 1 observations were presented by Huang *et al.* (2006).

In this article, we will concentrate on presenting our instrumentation and the data obtained from 52 local earthquakes during our Phase 2 operation from 8 May 2007 to 17 February 2008. Unfortunately, field operation was interrupted due to flooding of the HGSD station site in mid-February 2008; we resumed operation only recently. We have only done some preliminary analysis because we are waiting for more data from our Phase 3 operation, which just began in June 2008.

Phase 2 Operation (2007–2008)

Taiwan is situated on a complex plate boundary with high seismicity. The Philippine Sea plate is moving northwestward at about 70 mm/yr—subducting below the Ryukyu trench and subducted by the South China Sea plate from the west beneath the Manila trench. The HGSD station is located in eastern Taiwan and was established as a plate boundary observatory with geodetic, seismic, and strain instruments. We chose this station to observe rotational ground motions because this site was already well instrumented. Having other instruments at the same site to provide additional information will help us to study the translational and rotational motions.

The R-1 is a direct triaxial rotational velocity sensor with the highest sensitivity for its price in the commercial market. The principle of operation is electrochemical. The sensor element consists of a toroidal cavity and is completely filled with an electrolyte. A microporous ceramic plug containing four platinum grid electrodes is within the toroid. When angular motions are applied around this axis of the toroid, a pressure differential occurs across the sensor cell, which causes the electrolyte to flow and generates a current in the wire connected to the platinum grid. A more complete description with technical specifications of the R-1 sensor can be found at the manufacturer's website (http://www.eentec.com/).

Realizing that the R-1 rotational velocity sensor had not been independently tested, W. Lee persuaded the Central Bureau of Taiwan (CWB) in early 2006 to contract Kinemetrics, Incorporated for upgrading two of the CWB's six-channel K2 digital accelerographs to take an R-1 rotational velocity sensor as an external input. We call this instrument K2 + R1. The K2 is a well-known accelerograph made by Kinemetrics, Incorporated; a detailed description and technical specifications, including the transfer function of its internal accelerometer, can be found at the manufacturer's web site (http://www.kinemetrics.com/). R. L. Nigbor kindly tested these upgraded units in his indoor and outdoor testing facilities in southern California in the fall of 2006; a preliminary evaluation report was released by Nigbor and Lee (2006). After these two instruments were shipped back to Taiwan, C. C. Liu also tested these upgraded units in his laboratory.

Very recently, Nigbor *et al.* (2009) carried out an extensive test 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. The transfer function of the R-1 sensor can be found at the manufacturer's web site (http://www.eentec.com/). The instrument response is nearly flat from 0.1 to 20 Hz, as confirmed by Nigbor *et al.* (2009), and its self noise is $< 10^{-6}$ rad/sec root mean square in the same frequency band. Therefore, we concluded that the R-1 is capable of measuring rotational velocity expected from small ($M \sim 4$–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 and deployed at the HGSD station in April 2007 to start our Phase 2 operation. A new vault was constructed at the HGSD station to house the K2 + R1 instrument. In addition, a six-channel, 24-bit Quanterra Q330 datalogger was deployed to record ground acceleration using a Kinemetrics' EpiSensor and to record ground velocity using a Mark Product short-period seismometer (Model L-4A; 2 Hz natural frequency). Instruments in operation during our Phase 2 operation are shown in Figure 1. A closer look of the instruments deployed in the new vault for our Phase 2 operation is shown in Figure 2. The K2 + R1 instrument is at the left-hand side, the yellow box is the R-1 rotational velocity sensor, the three-component short-period seismometer is at the upper right-hand side, and the three-component EpiSensor accelerometer is at the lower right-hand side.

Since May 2007, the problems encountered in our Phase 1 operation have been corrected. From 8 May 2007 to 17 February 2008, over 50 local earthquakes were recorded by the K2 + R1 instrument. Locations of earthquakes with good (signal-to-noise ratio >~5) rotational motions recorded at the HGSD station are shown in Figure 3, using the earthquake catalog information published by the Central Weather Bureau (2007, 2008). Unfortunately, field operation was interrupted due to flooding of the HGSD station site in mid-February 2008; we just resumed normal operation in May 2008.

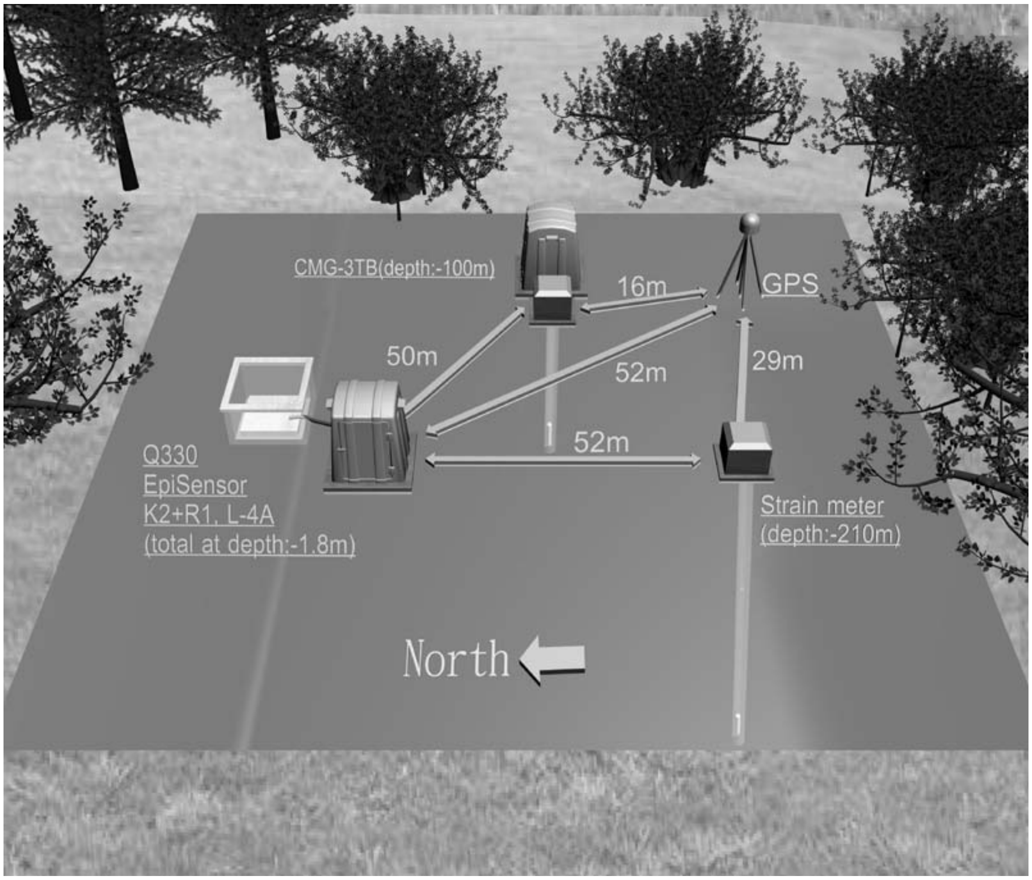

Figure 1. Instruments operated at the HGSD station during the Phase 2 operation (2007–2008). See text for an explanation.

Data Obtained during the Phase 2 Operation

In a numerical simulation, Bouchon and Aki (1982) obtained a maximum rotational velocity of 1.5 mrad/sec produced by a buried 30 km long, strike-slip fault with slip of 1 m (i.e., an $M \sim 6$ earthquake) in the vicinity of the source. Preliminary data analysis suggests that the observed peak rotational velocity (PRV) for $M \sim 5$ earthquakes in the midfield is at the mrad/sec level, many times larger than that expected from the classical elasticity theory.

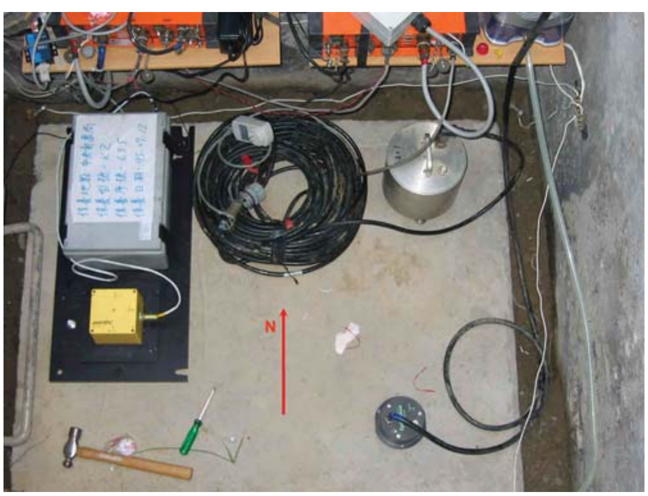

Figure 2. A closer look at the instruments deployed in the new vault for the Phase 2 operation (2007–2008). See text for an explanation.

The largest PRV recorded during our nine month Phase 2 operation 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 (coordinated universal time [UTC]). Figure 4 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, and the accelerometer response is flat from DC to 50 Hz (http://www.kinemetrics.com/). The peak ground acceleration (PGA) recorded is 0.47 m/sec^2, with much higher amplitudes for the two horizontal components than that for the vertical component. Figure 5 shows the amplitudes and spectra of rotational velocity from its external three-component rotational velocity sensor (Model R-1 by eentec) for the same earthquake. The plotted data have not been corrected for instrument response. Please note that the rotational velocity sensor is a much more narrowband instrument than the accelerometer, and its response is nearly flat from 0.1 to 20 Hz,

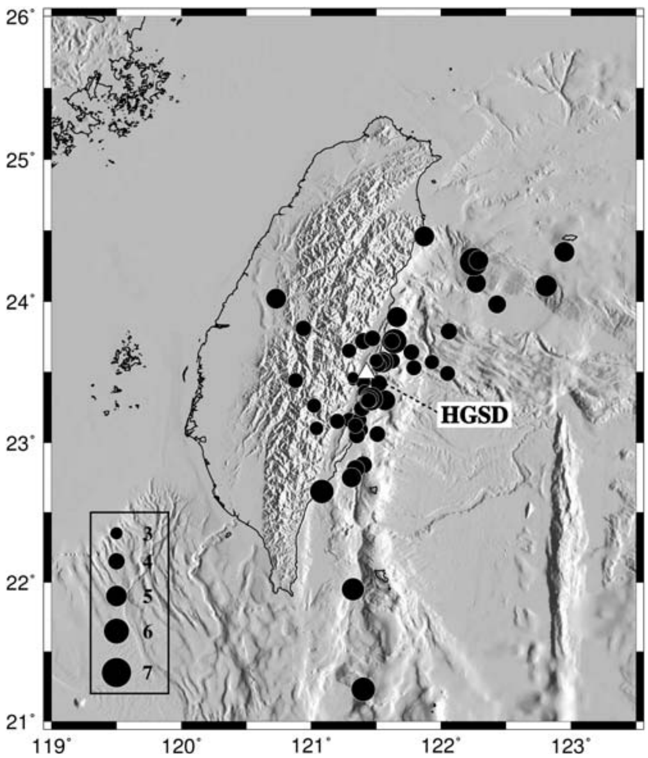

Figure 3. Location of earthquakes with good rotational motions recorded at the HGSD station in eastern Taiwan from 8 May 2007 to 17 February 2008. The size of the dot is proportional to the earthquake magnitude (M); sample dot sizes are shown in the legend.

as discussed in the previous section. The PRV recorded is 0.63 mrad/sec for the vertical component, with much higher amplitudes for the vertical component than that for the two horizontal components. The spectra in Figure 4 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 5 show that the dominant frequency band in ground rotational velocity is from about 2.5 to 5.5 Hz for the vertical component.

Table 1 provides a summary of our observations from 52 earthquakes during the nine month Phase 2 operation, which ended due to an unfortunate flooding of the station site. The hypocenter information was extracted from the seismological bulletins of the Central Weather Bureau (2007, 2008). The local magnitude (M_L) of these earthquakes ranged from 2.6 to 6.6, and the hypocentral distance from the HGSD station ranged from 14 to 260 km. The PGA was determined by searching for the maximum absolute value in the acceleration time-history record. The PRV for a given earthquake was determined in a similar manner from the corresponding rotational velocity time-history record. PGA ranged from 0.004 to 0.47 m/sec^2, or about 5%g, and PRV ranged from 0.004 to 0.63 mrad/sec.

The largest local earthquake during the nine month period occurred at 17:51 on 6 September 2007 (UTC) at a hypocentral distance of 133 km from the HGSD station. Its moment magnitude is 6.2 as determined by the Harvard Global CMT Catalog (http://www.globalcmt.org/). The PGA is 0.47 m/sec^2 and the corresponding PRV is 0.52 mrad/sec.

Figure 6 shows the PRV versus PGA and may suggest an approximate linear relationship between these two parameters, as previously noted by several authors. However, our data set is small and we will need far more data to establish any significant relationship. Nevertheless, Lee *et al.* (2009) performed a data fitting to these data and to the data presented by Takeo (2009), and they discussed this linear relationship.

Conclusions

In summary, our Phase 1 operation (2004–2006) was a learning exercise, and our Phase 2 operation (8 May 2007–17 February 2008) yielded some interesting records of rotational ground motions from over 50 local earthquakes during a nine month period. The local magnitude of these earthquakes ranged from 2.6 to 6.6, and the hypocentral distance ranged from 14 to 260 km. The largest PRV (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 on 23 July 2007. This value is many times larger than that expected from the classical elasticity theory. Previously, Takeo (1998) observed even much larger than expected rotational velocity in the source vicinity (at 3 km distance) of $M \sim 5$ earthquakes: the highest PRV was 26 mrad/sec from an M 5.2 earthquake. Therefore, PRV appears to have decreased by a factor of 40 from a near source to a midfield location.

Unfortunately, field operations were interrupted due to flooding of the HGSD station site in mid-February 2008; we just resumed normal operation in June 2008. We plan to deploy an accelerometer array with rotational sensors at a different site in eastern Taiwan than the HSDS site (due to flooding consideration) in the near future. Our goal will be to directly verify the rotational ground motions from local earthquakes with multiple sensors and to compare them with the rotational ground motions, which can be inferred indirectly from accelerometer array observations. We also need to record far more earthquakes with both rotational and translational ground-motion instruments to establish any relationships between these two types of ground motions, especially from local earthquakes that generate greater than 5%g PGA at our recording site.

Data and Resources

All seismograms described in this article were collected by the authors and will be archived at the web site of the International Working Group on Rotational Seismology

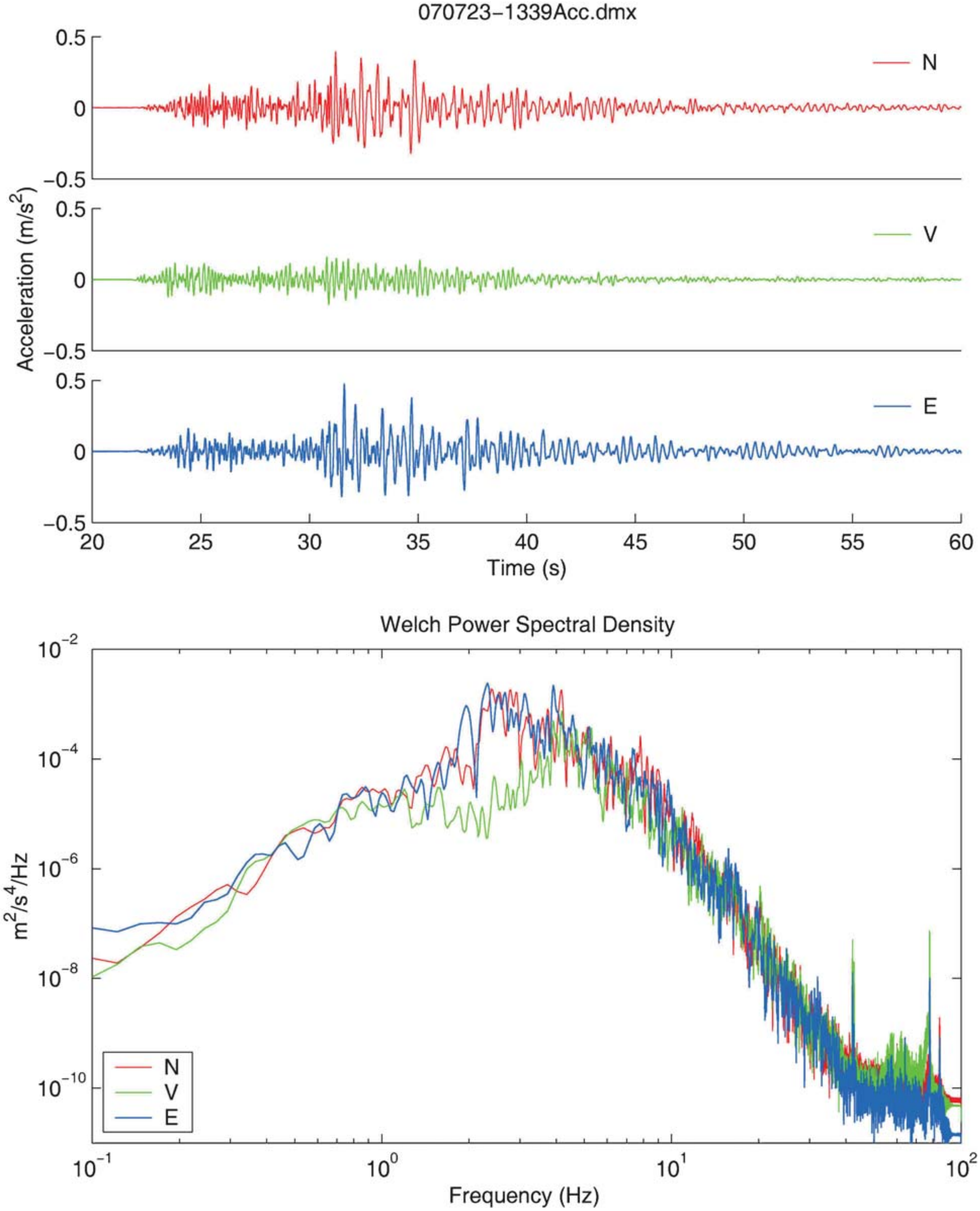

Figure 4. Amplitudes and spectra of translational acceleration recorded by the K2 + R1 instrument at the HGSD station from its internal three-component accelerometer for the earthquake on 23 July 2007.

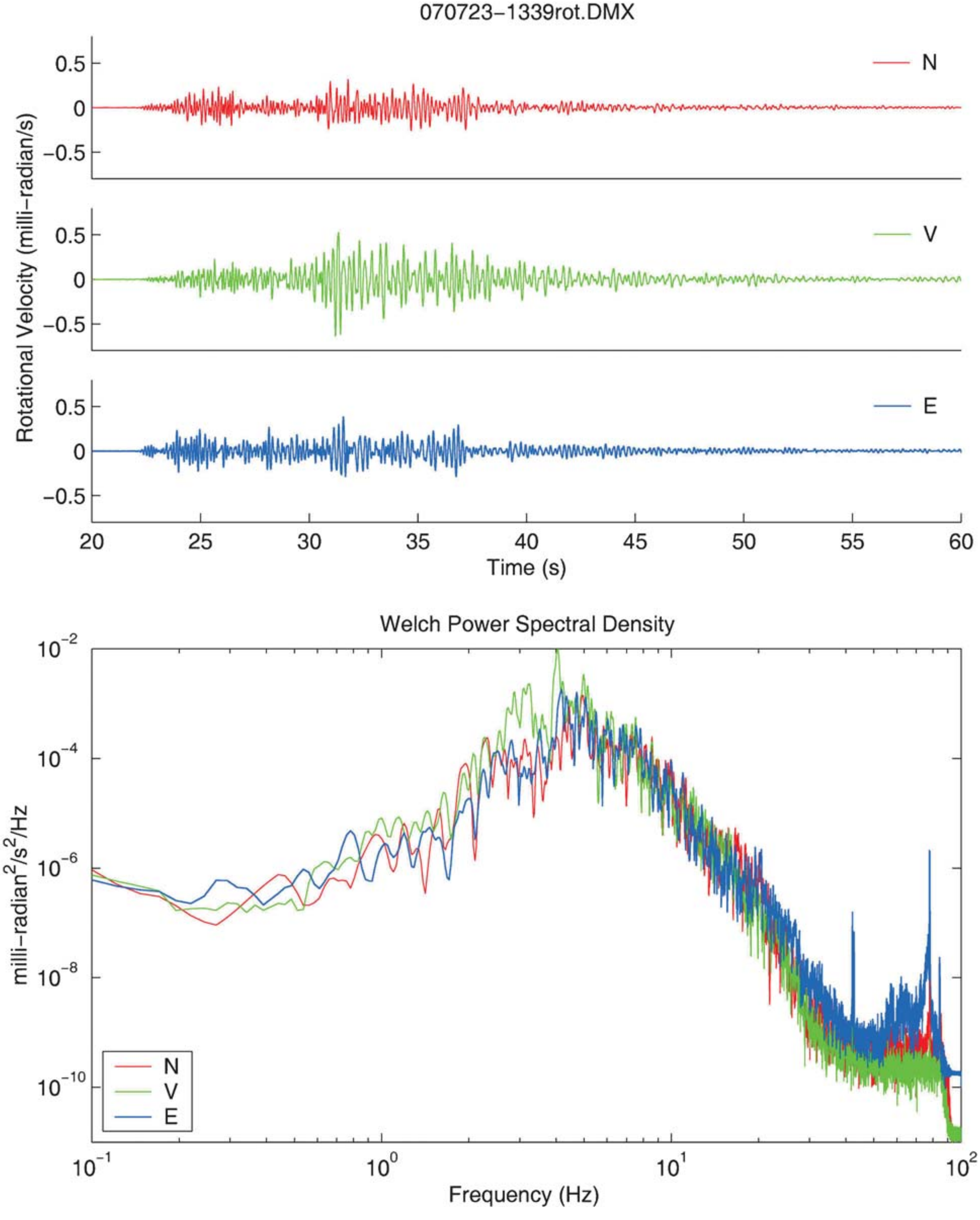

Figure 5. Amplitudes and spectra of rotational velocity recorded by the K2 + R1 instrument at the HGSD station from its external three-component rotational velocity sensor for the earthquake on 23 July 2007.

Table 1
A List of 52 Earthquakes with Good Rotational Ground Motions Observed during the Phase 2 Operation, with Observed Peak Ground Acceleration (PGA) and Peak Rotational Velocity (PRV)

Date (mm/dd/yyyy)	Origin Time (hr:min:sec)	Latitude (°)	Longitude (°)	Depth (km)	M_L	M_w	DataFile Name	Distance (km)	PGA (m/sec^2)	PRV (mrad/sec)
05/08/2007	11:02:38.42	23.58	121.62	25.6	3.79		BL004.EVT	33.9	0.011	0.017
05/10/2007	11:11:47.90	23.81	120.94	24.0	3.85	3.31	BL006.EVT	65.2	0.007	0.008
05/15/2007	17:16:12.22	23.44	121.32	12.6	2.57		BL007.EVT	17.4	0.009	0.012
05/15/2007	19:54:0.51	23.43	121.40	26.1	3.44		BL008.EVT	27.0	0.011	0.019
05/27/2007	13:01:20.30	23.09	121.38	20.7	3.52		BL010.EVT	49.3	0.007	0.009
05/29/2007	07:21:52.82	23.36	121.41	28.6	3.36		BL011.EVT	32.1	0.015	0.024
06/01/2007	03:51:22.37	22.84	121.40	6.9	4.18	3.91	BL012.EVT	72.6	0.008	0.015
06/15/2007	20:29:13.49	23.30	121.57	37.6	4.91	4.08	BL013.EVT	45.6	0.088	0.093
06/19/2007	15:07:43.55	24.35	122.95	55.9	4.91		BL014.EVT	190.9	0.014	0.016
06/21/2007	03:23:47.11	24.11	122.81	45.4	5.12		BL015.EVT	163.6	0.021	0.036
06/21/2007	04:08:17.42	21.23	121.40	71.0	5.68		BL016.EVT	260.4	0.013	0.017
06/25/2007	03:59:34.05	23.05	121.35	32.6	3.91		BL017.EVT	59.3	0.011	0.013
06/26/2007	14:47:36.25	23.16	121.29	5.8	3.51	3.36	BL018.EVT	39.7	0.012	0.011
06/30/2007	11:36:15.29	23.10	121.04	5.6	3.38		BL019.EVT	58.8	0.004	0.004
07/03/2007	11:55:23.09	23.72	121.40	22.3	4.00	3.55	BL020.EVT	33.7	0.042	0.047
07/16/2007	23:42:52.18	23.57	121.55	32.7	4.95	4.38	BL021.EVT	36.1	0.219	0.353
07/17/2007	22:42:31.92	23.57	121.54	33.1	4.23	3.63	BL022.EVT	36.1	0.072	0.098
07/18/2007	12:40:42.15	23.16	121.37	31.2	3.53		BL023.EVT	48.5	0.006	0.009
07/20/2007	22:07:33.25	23.79	122.06	23.7	4.05		BL024.EVT	76.6	0.010	0.012
07/23/2007	13:40:2.44	23.72	121.64	38.6	5.77	5.07	BL025.EVT	51.1	0.474	0.634
07/23/2007	14:04:41.66	23.72	121.62	36.6	3.80		BL026.EVT	48.7	0.010	0.013
07/29/2007	20:20:27.43	23.26	121.02	5.9	3.54		BL027.EVT	49.0	0.024	0.018
07/30/2007	13:12:31.99	23.46	121.32	9.0	2.86		BL028.EVT	14.3	0.017	0.025
08/01/2007	12:55:19.04	23.15	121.20	8.2	3.68		BL030.EVT	45.0	0.009	0.013
08/05/2007	00:18:55.07	23.57	121.93	16.3	3.53		BL031.EVT	54.9	0.007	0.014
08/08/2007	10:28:7.64	23.06	121.51	12.9	3.82		BL032.EVT	50.3	0.014	0.022
08/09/2007	00:55:47.36	22.65	121.08	5.5	5.68	5.09	BL033.EVT	99.8	0.054	0.045
08/10/2007	08:18:8.20	23.53	121.79	21.0	3.71		BL034.EVT	43.0	0.012	0.029
08/10/2007	12:48:55.63	23.64	121.77	21.4	3.90		BL035.EVT	44.4	0.023	0.056
08/10/2007	22:52:10.18	24.13	122.27	22.2	4.67		BL036.EVT	113.8	0.009	0.008
08/29/2007	03:00:16.45	21.95	121.32	6.8	5.33	5.12	DT002.EVT	171.2	0.016	0.013
09/03/2007	03:24:34.37	23.44	120.88	6.6	3.60		DT003.EVT	56.2	0.005	0.010
09/03/2007	07:47:35.98	23.55	121.52	29.2	3.55		DT004.EVT	31.4	0.013	0.023
09/04/2007	12:16:33.49	23.89	121.66	40.4	4.84	4.2	DT005.EVT	64.4	0.024	0.031
09/06/2007	17:51:26.92	24.28	122.25	54.0	6.63	6.17	DT006.EVT	132.8	0.469	0.523
09/07/2007	19:51:14.04	24.29	122.29	54.2	4.68		DT008.EVT	136.2	0.014	0.015
09/17/2007	20:13:17.94	23.65	121.29	7.9	3.57		DT010.EVT	23.5	0.021	0.037
09/18/2007	19:34:22.61	23.42	121.52	21.5	3.97		DT011.EVT	24.9	0.070	0.095
09/22/2007	06:27:4.51	24.46	121.87	22.5	4.77	4.16	DT012.EVT	118.6	0.009	0.010
10/31/2007	19:00:45.82	23.58	121.50	29.3	3.27		US002.EVT	31.8	0.009	0.015
11/01/2007	17:14:19.57	23.98	122.43	3.2	4.33		US003.EVT	116.1	0.005	0.009
12/24/2007	18:48:35.61	24.02	120.73	23.4	4.86	4.09	VA055.EVT	94.8	0.024	0.029
01/01/2008	07:32:23.13	23.24	121.39	38.1	3.90		VA056.EVT	47.3	0.013	0.019
01/08/2008	13:26:37.77	22.81	121.34	24.0	4.31	3.73	VA062.EVT	79.7	0.015	0.022
01/16/2008	09:19:58.75	23.49	122.05	35.3	3.64		VA065.EVT	73.0	0.012	0.019
01/20/2008	19:12:39.77	22.75	121.31	89.9	4.64		VA066.EVT	122.3	0.005	0.010
01/29/2008	18:33:38.14	23.74	121.47	9.1	3.79	3.1	VA067.EVT	29.3	0.010	0.014
02/02/2008	06:28:45.49	23.12	121.34	20.2	3.71		VA068.EVT	46.6	0.013	0.015
02/17/2008	20:33:2.32	23.31	121.46	28.3	5.43	5.03	VA069.EVT	34.9	0.322	0.494
02/17/2008	20:47:56.72	23.30	121.43	26.1	3.60		VA070.EVT	33.6	0.019	0.025
02/17/2008	20:54:34.39	23.31	121.45	26.8	4.10		VA071.EVT	33.6	0.057	0.086
02/17/2008	21:34:51.01	23.30	121.44	26.0	3.73		VA072.EVT	33.6	0.023	0.039

Note: the hypocenter is given by latitude, longitude, and depth; M_L is local magnitude as determined by the Central Weather Bureau; the DataFile Name is the original filename recorded by the K2; the distance measured is the hypocentral distance to the HGSD station in kilometers; PGA is the peak ground acceleration as observed by the K2 accelerometer in m/sec^2; PRV is the peak rotational velocity as observed by the R-1 rotational velocity sensor in mrad/sec.

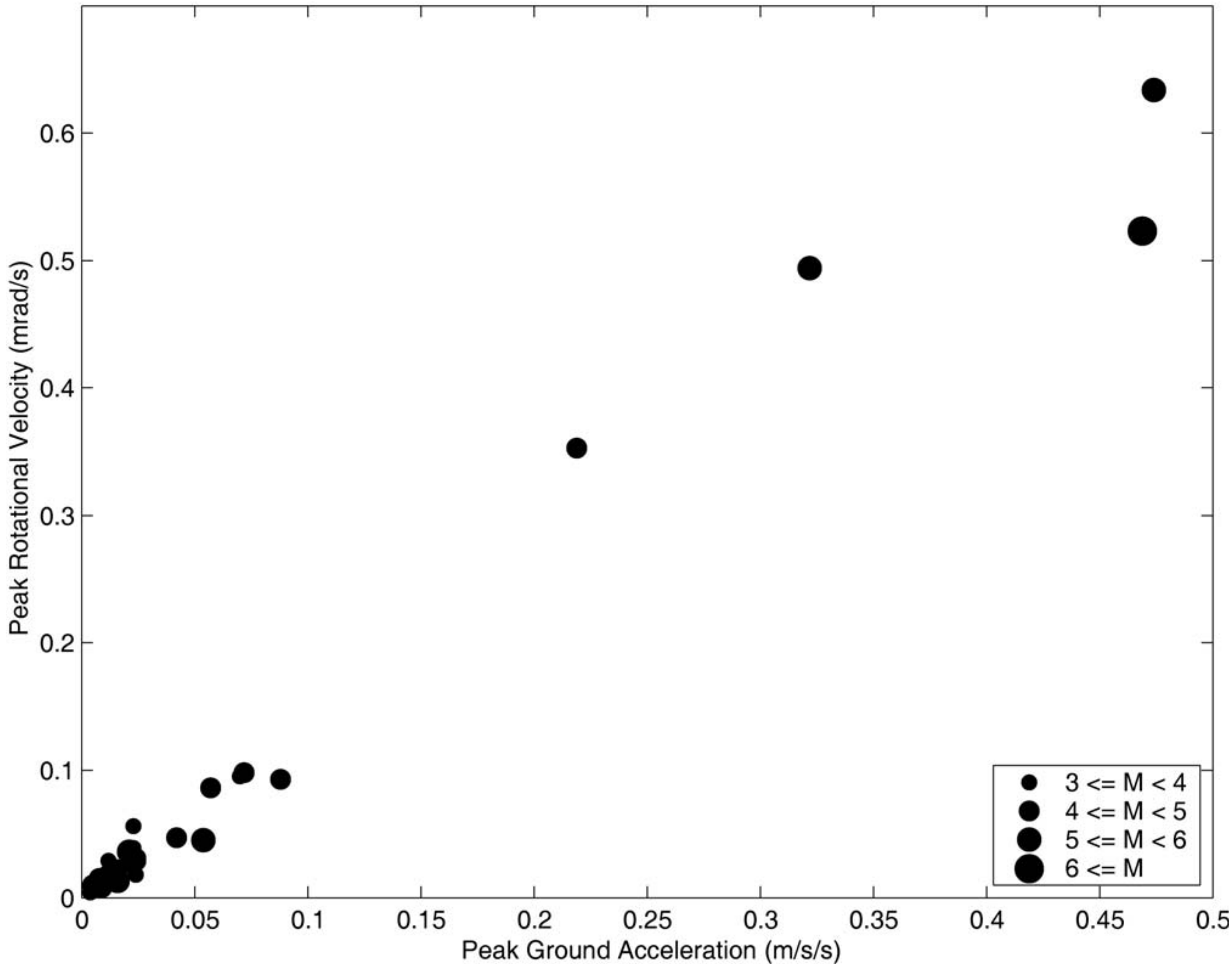

Figure 6. PRV versus PGA for the earthquake data set from 8 May 2007 to 17 February 2008. Dot size is proportional to earthquake magnitude as indicated by the legend in the lower right-hand corner.

(http://www.rotational-seismology.org/) for open access. All other data used have been published.

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