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NOTES AND CORRESPONDENCE

Seismic Observations in the Taipei Metropolitan Area Using the Downhole Network

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ABSTRACT

Underlain by soft soils, the Taipei Metropolitan Area (TMA) experienced major damage due to ground-motion amplification during the Hualien earthquake of 1986, the Chi-Chi earthquake of 1999, the Hualien earthquake of 2002 and the Taitung earthquake of 2003. To study how a local site can substantially change the characteristics of seismic waves as they pass through soft deposits below the free surface, two complementary downhole seismic arrays have been operated in the TMA, since 1991 and 2008. The accelerometer downhole array is composed of eight boreholes at depths in excess of 300 meters. The downhole array velocity sensor collocated with accelerometer composed of four boreholes at depths up to 90 meters. The integrated seismic network monitors potential earthquakes originating from faults in and around the TMA and provides wide-dynamic range measurement of data ranging in amplitude from seismic background noise levels to damage levels as a result of shaking. The data sets can be used to address on the response of soft-soil deposits to ground motions. One of the major considerations is the nonlinear response of soft soil deposits at different levels of excitation. The collocated accelerometer and velocity sensors at boreholes give the necessary data for studies of non-linearity to be acquired. Such measurements in anticipation of future large, damaging earthquakes will be of special importance for the mitigation of earthquake losses.

Key words: Taipei Metropolitan Area, Borehole, Accelerograph, Broadband, Nonlinear response

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1. INTRODUCTION

It is a well known phenomenon that local geological conditions can substantially change the characteristics of a seismic wave. In particular, a wave of certain frequencies can be amplified considerably by thick sections of unconsolidated near-surface deposits. Structural damage and consequent loss of life from modern earthquakes such as the 1985 Mexico, the 1989 Loma Prieta, California, and the 1995 Kobe, Japan, earthquakes imply that a major portion of the damage occurs in areas underlain by soft soils.

The Taipei basin is located between the Yangming Mountains and the Central Mountains in northern Taiwan. The interior is flat, and the area underlain by soft water saturated clays, sands, and silts. Taipei city is in the middle and slightly eastern part of the Taipei Basin. It is the largest and most densely populated city on the island of Taiwan and serves as its financial and governmental center. The city and surrounding Taipei County along with nearby Keelung City together form the TMA. In TMA, damage from the 1986 Hualien earthquake, 1999 Chi-Chi earthquake, the 2002 Hualien earthquake, and the 2003 Taitung earthquake was concentrated in the area underlain by soft soil deposits. In order to provide basic ground motion data to measure the re-

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sponse of these deposits at the TMA, it was decided in early 1990 to establish Taipei Basin Downhole Seismic Network (TBDSN). Such measurements of the next large damaging earthquake will be of special importance for mitigation of future earthquake losses.

The TBDSN is a local network of strong motion and broadband downhole seismic arrays distributing TMA. The network is designed to improve resolution for monitoring seismicity at the target fault in the TMA and to provide high quality data for research projects in local, regional and teleseismic seismology. Since 2008 the TBDSN has grown from the original 7 boreholes installed in 1991 - 2001 to 12 boreholes, including 8 strong motion downhole arrays and 4 boreholes with collocated sets of accelerometers and velocity sensor. Figure 1 illustrates the location of the initial and subsequent expansion of the downhole network. The boreholes with broadband installations are new to IES because of its round the clock monitoring of seismic activity in the TMA. The broadband and strong motion downhole arrays join to provide comprehensive data to study the amplification characteristics of soft soil deposits with different excitation levels in this seismically hazardous area. At present the TMA itself has relatively low seismic activity; however, it does provide IES with an observation tool to serve as a guide for future station installations in the Taiwan area.

This report describes the operational history of the downhole seismic network, their sites, technical efforts in instrumentations, and the recordings of seismic motions for local earthquakes as well as teleseismic events.

2. TBDSN OVERVIEW

2.1 July 1991 - June 1996

In 1990, Institute of Earth Sciences (IES) in the Academia Sinica was contracted by the Central Geological Survey (CGS) in the Ministry of Economic Affairs to execute a project entitled "An Integrated Survey of Subsurface Geology and Engineering Environment of the Taipei Basin." In this project, four borehole sites were chosen because of accessibility and of variation in subsurface structure. The borehole was drilled at the Wuku Sewage Disposal Plant (WK) and at the Panchiao Water Conservancy Bureau (BS) in 1993, at the Panchiao Vocational Advisory Committee for Retired Servicemen (TF) in 1994, and at the Luchou water pump station (LC) in 1995. All are located in the western parts of the TMA (Fig. 1). The locations of the arrays are listed in Table 1.

At each site, a concrete pad (150 cm × 150 cm) was poured at each borehole to accommodate the recorders, storage batteries, and electronic equipment. Another pad (30 cm × 30 cm, with 15 cm depth) was poured to hold the borehole sensors in position once they had been lowered to the proper depths. Each array consists of one surface sensor and borehole sensors at varying depths. The surface and borehole strong motion instruments are three-component Kinemetrics FBA23 and FBA-23DH with ±2 g dynamic range. The emplacement depths of the four arrays in the holes are listed in Table 1. At TF, the depth at the bottom of the borehole is below the bedrock interface. The recorders at all sites are

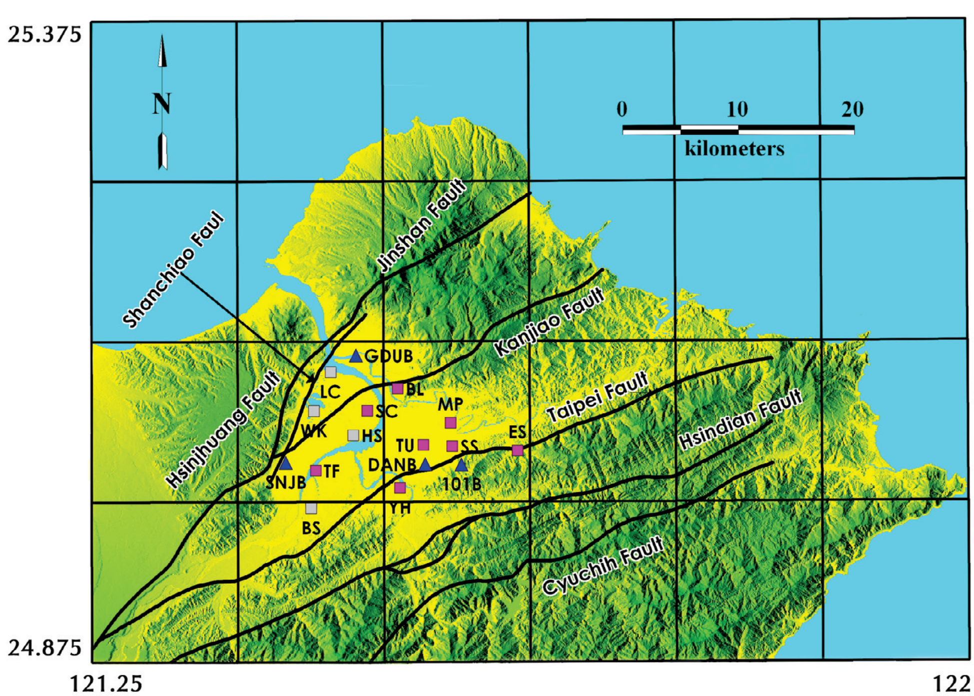

Fig. 1. The locations of the downhole arrays and their relationships to the faults around the Taipei metropolitan area. The accelerographic arrays with pink-square are in operation. The broadband arrays are triangulated.

Table 1. Parameters for downhole seismic arrays and their emplacement depths.

Stco	Lat. (E)	Lon. (N)	Operation period	Sensors	Depth (m)	Location
WK	121.44013	25.07112	199312 - 200503	FBA23 FBA23DH FBA23DH FBA23DH FBA23DH FBA23DH	0 30 60 90 141 350	Sewage Disposal Plant, Wuku
BS	121.43770	24.99520	199312 - 199812	FBA23 FBA23DH FBA23DH FBA23DH	0 25 59 80	Water Conservancy Bureau, Panchiao City
LC	121.45470	25.10130	199503 - 199906	FBA23 FBA23DH FBA23DH	0 100 300	Water Pump Station, Luchou City
HS	121.47370	25.05220	199601 - 199906	FBA23 FBA23DH FBA23DH	0 100 300	Chongshin Bridge, Sanchong City
TF	121.44470	25.02800	199502 -	FBA23 FBA23DH FBA23DH FBA23DH FBA23DH	0 22 60 110 300*	Vocational Advisory Committee for Retired Servicemen, Panchiao City
SS	121.55828	25.04346	199707 - 200109 200506 -	FBA23 FBA23DH FBA23DH FBA23DH	0 30 49 150*	Songshan Tabacco Plant, Xinyi District, Taipei City
MP	121.55721	25.06155	199909 -	FBA23 FBA23DH FBA23DH FBA23DH	0 26 46 100*	Minquan Park, Songshan District, Taipei City
TU	121.53382	25.04454	200303 -	FBA23 FBA23DH FBA23DH FBA23DH	0 21 50 220	National Taipei Univ. of Science and Technology, Daan District, Taipei City
YH	121.49760	25.01440	200305 -	FBA23 FBA23DH FBA23DH	0 50 198*	Renai Park, Yeong Ho City
BL	121.51193	25.08884	200306 -	FBA23 FBA23DH FBA23DH FBA23DH	0 27 70 230	Bailin Park, Shilin District, Taipei City
ES	121.61435	25.03986	200605 -	AS3257 AS3250 AS3250 AS3250	0 13 20* 50	Research Center for Environmental Changes of IES
SC	121.48594	25.07123	200803 -	AS3257 AS3250 AS3250 AS3250 AS3250	0 50 100 200 300	228 Park, Sanchong City
DANB	121.53520	25.02940	200509 -	AS3250 VSE355G3R	50 90	Daan Park, Taipei City
GDUB	121.47630	25.11450	200610 -	AS3250 VSE355G3R	50 150	Guandu Nature Park, Taipei City
SNJB	121.41609	25.03069	200711 -	AS3250 VSE355G3R	50 100	Life Hall Park, Hsinjhuang City
101B	121.56640	25.02910	200612 -	VSE355G3R	100*	Disaster Prevention and Response Act Division, Taipei City Fire Department

* *depth of boreholes down to the bedrock.*

19-bit Kinemetrics K2 models. These recorders handle up to twelve input channels at a high rate of 200 samples per second. Events are recorded in an event triggered mode. Absolute time and each of the various recording parameters are recorded simultaneously.

2.2 July 1996 - June 2001

The initial phase of the downhole observations in TMA was finished in June 1996. In order to continue providing basic ground motion data to evaluate site response effects in this area, the CGS decided to initiate the second phase of the program in the TMA to continue monitoring earthquakes.

The new boreholes are placed at six different sites on the eastern side of TMA (Fig. 1). They are at the Chongshin Bridge (HS) in the Sanchong City, at the Songshan Tabacco Plant (SS) in the Xinyi district, at the Minquan Park (MP) in the Songshan district, at the National Taipei Univ. of Science and Technology (TU) in the Daan district, at Bailin Park (BL) in the Shilin district and at Renai Park of Yengho City (YH). The downhole arrays at HS, SS and MP were completed in 1996, 1997 and 1999, respectively. The procedures of installation and hardware of borehole accelerometer are the same as the initial phase. The sensor at the bottom of the boreholes of SS and MP is below the bedrock interface. It should be noted that accelerometers were not installed at three drilled borehole sites of TU, BL and YH. Station descriptions are summarized in Table 1.

The downhole network operated quite reliably until late 1998, when Taipei's rapid transit Metro system was constructed and flood damage reduction improvements were carried out by the Panchiao and Lochou Water Resources Agencies, Taipei County Government. Four sites of the boreholes (BS, LC, HS, and SS) were removed because of their locations in construction areas. A detailed description of the installation and operation of the accelerometer downhole seismic network is provided by Wen et al. (1993), Wen (1994, 1995, 1999), and Wen and Yeh (1996, 1997, 1998).

2.3 2002 - 2003

In February 2002, the CGS concluded an agreement with IES to move six stations of the TBDSN to IES. This includes three existing stations (WK, TF, MP) as well as the three drill sites (TU, BL, YH). To ensure continuity in monitoring seismic events in the TMA, the IES contribution to the TBDSN new instruments for the three drilling sites. Hardware installation procedures were the same as prior downhole arrays and completed in June 2003. The emplacement depths of the accelerometers in the three holes are summarized in Table 1. The sensor at the bottom of the boreholes of BL and YH is below the bedrock interface. Figure 2 shows an example configuration of the borehole site at TU.

2.4 2004 - 2007

Seismic studies done between 1991 and 2004 in the TMA relied on free-field and downhole network used accelerographs as well. It is still difficult to use the data efficiently. This is because they were limited in their triggering scheme for large earthquakes. A question of particular interest concerns the ground response of soft soil deposits as modified by different ground shaking (i.e., non-linearity). The question of the extent to which weak motion signals can be used to predict strong-motion behavior remains unanswered; it is therefore important to place broadband borehole seismometers as elements of a seismic network for site response studies. For this purpose, two new projects entitled "Seismic Activity in the Taipei Basin and its Surrounding Area" and "Strong Motions, Active Faults, and Earthquakes

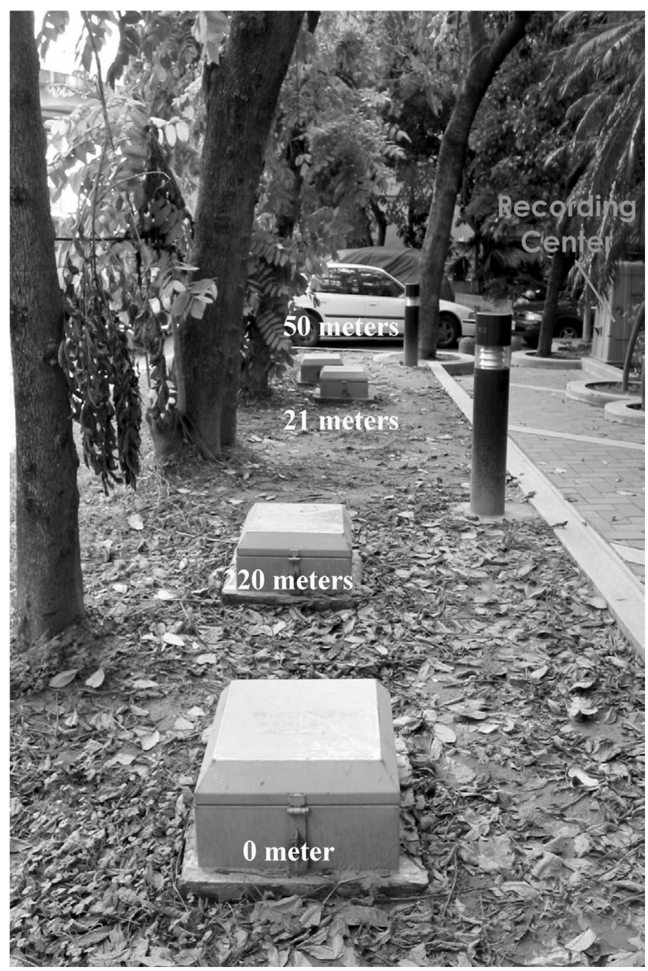

Fig. 2. The layout of accelerometer array at the TU borehole site. The emplacement depths of the accelerometers in the three holes are 21, 50, and 220 meters. An accelerometer was also placed at the surface next to the boreholes.

in the Taipei Metropolitan Area" (SAFE-Taipei) were initiated by CGS and Academia Sinica in 2004 and 2005, respectively. The two projects planned to add six boreholes as part of TBDSN to improve the ability for detecting microearthquakes as well as for monitoring region seismic activity at the magnitude 3+ levels induced by faults nearby the TMA. Selection of the boreholes is dependent on the site conditions such as geology, communications and accessibility, as well as the position of the present downhole network, which is situated mostly on the eastern side of the TMA.

Four of the new boreholes were designed to have a similar configuration with collocated sets of Tokyo Sokoshin AS-3250 accelerometers and VSE-355G3R velocity sensors. The four boreholes are at Daan Park (DANB), Guandu Nature Park (GDUB), Disaster Prevention and Response Act Division of the Taipei City Fire Department near Taipei 101 (101B), and Hsinjhuang Life Hall Park (SNJB). Accelerometers emplaced at a depth of 50 meters from the surface and velocity sensors at the bottom of the borehole, at either near 100 or 150 meters. The AS-3250 has the ability to record shaking levels as high as 2 g. The VSE-355G3R is intended to provide high resolution recordings ranging in amplitude from seismic background noise levels to damage inducing levels of 200 cm sec^{-1}. Their outputs are digitized with a 24-bit Q330 Kinematrics datalogger with 6 channel systems. The stations record continuously at 100 and 20 samples per second. An onsite backup capability was also installed in the form of 20 GB Baler-14 disk devices from Kinemetrics. Data from all broadband downhole arrays are transmitted continuously to IES using Digital Subscriber Line (ADSL). The ADSL transmissions permit the retrieval of critical event and instrument data in near real time. These data are especially useful in checking on the system health of the array and its data quality, and providing initial evaluations following a major event.

Two additional accelerometer boreholes at the Research Center for Environmental Changes hosted by IES (ES) and at 228 Park of Sanchong City (SC) were also constructed. Each borehole includes sensors located at depths ranging from the surface to different levels. The surface and borehole accelerometers are Tokyo Sokoshin AS-3257 and AS-3250, respectively. Events were recorded in an event triggering mode. Borehole ES is equipped with a 19-bit Kinemetrics K2 recorder and a 24-bit Tokyo Sokoshin SAMTAC-700 recorder is provided at borehole SC. Both boreholes record data at 200 samples per second.

Prior to installation, downhole velocity surveys measured both compressional-wave (Vp) and shear-wave velocity (Vs) profiles by using the suspension method every 0.5 meter down to bottom of the boreholes. Figure 3 shows the velocity structures at DANB, GDUB and SNJB. In general, the Vp and Vs increase with depth and are different from site to site. Such measurements are important to relate seismic response of sedimentary layers to the subsurface conditions at the borehole sites. A summary of the logs for each of the sites is given by the Ton Yuan Technology & Engineering Co., Ltd. (2005, 2006, and 2007).

During the expansion of TBDSN, the WK boreholes were shut in 2005 because the Water Resource Agency in Ministry of Economic Affairs decided to construct the Erchong Floodway to reduce flood damage caused by Dahan Shi in the raining season. In the meantime, the SS boreholes were reinstalled to continue providing seismic data.

3. SEISMIC OBSERVATIONS FROM TBDSN

3.1 Accelerometer Downhole Array Results

Since the accelerometer downhole array was installed in the TMA and thereafter through the end of 2007, there were no significant events in the vicinity of the TMA. To this end, a total number of twenty-nine earthquakes from 2003 to 2007 were selected to list in Table 2 as a result of

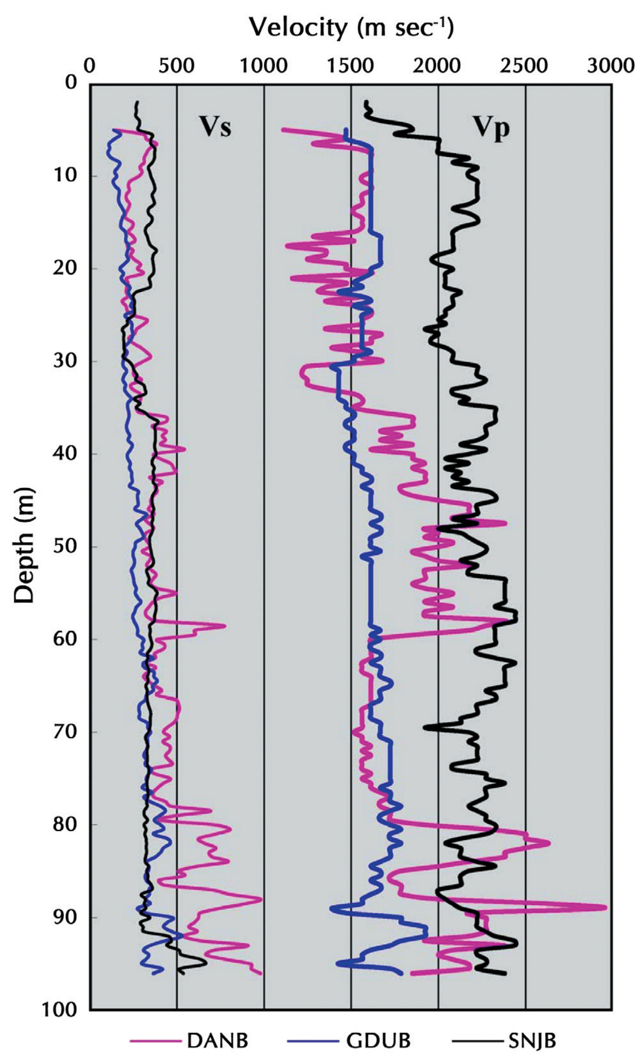

Fig. 3. The velocity structures of Vp and Vs at the DANB, GDUB and SNJB borehole sites.

Table 2. Parameters for earthquakes recorded by strong-motion downhole arrays and their PGA at surface.

Origin time (UT)	Epicenter		Depth (km)	Mag. (ML)	T	PGA (gals) at surface in vertical, east-west and north-sourth components							
	Lat (N)	Lon (E)				TU	SS	YH	WK	TF	ES	BL	MP
2003 06 09 01 52 50.57	23-30.22	121-40.95	32.3	6.5	5	8.1, 23.0, 23.7		5.8, 4.7, 5.6		13.7, 28.8, 28.6		12.4, 20.6, 28.2	5.5, 12.9, 17.1
2003 06 09 05 08 04.68	24-22.81	121-51.08	2.4	5.0	6	4.3, 4.9, 7.7		5.8, 4.9, 7.7	1.3, 3.5, 3.9	5.3, 16.0, 12.7		6.8, 10.1, 11.9	2.7, 7.5, 6.2
2003 07 18 02 41 20.26	24-35.10	121-50.21	74.4	5.1	5	3.7, 11.2, 5.5		3.7, 6.8, 6.1	2.4, 4.9, 5.2			7.4, 16.2, 12.3	3.4, 7.1, 4.9
2003 08 11 16 30 13.81	24-35.55	121-33.57	58.5	5.4	4	9.1, 28.2, 26.9			8.0, 26.6, 30.1	17.0, 47.5, 24.0			6.0, 26.7, 13.6
2003 11 12 00 02 35.91	24-27.20	121-57.18	21.3	5.4	5	4.9, 9.5, 5.8		2.4, 7.9, 7.3	1.0, 4.9, 1.7			6.9, 5.4, 7.8	3.1, 5.9, 5.8
2003 12 29 13 41 50.75	24-35.75	121-57.86	68.2	5.2	5	6.5, 10.4, 8.6		5.5, 10.0, 10.6	2.9, 14.5, 3.6			8.8, 10.3, 16.6	3.5, 5.7, 10.2
2004 05 01 07 56 11.09	24-04.55	121-31.69	21.6	5.2	6	2.4, 5.6, 3.0		2.7, 5.4, 5.6	5.4, 11.0, 13.2	2.8, 3.5, 4.7		2.2, 3.5, 4.0	1.8, 4.0, 3.2
2004 05 09 20 06 47.57	24-34.15	121-45.98	69.2	5.4	4	5.2, 11.9, 10.9				2.6, 4.5, 3.1		2.5, 4.5, 6.8	2.6, 6.0, 7.6
2004 07 06 07 32 02.77	24-53.83	122-15.94	6.2	5.2	4	4.2, 6.6, 6.8		2.5, 5.7, 4.2				3.9, 4.0, 5.9	4.2, 6.2, 5.9
2004 10 15 04 08 50.18	24-27.74	122-51.10	91.0	7.1	5	12.3, 39.5, 33.0		18.6, 27.0, 30.7		17.3, 26.7, 35.7		12.9, 17.2, 25.9	10.9, 27.8, 29.4
2004 10 23 14 04 27.51	25-00.80	121-33.83	9.5	3.7	4	15.3, 44.5, 42.1		26.8, 27.1, 24.6				12.9, 21.7, 15.6	8.5, 18.6, 20.6
2004 11 08 15 54 55.86	23-47.69	122-45.62	10.0	6.6	5	9.8, 24.8, 19.4		8.4, 23.0, 18.5		10.3, 28.6, 18.7		13.8, 25.7, 22.0	8.7, 23.1, 20.7
2004 11 11 12 16 44.50	24-18.70	122-09.48	27.3	6.0	5	3.1, 9.8, 6.5		6.9, 7.8, 6.9		4.9, 6.1, 6.9		3.1, 4.7, 5.5	3.4, 7.3, 5.7
2005 03 05 19 06 51.73	24-39.28	121-50.45	6.4	5.9	5	14.3, 27.0, 30.1		10.4, 15.2, 16.3		17.8, 19.1, 26.7		19.0, 17.5, 22.2	10.1, 25.7, 24.1
2005 03 05 19 06 51.73	24-39.28	121-50.45	6.4	5.9	5	12.0, 29.6, 32.9		9.2, 17.6, 26.2		17.2, 26.4, 20.6		14.1, 26.0, 28.8	13.0, 24.3, 30.3
2005 04 30 14 48 17.23	24-02.11	121-37.47	8.4	5.6	3	1.9, 4.3, 5.6		1.7, 3.5, 8.7					1.9, 3.4, 3.7
2005 06 01 16 20 05.66	24-38.20	122-03.98	64.8	6.0	3	6.8, 15.6, 14.4		8.6, 23.5, 18.7					5.7, 11.7, 14.6
2005 09 06 01 06 00.41	23-57.49	122-17.01	16.8	6.0	5	2.7, 5.4, 6.9	4.1, 6.8, 7.0	3.2, 5.8, 4.1				3.2, 4.8, 6.5	2.2, 6.1, 6.6
2005 10 05 16 16 35.14	24-50.62	121-38.16	73.4	4.8	5	3.1, 6.3, 9.4	3.4, 5.9, 11.6	3.9, 4.5, 3.6		4.1, 10.3, 15.4			2.2, 4.0, 10.4
2005 10 15 15 51 04.36	25-05.98	123-48.45	190.9	7.0	5	12.3, 39.5, 33.0	3.2, 6.1, 8.5	18.6, 27.0, 30.7				3.0, 5.0, 4.9	3.0, 4.4, 6.0
2005 11 29 22 41 49.84	24-45.18	122-02.02	68.0	5.5	5	4.7, 10.5, 8.1	10.5, 33.4, 25.2	13.0, 15.9, 12.8		4.6, 10.1, 9.9			4.9, 13.5, 13.0
2005 12 05 10 15 29.98	25-00.20	121-34.54	10.7	3.7	6	13.8, 40.1, 34.0	24.7, 41.0, 76.1	31.9, 25.9, 19.3		18.1, 58.7, 49.3		23.2, 12.1, 20.3	9.8, 33.6, 39.0
2006 04 28 09 05 26.96	23-59.12	121-36.64	9.8	5.2	6	1.2, 3.3, 2.7	1.7, 2.1, 3.1	0.8, 2.0, 2.4		1.4, 2.3, 2.5		2.1 4.0, 2.5	1.0, 2.3, 2.0
2006 07 28 07 40 10.43	23-57.97	122-39.48	28.0	6.0	5	2.7, 6.9, 5.7	4.0, 6.8, 8.0	2.1, 5.2, 5.6		3.4, 9.3, 7.4	4.1, 1.5, 8.1		
2006 10 12 14 46 29.29	23-57.83	122-38.71	25.3	5.8	6	1.7, 5.3, 4.9	2.6, 7.8, 6.6	1.7, 3.7, 4.8			2.6, 7.8, 5.6	1.8, 3.2, 4.9	0.9, 2.3, 2.4
2006 12 23 17 28 27.19	24-48.41	122-19.16	9.8	5.4	6	1.1, 2.8, 2.4	1.9, 5.5, 7.3	1.5, 3.6, 2.1			5.4, 6.8, 6.5	1.2, 1.3, 3.0	1.1, 1.5, 3.3
2007 03 08 15 37 36.50	24-32.62	121-54.65	70.4	4.7	5	4.0, 4.6, 3.4	4.3, 7.8, 8.7				9.9, 0.0, 12.9	1.2, 2.2, 2.5	1.7, 1.5, 1.8
2007 09 06 17 51 26.92	24-16.68	122-15.25	54.0	6.6	4		21.3, 29.3, 48.7				6.8, 11.9, 9.1	6.2, 11.3, 12.1	5.5, 10.0, 13.5
2007 09 22 06 27 04.51	24-27.83	121-52.01	22.5	4.8	4		2.7, 3.5, 5.2	3.2, 3.1, 2.8			5.7, 6.6, 7.1		0.7, 1.1, 1.4

Note: T: number of borehole arrays triggered by the event.

triggering more than three arrays for they have completed waveforms with excellent signal-to-noise ratios. Figure 4 shows the epicenter map of these events. The earthquake information and surface peak ground acceleration (PGA) are compiled in Table 2. As can be seen from Table 2, a wide range of PGA with different levels of excitation by different earthquakes was accumulated. The range of recorded horizontal PGA is from about 1 to 76 gals. The accelerations with broad intensity range recorded by the downhole arrays offer a good opportunity to study the difference of the amplification effects for a given site in response to different levels of excitation as well as for its behaviors with different geological conditions.

One earthquake with magnitude 3.7 occurred on 23 October 2004 has attracted much attention for its small hypocentral distance (< 4 km) and shallow focal depth (~10 km) to Taipei 101 building. This event was the most significant to occur in the TMA in the last 30 years. The epicenter distance is about of 4.8 km from TU. Figure 5 depicts 3-component accelerograms arranged from the bottom to surface sensor locations at boreholes TU for this event. At such a near-source distance, these recordings are dominated by primary S waves. These phases are important both for their direct association with the strongest ground motions of engineering interest, as well as for their frequency content which is of direct relevance to the distribution of heterogeneities of the fault plane. As shown in Fig. 5, the PGA increases from the bottom sensor locations up to the surface. PGA on

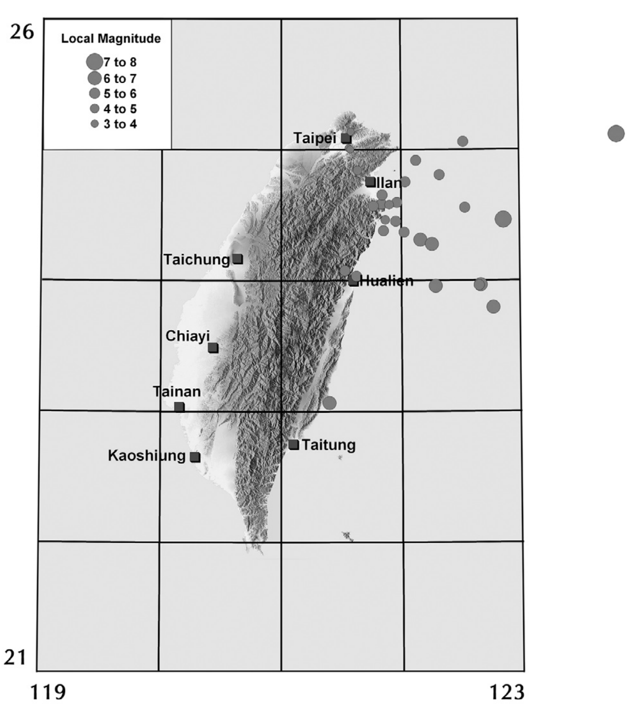

Fig. 4. The epicenter distribution of earthquakes recorded by the strong-motion downhole network during the period from October 2003 to December 2007.

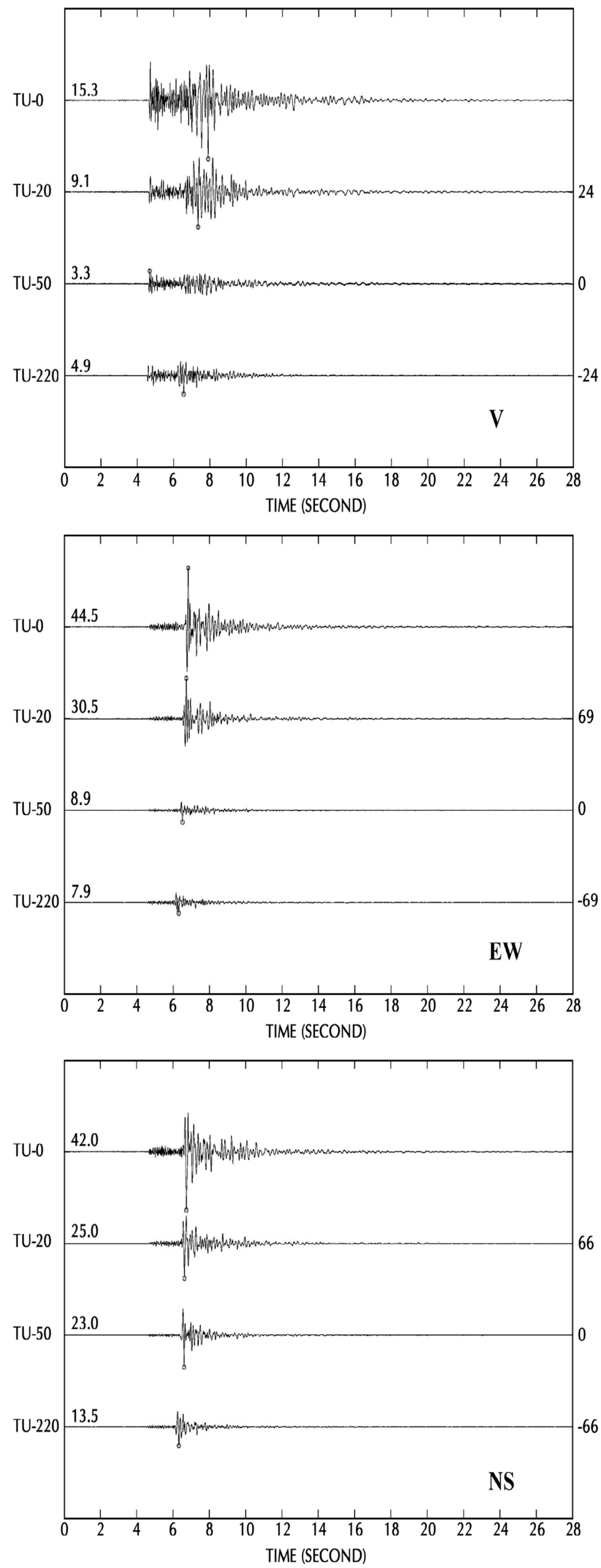

Fig. 5. The 3-component accelerograms of the 23 October 2004 from station TU. Each component is schemed in the same scale and arranged from the bottom to the surface. Station identification precedes seismograms. The peak value (cm sec^{-2}) as enumerated above each trace.

horizontal components is larger than those on the vertical components for the same depth, with level -50 meters horizontal PGA over seven times as large as the vertical ones. In the east-west (EW) component, the PGA increased from 8 gals at the bottom of the borehole up to 45 gals at the surface. The EW component amplification (surface over bottom) is a factor of 5.6. The amplifications (surface over bottom) at the other two components (vertical and north-south) are less than a factor of 3.2.

3.2 Broadband Downhole Array Results

Approximately 130 local and teleseismic earthquakes have been recorded by the broadband downhole arrays in the past three years. Figure 6 shows the epicenter map of local events as recorded by DANB since the beginning of operation. All local events range in magnitude from M_L 3.6 to 7.0 and are distributed within an area bound by 20.8 - 25.3°N and 120.1 - 123.1°E. As for teleseismic events, moment magnitude (M_w) ranged from 5.2 to 8.4.

Shown in Fig. 7 is an example of the accelerograms along the east-west direction from the first event (12:26) of 26 December 2006, Pingtung earthquake doublet. These accelerograms were recorded at the boreholes of DANB50 and YH-0 at free-surface, and two stations (TAP020 and TAP021) from Taiwan Strong Motion Instrumentation Program administered by the Central Weather Bureau. It is found that the data provided by the DANB50 preserve complete accelerograms do not miss the first motions and the latter arrivals from regional earthquakes because the recording is continuous. The complete seismic waveforms of earthquakes have important implications for attempts to evaluate the linear response of important structure in the TMA when major earthquakes occur. In the past design analysis, input motions for the selected safety evaluation earthquake are only scaled to PGA. However, this approach is now significantly modified. With stimulus from seismological studies of recent earthquakes (Bolt 2004), both amplitude and time-histories (duration) are used as supplements.

Figure 8 shows the epicenter map of the five teleseismic events during the seismic sequence that started on 9 September 2007, southern Sumatra, Indonesia 35 ~ 36° away from the TMA. Their Mw are in the range of 6.2 to 8.4. The five earthquakes were collected by DANB, GDUB and 101B. Figure 9 displays an example of 3-component seismograms at level -90 meters of DANB for three larger earthquakes, which were about 12 and 16 hours apart with different magnitudes (M_w = 8.4, 7.9, and 7.1) occurring just offshore of southern Sumatra, Indonesia on 12 and 13 September 2007. It can be seen that the significant ground-motion data were preserved completely from the borehole sensor. The recorded amplitudes decrease with earthquake magnitudes. At such a distant source-spacing, the effects of anelastic attenuation along the ray path could be identical for the three earthquakes. Hence, the nature of waveform for the earthquakes is due to the faulting process rather than path effect.

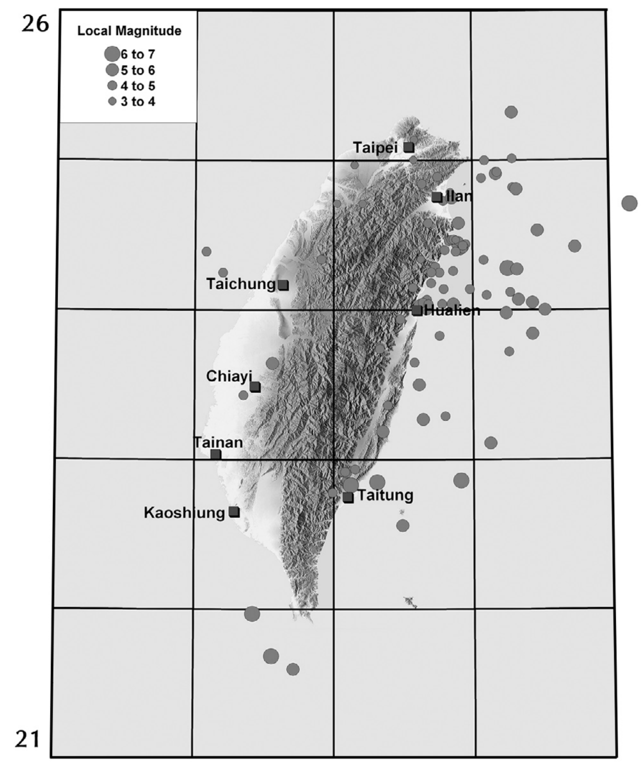

Fig. 6. The epicenter distribution of earthquakes recorded by the borehole site DANB since it began to operate in 2005 to December 2007.

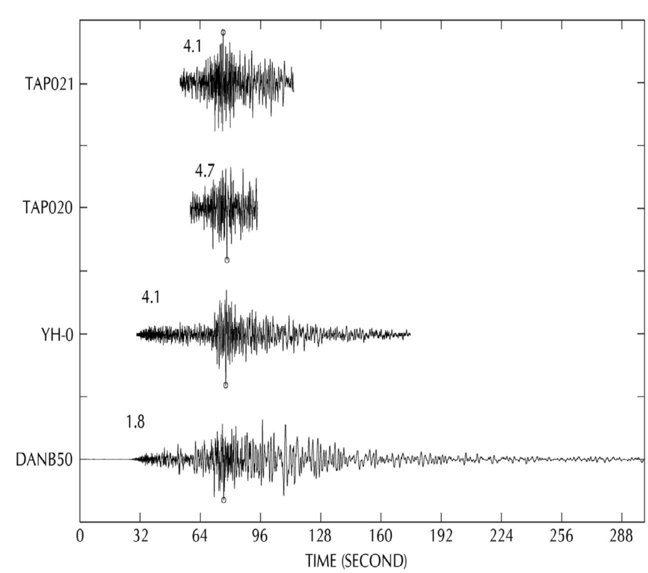

Fig. 7. The accelerograms of east-west component at stations DANB, YH, TAP020, and TAP021 for the first event (12:26) of 26 December 2006 Pingtung earthquake doublet, respectively. Each accelerogram is normalized to its peak value (cm sec^{-2}) as enumerated above each trace.

As seen in Fig. 8, several interesting observations concerning the earthquakes are that these events are close to each other and have the same focal depths with nearly identical focal plane solutions. This implies the earthquakes occurred under the same tectonic region and they are related to each other in some manner. Similar data set was also obtained by Berckhemer (1962). He compared the seismograms recorded at a station from earthquakes of the same epicenters and similar focal mechanisms, but of different magnitudes. Using the data given by Berckhemer (1962), Aki (1967) constructed the scaling of the earthquake sources of moderate to large earthquakes from the relation of seismic moments and corner frequencies of far-field source spectra on the basis of the assumption of similarity of earthquake source by Tsuboi (1940, 1956, 1958, 1965). Under the assumption of similarity, the sets data (shown in Fig. 9) also can provide an opportunity to understand the source characteristics for moderate to large earthquakes.

4. CONCLUSIONS

By combining accelerometer and broadband downhole arrays, a network of seismographs in shallow boreholes dispersed over the TMA was formed. The network includes eight sites with accelerometers and four sites with velocity broadband sensors. The two types of arrays provide complementary data not previously available in a wide dynamic range of signals at different levels and complete seismic waveforms (time-histories) for the local, regional and teleseismic earthquakes in the TMA. Such records will provide greater confidence to estimate precise ground response at the location of each borehole as well as to perform a more detailed analysis and investigate the ground response in the TMA.

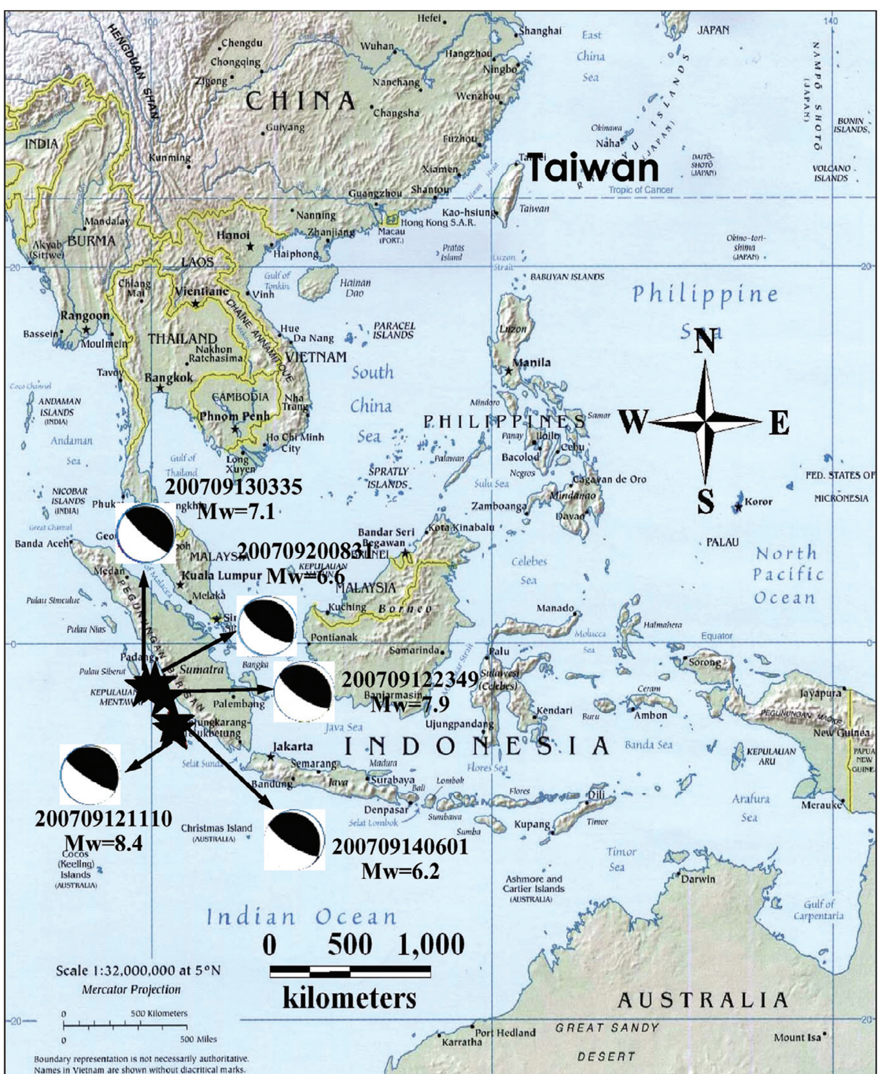

Fig. 8. The epicenter of teleseismic sequences that started on 9 September 2007 in southern Sumatra, Indonesia. At station DNAB from these distant events register the same epicenter, the same focal depth, and the same focal mechanisms, but of different size.

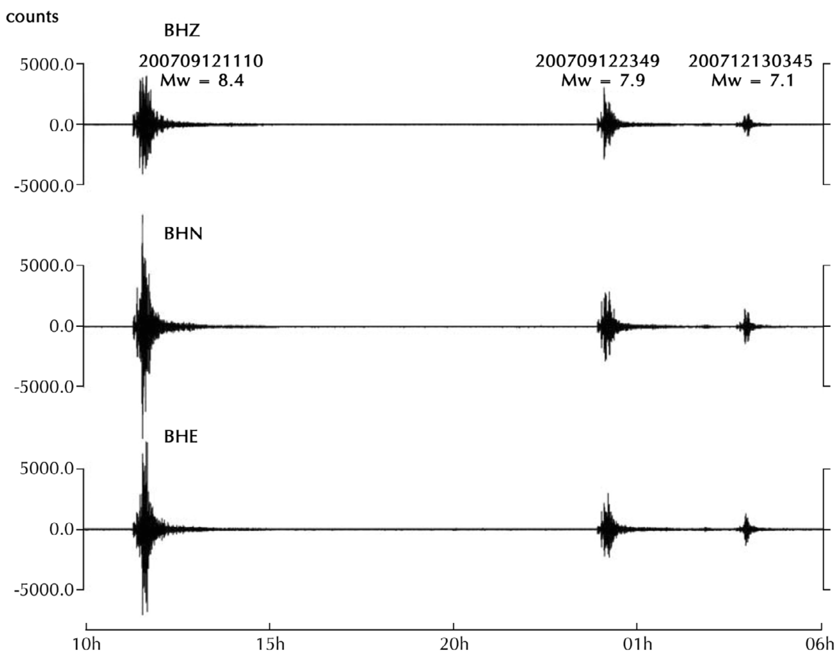

Fig. 9. Ground velocities from 12 September 2007 in southern Sumatra, Indonesia. The earthquakes that were well-recorded by the DANB broadband downhole seismic station at level -90 meters.

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