Instrument Testing and Evaluation for the Taiwan Strong-Motion Instrumentation Program

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INTRODUCTION

Taiwan is located on the boundary between the Eurasian and Philippine Sea plates where active collision and subduction are taking place, resulting in very high seismicity in the region [Tsai et al., 1977; 1981]. Numerous damaging earthquakes occurred in the past, e.g., the recent 1999 Chi-Chi earthquake which struck the central part of Taiwan, resulted in the loss of over 2,400 lives, and 11,300 were injured. About 51,753 houses were completely destroyed and 54,406 were partially damaged. The economic losses were estimated to be more than 10 billion U.S. dollars [National Fire Agency, 2003].

The importance of deploying strong-motion instruments has long been recognized in Taiwan because these instruments provide the critical acceleration data for structure designs in order to reduce seismic risk. Many instrumentation programs, such as SMA, SMART-1, LLSST, SMART-II, HLSST, TSMIP, and SAFE-T etc., had been deployed by the Institute of Earth Sciences (IES) and by the Central Weather Bureau (CWB) in last thirty years [Shin et al., 2003; Wen et al., 2004] . Data recorded at these arrays are available through the Data Management Center of IES at http://dmc.earth.sinica.edu.tw/Seismology, or Data Service Center of Central Weather Bureau at http://e-service.cwb.gov.tw. Table 1 summarizes the characteristics of these strong-motion arrays. We will now summarize the instrument testing and evaluation for the Taiwan Strong-Motion Instrumentation Program (TSMIP), and hope that our experience will be useful to others.

THE TAIWAN STRONG MOTION INSTRUMENTATION PROGRAM

The Taiwan Strong Motion Instrumentation Program began in 1991 by the Seismological Center of the Central Weather Bureau [Shin, 1993]. The main purpose of this program is to collect high-quality digital recordings of strong ground shaking from earthquakes, both at free-field sites and in man-made structures. These data are crucial for improving earthquake-resistant designs of buildings, bridges, and dams, and for understanding the earthquake source mechanisms, as well as seismic wave propagation from sources to the

sites of interest, including local site effects [Shin et. al, 2003]. By the end of 2005, a total of 688 free-field accelerographs and 61 structural arrays (each with 30 or more uni-axial accelerometers) had been deployed in nine metropolitan areas. Locations of the free-field accelerographs and structural arrays are shown in Figure 1. About 15% of the free-field accelerographs (all capable of data-stream output) are being continuously telemetered to the CWB Headquarters for real-time monitoring and rapid release of earthquake information (source parameters and a shake map) in about one minute after an earthquake occurred [Teng et. al, 1997].

CWB INSTRUMENTATION SUBCOMMITTEE

The resolution and dynamic range of accelerographs was in the range of 45 to 66 dB for most instruments in Taiwan during the 1970s and 1980s. Because the 16-bit digital accelerographs were being developed in the early 1990s, the TSMIP played an important role in advancing the standards of strong-motion accelerographs by enlisting experts to contribute their expertise on this instrumentation program. The CWB Advisory Committee established its Instrumentation Subcommittee (chaired by Y. B. Tsai) since 1991. It also established a long-term international cooperative program with the University of Southern California (USC) and the U.S. Geological Survey (USGS). The goals and objectives of the subcommittee are:

1. To establish procurement standards and technical specifications for sensors, data loggers, and other hardware components;
2. To evaluate the cost-effectiveness of commercially available accelerographs with features that meet the scientific and engineering requirements;
3. To standardize the data format, data transmission protocols, and data processing software to ensure that data from different manufacturers can be easily merged and analyzed using the IASPEI and CWB developed software;
4. To document the testing and evaluating procedures which may be served as a reference for other institutions in their procurement of accelerographs; and
5. To encourage development of new instruments.

STANDARDIZATION OF PROCUREMENT PROCEDURES

W. H. K. Lee, a member of the CWB Instrumentation Subcommittee, has been responsible for the instrument specifications and software development of the TSMIP. After several years of iterations, the TSMIP procurement procedures that meet the government's regulations have been standardized as shown in the following steps [Lee, 1993]:

(1) Preparing a draft of the technical specifications for the strong-motion instruments to be procured in the coming fiscal year;
(2) Circulating the draft among manufacturers and instrument experts for comments and suggestions, and then revising the draft;
(3) Announcing the finalized technical specifications with an invitation for bids

(bidders are required to submit detailed technical proposals and production models of accelerographs for evaluation);

(4) Performing a technical compliance test for the submitted accelerographs, including shake table, laboratory, and field test; test procedures are included in the technical specifications;
(5) Evaluating the results of the technical compliance test, and determining the qualified accelerographs;
(6) Announcing the successful bidder according to the procurement regulations of Taiwan; and
(7) Performing the acceptance test for the delivered accelerographs, ensuring that every unit meets the technical specifications.

TESTING AND EVALUATION

During the past 14 years, TSMIP purchased digital strong-motion accelerographs from Geotech, Kinemetrics, Terra Tech, and Tokyo Sokushin. All the purchased accelerographs had been subjected to technical compliance tests and evaluations by a panel of international experts. These purchased accelerographs passed the tests before they were qualified for bidding. Since 1995, any new accelerographs (i.e., those not supplied to TSMIP before) must conduct the tests in an appropriate laboratory by the bidder at their own expenses and must include the following tests:

- System response to vibration
- System static accuracy
- Digitizer performance
- Realtime digital data stream output
- Timing system
- Utility software operation
- Packaging and Overall Construction.

A bidder must submit a report of the test results in their proposal (including computer readable data files and the required software), and also must submit the proposed model for test — at the CWB Headquarters with regards to its static accuracy and Internet connection, and at the CWB Hualien Station for a field test of about 2 weeks. Acceptance tests were also conducted at CWB when the accelegographs were delivered. Power consumption, sensitivity, linearity, GPS timing, and DC-level drift etc., would be checked again to verify that the delivered instruments meet the TSMIP technical specifications.

Under CWB support, operation and routine functional tests were performed by five academia groups to support field operation and verify ongoing performance of the deployed accelerographs. These routine functional tests may include sensor, recording unit, GPS, triggering, power system, and noise level etc. If any accelerograph fails to meet any one of the tests, it will be returned to the supplier for repair or replacement. Vendor or its designated agent provides full warranty for three years after the final acceptance. This warranty includes parts and labor for fixing any breakdown of the accelerographs and GPS timing devices within a reasonable period of time.

FACILITIES FOR PERFORMANCE EVALUATIONS

The following facilities are available for performance evaluation. We encourage manufacturers to submit their instruments for performance evaluations:

(1) The instrument pier at the basement of the CWB Hualien Weather Station (Figure 2), near the most seismic active area of Taiwan. It surface area is about 2 m by 3 m; several accelerographs can be installed for simultaneously recording.
(2) The instrument pier at the IES YHNB Broadband Station, 2.5 m by 2.5 m; a very quite site suitable for self-noise test.
(3) A precision Tilt Table, controlled by a stepping motor (0.008°/step); with data acquisition device and Labview controlled program, it can be used to check sensitivity, linearity, and hysteresis of accelerometers automatically.
(4) A CT-EW1 Calibration Table, designed by Erhard Wielandt, can be used for the absolute calibration of broadband, intermediate and even short-period seismic sensors.

CURRENT AND FUTURE WORK

MEMS Accelerometers

Micro Electro-Mechanical System (MEMS) accelerometers with low noise and high dynamic range have recently been used in accelerographs. The main advantages are: low cost, modest power consumption, wide bandwidth, excellent stability, etc. There were two manufacturers proposed this kind of accelerographs to the TSMIP in 2005, but neither of them was well prepared for the compliance test. The proposed models could not meet the TSMIP technical specifications. However, MEMS accelerometers have been used in many seismic sensing applications, and the ANSS program has also deployed some MEMS accelerographs in their dense urban networks. We are now conducting extensive field tests of multiple co-located accelerometers (recorded by the same model of data loggers in continuous recording mode) and co-located accelerographs (recorded in triggered mode) in Taiwan. The data will be used for evaluating the field performance of accelerometers and accelerographs by different manufacturers, and for developing a "performance based" specifications for use by the TSMIP in the future procurements.

24-Bit Digital Accelerograph

Recent technological advances make it easy to implement a data logger with 24-bit high-resolution ADCs. Many manufactures applied this technology to their new generation accelerographs, which can offer very high resolution and dynamic range to record ground motions. Since 2002, TSMIP began purchasing 24-bit accelerographs to replace their aging 16-bit accelerographs now in service. The preliminary comparison results indicated that the 24-bit accelerographs performed quite well in a controlled environment facility. To minimize contamination of the ground motions by man-made structures, most TSMIP free-field stations are situated on open field locations. All components of an accelerograph are installed on a small reinforced concrete pad and protected by a lightweight fiberglass

enclosure. Recent observation shows this kind of installation may not be fully acceptable for a 24-bit accelerograph. The temperature variations within the enclosure can easily exceed 10°C during day and night, and will cause a DC-drift on 24-bit digitizers (see Figure 3). In order to provide the stable baselines required for double integration of acceleration signals, much as the broadband stations, heavy thermal insulation or subsurface enclosures may be needed for installing the 24-bit accelerographs, and if possible, technology should be developed to compensate the DC drift due to thermal variations.

Strong-Motion Velocity Seismometer

In early 2004, an invitation was sent to all known manufacturers requesting their voluntary participations in a field test of multiple accelerographs in Hualien. TSMIP are particularly interested in the new broadband velocity senor VSE-355G3 made by Tokyo-Sokushin that is capable of functioning up to 2g ground motions. After several months testing, CWB purchased one and installed it at the instrument pier of the Hualien Station. In the meantime, IES also purchased a downhole version of VSE-355G3, and installed it at the Taipei Basin for monitoring the long-period basin response. VSE-355G3 has a similar type of response as STS-2, with a corner frequency at 120 sec and clipping level at ± 2m/s. The nominal dynamic range is about 146 dB. Clinton and Heaton [2002] demonstrated several advantages of this instrument:

(1) The ability of the instrument to resolve long-period (> 30 sec) motions is much better than that of a strong motion accelerometer;
(2) Recovery of ground displacement is likely to be more stable from such a long-period low-gain broadband seismometer;
(3) Similar ability to recover ground accelerations; and
(4) It would recover on-scale all motions relevant to structural engineering, and it would record long-period motions with accelerations too small to be recorded by traditional accelerometers.

Figure 4 shows observations at station YHNB, from the earthquake of 5 September 2004, M 7.4 near the coast of Honshu, Japan, at a distance of 1790 km. Coherence of recorded data between the STS-2 and VSE-355G3 are nearly perfect. As another example, observations from an M 7.0 earthquake at a distance of 158 km are shown in Figure 5. The records of VSE-355G3 and Episensor are still within their clipping limits, while that of the STS-2 clipped. Therefore, recovery of ground displacements is much easier from the VSE-355G3 low-gain broadband seismometer.

Monitoring Rotational Motions

The 50-plus near-field strong-motion records of the 1999 Chi-Chi (Taiwan) earthquake indicate that the ground motions near the 100 km rupture are complex, and it is not easy to double integrate the recorded accelerations to reasonable displacements as independently observed. We suspected that in the near-field of an earthquake rotational ground motions may not be negligible as compared to the translational motions according to [Trifunac and Todorovska, 2001]. Therefore, it is not possible to compute reliable permanent displacements of the ground (or of structures) without simultaneously recording rotations during the strong shaking [Takeo, 1998]. IES began field tests of triaxial rotation transducers at Station HRLT since December 2000 and at HGSD since July 2004.

Preliminary observations suggest:

(1) Angular rotation is important even in the mid-field of an earthquake;
(2) Similar to Takeo (1997) observation in Japan [Evans et. al., 2006], the measured peak rotation velocity values of about 2 milli-radian/sec at the HGSD station for magnitude 5+ earthquakes are much higher than the theoretically predicted values;
(3) A more sensitive and wide dynamic range transducer is needed for measuring rotational motions; and
(4) Since a well calibrated sensor is very important for us to have confidence in its recorded rotational motions, we should conduct proper tests in an appropriate testing facility as soon as possible.

At the recent workshop on "Measuring the Rotation Effects of Strong Ground Motion" held simultaneously in Menlo Park and in Pasadena on February 16, 2006, it was generally agreed by the experts that measuring rotational motions should be made in the free field and in buildings as soon as possible. We plan to deploy more triaxial rotation transducers in two more sites in Taiwan later this year. If rotation motions proved to be important, then we will recommend that TSMIP includes rotation transducers in their annual purchase of new accelerographs.

CONCLUSIONS

Over 1000 three-component accelerographs (in free-field and in equivalent structural arrays) were deployed by the TSMIP during its first phase in 1991-1996, just before the Mw=7.6 Chi-Chi earthquake in September 21, 1999. This dense network of accelerographs (with station spacing of 2 to 5 km) recorded the main shock and thousands of aftershocks [Lee et al., 2001; Shin et al., 2003], with a data volume that exceeded all the strong-motion recorded obtained for the entire world since measurements began 70 years before. This success of TSMIP was beyond our expectation, and our efforts in instrument testing and evaluation before and after purchase paid off handsomely.

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Table 1. Summary of Strong-Motion Networks/Arrays in Taiwan.

Network/Array Name	Sponsor / Operator	Number of Accelerographs or Arrays	Type of Accelerograph	Operation Period
Strong-Motion Accelerographs Network (SMA)	IES	79 structural	Analog & 12-bit Digital	1970 - 1991
Strong-Motion Array in Taiwan, Phase I (SMART1)	UCB/IES	43 surface ground	12-bit Digital	1980 - 1991
Lotung Large Scale Seismic Test Array (LSST)	EPRI, TAIPOWER / IES	15 surface ground 10 downhole 14 structural	12-bit Digital	1985 – 1993
Strong-Motion Array in Taiwan, Phase II (SMART2)	IES	45 surface ground 4 downhole	16-bit Digital	1993 -
Hualien Large Scale Seismic Test Array (HLSST)	EPRI, TAIPOWER/ IES	15 surface ground 12 downhole 15 structural	16-bit Digital	1993 - 2002
Downhole Accelerometers Array in Taipei Basin (DART)	CGS / IES	10 surface ground 30 downhole	16-bit Digital	1994 -
Taiwan Strong-Motion Instrumentation Program(TSMIP)	CWB	688 free-field 61 structural arrays	16/24 bit Digital	1991 -

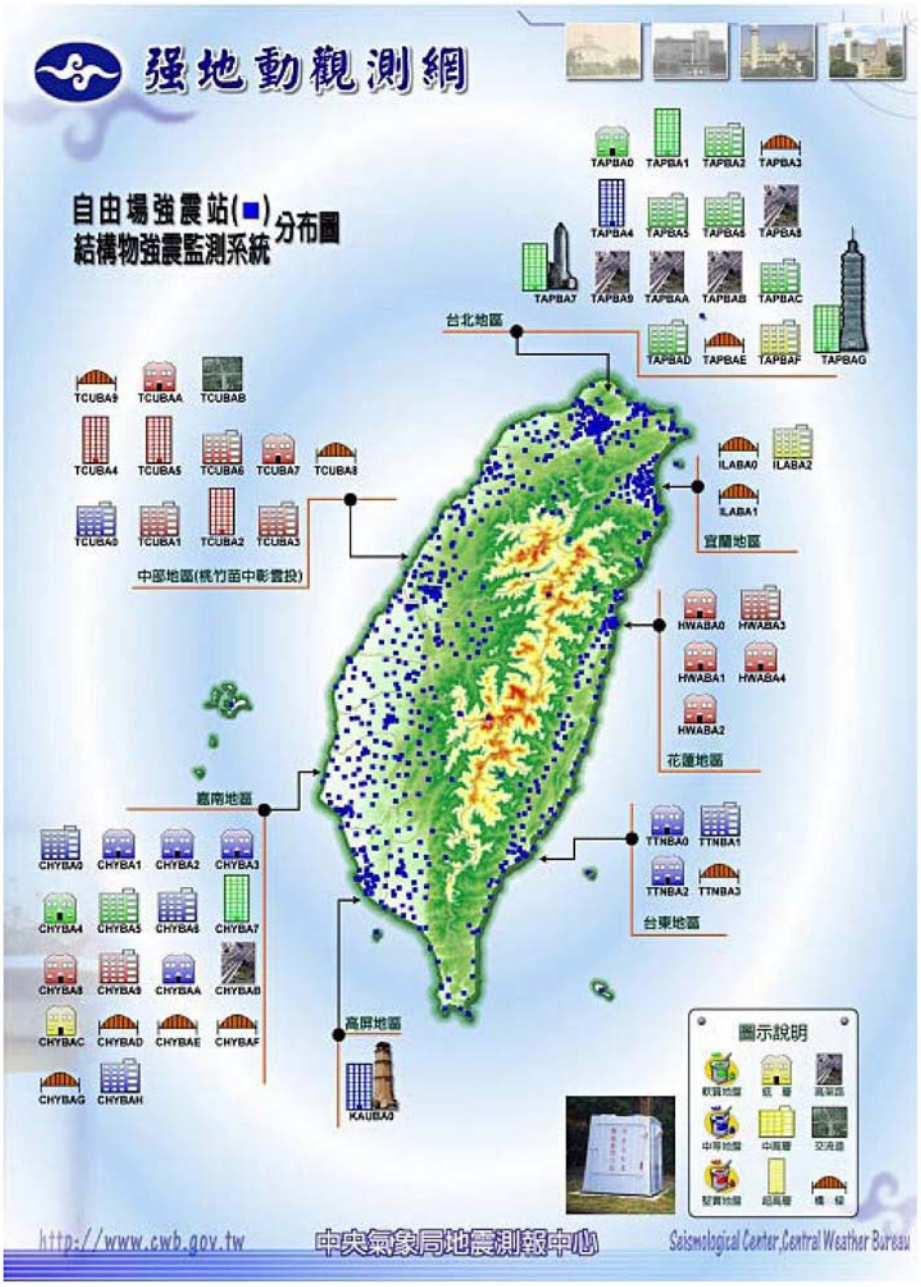

Figure 1. Distribution of TSMIP instruments, including 688 free-field stations and 61 structural arrays.

Figure 2. A photo of the instruments on the seismic pier (2 by 3 meters) at the Hualien Seismic Station (HWA) is shown.

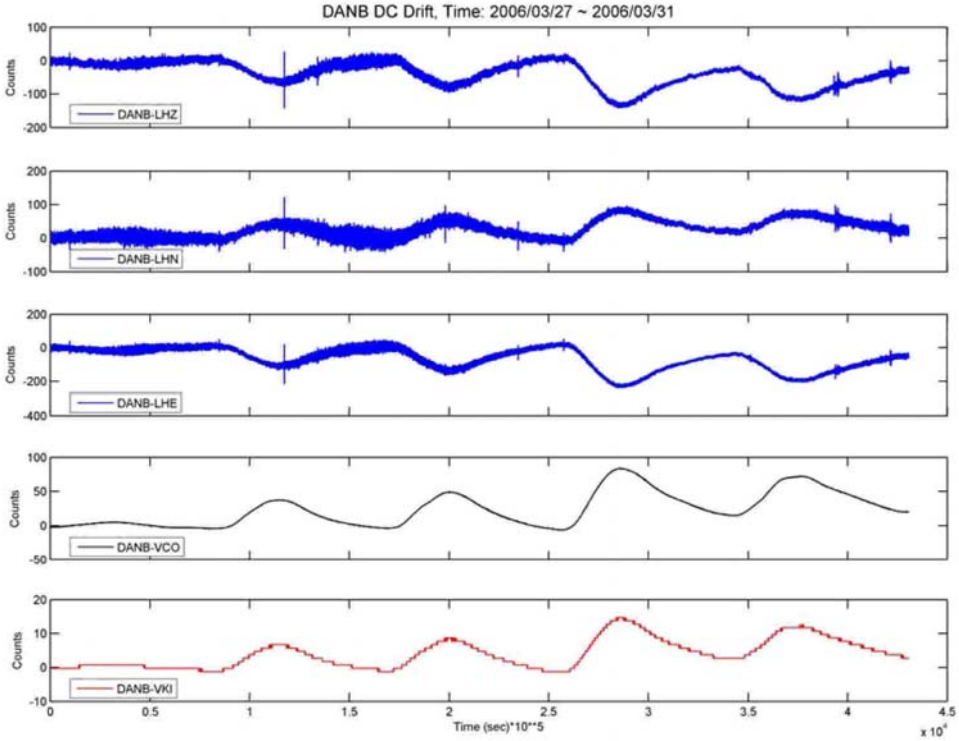

Figure 3. DC drifts of a Q330 digitizer due to thermal variations in the field.

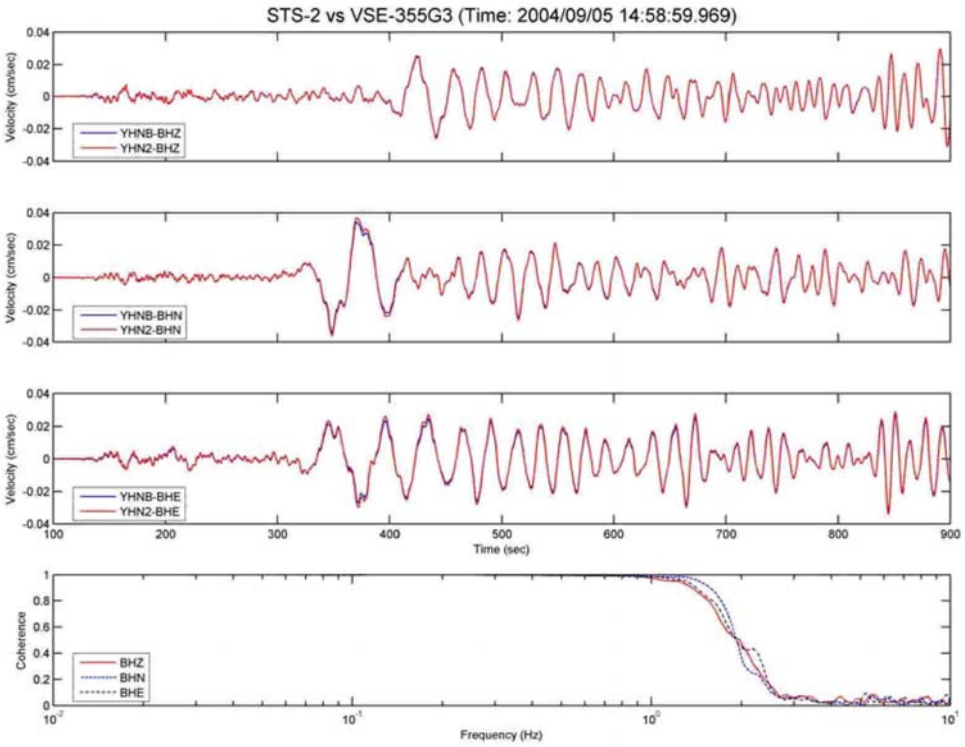

Figure 4. Coherence functions between recorded data of STS-2 and VSE-355G3 for Event 2004/09/05 (M = 7.4, Epidistance = 1790 km).

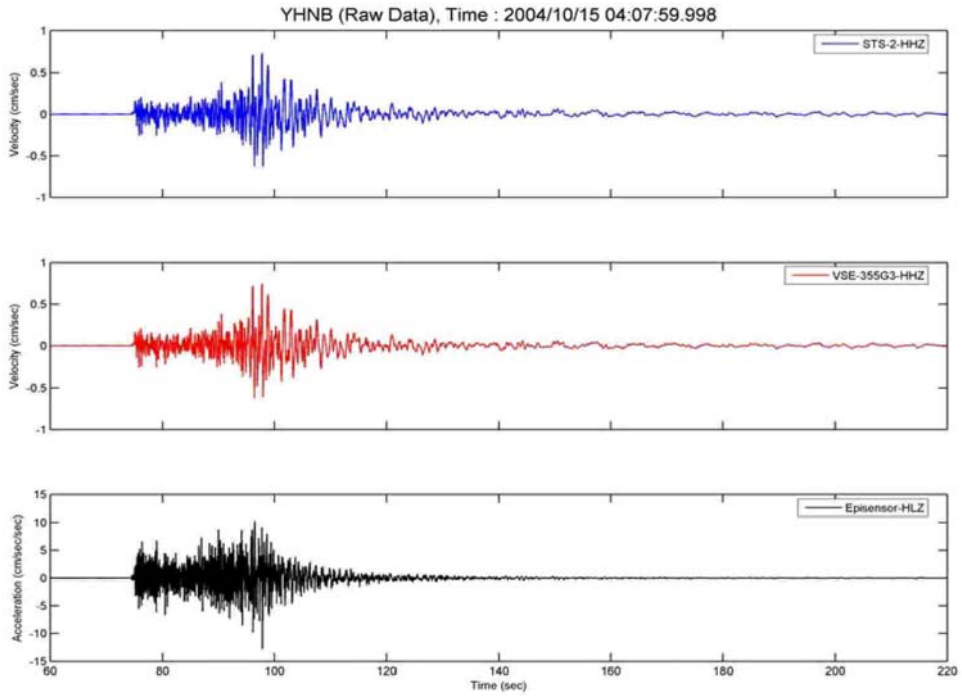

Figure 5a. Recorded data for Event 2004/10/15 (M = 7.0, Epidistance =158 km).

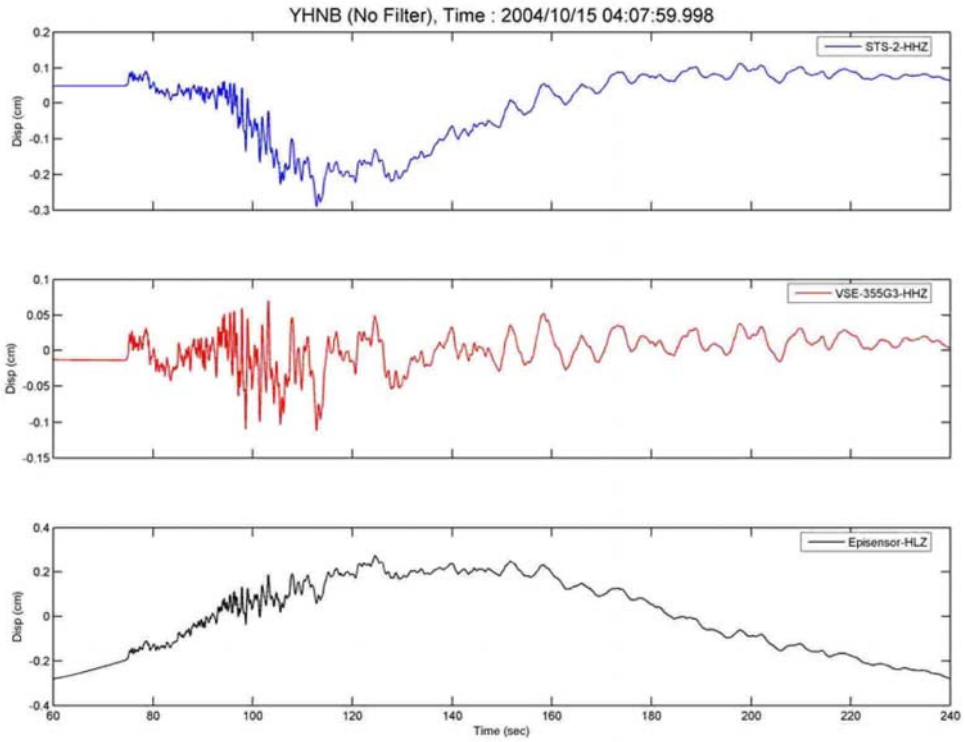

Figure 5b. Recovering the data to displacement (with no filter used).

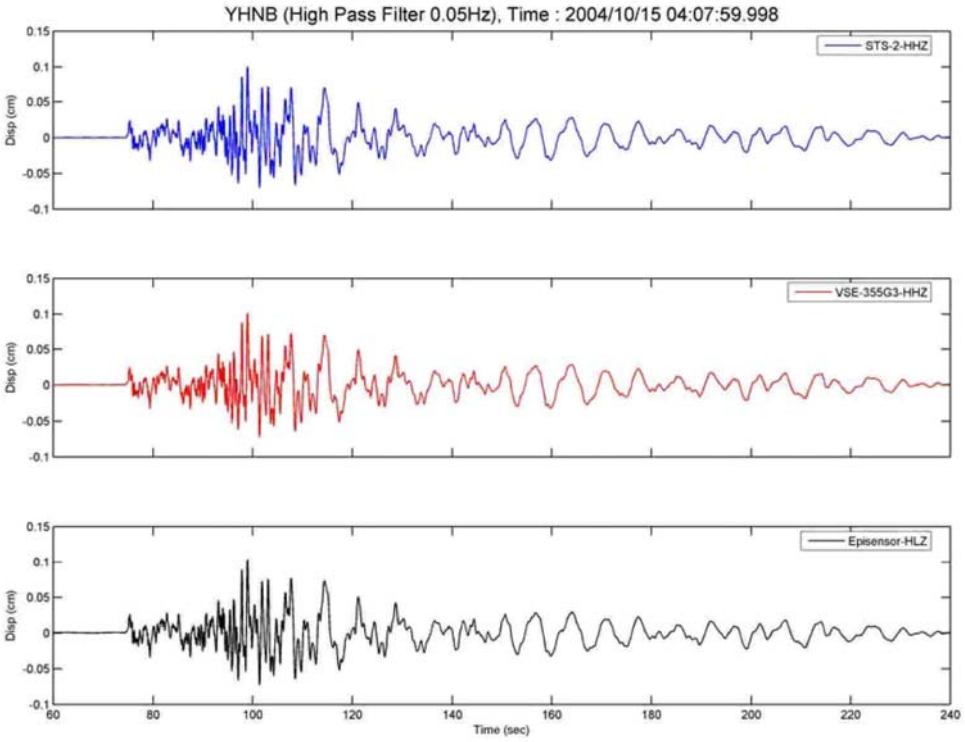

Figure 5c. Recovering the data to displacement (with 0.05 Hz high pass filter).