# Applications and Challenges of Strong Motion Instruments for Strong Motion Observation in China

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## *Abstract:*

Strong motion instruments play an important role in Chinese strong motion observation. The historical development and current status of strong motion instruments are presented in this article, and the role of the United States, Japan and China in their development is discussed. Strong motion records from around the world documenting, such typical abnormal waveforms as spikes, asymmetric waveforms, baseline drift, waveform mirroring and waveform duplication) are briefly discussed, even though the causes of such abnormalities have yet to be researched in depth and tests still are needed to help eliminate them. We believe that by studying abnormal waveforms in strong motion records, we can solve the existing problems of instruments and help develop new types of strong motion instruments. Corrections for instrument response errors in force-balance accelerometers with a band range of 0 to 30 Hz are briefly analyzed, and we believe that strong motion records obtained by early digital strong motion instruments are in need of correction. Every high-magnitude earthquake will bring challenges and opportunities for improving strong motion instruments. There is no exception in China. Earthquake prevention and disaster risk reduction became a major priority after the M8.0 Wenchuan earthquake. China has developed a seismic-intensity rapid reporting system and constructed an early warning network, and as a result has a strong need for high-quality strong motion instruments. At the same time, the continuous innovation and diversified development of strong motion observation requires higher-performing instruments that are multifunctional, intelligent, portable and easy to operate. So, strong motion instruments still need to be improved in reliability, timeliness and intelligence. Finally, it is important to keep track of new methods and technology in strong motion observation, and new instruments should be developed to meet China's current needs.

*Keywords: strong motion observation; strong motion instruments; abnormal waveforms; strong motion records; instrument response errors corrections*

## 1. Introduction

The three pillars of earthquake engineering research are strong motion observation, seismic damage investigation and vibration tests. Strong motion observation data are fundamental to earthquake engineering, allowing researchers to understand ground motion and structural response characteristics, study the ground-motion parameters that cause structural damage, and model the relationship between those parameters and magnitude, distance and site condition. They also provide support for ground-motion prediction and structural seismic design. In particular, high-quality strong motion records from high-magnitude earthquakes are of great significance to the development of earthquake engineering. Analysis of strong motion records can improve structural seismic design, rapid earthquake-intensity reporting and early warning of earthquakes. However, first-hand ground motion or structural information for earthquake engineering research is obtained by strong motion instruments. Strong motion seismology uses special sensors, called accelerometers, to record large-amplitude ground motions and the response of engineered structures to these motions. This information is used to upgrade building codes, design earthquake-resistant structures, and predict strong shaking patterns from large earthquakes in the future. Rapid reporting of shaking levels also helps to focus emergency response efforts on areas where damage is likely to be greatest. Recordings of large-amplitude seismic waves near the earthquake source can be used to investigate fault motions that produce earthquakes. Strong motion instruments are thus at the heart of strong motion observation.

The history of strong motion instruments is reviewed briefly in this article. Typical abnormal waveforms and instrument response errors for force-balance accelerometers are then outlined. This is followed by a discussion of opportunities and challenges for using strong motion instruments in observations. Finally, this paper suggests ways to improve strong motion instruments and suggests some directions for the development of new types of strong motion instruments.

## 2. History and Status of Strong Motion Instruments

Although the desire to understand earthquake phenomena is as old as the classical civilizations, it took too much time for quantitative measurements on strong motion[1]. The oldest instrument for judgment of direction in strong motion is almost 1,900 years old. In 136 A.D., the Chinese scientist Chang Heng designed the world's first seismograph. And the seismoscope can indicate the direction of a strong motion pulse by the tipping a vertical cylinder [2]. The falling cylinder, or some kind of a pendulum would cause a ball to be released from the mouth of a dragon into the mouth of a waiting frog[3,4].Traditional seismic instruments were developed in the 19th century, and the technology improved throughout the 20th century. Strong motion instruments were developed in the 1930s to measure strong ground motion. In 1929, during an engineering conference in Tokyo, John Freeman and Prof. Kyoji Suyehiro called for the design and construction of an instrument that would record strong vibrations of the ground and structures during an earthquake. In 1931, the United States Congress commissioned the United States Geological Survey (USGS) to create a national strong motion observation program, including the development of strong motion instruments. In 1932, the United States developed the first strong motion instrument (including accelerometer) in the world; its design is shown in Fig. 1. It was first deployed in Los Angeles, and its first acceleration record was obtained on March 10, 1933 from an earthquake in Long Beach. This occasion marked the birth of modern earthquake engineering [5].

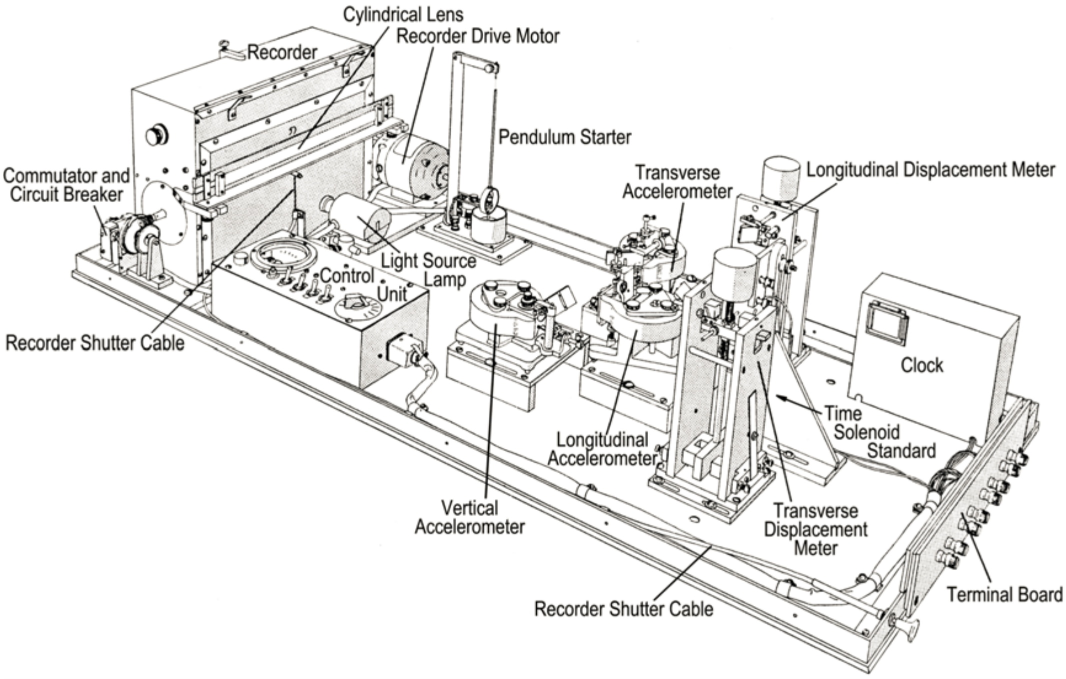


Fig. 1: Internal Structure of the First Strong Motion Accelerograph [1]

The US, Japan and China have taken an active part in the development of strong motion instruments. In the 1970s, the United States developed the first generation of SMA-1 optical-recording strong motion instruments, followed by the second generation of SMA-2 and SMA-3 analog-tape-recording strong motion instruments. However, these devices had several shortcomings, such as a narrower dynamic range and incomplete records. In the 1980s, the United States developed the third generation of DSA-1 and PDR-1 digital-tape strong motion instruments; these still had some problems, such as false triggering and the requirement for special playback equipment. The fourth generation of strong motion instruments in the United States was SSR-1 solid-state storage digital strong motion instruments, which convert readings into digital signals stored in SRAM memory through A/D conversion. Data is recovered via a com port connection. In the 1990s, Etna, K2 and solid-state digital storage strong motion instruments offering a wide dynamic range were introduced in the US [6]. At the beginning of the 21st century, basalt and obsidian strong motion instruments were introduced by Kinemetrics Inc., who replaced the old technology with an embedded system structure, ushering in the second wave of digital strong motion instruments. At present, ROCK+ (Model: Obsidian) is Kinemetrics' new generation Seismic Monitoring Recorder; its specifications are as follows, making it as the most popular strong motion instrument in the world at present:

1. More RAM: 1GB vs. 512MB in the original basalt;
2. Double slot storage: 2x SDHC card: 14GB for system, 132GB for data;
3. Low data latency of 0.1 second per package;
4. USB port, allowing connection to laptops;
5. USB hosting: thumb drives mounted when plugged in, for offloading data; Wi-Fi or cellular adapters for network connections;
6. Timing accuracy: <1 microseconds of UTC with GPS or PTP;
7. More scalable software architecture and more flexible application. The Application Programming Interface (API) allows users to develop add-on modules and upgrade the internal software to tailor it, e.g. to report seismic intensity values;
8. Support for multiple output file formats: Rock+ supports most common formats in the seismic research field, including Kinemetrics' EVT, MINISEED, SAC, COSMOS, MATLAB, SUDS, SEISAN, ASCII, etc. Users can also supply their own formats with add-on modules;
9. Specialized fourth and eighth channel design for early warning purposes: three channels for accelerometer and one channel for a short period seismometer to obtain P-Waves;
10. Sample rate of up to 5,000 SPS;
11. Acceptance of a wider DC input range of 9-28 VDC (>15.5VDC for Battery Charger Operation), and support for longer sensor cables.

Strong motion observation in the engineering field began in the 1950s in Japan. The 1948 Fukui earthquake made researchers realize the necessity of conducting strong motion observation. A group of professors, researchers and engineers accordingly organized the Strong Motion Accelerometer Committee to develop strong motion instruments in 1951. The prototype instrument was manufactured in 1953 and named SMAC after the committee's initials. The Strong Motion Earthquake Observation Committee was established in 1956 to maintain strong motion instruments, process data, and publish records. After the disastrous 1995 Hyogo-ken-nanbu (Kobe) earthquake, the Special Measure Law on Earthquake Disaster Prevention (implemented on July 18, 1995) was passed to protect lives and property from earthquakes. The law established the Headquarters for Earthquake Research Promotion as a branch of the Prime Minister's Office for the unified promotion of earthquake research. The National Research Institute for Earth Science and Disaster Prevention (NIED), part of the Science and Technology Agency, constructed a large network of strong motion instruments in 1996, called K-NET, which consists of 1,000 observation stations deployed all over Japan at roughly 25 km intervals. NIED also deployed high sensitivity seismographs (Hi-net) and digital strong motion seismographs (KIK-net) across Japan, at 660 strong motion observation stations on the surface and over 100 meters underground. To measure JMA seismic intensity and offer near real-time data communication, NIED developed a new type of instrument, the K-NET02. If the earthquake is detected by strong motion instruments, the information will be automatically conveyed to a data management center within a matter of seconds. In addition, the devices' measurement range increased from 2,000 Gal to 4,000 Gal, and they feature a 132dB dynamic range for analog to digital conversion [7].

The Institute of Engineering Mechanics within the China Earthquake Administration (hereafter abbreviated IEM) pioneered strong motion observation in China. In March 1962, an earthquake of magnitude 6.1 was induced by Xinfengjiang Reservoir in Guangdong, which prompted researchers to study the mechanism of the crack and build China’s first experimental observation station in Xinfengjiang Dam. IEM developed RDZ-12-66 multichannel recording galvanometer strong motion accelerometers in 1966. Hundreds of fixed and mobile stations were successfully established using these devices, obtaining high quality records [8].

The China Institute of Water Resources and Hydropower Research subsequently developed SG-68 galvanometer strong motion instruments. In the 1980s, DCJ, RLJ and differential-capacitance force-balance accelerometers were developed by IEM. The GQIII and GQIIIA three-component direct optical-recording strong motion instruments were then jointly developed by IEM and the Seismic Instrument Factory; these devices perform similarly to SMA-1 instruments [9].

In 1988, SCQ-1 digital tape-recording strong motion instruments were developed. In the 1990s, these were superseded by SLJ-100 force-balance accelerometers, which are comparable to the most advanced international instruments and offer stable and reliable performance; at present they account for over 90% of the domestic market. In addition, the China Institute of Water Resources and Hydropower Research produced the EDAS-A and EDAS-B three-channel and six-channel digital strong motion instruments, which are used in dams and have obtained more than 150 acceleration records.

With the rapid development of digital strong motion observation technology, strong motion instruments have developed gradually from traditional analog film recording to digital recording, which not only greatly speeds up analysis but also enhances the reliability of data. Because digital strong motion instruments have wide dynamic range, wide frequency band, strong pre-storage capability, high absolute time scale precision, and allow for remote control and real-time data communication [10], they have become the standard in China.

In 2008, the Wenchuan earthquake (measuring 5.12 on the Richter scale) stimulated the development of digital strong motion instruments in China, such as the Beijing GangZhen Instrument & Equipment Co., Ltd BBAS-2, Zhuhai, Taide TDA-33M. At the same time, some new international models have entered the Chinese market, such as the basalt and obsidian instruments from Kinemetrics and the 130-SMA/9 from Reftek.

## 3. Analysis of Abnormal Waveforms in Strong Motion Records and the Limitations of Strong Motion Instruments

Inaccurate data in some strong motion records have a negative effect on research. Typically, singular waveform data needs to be summarized and analyzed, which can provide reference for the design, improvement and use of strong motion instruments.

The spike at the beginning of a record is shown in Fig. 2. The problem may be caused by a cache connection error or the failure to clear the cache, which may be caused by a software problem or noise introduced by an internal power-supply spike, which in turn is a ripple effect from the external power supply. The spike at the end of a record is shown in Fig. 3, which may be due to redundant data written at the record's end. The phenomenon of equally spaced noise is shown in Fig. 4; the frequency is roughly 1Hz, and appears only in the vertical direction. We suspect this is caused by the vertical pendulum. The asymmetric waveform phenomenon shown in Fig. 5 may be due to the "trampoline effect" [11, 12] or may be caused by a stuck accelerometer during earthquakes. Obvious baseline drift in the acceleration time history is shown in Fig. 6. This may be caused by a stuck accelerometer and a zero shift of the sensor caused by the inclination of the instrument base during earthquakes. A mirrored waveform is shown in Fig.7. According to Zhu Jiangang and other researchers [13], this type of problem occurs when the pre-event cache content or location is incorrectly recorded. In addition, there has been a phenomenon in recent years in which two channels have records while the third channel gets no records, which is probably caused by a faulty accelerometer.

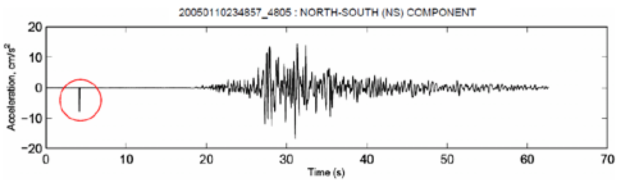

Fig. 2: Spike at the Beginning of a Record [6]

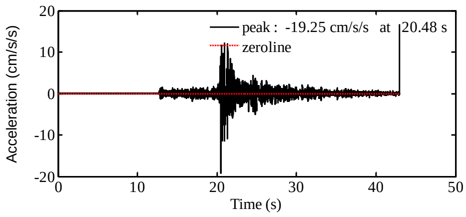

Fig. 3: Spike at the End of a Record [7]

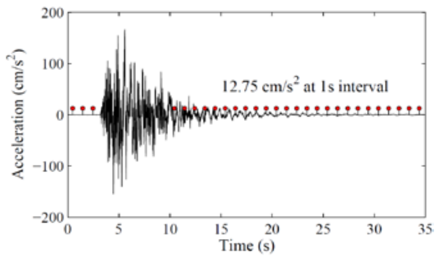

Fig. 4: Spike with Repeated Intervals [7]

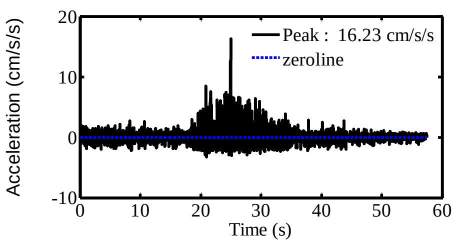

Fig. 5: Asymmetric Waveform Phenomena [8]

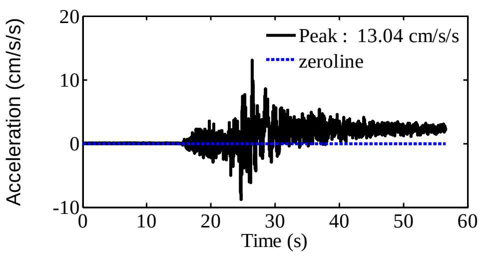

Fig. 6: Baseline Drift across Acceleration Time History [8]

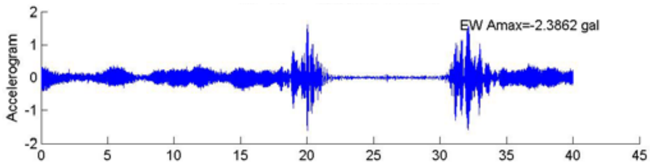


Fig. 7: Waveform Duplication

Analysis of such faulty data demonstrates that the quality of strong motion instruments is very important for reliable strong motion records. Zero line adjustments were made on strong motion records from the 5.1 Lighthouse earthquake in Liaoning Province on January 23, 2013, by Liang Yongduo [14]. The original acceleration peak was reduced by about 20%, demonstrating zero drift in the instrument. Therefore, instruments should be calibrated regularly to avoid getting stuck and to avoid zero drift, which can lead to inaccurate records.

## 4. Analysis and Calibration of Accelerometer Response Errors

Digital strong motion instruments have been used in the China Strong Motion Network and mobile strong motion observations. The accelerometers typically used over time are as follows: the Kinemetrics FBA-3 and FBA-13 force-balance accelerometer in the 1980s; the IEM SLJ-100 force balance accelerometer in the 1990s; and most recently the Kinemetrics ES-T force balance accelerometer. Digital strong motion instruments have many advantages over analog instruments, including a greater dynamic range, a wider frequency band, absolute time scales and a complete waveform. Nonetheless, the frequency range for earlier force balance accelerometers is relatively narrow (0 to 30 Hz), so strong motion instruments should be calibrated [15,16]. The acceleration frequency response range can be extended through instrument correction, and acceleration records have no high frequency distortion between 0 and 50 Hz, which is the frequency range of interest in engineering earthquake resistance.

## 5. Opportunities and Challenges in the Development of Strong Motion Instruments

For thirty years, strong motion instruments had great success in strong motion observation. NIED created the K-NET and KIK-NET strong motion observation network with nodes at intervals of 25 km after the 1995 Kobe earthquake [7]. Several acceleration records, of which PGA is larger than 1G, were captured during the magnitude 3.11 earthquake in 2011. Taiwan completed the layout of the SMART-1 array in 1990, and a large number of high-quality strong motion records [17] were obtained on September 21, 1999. Since 2008, the instruments used in digital strong motion networks have been Chinese digital strong motion instruments, such as the GDQJ-II, GDQJ-1A, GSMA-24IP, Etna, K2, GSR-18, and MR-2002. Most sensors are SLJ-100 force-balance accelerometers [18]. In addition, strong motion arrays such as the Yunnan Xiaojiang faults array, Tonghai 3D field array, Shanghai World Financial Center structure array [19] and Zigong terrain influence array [20] obtained many strong motion records in the 5.12 Wenchuan earthquake. These records are of great significance to the study of near-fault seismology and earthquake engineering.

As seismic theory research has developed, awareness of earthquake prevention and disaster reduction has continuously improved. Breakthroughs in early earthquake warning technology and earthquake-intensity rapid-reporting and the need for strong motion observation of large building structure have encouraged further developments in strong motion instruments. However, deployment of emergency rescue was delayed in the May 12, 2008 M8.0 Wenchuan earthquake due to the lack of credible earthquake-intensity rapid-reporting systems [21]. It is clear that to best respond to earthquakes, we need to know the distribution of ground-motion intensity as well as the location and magnitude of an earthquake as soon as possible. This requirement has stimulated the development of a rapid-response system for large earthquakes. Strong motion digital technology makes it possible to provide complete information on large earthquakes rapidly as they occur. The reliability of several instrument intensity algorithms was studied by Yushi Wang using data collected during the Wenchuan and Lushan earthquakes [22, 23, 24]. He suggested applying the instrument intensity algorithm proposed by Yifan Yuan, which employs spectral intensity to determine algorithm intensity, or using absolute acceleration response spectrum as the parameter for determining instrument intensity before interpreting strong earthquake data. In addition, the China Seismological Bureau issued the “Interim Procedures for the Calculation of Instrumental Seismic Intensity” on March 1, 2015, to promote rapid earthquake reporting and response in China. Xianlong He [25] introduced a new method to improve the accuracy of a single hole-shear wave velocity method based on cross-correlation functions. If this algorithm is embedded in strong motion instruments, it provides convenient site information for strong motion stations.

Continuous innovation in strong motion observation has placed higher requirements on instruments’ performance. For example, greater dynamic range, higher sensitivity, intelligent positioning and more durable downhole accelerometers need to be developed for studying three-dimensional ground motion; observation equipment must be developed to record torsion vibration; and earthquake alarms and warning systems call for strong motion observation systems with higher efficiency, higher reliability and higher accuracy.

In recent years, earthquake alarms and monitoring equipment used in high-speed railways in Beijing, Shanghai, Tianjin, Shijiazhuang, Wuhan, and Lanzhou have mostly made use of the low-delay data transmission of digital strong motion instruments (such as Basalt and TDE). Structural health monitoring systems require strong motion observation systems with clock synchronization, multi-channel recording and wireless sensors; in addition, if algorithms to assess the integrity of structures are embedded in instruments, structural health can be judged rapidly through records obtained from sensors placed on key parts of buildings. Conventional network telemetry [26] and observation of strong ground motion in the sea floor call for the development of multi-function, intelligent, embedded strong motion instruments.

In addition, accelerometers must become even easier to operate and more fully automated, so that they will automatically level themselves and point due north so as to reduce directional error. Strong motion instruments should also automatically troubleshoot to solve even complicated malfunctions, thereby reducing maintenance workload in the strong motion network.

## 6. Conclusion

China attaches great importance to technological developments in earthquake prevention and disaster reduction. In recent years, much funding has been devoted to the construction of a strong motion observation network to ensure seismic-intensity rapid reporting and early warning, which brings both opportunities and challenges for manufacturers of strong motion instruments. Inaccurate readings in the existing strong motion records should be studied to uncover and remedy the defects of strong motion instruments to increase observation efficiency. Drawing on new methods and new technologies for strong motion observation and developing advanced instruments suited to strong motion observation in China will have major economic and social benefits. At the same time, it is important to recognize that a team of highly trained experts is required to develop such instruments.

## 7. Acknowledgements

This work was financially supported by Specific Item of Fundamental Scientific Research in Institute of Engineering Mechanics Fund (2014B02), Natural Science Foundation of Heilongjiang Province in China (E2015069 and E2015070), National Natural Science Foundation of China Fund (51308517 and 51508419).

The authors would like to thank Outhay Viengkhou, Kinemetrics General Sales Manager, and Zhi-yun Chen, Richenkine CEO, for their support and for providing invaluable research material.

## References

[1] Vitaliano DB (1973). Legends of the Earth. *Bloomington*, IN: Indiana Univ. Press.

[2] Needham J (1959): Science and Civilization in China. Cambridge, U.K.: Cambridge Univ. Press, 624–635.

[3] Milne J (1886): Earthquakes and other Earth Movements. *Appleton*, New York.

[4] Imamura A (1939):Tyoko and his seismoscope. *Japanese Journal of Astronomy and Geophysics*, 16: 37-41.

[5] Trifunac M.D (2009): 75th anniversary of strong motion observation: a historical review. Soil *Dynamics and Earthquake Engineering*, 29:591-606.

[6] Xiangsheng Duan, Xiyuan Zhou (2010): Principles, methods and engineering examples of civil-engineering monitoring and health diagnosis. Beijing: China Building Industry Press.

[7] Toshihide Kashima (2000): Strong Earthquake Motion Observation in Japan. Available at: http://iisee.kenken.go.jp/staff/kashima/soa2000/soa.htm

[8] Li Shabai (1987): Recent developments in the strong motion accelerometer. *Instrument*

*development*, 1:28-34.

[9] Lili Xie, Kezhong Peng (1984): Digital era of strong motion observation[J]. *Recent Developments in World Seismology*, 7:4-8.

[10] Gao Guangyi, Yu Haiying, Li Shanyou (2001): The strong motion observation in the mainland of China. *World Information on Earthquake Engineering*, 17(4):13-18.

[11] Baofeng Zhou (2012): Some key issues on the strong motion observation. Harbin: Institute of Engineering Mechanics, China Earthquake Administration.

[12] Xiaojun Li, Ruizhi Wen, Haiying Yu (2009): Wenchuan 8.0 earthquake-aftershock observation stations uncorrected fixed acceleration records. Beijing: Seismological Press.

[13] Jiangang Zhu, Chaohui Zhou, Min Lai, Dahu Li (2006): The use of defective strong motion accelerograph and data processing. *Exchange anthology on the 30th anniversary of Songpan-Pingwu earthquake*: 272-276.

[14] Yongduo Liang, Jinzheng Jiang, Ying Li (2015): Analysis of Ms5.1 strong motion records of Liaoning Lighthouse. *Seismological and geomagnetic observation and research*, 36(5):25-29.

[15] Haiying Yu (2006): The Analysis of instrument response errors for Force-Balance Accelerometer and their correction method. *Earthquake Engineering and Engineering Vibration*, 26(6):200-203.

[16] Haiying Yu (2007): Review of the analysis of errors and the correcting method of the strong motion accelerograms. *Chinese Journal of Scientific Instrument*, 28(S4): 175-177.

[17] Strong motion array in Taiwan, phase I (SMART1) (2000): Available at: http://www.earth.sinica.edu.tw/~smdmc/smart1/smart1.htm.

[18] Haiying Yu, Dong Wang, Yongqiang Yang, Quancai Xie, Wenxiang Jiang, Baofeng Zhou (2009): The preliminary analysis of Strong Ground Motion Records from the Ms8.0 WenChuan, China Earthquake. *Earthquake Engineering and Engineering Vibration*, 29(1):1-13.

[19] Yongnian Zhou (2011): Strong motion observation technique. Beijing: Seismological Press.

[20] Earthquake Disaster Prevention China Seismological Bureau (2008): Wenchuan 8.0 earthquake uncorrected acceleration records. Beijing: Seismological Press.

[21] Tian Yu, Ming Lu (2013): The application of random method in seismic-intensity rapid reporting. *Seismic and geomagnetic observation and research*, 34(5/6):271-276.

[22] Yushi Wang, Xiaojun Li, Zehong Mei, Yan Liu (2013): Reliability comparison of instrumental seismic-intensity algorithms in 2008 Wenchuan earthquake and 2013 Lushan earthquake. *Seismological journal*, 35(5):758-768.

[23] Wang Yushi, Li Xiaojun, Zhou Zhenghua (2013): A new instrumental measure of epicentral shaking intensity in Western China. *Bull Earthquake Eng*, 11: 913-924.

[24] Wang Yushi (2010): Analyses of strong ground-motion intensity and its characteristics. Harbin: Institute of Engineering Mechanics, China Earthquake Administration.

[25] Xianlong He, Lizhen Zhao (2010): Analysis of shear wave velocity based on multiple cross-correlation functions. *Rock and Soil Mechanics*, 31(8):2541-2545.

[26] Shuangjiu Yu, Fuliang Sun (1991): Suggestions for the construction of the strong motion station network. *World Earthquake Engineering*, 1:29-31.