Some Thoughts on the Earthquake Science Experimental Site — The Underground Cloud Map

CHEN Yong¹,², XU Yihe¹,³, CAI Huiteng¹,⁴ and LI Wen¹,⁵

1) School of Earth Sciences and Engineering, Nanjing University, Nanjing 210046, China
2) Institute of Earthquake Forecasting, CEA, Beijing 100036, China
3) Key Laboratory of Seismic Observation and Geophysical Imaging, Institute of Geophysics, CEA, Beijing 100081, China
4) Fujian Earthquake Agency, Fuzhou 350003, China
5) Geophysical Exploration Center, CEA, Zhengzhou 450003, China

The Western Yunnan Earthquake Prediction Test Site set up jointly by the China Earthquake Administration, the National Science Foundation Commission of America, and United States Geological Survey has played an important role in development of early earthquake research work in China. Due to various objective reasons, most of the predicted targets in the earthquake prediction test site have not been achieved, and the development has been hindered. In recent years, the experiment site has been reconsidered, and renamed the “Earthquake Science Experimental Site”. Combined with the current development of seismology and the practical needs of disaster prevention and mitigation, we propose adding the “Underground Cloud Map” as the new direction of the experimental site. Using highly repeatable, environmentally friendly and safe airgun sources, we could send constant seismic signals, which realizes continuous monitoring of subsurface velocity changes. Utilizing the high-resolution 3-D crustal structure from ambient noise tomography, we could obtain 4-D (3-D space + 1-D time) images of subsurface structures, which we termed the “Underground Cloud Map”. The “Underground Cloud Map” can reflect underground velocity and stress changes, providing new means for the earthquake monitoring forecast nationwide, which promotes the conversion of experience-based earthquake prediction to physics-based prediction.

Key words: Earthquake Science Experimental Site; The Underground Cloud Map; 4-D seismology; Airgun

¹ Received on September 18, 2018, revised on November 21, 2018. This project is sponsored by the National Natural Science Foundation of China (Grant Nos. 41790463 and 41674058).
1 REVIEW

On January 24, 1980, the Protocol on Science and Technology Cooperation among the State Seismological Bureau of the People’s Republic of China, the U. S. National Science Foundation, and the U. S. Geological Survey of the Ministry of Internal Affairs, was signed in Beijing (Wu Ninyuan et al., 1981). In order to carry out Sino-US cooperation, the Chinese side has opened up two regions for earthquake prediction research, namely Beijing-Tianjin-Tangshan-Zhangjiakou and West Yunan as experimental sites. During the cooperation period, the State Seismological Bureau invested more than 10 million yuan (RMB) for the construction of the two experimental sites. The US also provided 129 instruments worth $2.5 million. China and the United States also jointly invested in the construction of China’s Digital Seismic Network (a total of 9 stations) (Gu Ping, 1985; Wei Yiqing et al., 1993).

The cooperation between China and the United States of America in the construction of the earthquake prediction experimental site has promoted the upgrade of seismic instruments and observation equipment. According to the provisions of the agreement, the areas of cooperation cover the communication of earthquake precursors and forecasting techniques, intraplate active faults and the associated earthquakes, earthquake engineering and hazards mitigation, deep crustal structure, rock mechanics laboratory, construction of ultra-long-period seismic stations, and exchange of films of seismograms (Gu Ping, 1985). During the implementation of the protocol, Chinese and American scientists and engineers communicate frequently (Gu Ping, 1987). From 1980 to the end of 1984, both sides communicated with each other 253 times—the United States came to China 155 times, and the Chinese went to the United States 98 times. The earthquake prediction experimental site has played a good role in promoting the development of earthquake research in China.

Until the end of the 20th century, the earthquake prediction experimental sites were successively carried out in Shanxi and Xinjiang. Many technical backbones of the China Earthquake Administration, such as Ding Guoyu, Mei Shiron, Ma Zongjin, Chen Xilinian, Xu Houze, Yao Zhenxing et al., have all worked on the site. The targets of these experimental sites are mainly “monitoring and forecasting”. The key idea was to select high seismicity areas as “earthquake prediction experimental sites”, and predicting earthquakes by precursor methods based on high-density multi-discipline observation systems. The limitations of various empirical methods have also been evaluated (Chen Xilinian, 1987; Mei Shiron, 1994; Ma Zongjin, 2000). However, the recurrence period of earthquakes (especially large earthquakes) is too long to achieve the original targets within the limited execution time of experimental sites. The Beijing-Tianjin-Tangshan-Zhangjiakou experimental site is rarely mentioned nowadays.

The exception is the Western Yunnan Earthquake Prediction Experimental Site. This site was set in Dali, Yunnan for 35 years and is still working now. Most of the people who set up the site have now retired, and several respected elders have passed away. Why we chose West Yunnan as a laboratory site in the early 1980s? Because there are many earthquakes in this area, so there were many opportunities to practice and the Red River fault is also in this area. The Red River flows across north to south through the West of Yunnan Province. The earthquakes in West Yunnan occur mostly near the Red River fault (and the fault zones formed by many faults around it). Separated by Dali (Midu), the north segment of the Red River fault has high seismicity while the southern segment is relatively quiet. As pointed out by the famous American geologist Clarence R. Allen while signing the protocol, the distinct seismicities in the two segments make it a perfect region for studying the relationship between earthquake mechanism, fault and earthquakes, as well as for basic frontier issues of seismology (Wu Ninyuan et al., 1981).
Moreover, the Red River fault is located in the southeastern edge of the Qinghai-Tibetan Plateau, which contains many scientific problems.

During the 1990s, the leadership system, funding sources, and management of the Western Yunnan Experimental Site changed several times, and these changes affected its development. Since 2015, the issues related to the Experimental Site of the West Yunnan Earthquake Prediction came into the spotlight once again. The core issue of the discussion is the orientation of the experimental site and its top-level design. At a consultation meeting in 2017 to discuss the Western Yunnan Experimental Site, the Science and Technology Commission of the China Earthquake Administration refused to use the name of the “Earthquake Prediction Experimental Site”. Instead, they suggested “Earthquake Science Experimental Site”, considering the development of the times.

Taking this opportunity, we make some suggestions for the future development of the seismic science experimental site based on the latest developments in seismology. We hope to borrow the advanced ideas of meteorology and promote the further development of seismology and the research on earthquake prevention and disaster mitigation.

2 3-D AND 4-D

To detect the inside of an object from outside, three elements are required: a field (wave) source that can penetrate the object, a receiver covering various azimuths on the outer surface of the object, and a data analysis and imaging method. Seismic waves can penetrate the interior of the Earth. The three main sources of seismic waves are natural earthquakes, ambient noise, and active sources.

In the 20th century, the overall structure of the Earth’s interior is obtained using natural earthquakes, providing important seismological evidence for the plate tectonics theory. Seismic data from 6,500 earthquakes with $M \geq 6.0$ are involved, which represents the glorious era of 3-D seismology (Dziewonski A.M. et al., 1981; Kennett B.L.N. et al., 1991, 1995). However, if you want to study the shallow structure of the Earth (compared to the Earth’s radius of 6,371 km), the deficient number and uneven distribution of natural earthquakes cause insufficient imaging accuracy and resolution.

One of the most important breakthroughs in seismology since the 21st century is utilizing of ambient noise in the imaging of shallow crust structures (Shapiro N.M. et al., 2005). Ambient noise research opens up a new field of seismology that can obtain high-resolution shallow structures without waiting for earthquakes or using active sources. The imaging resolution of this method depends mainly on station density. Consequently, the number of seismic stations and the density of stations deployed for ambient noise study is so high that it is unimaginable in traditional seismology (Lin Fanchi et al., 2013). The ambient noise tomography method based on short-period dense array can effectively obtain the fine structure model of the shallow crust (such as urban areas, fault zones, etc.), and provide an important background velocity model for assessment of urban earthquake hazards and seismotectonic study of fault zones (Li Cheng et al., 2016). The ambient noise method is essentially a random statistical method. In order to obtain the results, it is necessary to accumulate a large amount of data for a long time. Studying the deep upper mantle structure (the scale of tens of thousands of kilometers) requires noise data of years to obtain reliable long-period surface waves of 100–400s from the global network (Nishida K. et al., 2009). Imaging crustal structure of Sichuan-Yunnan (a few hundred kilometers scale) use the shorter period surface wave of 5–50s, which requires continuous data of the regional network for at least one year (Yao Huajian et al., 2006, 2008). To study the shallow crustal structure of the Taipei Basin (10km scale), one month of noise data is sufficient to retrieve short period
surface waves of 0.3–4.0s (Huang Y. C. et al., 2010). The smaller the scale of seismic array, the higher surface wave frequency can be recovered, and the shorter the continuous noise time required. Subsequently, it is more sensitive to the shallow structure. Ambient noise has considerable advantages in 3-D survey of velocity structures.

Active sources can also generate seismic waves. During the past 10 years, we have introduced airguns used in marine seismic exploration to excite seismic waves in reservoirs of limited volume, resulting an environmentally friendly active source (Chen Yong et al., 2007; Wang Baoshan et al., 2012; Chen Yong et al., 2017). Two significant progresses have been made. Firstly, the high repeatability of the airgun source was discovered. Utilizing the source characteristic, it is possible to achieve large-scale surveys using small energy sources by stacking and correlation techniques (Chen Yong et al., 2017). Secondly, using movable active sources, we can form multi-source-multi-receiver observation systems, which can be used to obtain high resolution subsurface structures (Zhang Yunpeng et al., 2016; She Yuyang et al., 2018; Tian Xiaofeng et al., 2018). For example, we conducted an earthquake experiment in the Anhui segment of the Yangtze River, using airguns towed by a ship as the source. The seismic wave was continuously excited, and was received on both the southern bank and the northern bank of the river. The shallow structures in the adjacent region of Yangtze River were obtained (Fig.1). The area along the Yangtze River showed a low velocity. High velocity zones are coincided with ore concentration areas previously discovered by geologists. Compared to natural earthquakes and ambient noise, active sources have greater potential for 4-D detection, although all three types of sources can perform 3-D surveys.

Fig.1  An example of an underground structure (3-D) obtained using airgun sources in 2015

The shear velocity obtained from surface wave tomography is shown. M1: Anqing ore concentration area; M2: Lucong ore concentration area; M3: Tongling ore concentration area; M4: Ningwu ore concentration area (Courtesy of She Yuyang et al., 2018)

The structure of the Earth’s interior and its changes have been one of the main contents of geophysical research. Using increasingly dense seismic station data, we have access to the Earth’s
interior structures at a high resolution. Many of Earth's hazards are subject to changes in the stress state, in addition to the static stress state of the Earth. For example, the stress accumulation in the Earth's medium is an important factor in the seismogenic process of earthquakes. Monitoring the weak changes in the Earth provides us an opportunity to study the earthquake process and even find the precursors of the earthquake.

Since it is difficult to directly measure the Earth's interior, we can only study the changes in the Earth by analyzing seismic waves. Seismic waves are most sensitive to wave velocity, and the velocity can directly reflect the physical parameters such as the state of stress and material composition. Therefore, change of seismic wave velocity are widely used to study the internal structural changes of the Earth.

In comparison to the study of the Earth's static structure, research on the changes of the Earth's medium (4-D seismology) is still less developed. In the industry, 4-D seismology has made some progress in data acquisition and data processing, and there is an increasing number of application examples. The petroleum industry has achieved great success in monitoring hydrocarbon migration and production processes using 4-D seismic methods. However, the progress in the study of subsurface changes related to seismic activity is relatively slow. The reason is that the wave velocity changes associated with oil and gas processes (and carbon dioxide injection, etc.) are large and the wave velocity changes associated with seismic activities are small.

According to the source used, the 4-D seismology methods for studying seismic-related changes in subsurface structures can be divided into: passive 4-D seismology and active 4-D seismology. Passive 4-D seismology uses natural seismic signals and noise signals observed by seismic stations. The seismic and noise characteristics at different times are compared to obtain the temporal changes of the subsurface medium.

The energy of an earthquake is likely to be received by many stations, but the distribution of earthquakes is very uneven in space and time. At the same time, there are large errors in the location of the natural earthquake and the origin time. Therefore, the use of natural earthquakes to study the variation of subsurface media is very limited, which in turn limits the use of natural earthquakes. In recent years, seismic noise has gradually been used as a source for imaging subsurface structures. Recently, researchers have used seismic noise to study the variation of temporal changes of subsurface structures. However, since the noise energy is small, it is necessary to stack seismic data for a long time to obtain a reliable signal with sufficient signal-to-noise ratio. Furthermore, only the surface waves can be obtained by using the noise nowadays, instead of the complete response. Therefore, ambient noise can be used for long-term average changes in deep structures or for large changes associated with events such as earthquakes.

In order to overcome the problems of passive sources, it is important to use active sources to send seismic waves into the ground for underground media monitoring and to develop active 4-D seismology. Although the idea of using active sources to study subsurface changes can be dated back to the 1970s, or even earlier, accuracy was limited and related research was once stalled, due to the limited techniques at the time. Nowadays, active sources for high-precision temporal monitoring are available, due to the development of the following technologies: ① the development of the active source. The green source represented by the airgun source is sustainable and highly repeatable; ② the development of GPS technology provides a highly synchronized clock for our observations; ③ the development of data processing methods and the relatively mature delay estimation technology in communication theory is applied to seismic data processing, which makes obtaining high-precision measurements possible.
3 “FENGYUN” IN THE SKY AND “CLOUD MAPS” UNDER THE GROUND

How to take advantage of seismological 4-D detection? Let’s start with the revelation of meteorology. Satellite cloud maps appeared in the 1960s (Bristol C. L. et al., 1966). In the following 30 years, this technology was widely applied in many countries. China’s “Fengyun” meteorological satellite is an outstanding example (Yang Jun et al., 2011). Satellite cloud maps is not only used to understand the structure of the cloud (3-D), but more importantly, to understand the movement of the clouds (4-D) (Platnick S. et al., 2003). The detection of atmospheric motion is crucial for weather forecasting. Numerical weather forecast would have made limited progress without the observations of the satellite cloud map. The same is true for seismology. Seismology relies heavily on mathematics and numerical simulation has always been the strength of seismology. However, if no new type of observation data is provided, the application of numerical simulation will be limited.

The satellite operates in space above the Earth, observing the cloud image above the entire Earth, which is a full-field observation, instead of a single-point observation. This is the key idea for seismology to study meteorology.

Imagine a movable active source system as the “Fengyun” satellite installed in the “Earthquake Science Experimental Site”, together with the newest development of data acquisition techniques and data processing methods, it is possible to achieve engineering innovation in the terms of technology integration (engineering innovation is very important for scientific innovation). Then it can be used to make an underground cloud map of the “Earthquake Science Experimental Site” area. The cloud map will reflect the wave velocity changes and stress changes of the subsurface medium, and begin to explore the transition from the empirical prediction of the earthquake to the physical prediction.

4-D seismology is a cutting-edge technology. Its development faces many challenges, such as improving the timing and punctuality of existing stations in terms of hardware, and establishing a network consisting of multiple active sources and multiple receiver stations to form the ability of the continuous monitoring of the subsurface medium. In analysis and processing, focus should be placed on subsurface velocity changes, especially ones related to seismic activity. If one correlation is found, the size and spatial distribution of changes are the next target, as well as how to confirm the relationship between velocity changes and the changes of stress state and physical properties of the subsurface medium.

The traditional practice of monitoring and forecasting in the “Earthquake Science Experimental Site” should not be affected, but the positioning of the “Earthquake Science Experimental Site” should be clear, that is developing, examining and improving the “Underground Cloud Map” technology. It is not necessary to wait for the occurrence of earthquakes and will provide new means for nationwide earthquake monitoring and forecasting in future.

4 SUMMARY

3-D seismology has made great contributions to the construction of physical models at different scales of the Earth. With the improvement of observation accuracy and the development of focal technologies (such as ambient noise and airguns), 4-D seismology has gradually revealed its potential for monitoring disasters, such as volcanoes, earthquakes, etc. This paper proposes to establish an “Underground Cloud Map” technology system with 4-D seismology as the core technology. The system should have a complete process from excitation, reception to real-time
processing, while establishing two different standard technical systems for different detection purposes (large areas and urban areas). The completion of the system will provide new means for earthquake monitoring and prediction, and promote the exploration and development of physically seismic prediction.

REFERENCES


Lin Fanchi, Li Dunzhu, Clayton R.W., Hollis D. High-resolution 3D shallow crustal structure in Long Beach, California; Application of ambient noise tomography on a dense seismic array [J]. *Geophysics*, 2013, 78 (4); Q45–Q56.


Pang A.J., Li Shengrong, Santosh M., Yang Qingyu, Jia Baojian, Yang Chenglong. Geochemistry, and zircon U-Pb and molybdenite Re-Os geochronology of Jilongshan Cu-Au deposit, southeastern Hubei Province, China [J]. *Geological Journal*, 2014, 49 (1); 52–68.


About the Author

CHEN Yong, born in 1942, is an academician of Chinese Academy of Sciences and the World Academy of Sciences for the Advancement of Science in Developing Countries, also a professor of Nanjing University. His research mainly focuses on experimental rock physics, seismic hazard assessments, and more recently on active source seismology. E-mail: yongchen@seis.ac.cn