Application of large capacity air gun in three-dimensional crustal structure exploration of the Pearl River estuary area

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Abstract: The air gun source has been widely used as an artificial source in seismic exploration of the sea area because of its simple operation, low risk, automatic continuous operation and almost no influence on the observation environment. In 2015, we carried out the 3-D crustal structural exploration project in the Pearl River estuary, 13 seismic sounding explorations were set up in the sea area, and activated air gun source for more than 12,000 times. Through records of ocean bottom seismograph (OBS) and fixed seismic stations, we found that seismic records of OBS can be clearly identified Pg, PmP, and other phases, the records of the fixed seismic stations can be clearly identified the air gun shot events. The results show that the energy of the air gun shot in this field exploration is quite good, and data can support the study of the three-dimensional structure of the crust in the sea by air gun shot records of seismometers.

1. Introduction

In recent years, with the increase in observational data, people have begun to use repeated earthquakes, noise and other seismic sources to study underground medium changes. Subject to source location and time accuracy, resolution of the time and spatial based on earthquake, noise and other passive seismic observations is limited. It is hard to use natural seismic records to study the fine structure of the crust in the relatively stable area with minor background seismicity, liking Pearl River estuary. In recent years, the underground structure of the Pearl River Delta region has been studied by noise imaging, some information on the crustal structure of the Pearl River estuary area has been obtained. However, due to the low reliability of the passive source, the resolution is relatively low, these studies cannot give a fine result of the regional crustal structure and fault structure.

Since the excitation frequency and the excitation time can be precisely controlled, which can eliminate the uncertainty of the results caused by the uncertainty of the source, the method of seismic waves activated by artificial shocks in the seismic exploration is developing rapidly. People have gradually developed a variety of artificial seismic source to provide seismic waves, including explosives source, vibration source, drop hammer source, spark source, gas explosion source, air gun source, ramming source, ACROSS source, piezoelectric ceramic source, induced shock source, etc. Among the marine artificial seismic sources, the development of air gun source is the fastest. The air gun source, which was invented by Chelminski [1] of Bolt Corporation, USA, Ziolkowski A [2] and Schulze-Gattermann R et al.
established a theoretical model of the air gun array based on the theory of the attenuation mode of the bubble oscillation, the oscillation period and the oscillation model. It laid a good theoretical basis for the establishment of air gun array. In 1983, Bolt's patent for air gun was invalid, air gun theory and technology has been rapidly developed, and the application of air gun in the marine sciences achieved a great success. According to statistics, more than 95% of the marine seismic sources are the air gun sources [7, 11].

In 2001 and 2004, the South China Sea Institute of Oceanology, CAS, cooperated with the Earthquake Administration of Guangdong Province, shoot twice with air gun in the north of the South China Sea while the receivers were set up in the land to take an onshore-offshore deep seismic experiment. The surveying lines are located in the coastal fault zone near NanPeng island [9] and DanGanDao island [10]. Especially in 2004, the South China Sea Institute of Oceanology, CAS, used the newly equipped large-capacity air gun array (4 combined 1,500 cubic inches of air guns with a total capacity of 6,000 cubic inches) on the "Experimental No. 2" shipboard, carried out the sea and land joint detection, the land fixed seismic station more than 250 kilometers outside the source can receive a clear air gun signal to identify the Pg, Pn, PmP and other phases, the air gun excitation effect reached the advanced world level [10]. In July 2010, it was the first time that the OBS received the signals active by the air guns as the source in the Pearl River estuary and the outer sea area of Yangjiang, where obtained the structural features of the coastal fault zone [12]. After more than ten years of experiments, the method of using air gun(s) as source, OBS and fixed seismic network as receiver becomes an effective means to study the deep crustal structure of the sea-land transition zone [4-7, 9, 11-13].

2. Three-dimensional crustal structure exploration in the Pearl River estuary area in 2015
In the year of 2015, we have conducted a large-scale onshore-offshore seismic experiment to study the three-dimensional crustal structure in the Pearl River estuary region. We have set up 414 sets of seismic observation instruments in the observation area of land and sea area, including 256 sets of PDS-2 seismometers for two-dimensional wide-angle refraction/reflection observation of sea and land, 40 sets of seismometers from China Array for mobile observation, 60 sets of fixed seismic stations from Guangdong seismic network, and 58 sets of OBS in the sea area. After the completion of the observation system, we made 6 explosions in the land, each source of explosion equivalent in 1-2.5 tons TNT, and more than 12,000 air gun sources are shoot in the sea area, the entire observation time was as much as 35 days (Fig. 1).
3. The air gun source characteristics in three-dimensional crustal structure exploration of the Pearl River estuary

Air gun is an important active seismic source that uses the instantaneous release of high pressure air to create a source of seismic waves. With the advantages of eco-friendly, economic, high controllable and high repeatable in a long time, the air gun source is widely used in modern marine seismic exploration and becoming more important and indispensable. The air gun used in this exploration experiment was 1500LL large-capacity air gun produced by Bolt Corporation, USA, with single gun capacity of 1500 in$^3$ (about 24.6L). It has the characteristics of large excitation energy, low basic frequency and high signal-to-noise ratio, which is designed for exploring the deep crustal structure. It can record the refraction and reflected waves from the lower crust and even from the upper mantle [9, 15]. In 2004, the Pearl River estuary experiment found that the seismic wave excited by the air gun array produced a clear and continuous PmP wave [9] at the ZHQ station with a distance of more than 255km from the source, indicating that the large capacity air gun is an ideal source for the deep crustal structure study.

In 2015, we have used 4 air guns (total capacity is 6000 in$^3$) sunk to the sea depth of 10 m, with air gun spacing $>4$ m, towed at the speed of 4-4.5 at the stern, and the excitation interval was 60-80 seconds. The working pressure of air guns was 2000 psi (about 13.8 MPa), the maximum amplitude spectrum was 14 Hz, the peak value of the main pulse of the excited wavelet was 6.0 Mpa·m, and the energy released was 6.68$*10^6$J.

4. OBS records of the air gun source

The work of OBS recovery lasted more than two months after all air gun experiment. With the collecting all the recovered OBS data, we sorted all the OBS recorded air gun shots data, and processed OBS single seismic record profile (Fig. 2).
Figure 2. OBS single seismic record profile of air gun sources

It can be seen from the single seismic record section that OBS has a good record of air gun shot in the sea. Taking OBS33 as an example (Fig. 3), we can clearly identify the phases such as Pg, PmP and PcP, where Pg can be traced to 30 km, PmP can be traced from 45 km to 85 km, PcP can be more clearly identified at 25 km to 35 km. These phases reflect the regional crustal structure feature, which bolster our confidence to the further study in the crustal structure with those data obtained from this onshore-offshore experiment.

Figure 3. OBS33 single seismic record profile of air gun sources
5. The air gun source records of fixed seismic station in DanGanDao island (DGD)
We selected the seismic records of the fixed seismic station(DGD) in the DanGanDao island to analyze the signals produced by the air guns (Fig. 4). The recorded signals of air gun shots in DGD are clear, highlighted after the linear superposition. The island is in the open sea out of Hong Kong, consisted of Mesozoic granite, which is obviously weathered in the surface, where the DGD station is located. The DGD station is about 45 km away from the stack air gun shots point (in Fig. 2, around of OBS38), which has a good record of the air gun shots signal. After sorting them in accordance with the time of the shots, we can see Pg and PmP, and then the Pw (P wave transmitted in the water) with the maximum energy, according to the exploration experiment before in the Pearl River estuary and other information, we calculate that the phase time is matched. This observation verifies some of our previous work, for instance, the P wave velocity measurement at the Pearl River estuary [12]. Between Pg and PmP phase, there is a very obvious high-energy signal, according to the speed structure and seismic ray theory, etc., we think that the phase is PcP, which may be the reflected waves from the basalt and granite interface. However, this phenomenon may also be resulted in the local crustal structure, such as P wave reflected in the water at the bottom of the ship or reflected through other interface, amplified by the superposition effect, an obviously high energy phase which is stronger than Pg and PmP phase shown. Those phases and things are our future research directions. And, it is these appearances, which are different than what we expect, bring more information of the underground than before.
6. Conclusion and expectation
In 2015, we carried out the three-dimensional crustal structure exploration, which mainly for the coastal fault zone in the Pearl River estuary area. From the results of the air gun shots signal recording, both the fixed DGD station and the OBS recorded the sea air gun shots event clearly. We can identify Pg, PmP and other phases, and in some stations, can identify the PcP phases, indicating that in this exploration experiment the air gun and the observation stations worked in good condition.

The next step, we will study the two-dimensional and three-dimensional crustal structure of the Pearl River estuary area by further processing the records of artificial seismic source. Combined with regional geological background, gravity and magnetic field, regional stress field distribution and other information, we will study the characteristics of the crustal structure and the deep structure of the coastal fault zone, and we also wish to study the potential earthquake risk in the Pearl River estuary.

Acknowledgments
Funding for the field work has primarily come from China Earthquake Administration and the People’s Government of Guangdong Province. Teams from the Guangdong Earthquake Administration, CEA, South China Sea Institute of Oceanology, CAS, and Geophysical Exploration Center, CEA participated the field work. In addition, the China Seismic Array provided over 60 instruments for observation, and The Geophysical Exploration Center, CEA, provided over 300 instruments for observation. Support for field work was also provided by the People’s Government of Guangzhou, the People’s Government of Shenzhen, the People’s Government of Dongguan, the People’s Government of Jiangmen, the People’s Government of Foshan, the People’s Government of Zhaoqing, the People’s government of Huizhou. The data processing and interpretation is support by the National Natural Science Foundation of China 41676057. The public domain GMT package [Wessel and smith, 1995] was used to produce some of the figures.
References

[1] Chelminski S. V., Pressurized gas discharge apparatus for use as a down-bore seismic impulse source: US, US 3997021 [P]. 1976.

[2] Ziolkowski A. Design of a Marine Seismic Reflection Profiling System using Air Guns as a Sound Source [M] // Geophysical Journal of the Royal Astronomical Society. 1971: 499-530.

[3] Schulze-Gattermann R. PHYSICAL ASPECTS OF THE "AIRPULSER" AS A SEISMIC ENERGY SOURCE [J]. Geophysical Prospecting, 1972, 20 (1): 155-192.

[4] McIntosh K, Nakamura Y, Wang T K, et al. Crustal-scale seismic profiles across Taiwan and the western Philippine Sea [J]. Tectonophysics, 2005, 401 (1): 23-54.

[5] Nazareth J J, Clayton R W. Crustal structure of the Borderland-Continent Transition Zone of southern California adjacent to Los Angeles [J]. Journal of Geophysical Research Solid Earth, 2003, 108 (B8): 183-187.

[6] Qiu Xuelin, Shi Xiaobin, Yan Pin, et al., Advances in Deep Earthquake Detection and Research of Crustal Structure in the Northern South China Sea [J]. Advances in Natural Science, 2003, 13 (3): 231-236.

[7] Qiu Xuelin, Chen Yong, Zhu Rixiang and so on. Application of Large Capacity Air Gun Source in Sea - Lu Joint Test: Analysis of South China Sea Test Results [J]. Science Bulletin, 2007, 52 (4): 463-469.

[8] Zhao Minghui, Qiu Xuelin, Xia Shaokhong and so on. Large volume air gun source and its waveform characteristics [J], Chinese Journal of Geophysics, 2008, 52 (2): 558-565.

[9] Zhao Ming-hui, Qiu Xuelin, YE Chun-ming, et al. Analysis of crustal structure on both sides of the sea fault in the northeast of the South China Sea and the crustal structure on both sides of the coastal fault zone [J], 2007, 47 (5): 845-852.

[10] Xia Shaohong, Qiu Xuelin, Zhao Minghui, et al. Study on sea-land seismic survey and deep crustal structure in Hong Kong [J]. Advances in Geophysics, 2008, 23 (5): 1389-1397.

[11] Xia Shaohong, Qiu Xuelin, Zhao Minghui, et al. Ecological analysis of crustal average velocity and Moho depth in the continental boundary of the South China Sea [J]. Journal of Tropical Oceanography, 2010, 29 (4): 63-70.

[12] Cao Jinghe, Sun Jinlong, Xu Huilong, et al. Seismological characteristics of the coastal fault zone in the Pearl River estuary [J]. Journal of Geophysics, 2014, 57 (2): 498-508.

[13] Xu Huilong, Xia Shaohong, Sun Jinlong, et al. Preparation of sea-land combined deep earthquakes in the northern South China Sea and its geological significance [J]. Journal of Tropical Oceanography, 2012, 31 (3): 21-27.

[14] He Hanyi. High-resolution seismic technology at sea and its application. Beijing: Geological Publishing House, 2001, 52-77.

[15] Yao Dao-ping, Zhang Yifeng, Yan Pei, et al. Study on sea-land combination of large-capacity air guns in the Taiwan Strait [J]. Acta Seismic Journal, 2016, 38 (2): 167-178.