A towed-type shallow high-resolution seismic detection system for coastal tidal flats and its application in Eastern China

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Abstract
Restricted by detective equipment and tidal influence seriously, coastal tidal flats are often treated as the transition belt of paralic zone in terms of seismic detection, causing low exploration degree and accuracy in these areas. What is worse, conventional shallow seismic method has a complex system and low acquisition efficiency, which cannot meet the requirements for high-efficiency acquisition in tidal flats. To solve these problems, a towed shallow seismic detection system is specially established for coastal tidal areas, mainly including electric spark source and towable ship-type geophone strings. After comparisons, some advantages of this method are obtained, such as high efficiency, low cost and reliability. Furthermore, its detective accuracy and depth can reach the meter level and more than 800 m, respectively. Then, a series of shallow seismic processing methods are improved for coastal tidal flats. Deconvolution and velocity analysis are emphatically introduced to multiple-wave attenuation. A short array of this towable detection can keep a far more effective wave from being cut off because of its small NMO stretch. Last but not least, the towable method in coastal tidal-flat zones can successfully identify the stratigraphic structure, interface, palaeo-channel, concealed active fault and submarine shallow gas in Jiangsu Coast, Eastern China, which has great practical results and significance for geological and environmental surveys, as well as scientific geo-hazard prevention and mitigation in these areas.

Keywords: coastal tidal flats, towed type, high-efficiency acquisition, high resolution, shallow geological information

1. Introduction
Coastal tidal flats are formed by the interaction of terrestrial and marine processes, which refer to the tidal zone between the high and low tide line (Wang \textit{et al.} 2000; Dyer 2003; Reise 2005; Wang \textit{et al.} 2020). Generalised tidal flats also include some undeveloped supratidal zones and underwater shoals that are difficult to expose at low tide. Moreover, in well-developed coastal areas, tidal flats can reach more than 10 km in width with a small slope; these are composed mainly of fine silt to fine-grained clay sediments (Holland & Elmore 2008; Murray \textit{et al.} 2012). About 70% of the global extent of tidal flats are found in three continents (Asia (44%
of total), North America (15.5% of total) and South America (11% of total), with 49.2% being concentrated in just eight countries: Indonesia, China, Australia, the United States, Canada, India, Brazil and Myanmar (Murray et al. 2019). What is more, coastal tidal-flat zones are important reserved resources for the future development, with great economic, environmental, ecological and energy value, having great potential for development and use (Lotze et al. 2006; Barbier et al. 2011; Murray et al. 2015; Chen et al. 2016; Bearup & Blasius 2017; Xia et al. 2017).

Tidal-flat zones are normally restricted by the coastal tide, complex surface environment and lack of a special detection system. Therefore, it is impossible to carry out geological exploration from the surface in these areas with simple land-surface or marine-detection equipment. In addition, the effective time for data acquisition is quite short in coastal tidal regions. To solve these problems, seismic exploration studies in these areas begin early (Lauhoff & Sheriff 1979). Coastal tidal flats are often treated as the transitional belts of the paralic zones. Multiple shooting sources, various geophone receivers, land and sea observation systems and targeted seismic data processing are all integrated in the studies (Hadidi & Smith 1990; Lafehr et al. 1990; Yates et al. 2012). Meanwhile, a set of exploration studies for deep oil and gas resources in coastal tidal regions have been completed by oil companies, which combine the seismic technologies of surface land and shallow sea (Song 2005; Cui et al. 2006; Cui & Cao 2008; Chen et al. 2011). Although the requirements for resource detection can be met, coastal tidal flat in seismic explorations has not been treated as a single target area, resulting in low detection accuracy for shallow strata. Furthermore, seismic acquisition efficiency has not been fully taken into consideration in such areas. Therefore, it is too hard to reach the targets in coastal tidal regions, such as high-accuracy geological survey, determination of shallow stratum structure and delineation of concealed active fault distribution.

Shallow seismic detection, combined with effective reflection processing, has been widely used in many respects on land, including identification of subsurface geological structures, active faults, urban underground spaces, land natural gas hydrates and metal ores (Miller & Steeple 1994; Improta & Bruno 2007; Giustiniani et al. 2008; Improta et al. 2010; Heinonen et al. 2012; Yordkayhun & Na Suwan 2012; Ishiyama et al. 2013; Xu et al. 2016; Yue et al. 2017; Gu et al. 2018). Compared to traditional shallow methods, the land-streamer system comprising towed geophones is proposed to improve seismic acquisition on land, especially flat areas like highways, icy ground and dams. Potential advantages of this innovation are no need for geophone planting, automated roll-along, fewer field personnel, a significant increase in acquisition speed and a marked decrease in survey costs (Van der Veen & Green 1998; Van der Veen et al. 2001; Moura & Senos Matias 2011; Brodic et al. 2015; Schenato et al. 2017; Kammann et al. 2019). Above all, they bring new thoughts to shallow seismic studies in coastal tidal flats.

Influenced by the Yangtze River, the Jiangsu Province has a large number of typical coastal tidal-flat resources among the coastal provinces of China, which accounts for a quarter of the total tidal flat of the country (Zhu et al. 1998; Wang & Wall 2010; Zhang et al. 2019). A shallow seismic method that uses the rolling array with a hammering source and 60-Hz geophones is applied to the coastal tidal flat in Rudong County, Jiangsu Province, China (Zhang et al. 2018). Through this study, the internal layers and bottom interface of Quaternary in the survey area have been detected effectively. In addition, the existence and distribution of concealed active faults and shallow gas have been made clear. However, in terms of shallow seismic application in coastal tidal-flat areas, conventional exploration method is relatively complex, which requires a great deal of manpower, material resources and time to arrange the equipment. Meanwhile, due to the tidal time constraints, daily acquisition efficiency is quite low and it is difficult to carry out large-scale work for tidal-flat zones. Therefore, it is urgent to develop an improved shallow seismic detection that can acquire seismic field data in coastal tidal regions much more quickly and efficiently.

A conventional land-streamer system cannot be directly used on the particular surface of coastal tidal-flat environments without reconstruction. Therefore, a towed-type high-resolution seismic detection system for tidal flats is designed in this study, which can solve exploration problems in these areas such as insufficient shallow detection accuracy, low seismic acquisition efficiency and high detection cost. First, electric spark source and reconstructive towed ship-type geophones are applied to the detection system, which are perfect for the surface environment in tidal flats. In addition, the advantages of this method are discussed in the three aspects of system, efficiency and effectiveness. Second, a set of shallow seismic processing steps for coastal tidal-flat areas are proposed to obtain high-quality results. At the same time, two significant key steps for extracting signal are specially listed. Finally, some types of shallow geological information in coastal tidal flats in Eastern China can be detected effectively through the practical application of this towable method.

2. Overview of the study area

The study area is located in Rudong County, Nantong City, Jiangsu Province, China, which is an area of rich coastal beach resources in this country. As shown in figure 1, this region is close to the Yellow Sea. The surface of coastal tidal flat is mainly composed of consolidated silt. After the ebb tide, vertical tidal flats can extend more than 10 km from west to east, and the overall terrain is flat with an elevation drop of less than 1 m. In the study area, the daily time interval between ebb and flood tide is about 5 hours. People can walk
and vehicles can drive on the coastal tidal flats during this period, which is favorable for seismic exploration. In addition, the Quaternary strata are well-developed in the study area, with a thickness of about 300 m. The buried depth of bedrock is from 700 to 1400 m. The surface consists of mainly coastal-shallow marine sediments and delta frontal-tidal-flat sediments. Meanwhile, the lithology is mainly silt, sand clay, fine sand, coarse sand and gravelly coarse sand. The thickness of each lithology can be as thin as a few meters, or as thick as tens of meters (Wang et al. 1999, 2002). Due to the flood and ebb tides in coastal tidal flats, the surface and underground are saturated by seawater. This is perfect for the propagation of seismic waves and has no influence on the surface low-velocity zone.

3. Data acquisition system

It is quite difficult to carry out complex seismic exploration work in tidal flats due to the short time between daily flood and ebb tides, which is no more than 5 hours every day. How to ensure the quality of seismic data acquisition and workload of the daily task design within a limited time is a key factor for improving the efficiency of seismic data acquisition in tidal flats. We put forward a towed-type shallow seismic detection system to improve acquisition for these areas. Three advantages of this system are discussed in this paper, including acquisition system, efficiency and effectiveness, as follows.

3.1. System and parameters

The diagram of a towed-type shallow seismic detection system for coastal tidal flats is displayed in figure 2. It can be seen from the figure that the system includes the towable vehicle, electric spark source and 24-channel towed ship-type geophones. Field data acquisition in coastal tidal zones can be carried out using forward rolling towable vehicles.

Figure 3 shows the specific components of the towable seismic system. They include drilling a well at a depth of 1 m on the tidal-flat surface, burying the shooting cable head of the 40 000 J electric spark source (figure 3a) into the well and filling it with water as a source point (figure 3b). At the same time, the conventional geophone strings are fixed in the 10 kg self-made metal device to form the towable ship-type geophone strings (figure 3c), which are connected to the geode station by the towed cable with a fixed channel space (figure 3d). To adapt to the surface environment of coastal tidal flats, all seismic acquisition equipment is treated with waterproof transformation.

To achieve the purpose of detailed detection of shallow geological structures in coastal tidal-flat zones, the key parameters of this seismic detection for field data acquisition are listed in Table 1 with a unilateral shooting pattern. Through repeated tests, the optimal parameters in sequence confirm that channel interval is 3 m, shot interval is 6 m, minimum offset is 6 m, sampling interval is 0.25 ms, receiving gather is 24 channels and is up to sixfold better.

3.2. Acquisition efficiency

For shallow seismic areas in coastal tidal flats, the most important thing in terms of field acquisition is work efficiency. Statistic comparisons between conventional...
rolling-type and towed-type detection proposed in this paper are shown in Table 2 and Figure 4, which are based on the full use of effective work time between rising and ebb tidal. They specifically include geophone weight, the number of geophones, analog cables, digital cables, geode stations, technicians and workers, as well as the daily completed workload in the tidal flats.

Generally, it can be seen in Table 2 that the towable shallow seismic method has less equipment and personnel than the rolling one. To be specific, 168 geophones, 14 analog cables, six digital cables, seven Geode stations and 14 people are needed in the rolling-type method to reduce effective working time to the greatest extent. In contrast, for towed-type seismic detection, only 24 self-made ship-type geophones, one analog cable, one Geode station and five people are needed to complete the field data acquisition task in the coastal tidal flats. What is more, the geophone weight of the towed-type method is 5.5 times as much as the rolling-type, which is beneficial for detector-ground coupling in tidal-flat zones. In addition, the ship shape can be better for dragging along the mud-mixed surface of coastal tidal regions. Therefore, a lot of effective time can be saved for seismic source shooting, data receiving and recording using the towable method, which helps a lot to enhance workload.

Figure 4 shows the daily workload of two-kind seismic detections for five consecutive days in coastal tidal zones. It is not hard to find that the daily maximum and minimum data acquisition workload of the rolling-type are 72 and 60 shots, respectively, with an average of 65.8 shots. However, they are 130 and 120 for the daily maximum and minimum data acquisition workload in sequence for the towable type, with an average of 124.2 shots. Therefore, a significant conclusion can be drawn that the acquisition efficiency of towed detection is nearly twice that of the rolling one.

Because of the simple system and easy mobility, towed-type seismic detection in coastal tidal flats can neglect the time spent on equipment arrangement, connection and disassembly. Much time can be saved to use in seismic effective acquisition, so this method increases the average...
daily workload a lot within the limited, precious time for working in these regions.

3.3. Effectiveness analysis

Continuous single-shot records and their frequency spectrum of towed shallow seismic detection in tidal-flat areas for quality control are shown in figure 5. Band-pass filter and gain compensation are applied to quality control. Although some noise on the seismic record is shown in figure 5a, the reflected wave of the hyperbolic type is good in event continuity with strong energy. The two-way effective wave time can reach 0.8 s, which means one can obtain the subsurface strata information in coastal tidal flats of more than 800 m. Benefiting from the electric spark source, figure 5b shows that the main frequency is located at about 130 Hz and the effective frequency band is mainly distributed from 80 to 240 Hz. Therefore, the towable seismic method in tidal-flat areas achieves a high resolution, which can reach the meter level and be good for shallow detailed exploration.

The advantages of this method proposed in this paper are further verified, which lays a foundation for the subsequent shallow seismic processing and imaging in coastal tidal flats.

4. Processing and imaging

The effect of seismic processing in coastal tidal areas directly affects the quality of shallow geological and tectonic surveys. It is necessary to minimise the damage to the effective signal and retain the original appearance of the reflected wave. Both signal-to-noise ratio (SNR) and resolution of seismic results in tidal-flat zones should be optimised in the process. After comprehensive analysis of field data acquired by the towable seismic method, a flow chart of seismic processing
is made for these regions. Then, some important steps and their results are emphatically introduced.

4.1. Analysis of field data

Comprehensive analysis of the field data is one of the key steps in seismic signal processing. Work flow and method combination for extracting effective signals in coastal tidal flats can be reasonably determined only when the differences between noise and signal have been made clear and the difficulties of shallow seismic processing have been understood.

By analysing the original records from coastal tidal zones shown in figure 6, it is found that the wave group characteristics of all kinds of noise and reflected signal are obvious. More specifically, the effective wave is hyperbolic and continuous. However, interference waves mainly consist of low-frequency noise, surface waves, acoustic interferences, random noise and interlayer multiple waves. To be honest, the overall SNR and resolution of seismic records in coastal tidal flats are not very high. Furthermore, the amplitude energy of the single-shot record varies greatly from shallow to deep, and horizontal differences between various seismic records also exist.

Figure 7 displays the flow chart of seismic processing in tidal-flat areas, which mainly comprises the definition of the observation system, data loading, prestack noise attenuation, true-amplitude recovery, deconvolution, velocity analysis, normal move out (NMO) and cutting as well as stack imaging. Among them, the third to sixth steps require multiple iterations to gradually eliminate all types of noise and retain effective seismic information to the greatest extent, which can improve SNR and resolution of seismic data. In addition, various deconvolution methods and high-precision velocity analysis are significant for shallow seismic processing in coastal tidal flats, because of multiple-wave development. Meanwhile, the small NMO stretch is one of the advantages of the towed-type method.

4.2. Deconvolution

Affected by the differences in surface geological conditions, the shape of the seismic wavelet (amplitude spectrum and phase spectrum) often changes during propagation. On the one hand, a seismic frequency generated under the
conditions of hard surface or water saturation in tidal flats can be higher, but when generated under soft surface conditions is relatively lower. This difference may affect the final stack. On the other hand, the particularity of stratigraphic structure in coastal tidal flats results in multiple-wave development in the seismic records, which brings some confusion to seismic interpretation. To solve these issues, different deconvolution methods are needed on the premise of ensuring the SNR, which directly relate to the quality of stack section and imaging effect.

Considering the inconsistency of source and receiver caused by the different surface conditions in the study area, surface consistency deconvolution can effectively improve the consistency of a seismic wavelet. It can also make the seismic wavelet better shaped and unified, enhancing the lateral consistency of seismic data. Multi-channel prediction deconvolution can further suppress the wavelet, increase the main frequency and broaden the frequency bandwidth of the data by a reasonable prediction length. According to the periodicity of near and far offsets in the linear $\tau-\rho$ domain, the multiples can be suppressed by deconvolution in the linear $\tau-\rho$ domain. Therefore, based on an Omega seismic processing platform, the three deconvolutions mentioned are combined to improve the resolution of seismic records and suppress multiple waves in coastal tidal-flat zones.

Figure 8 shows the seismic results before and after deconvolution. It can be seen that seismic event quality in figure 8b is much better than that in figure 8a. The continuity and resolution are significantly increased after deconvolution, especially at 0.46 s marked by the red arrows. Furthermore, some multiples located around 0.35 s and marked by the green arrows are suppressed to some extent.

The obvious results of multiple-wave suppression in coastal tidal flats can be seen in the stack section comparison in figure 9. Compared with figure 9a, some multiples are attenuated efficiently in figure 9b after deconvolution. What is more, traceability and SNR of seismic stack section are improved a lot in figure 9b, which contributes to seismic interpretation.

Frequency spectrum comparison of the seismic record before and after deconvolution is displayed in figure 10 parts a and b, respectively. It is easy to see that the main frequency has been enhanced from 130 to 180 Hz and the frequency bandwidth has also been broadened, which helps a lot to improve the seismic resolution.

Figures 11a and 11b shows the single-shot comparison of autocorrelations before and after deconvolution. After deconvolution, the seismic wavelet is significantly improved. More precisely, the periodic side lobe on autocorrelation function is obviously suppressed and the main lobe is prominent, which is shown in figure 11b. Therefore, the resolution and wavelet continuity of single-shot record are enhanced to a certain extent. In addition, multiples in coastal tidal regions are attenuated by the deconvolution methods, which can be also obtained from figures 8 and 9.

4.3. Velocity analysis

To achieve the purpose of detailed velocity analysis, the number of velocity control points should be increased as many as possible, and the distance between adjacent velocity control points should be reduced. As the underground media in the coastal tidal-flat study area shows a good stratification, only a little change lies in the lateral velocity. After testing, an interval of 50 CMPs is determined for selection as the distance of adjacent points, which can effectively control the velocity field in this zone. Furthermore, some things should be taken into consideration when accurately picking up the velocity, including the position of energy group, quality control of gathers and stack interval result.

When there is an interface with a large difference in the underground reflection coefficient, there will be multiple waves between layers. This phenomenon is more common when picking up the detailed velocity in coastal tidal flats. Figure 12 shows the velocity spectrum generated by the CMP gathers after deconvolution. As a general rule, the velocity of multiple waves is lower than that of the effective reflected waves. Therefore, it is necessary to deliberately avoid the low velocity marked by green arrows but select the high one in figure 12. This is the only way we can eliminate the influence of multiples to the greatest extent. Furthermore, the adjustment of velocity is also a process of iteration with prestack noise attenuation and deconvolution.
4.4. **NMO and cutting**

The NMO function is to eliminate the influence of offset on the propagation time and flatten the events in the CMP gathers. In the case of shallow layers and large offsets, stretch distortion often occurs, the waveform is lengthened and moves to the low-frequency direction, which directly affects the quality of stack imaging. Generally, the problem of NMO stretch distortion is overcome by a seismic cutting method.

Figure 13 displays the single-shot result comparison before and after NMO as well as cutting for the shallow geological survey by towed-type shallow high-resolution seismic detection in coastal tidal flats. It can be seen from the figure that there is only a little NMO stretch distortion by 24-channel short arrays in acquiring seismic data than in a long array. To be specific, only shallow events distributed between 0 and 0.03 s have stretch distortion, which are shown in figure 13a and 13b, respectively. Therefore, it is only
required to cut off this small part of the event in the process. As shown in figure 13c, the effective seismic information can be retained as much as possible and a smaller NMO stretch in shallow seismic conditions is also an advantage of short arrays through the towable seismic method.

4.5. Stack imaging

After a series of targeted methods in shallow seismic processing in coastal tidal flats, the stack imaging section and frequency spectrum of towed-type shallow seismic processing in coastal tidal regions are displayed in figure 14. From the overall of seismic results, it can be found that the characteristic of seismic wave is quite clear, the stratigraphic continuity is good and the event energy is strong. In addition, it can also be seen from figure 14a that the structural form is obvious with high resolution and SNR.

As shown in figure 14b, the effective bandwidth in frequency spectrum is distributed between 80 and 280 Hz and the main frequency located around 180 Hz. Therefore, the detection accuracy of this method can be at the meter level, which provides reliable data support for detailed detection of shallow geological structures in tidal-flat zones.

5. Application and interpretation

Through the towable shallow high-resolution seismic method proposed in this paper, three practical applications in coastal tidal flats in Jiangsu Province, Eastern China are illustrated in this section, which shows their practical value in environment, geology and geological disaster. Specifically, shallow geological structures can be detected and verified effectively. The location of palaeo-channels, concealed active faults and submarine shallow gas can also be determined by this method.

5.1. Shallow geological structure

Figure 15 shows the interpreted depth section of a survey line in the study area and the lithology of a geothermal borehole nearby. First, 10 groups of shallow reflected interfaces are identified. According to the evidence from the wells that the stratum with thick clay aquiclude in the middle and
lower reaches of the Yangtze River are used as identification marks for the bottom interface of Quaternary. Based on this evidence as well as the energy and continuity of wave groups, drilling and other regional geological information, we can conclude that $T_0$ is the bottom interface of Quaternary in this section.

Meanwhile, it can be further inferred that $T_{0-1}$, $T_{0-2}$ and $T_{0-3}$ are the internal stratum of the Quaternary; $T_1$, $T_2$, $T_3$ and $T_4$ are the Neogene internal interfaces and $T_5$ is the top interface of bedrock in coastal tidal flats. What is more, predicted results coincide well with the lithologic interfaces from the geothermal borehole located at the CDP of 2120. In addition, a palaeo-channel marked by a red line is identified in figure 15 due to the seismic facies.

### 5.2 Concealed active faults

The existence of faults in the seismic section can be inferred by the conversion of strong phases, the relationship of upper and lower wave groups and the obvious increase or decrease of seismic events. However, the reflected wave group on the seismic section in tidal-flat areas is the soft soil stratum without cemented diagenesis. Therefore, the fracture zone has not developed by the slipping of faults, which makes it more...
difficult to determine the fault in soft soil stratum than in the cemented diagenesis stratum.

According to the energy and continuity of events on the seismic section shown in figure 16, two groups of faults named $F_1$ and $F_2$ can be identified effectively through the towed-type high-resolution shallow seismic detection. The two faults have the same tendency as SE. $F_1$ breaks the $T_0$ reflection interface, but does not extend upwards or downwards. However, $T_1$ is broken by $F_2$, which continues to extend upwards to the shallow reflection interface of $T_{0.3}$ around 0.11 s. The existence of concealed active faults is easily induced offshore geological hazards, which poses a serious threat to the environmental stability in coastal tidal regions. Therefore, the location of environmental engineering should be far away from the concealed active faults in these areas.

5.3. Submarine shallow gas

Submarine shallow gas is also a kind of marine geological disaster, which generally refers to the gas accumulated in the shallow layer of the seabed, sometimes existing as gas bearing sediment, an air bag in a supernormal pressure state or directly ejecting into the seabed (Borges et al. 2016; Sierra et al. 2020). A shallow gas is successfully detected in the coastal tidal-flat study area by the towed-type shallow high-resolution seismic method, as shown in figure 17. It is seen that there is no continuous and traceable reflected wave between the CDP of 700 and 1050 below 0.1 s, appearing as a blind zone. However, seismic events above 0.1 s are clear and continuous, indicating that the surface shooting and receiving conditions are good in this area. It is inferred that a seismic wave cannot penetrate the occurrence stratum of shallow gas in the seabed during the propagation. At the same time, the reflection information of the underlying stratum is also missing. Therefore, a blind zone of reflected wave appears on the seismic section, which may be caused by the shallow methane gas reservoir.

Furthermore, it is formed through the decomposition of marine organisms by the methane bacteria during seabed deposition and gradual transformation into gas. The natural gas in the deep seabed rises to the shallow seabed along the fault planes, fractures and pores of the rock layer, which is covered by the impervious stratum such as clay. Therefore, it cannot move upwards to release, and gathers in this area to form a high-pressure shallow air bag. However, the existence of shallow gas in coastal tidal flats is a big potential safety hazard for the offshore environment. It easily induces coastal disasters. It is necessary to avoid such areas for dam construction, port location and wind-power infrastructures.

6. Conclusions

First, the towed-type shallow high-resolution seismic system for coastal tidal flats is designed in this paper, which has the advantages of high acquisition efficiency, low cost and reliability. This also obtains a meter-level detection accuracy and great detection depth at more than 800 m. Second, different deconvolution methods and high-precision velocity analysis are significant for multiple-wave attenuation and seismic resolution in coastal tidal flats. A 24-channel short array has a small NMO stretch, which can retain effective shallow information as much as possible. Finally, shallow geological structure and interface in coastal tidal zones can be effectively detected and verified. The location of
paleo-channels, concealed faults and shallow gas can also be determined. This contributes a lot to support the environment, geology and geo-hazard survey in these areas. In addition, enhancing the maximum fold on the premise of ensuring acquisition efficiency can be further studied for the next step, which may effectively improve the seismic event continuity and be more universal in coastal tidal flats.

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Conflict of interest statement

None declared.

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