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An Experiment of the Actual Vertical Resolution of the Sub-bottom Profiler in an Anechoic Tank

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Sub-bottom profiler (SBP) is an acoustic instrument commonly used to survey underwater shallow geological structure and embedded objects whose most important performance parameter is the actual vertical resolution. This paper presented a methodology to measure and evaluate the actual vertical resolution of SBP based on an experiment in an anechoic tank, which was divided into three components: building of artificial geological model, measurement of acoustic parameters, and determination of actual vertical resolution of the acoustic profiles. First, the wedge-shaped geological model, whose thickness could be accurately controlled, was designed and built in an anechoic tank to try to directly measure the vertical resolution of SBP. Then, the acoustic pulse width of SBP was measured to calculate the theoretical general vertical resolution and extreme vertical resolution. Finally, based on the acoustic profiles obtained in the experiment, the method which was used to evaluate the actual vertical resolution by measuring the duration of reflection event was put forward. Due to comparing measurement data of different parameter settings of the SBP, the study has revealed that the SBP had the lowest resolution in the 4 kHz–500 μs setting, which was 226.5 μs, or 36.2 cm, and the highest resolution in the 15 kHz–67 μs setting, which was 72.7 μs, or 11.6 cm. The vertical resolution decreased with the increase of the pulse width. The results also showed that the actual resolution was close to the theoretical general resolution and far from the extreme resolution.

Keywords: sub-bottom profiler (SBP); pulse width (PW); vertical resolution; duration of reflection event (DRE).

1. Introduction

Acoustical imaging can be used for presentation (monitoring) of the current state of sound intensity distribution leading to characterisation of sources in observed underwater regions. This can be represented in the form of an acoustic characteristic of the area, for example as a spectrogram (Grelowska, Kozaczka, 2014). Sub-bottom profiler (SBP) is a widely used geophysical survey instrument based on the principle of acoustical imaging, which can continuously detect submarine sedimentary sequence and embedded objects (Godø *et al.*, 2010; Kozaczka *et al.*, 2013). With the law of propagation and reflection of the sound wave, the SBP can acquire intuitive geological profiles of the seabed. In recent years, with the large scale development of marine oil and gas, the growing interest in the underwater archaeology, and the increasing number of all kinds of marine engineering construction, as well as the frequent occurrence of marine geological hazards, the SBP has been largely introduced and widely applied in many administrative departments, research institutes, universities and colleges, military institutes, survey and mapping institutes, etc. (Chronis *et al.*, 2013; Smith *et al.*, 2013).

In many diverse marine fields qualitative and quantitative geophysical knowledge of the uppermost part of the seafloor sediment is of paramount importance (Grelowska, Kozaczka, 2010b). In order to study the subtle geological characteristics of seabed stratigraphy and find small objects buried by seabed sediments, we always try our best to require the best possible vertical resolution of the SBP. The vertical resolution of SBP is defined as the thinnest part of the layer that can be differentiated in the acoustic profile. It depends on the frequency and pulse width (PW) of the low-frequency acoustic signal generated by the sound source (or the secondary signal for parametric SBP). Generally speaking, the higher the frequency of the signal, or the shorter the PW, the better the vertical resolution of SBP.

The most important performance parameters of SBP are its vertical resolution and penetration depth. Theoretically, the penetration depth into the seafloor is mainly controlled by the attenuation, absorption, and reflection in sediment, by SBP properties like source level and directivity, and by environmental conditions like the noise level. But the vertical resolution of SBP is mainly determined by the pulse width (PW) of the acoustic wave (Grelowska, Kozaczka, 2010a). As shown in Fig. 1, let Δh denote the thickness of the wedge shaped thin layer, let v denote the sound velocity of the thin layer, let τ [s] denote the PW of acoustic wave, let λ [m] denote the length of the pulse, let Δt denote the time difference between the echoes from the top and the bottom interfaces of the thin layer, let R_1 and R_2 denote the reflection coefficients of the top and bottom interfaces, respectively:

1) When $\Delta t > \tau$, $\Delta h > \lambda/2$, the two reflection signals are easy to distinguish.
2) When $\Delta t = \tau$, $\Delta h = \lambda/2$, the two reflection signals are connected together, and can be distinguished. Generally, at this time, the thickness of the thin layer is defined as the vertical resolution of SBP, that is $\Delta h = \lambda/2$, which is called the general resolution.
3) When $\Delta t = \tau/2$, $\Delta h = \lambda/4$, small parts of the two reflection signals are stacked together and can't be separated completely. Because of the interference effect of the sound wave, the overlapping parts will reduce when R_1 and R_2 are all negative (minus) or increase when they have the opposite sign. At this time, the two signals can be barely distinguished. Here, the thickness, $\Delta h = \lambda/4$ is called the extreme resolution of SBP.
4) When $\Delta t < \tau/2$, $\Delta h < \lambda/4$, the two reflection signals overlap, unable to be distinguished.

In fact, the vertical resolution of SBP is limited by some other factors, such as beam angle, receiver bandwidth, sampling rate, and print resolution of the recording paper, etc. (Wang *et al.*, 2013). In practical

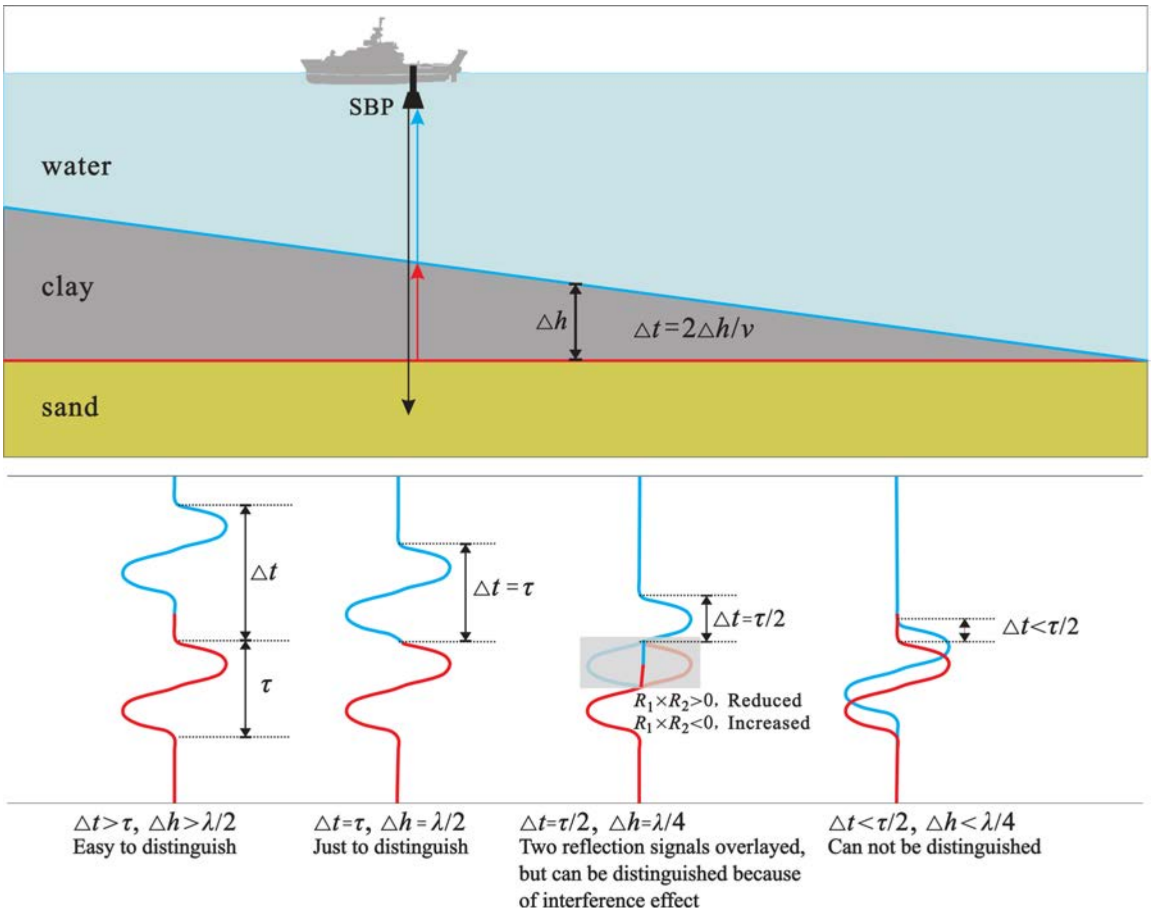

Fig. 1. Definition of the vertical resolution of SBP. τ is the pulse width (PW), $\Delta h = \lambda/2$, the general vertical resolution, and $\Delta h = \lambda/4$, the extreme vertical resolution.

applications, users are more concerned about the actual vertical resolution. In order to evaluate the actual vertical resolution of SBP, we built a "wedge" geological model in an anechoic tank, in which the thickness of every layer could be accurately controlled. Then, the geological profile of the centre line of the model was drawn by accurate measurement and the physical parameters of SBP were measured. Finally, by comparing the geological profile and the acoustic profiles obtained from the experiment, we attempted to study the actual vertical resolution of the SES-2000 parametric SBP.

2. Methods

2.1. Artificial geological model in an anechoic tank

As shown in Fig. 2a, the wedge shaped geological model, whose thickness of every layer could be accurately controlled, was built in the middle area of an anechoic tank (10 × 4 m). Both sides of the tank were covered with sound absorbing material to reduce the reverberation effect and to acquire pure reflected signals of typical objects.

Initially, the bottom of the tank was an inclined concrete plane (Fig. 2c). A clay layer, whose top interface was approximately horizontal, was paved on the concrete surface, forming a wedge shaped layer with a thickness of 0.1–1.4 m. After the clay was rammed, a sand layer with an approximate thickness of 0.7 m was paved and rammed. Then, a hanging steel pipe with a diameter of 10 cm was fixed along the width direction. The suspended height of the pipe was 0.48 m. Finally, the fresh water was injected into the tank to a depth of about 5 m. After more than two months of settling and compacting, the vertical resolution experiment of SES-2000 parametric SBP was conducted in the tank (Fig. 2b).

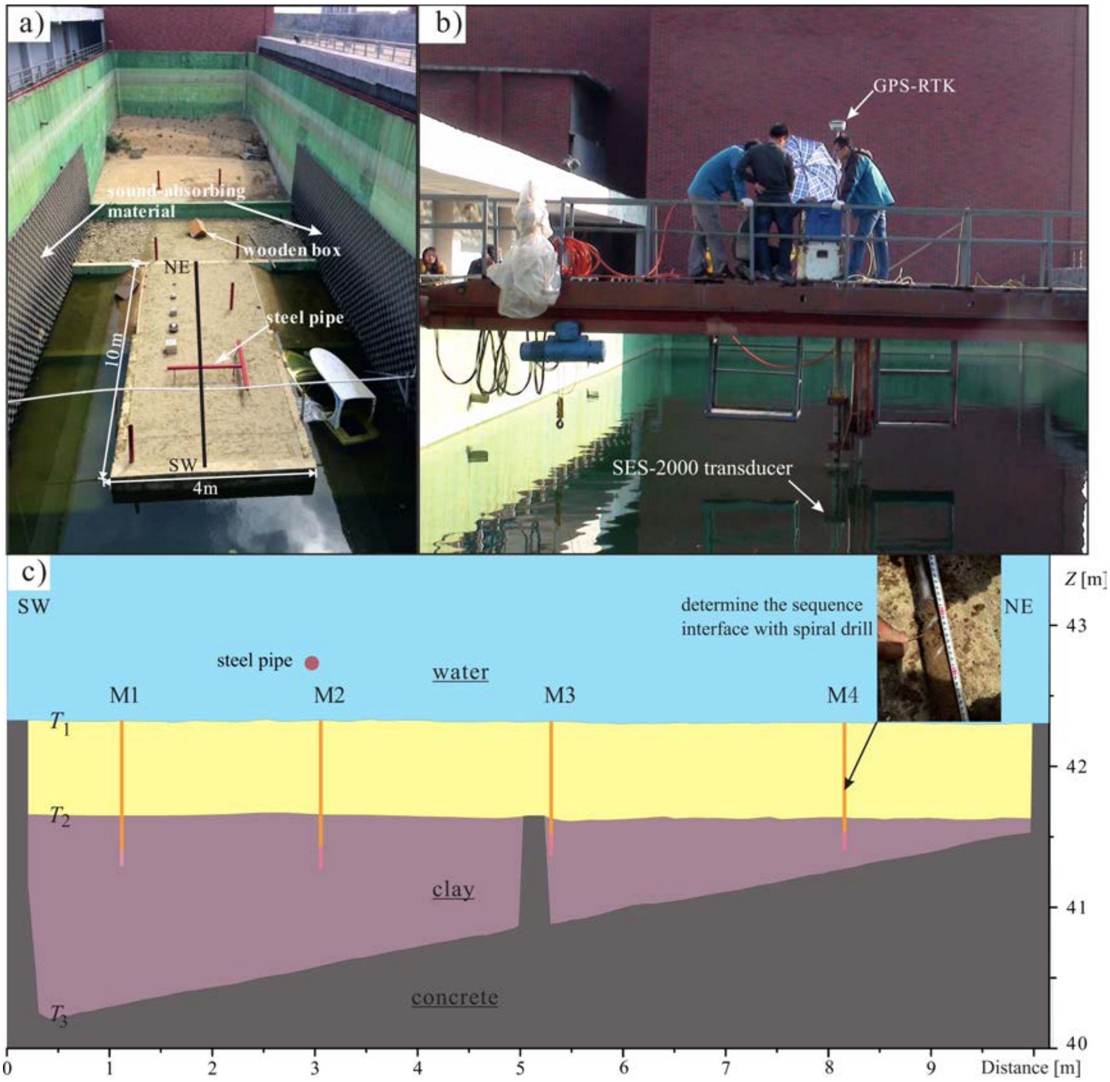

Fig. 2. Artificial geological model in an anechoic tank whose sides were covered with sound-absorbing material; a) location of the geological model and targets, b) the vertical resolution experiment of the SES-2000 SBP, c) the actual geological profile of centre line (NE-SW) of the artificial model.

In the process of paving the layer, in order to accurately control the thicknesses of clay layer and sand layer, we measured the elevations of the three interfaces (T_1, T_2, T_3), respectively, using a total station and 3D laser scanner. The results showed that the elevation of the same point of every interface was approximately equal (the errors were less than 5 mm). In addition, after the sand layer had been paved and rammed, four geological samplings were extracted using micro spiral drill to reach the depths of sand-clay interface (the upper right corner of Fig. 2c). Unfortunately, the interfaces measured with the spiral drill were 10–20 mm deeper than the results of the total station and 3D laser scanner. Perhaps, the reason was that the sand could not slide freely on the blades during sampling, which led to the inaccurate position of the interfaces. Therefore, considering the denser sampling points of the 3D laser scanner, the geological profile of the experimental line of SBP was drawn according to the 10 cm interval data from the scanner (Fig. 2c).

2.2. Acoustic parameters measurement

SES-2000 SBP is an instrument that uses the parametric acoustical effect (difference frequency principle) to measure water depth and detect sub-bottom profile. It emits two slightly different high frequency acoustic signals (about 100 kHz, F_1, F_2, so called primary frequencies, $F_1/F_2 \approx 1$) simultaneously with a very narrow beam and almost no sidelobes. These two signals interact in the water. There are new frequencies generated (so called secondary frequencies), e.g. the difference frequency of the transmitted waves. The difference frequency $F = |F_2 - F_1|$ (in the range of 4–15 kHz) is low enough to penetrate the seafloor. The reflected primary-frequency signals (about 100 kHz) can be used for exact determination of water depth even in challenging situations, e.g. soft sediments on top of the seafloor (Wunderlich, Müller, 2003; Wunderlich *et al.*, 2004).

SES-2000 SBP has a variety of optional frequency and PW settings. In order to obtain the actual value of the PW, the acoustic signals of different settings of SBP were acquired and analysed in the anechoic tank using Reson TC-4014 standard hydrophone and Agilent U2531A signal collector. However, since the anechoic material could not be fully suitable for the spectrum of acoustic signals, some of the wall reflection waves were also collected simultaneously.

After filtering noise in the signals, the PW could be measured directly from the time amplitude curve (in Fig. 3a1, the actual measured PW was 268 µs, and in

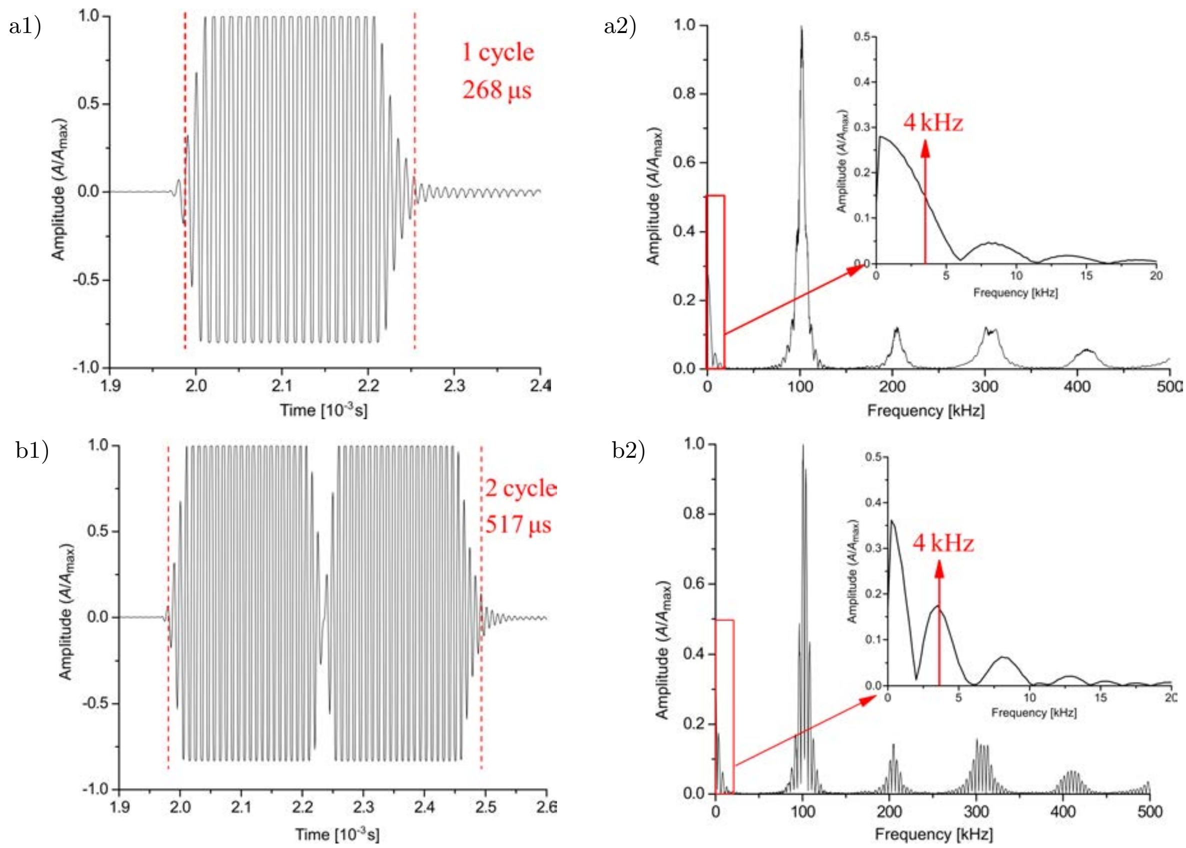

Fig. 3. Acoustic parameters measurement at 4 kHz setting: a1) was a time amplitude signal at 250 µs PW setting, its measured PW was 268 µs, and a2) was its frequency spectrum; b1) was a time amplitude signal at 500 µs PW setting, its measured PW was 517 µs, and b2) was its frequency spectrum.

Fig. 3b1, the actual measured PW was 517 μs). After fast Fourier transform (FFT) to the signals, the values of the primary frequency and the secondary frequency were obtained, and could be further analysed (Figs 3a2 and 3b2).

All the frequency and PW settings of SBP were tested in the experiment. In this paper, the nominal values and measured values of PW at 4 kHz setting (nominal PW were 250 μs and 500 μs) and 15 kHz setting (nominal PW were 67 μs, 133 μs, 200 μs, 267 μs and 333 μs) were compared respectively (Table 1). The results showed that the measured values of PW were 17–26 μs larger than the nominal value.

Table 1. Comparisons between nominal PW and measured PW of SES-2000 SBP.

Frequency [kHz]	PW control	Nominal PW* [μs]	Measured PW [μs]	Deviation [μs]
4	1	250	268	18
	2	500	517	17
15	1	67	91	24
	2	133	155	22
	3	200	221	21
	4	267	293	26
	5	333	352	19

* Innomar Technologie GmbH. (2010), User's Guide of SES-2000 SBP.

In addition, as can be seen from the signal spectrums in Figs 3a2 and 3b2, when frequency setting was 4 kHz, the primary frequencies acquired from different PW settings were all about 100 kHz, but the spectrums were obviously different near 4 kHz. A similar phenomenon took place when the frequency setting was 15 kHz. The spectrums from all five PW settings were also significantly different. There was no dominant amplitude in the vicinity of 15 kHz when the PW setting was at minimum. The dominant amplitude near 15 kHz became obvious with the increase of PW (Fig. 4).

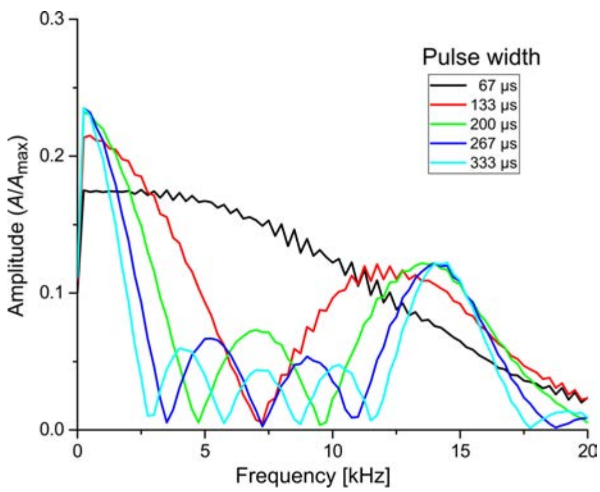

Fig. 4. Comparison of frequency spectrums of signals from different PW settings of SES-2000 SBP at 15 kHz. The dominant amplitude near 15 kHz became obvious with the increase of PW.

2.3. Vertical resolution experiment of SBP

Laboratory experiments are ideal to understand physical process and to optimise data collection strategies. It is particularly relevant as sea trials are expensive, difficult to conduct, and generally impossible to repeat (Blondel, Pace, 2009). There are seven optional frequency settings for SES-2000 standard SBP (4 kHz, 5 kHz, 6 kHz, 8 kHz, 10 kHz, 12 kHz, 15 kHz). And there are 2–5 optional PW settings for each frequency (Wunderlich, Müller, 2003). In order to find out the actual resolution of all the optional parameter settings, we carried on a test to all the setting of the SBP. The accuracy of the sea bottom structure investigation needs correct configuration of research equipment and proper calibration of peripheral devices which provide necessary data to measurement system (Kozaczka *et al.*, 2012). In our experiment, the GPS-RTK system was used to provide position data of the SES-2000 transducer in the experiment. By comparing all the acoustic images, it was found that the profile obtained by the combination of 15 kHz–67 μs was the best and the most readable (Fig. 5). However, as it could be seen from the figure, there were several regular interfering waves on the profile, which might be reflections from the iron frame used to install the transducer.

Based on the fluid theory, Grelowska and Kozaczka (2010a) acquired the calculated reflected pulses of a seabed model composed of following layers: clay, fine silt, fine sand, coarse sand, and the bottom layer is medium sand. And then, the antenna properties (e.g. beam pattern), sounding pulses shape, depth, angle resolution, and time series of pulses reflected from known type of layers were collected in laboratory investigation by Grelowska *et al.* (2013), which gave satisfactory additional knowledge for interpretation to the acoustic profiles.

In our experiment, four typical traces (P1, P2, P3, P4) of SBP from Fig. 5 were drawn in Fig. 6 to obtain pure reflected signals of several kinds of typical objects.

P1 was the reflection signal of underwater concrete block. There should be no other acoustic impedance interface below the bottom of the water because of the concrete, so the other signals of high energy were obviously reverberation waves.

P2 was the reflection signal of the hanging steel pipe. It can be observed that the reflection energy

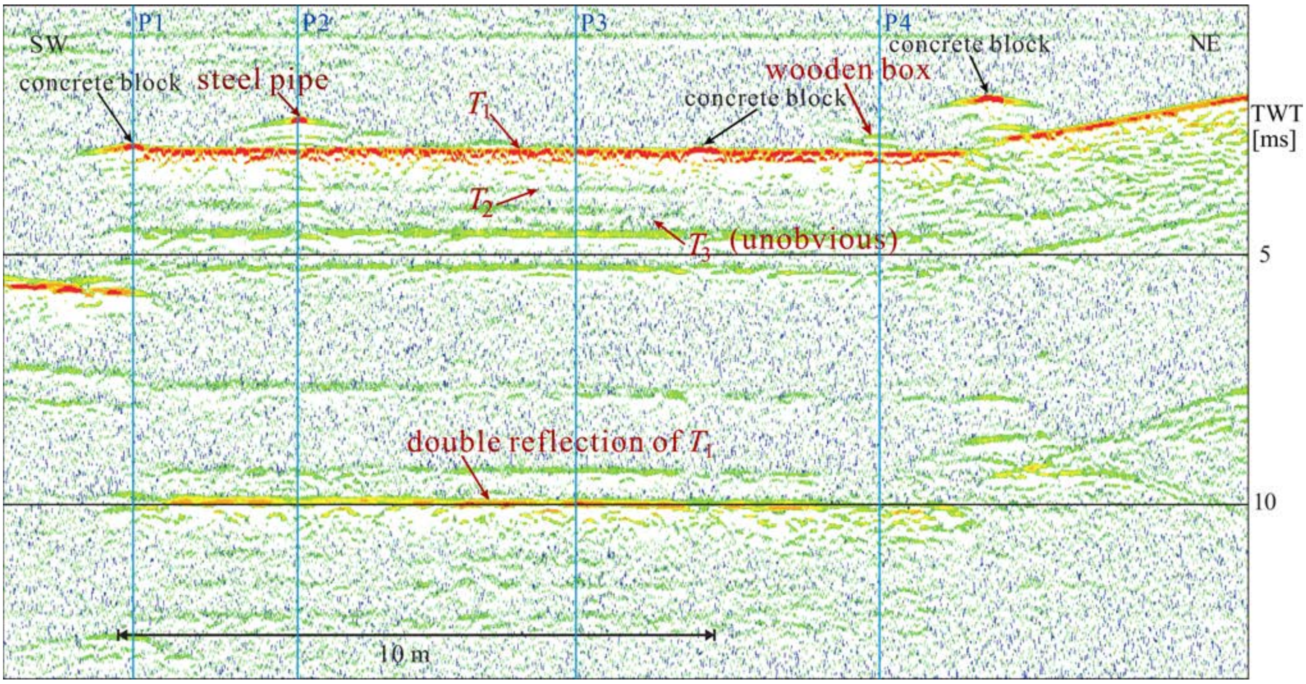

Fig. 5. Profile of the actual resolution experiment of SES-2000 SBP, frequency setting was 15 kHz, and PW setting was 67 μs. T_1 was the reflection event of water-bottom interface. T_2 was the reflection event of sand-clay interface. T_3 was the reflection event of clay-concrete interface.

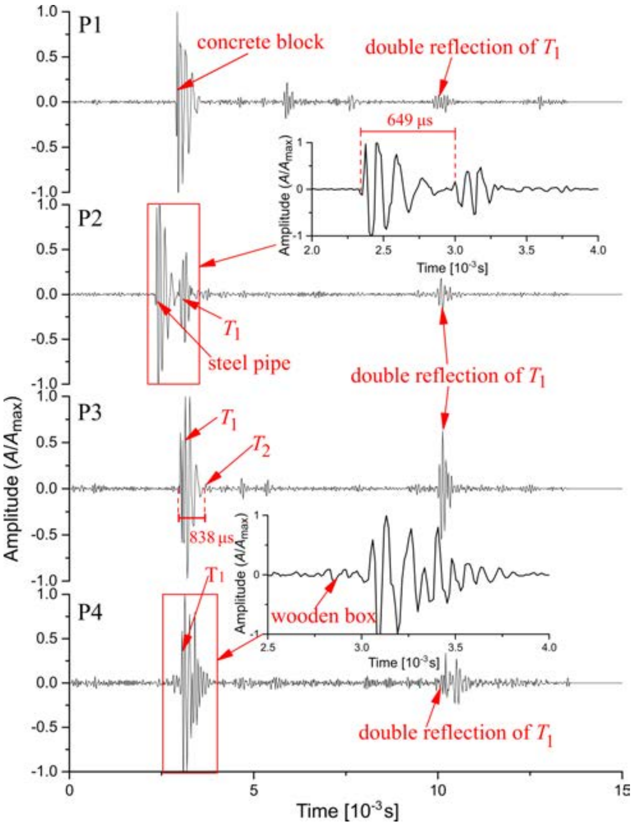

Fig. 6. Time amplitude signals of four typical traces of SBP: P1 was the reflection of concrete block, P2 was the reflection of hanging steel pipe, P3 was the reflection of sand-clay interface, P4 was the reflection of wooden box, their locations were shown in Fig. 5.

of the steel pipe was the highest, and the one of the water-bottom interface (T_1) followed it. The height of the steel pipe could be judged to be 649 μs (two way time). So depending on the measured sound velocity in water (1480 m/s), we could calculate that the hanging height was 0.48 m (equal to its actual height). In the sub-bottom profile in Fig. 5, the steel pipe was displayed in the form of typical diffraction hyperbolas (Levchenko, 2006).

P3 was the reflection signal of artificial layers. The reflection energy of the water bottom (T_1) was the highest. The reflection of the sand-clay interface (T_2) was very weak but it can be tracked. The reflection of the clay-concrete interface (T_3) could not be found. Here, the thickness of the sand layer was 838 μs (two way time). According to the sound velocity in sand (1600 m/s), the thickness of the sand layer was 0.67 m.

P4 was the reflection signal of the wooden box in the water bottom. It could be seen that the sound energy was very weak.

3. Results

Although the artificial geological model could accurately control the thickness of the layer, due to the lack of the natural evolution of the depositional environment and slow dynamic process the effective acoustic reflection interface could not be formed (in Fig. 5, interface T_3 could not be identified), leading to the fact that the envisaged method using wedge shaped layer to evaluate the actual vertical resolution of SBP could not achieve expected results.

However, due to comparing the acoustic profiles of the same frequency settings and different PW settings, the study revealed that the smaller the PW, the shorter the acquired duration of the reflection event, and the better the readability of the acoustic profile is. On the contrary, the greater the PW, the longer the duration of reflection event, and the worse the readability of the acoustic profile.

Based on the results of this experiment, the paper presents the method of "duration of reflection event" to evaluate the actual vertical resolution of SBP. The reflection event is the line of the extreme values of the same vibration phase (wave crest or trough) in the SBP profile. Generally speaking, there will be a discernible regular reflection event in the profile at the boundary of sedimentary sequences, which will be interpreted as the sequence boundary. Obviously, the longer the duration of the reflection event, the harder it is to distinguish a thin layer. On the contrary, the shorter the duration of the reflection event, the easier it is to distinguish a thin layer. That is to say, the duration of the reflection event determines the minimum thickness of the vertical layer that can be identified and interpreted in the SBP profile, i.e., the actual vertical resolution.

As shown in Figs 7 and 8, taking the water-sand interfaces as examples, the duration of the reflection event at the same position of different profiles at different PW settings could be measured (time as the unit for convenience). Since the acoustic profile was a kind of two way time image, 1/2 of the measured value could be used to represent the actual vertical resolution of SBP. Thus,

$$R_m = \frac{\mathrm{DRE}_m}{2}, \tag{1}$$

where R_m is the actual vertical resolution or measured resolution [µs], DRE_m is the duration of the reflection event [µs].

We know from Sec. 1 that the general resolution of SBP is in theory equal to 1/2 of the measured PW, while the extreme resolution is equal to 1/4 of the measured PW. Thus,

$$R_g = \frac{\mathrm{PW}_m}{2}, \tag{2}$$

$$R_e = \frac{\mathrm{PW}_m}{4}, \tag{3}$$

where R_g is the general resolution [µs], R_e is the extreme resolution [µs], PW_m is the measured PW [µs].

Based on the measured values of PW in Table 1 and Eqs (2) and (3), the general resolution and the extreme resolution could be calculated. And the actual resolution could be calculated from DRE_m (Figs 7 and 8) by Eq. (1), too.

Table 2 shows the results of the general resolution, the extreme resolution, and the actual resolution of the SES-2000 SBP of seven settings at 4 kHz and 15 kHz. It could be seen from Table 2 and Fig. 9 that the actual resolution of SES-2000 decreased with the increase of PW. It was close to the theoretical general resolution and far from the extreme resolution. Assuming that the sound velocity was 1600 m/s, among these

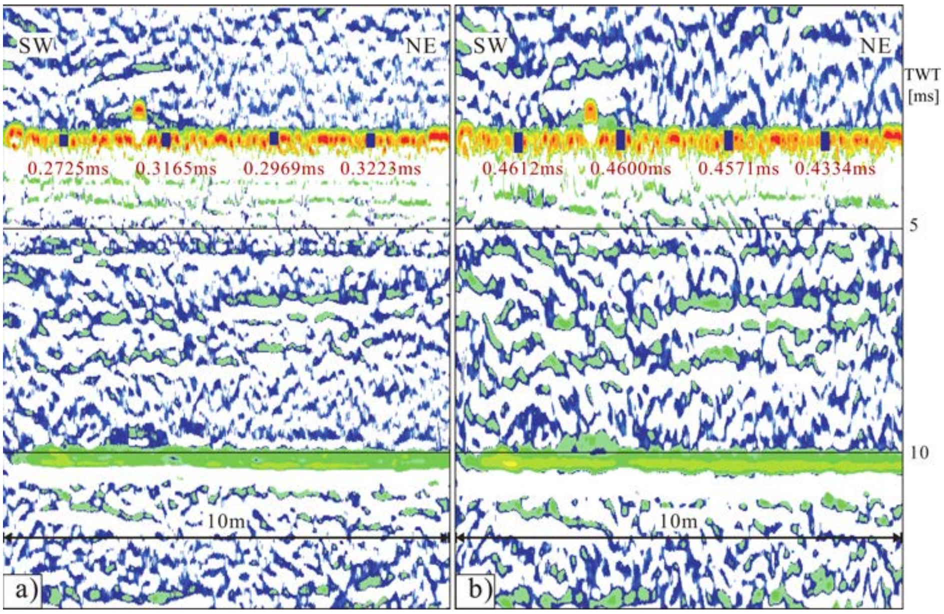

Fig. 7. Duration of the reflection event samples of SES-2000 SBP at 4 kHz: a) nominal PW was 250 µs, measured resolution was 151.1 µs, b) nominal PW was 500 µs, measured resolution was 226.5 µs.

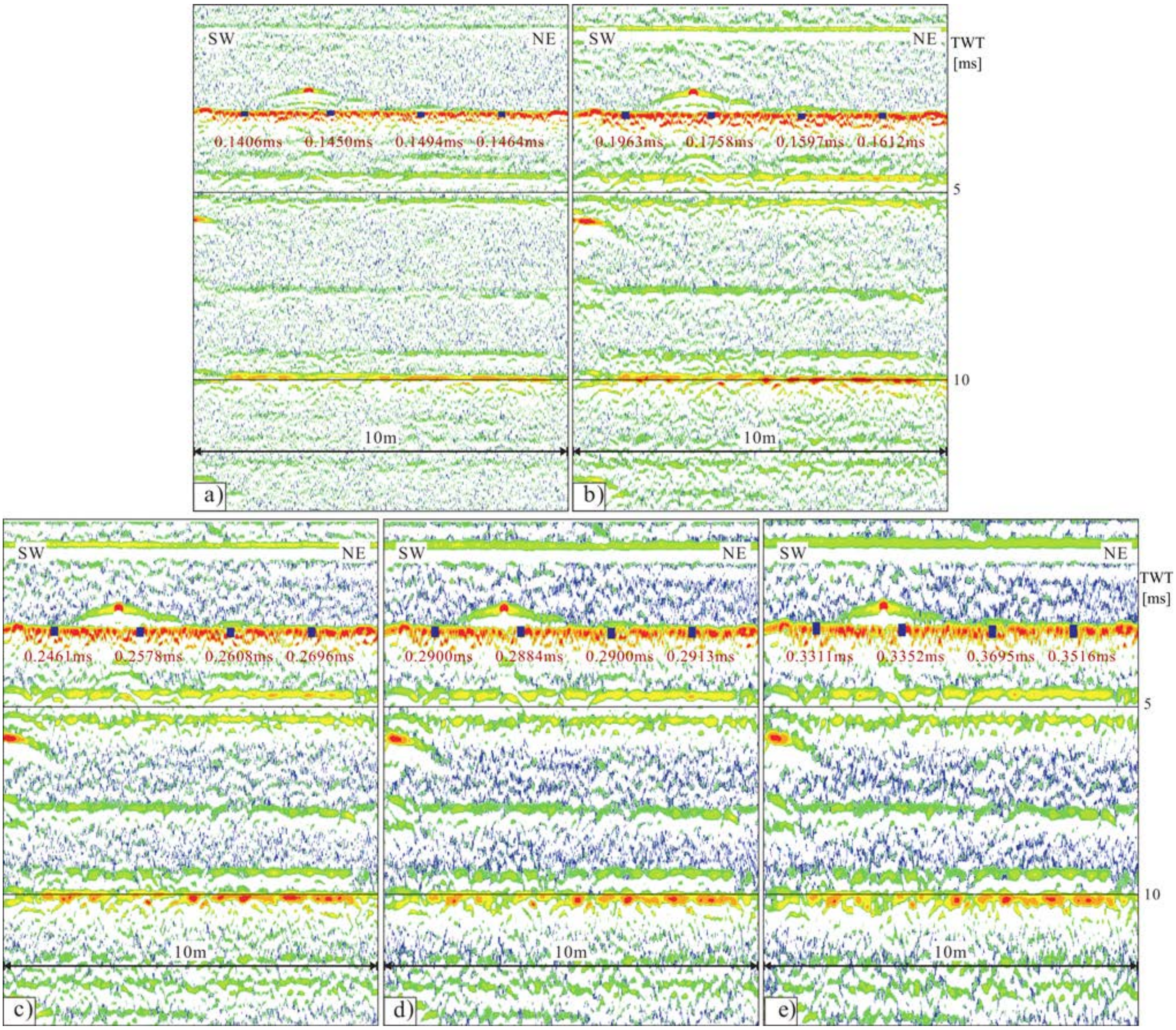

Fig. 8. Actual resolution samples of SES-2000 SBP at 15 kHz: a) nominal PW was 67 μs, measured resolution was 72.7 μs, b) nominal PW was 133 μs, measured resolution was 86.7 μs, c) nominal PW was 200 μs, measured resolution was 129.3 μs, d) nominal PW was 267 μs, measured resolution was 145.0 μs, e) nominal PW was 333 μs, measured resolution was 173.5 μs.

settings, the actual resolution of 4 kHz–500 μs setting was the lowest, which was 226.5 μs, or 36.2 cm, while the actual resolution of 15 kHz–67 μs setting was the highest, which was 72.7 μs, or 11.6 cm.

Table 2. Comparison of the theoretical and measured resolutions of SES-2000 SBP.

Frequency [kHz]	PW control	Theoretical resolution [μs]		Measured resolution R_m [μs]				
		R_g	R_e	No. 1	No. 2	No. 3	No. 4	Average value
4	1	134.0	67.0	136.3	158.3	148.5	161.2	151.1
	2	258.5	129.3	230.6	230.0	228.6	216.7	226.5
15	1	45.5	22.8	70.3	72.5	74.7	73.2	72.7
	2	77.5	38.8	98.2	87.9	79.9	80.6	86.7
	3	110.5	55.3	123.1	128.9	130.4	134.8	129.3
	4	146.5	73.3	145.0	144.2	145.0	145.7	145.0
	5	176.0	88.0	165.6	167.6	184.8	175.8	173.5

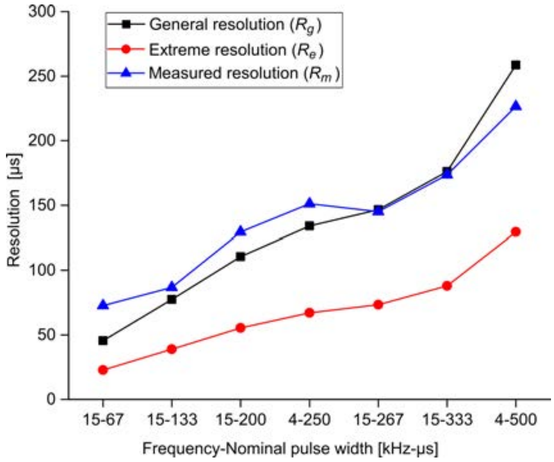

Fig. 9. Comparison of three kinds of vertical resolution of SES-2000 SBP. The measured resolution decreased with the increase of PW, close to the theoretical general resolution and far from the extreme resolution.

4. Discussion

In this experiment, we studied the vertical resolution of SBP in three steps, which were artificial geology model in an anechoic tank, acoustic parameter measurement, and the actual vertical resolution measurement. The problems found in the experiment were discussed as follows.

A very thin layer was required to study the actual vertical resolution of SBP. Although the artificial geological model could accurately control the thickness of the layer, due to the lack of natural sedimentary environment evolution and slow dynamic process the effective acoustic interfaces could not be formed. And the thin sequence could not be formed in the acoustic profile either. However, in the marine sedimentary environment, this wedge shaped thin layer was easy to found. Therefore, the next step was to find this kind of representative layers in offshore and carry out more experiments to acquire the actual vertical resolution of SBP.

A large tank with a high sound absorbing performance and measurement platform equipped with a high precision gyroscope, hydrophone lifting device, control device, and recording equipment were required to measure the important acoustic parameters of SBP such as frequency, PW, beam angle, and source level. The water depth was so shallow in this experiment that the reverberation interference was very strong. Furthermore, because of the installation restrictions, many iron reflector were present near the transducer, acting as the source of noise, which resulted in poor quality profiles.

5. Conclusion

SES-2000 SBP is a very effective tool to detect the seabed subtle geological structure and embedded objects. Based on our experiment, the following conclusions can be drawn.

It may be feasible to construct the artificial geological layer but it is difficult to achieve the effect of a wedge shaped thin layer. Fortunately, satisfactory results had been obtained in the measurement of acoustic physical parameters of SBP like frequency and PW which helped determine the vertical resolution. The results showed that the measured values of the PW were 17–26 μs larger than the nominal values. Different experimental conditions may have caused the errors. Therefore, in the measurement of these key parameters, we need to apply some restrictions on the environmental conditions, such as water temperature, air temperature, water salinity, etc. It is also more important to form a set of standard operating procedures to conduct the measurements.

The method of duration of reflection event had been proved to be effective to measure and evaluate the actual vertical resolution of SBP. The actual resolution of SES-2000 decreased with the increase of PW. It was close to the theoretical general resolution and deviated strongly from the extreme resolution. Among these settings, the resolution of 4 kHz–500 μs setting was the lowest, which was 226.5 μs, or 36.2 cm, while the resolution of 15 kHz–67 μs setting was the highest, which was 72.7 μs, or 11.6 cm. Therefore, in the absence of other requirements, the PW should be smaller to obtain higher resolution profiles in the acquisition of data. It is worth noting that the actual resolution was related to the environmental conditions and the geological conditions of the seabed. Thus, different results could be obtained if measured in different conditions.

Acknowledgments

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