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Underground Sonar Using Shear Waves -Resolution improvement Using Pulse Compression and Dynamic Focusing-

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A method using shear waves has been proposed to detect buried relics and ruins at shallow depths. Pulse-compression processing is examined for improving the underground imaging resolution. Down-chirp signals (800 to 300Hz) can be generated using a super-magnetostriction vibrator as a sound source.

First, pulse compression is simulated in the lab to confirm the axial resolution of underground images. The axial resolutions are smaller than 0.2m when the range of start and stop frequencies are more than 700Hz in the simulation.

Then, its exploration experiment is carried out where the buried position has already known. The underground images obtained from exploration experiment confirm that the images by the pulse compression have almost the same axial resolution as by the result of the simulation.

The underground images are obtained from these experiments. We confirmed the effectiveness of the pulse-compression method for improving resolution.

1 Introduction

An electrical method using a metal detector and an electromagnetic method using a ground-penetrating radar (GPR) have been widely used to detect buried relics. However, in marshes or swamps where the moisture content is high, electric and electromagnetic signals are strongly attenuated by the presence of water and electrolytes. In order to overcome this problem, a method using shear waves [1,2] has been proposed to find buried objects through underground imaging.

In our past research, a hammer method, in which a sound source is hit directly by a hammer, was used for making underground images. Although this method is easy to use, improving the underground image's resolution is difficult because the frequency and the waveform cannot be changed arbitrarily. However, a super-magnetostriction vibrator [3] can change the frequency and the waveform easily at low frequencies (0 to 3kHz). This characteristic is beneficial in our experiment. Therefore, we employ a super-magnetostriction vibrator as a sound source instead of a hammer. Two methods are considered for improving the resolution of underground images using this vibrator, using high frequency and using pulse compression. Pulse compression [4] is widely applied for radar and modulation signals such as M-sequence; FSK and chirp signals are used for pulse compression. We employ chirp signals applied by a window function for smooth movement of the vibrator.

To confirm the axial resolution of underground images, pulse compression is simulated. And, to confirm the lateral resolution, dynamic focusing is simulated in our laboratory. Then, its exploration experiment is carried out where the buried position has already known. The underground images are made by using a stacking method of reflected scattered waves.

2 Paper submission

2.1 Experimental instruments

We used the super-magnetostriction vibrator (Moritex Corp, AA140J013-MS1) as is shown in Fig.1 (a). To generate the shear waves, this vibrator was set on the sound source of aluminum that is attached of spike as is shown in Fig.1 (c). The resonance frequency of this vibrator is 2.3 kHz. The displacement of this vibrator with the frequency changes is as shown in Fig.2. When this vibrator drives at the frequency of 200Hz, its displacement is 140μm which is very big vibration. It is possible for this vibrator to drive with the displacement bigger than 60μm at the frequency domain (300 to 800) that we use. Besides, we used the geophones for the shear waves which are the speed sensors as the receivers. The generated sound waves are recorded simultaneously in a seismically operation equipment (Oyo Corp, McSEIS-SX, MODEL-1125R) as is shown in Fig.1 (b).

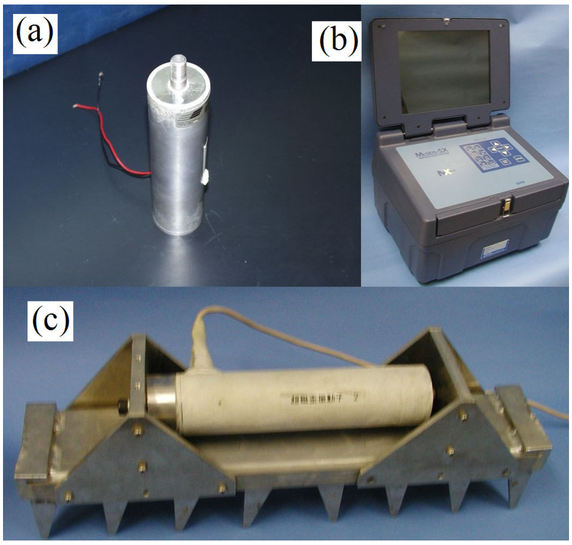

Fig.1 Experimental instrument.
(a)Super-magnetostriction vibrator, (b) Sound source for shear wave, (c)McSEIS-SX

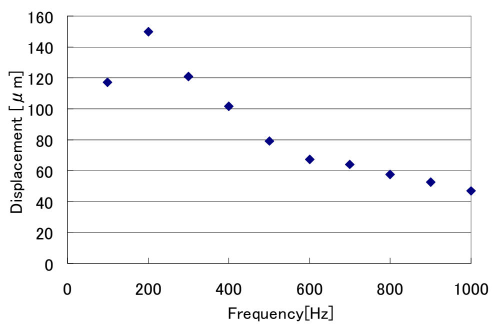

Fig.2 Characteristics of super-magnetostriction vibrator.

2.2 Output waves

The received waveform should look like the output waveform so that the pulse compression is the correlation processing. We employed chirp waves applied by window function for smooth movement of the vibrator. The window function is as shown in eq. (1) and sample of output wave applied window function is as shown in Fig.3. This function is used as a frequency-dependent filter.

$$f(x) = \begin{cases} x^k(1-x)^k & 0 \le x \le 1 \\ 0 & etc. \end{cases}$$

$$F(a) = \frac{\int_0^k x^k(1-x)^k dx}{\int_0^1 x^p(1-x)^k dx} \qquad (1)$$

$$0 \le a \le 1$$

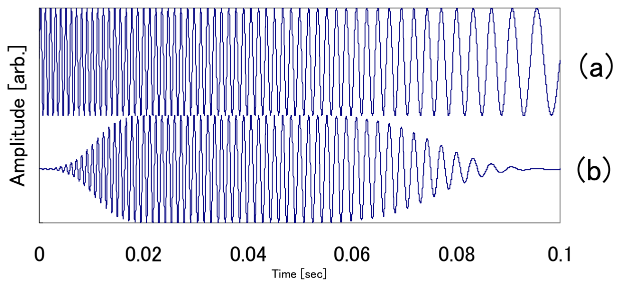

Fig.3 Sample of output wave.
(a) Normal chirp wave.
(b) Applied window function.

2.3 Computational simulation method

The propagation waves are assumed to be the shear waves, and the sound speed is assumed to be 140m/s. The reflection point is decided and the propagation distance is calculated. Delay time is calculated from the propagation distance. Gain was in inverse proportion to the square of the propagation distance in consideration of damping. The computational simulation is shown in eq. (2) and Fig.4.

$$S_r(t) = S_{out}(t - \frac{d1 + d2}{v}) \times \frac{1}{(d1 + d2)^2} \qquad (2)$$

Here, *Sr*, S_{out}, *v*, t, *d1* and *d2* are defined as the received waves, output waves, sound speed, time, distance from a sound speed to a reflection point, and distance from a reflection point to a receiver, respectively.

The images are made by using a stacking method of reflected scattered waves [1]

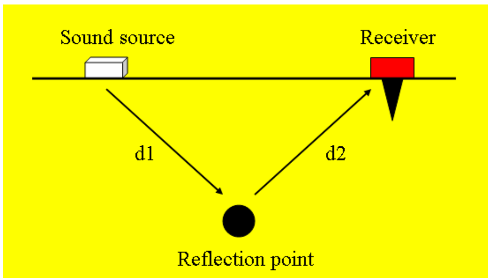

Fig.4 Computational simulation method.

3 Measurements of axial resolution by simulation

3.1 Measurement method

The axial resolution was confirmed from the images made by the simulation.

Twelve receivers were arranged in a line at 0.5m intervals on the ground. A sound source was moved between two receivers in turn and two virtual reflection points were set up as Fig.5. Value X in the image was assumed to be an axial resolution.

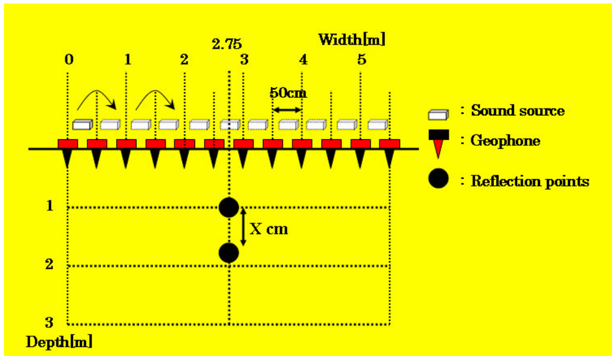

Fig.5 Measurements method of axial resolution.

3.2 Simulation results

The measured axial resolution is shown in Fig.6. In this figure, a horizontal axis Δf shows the difference between the stop frequency and the start frequency. The stop frequency of all data is 300Hz. The axial resolution of the image by using the pulse compression was higher than that of the image by the hammer method. Then, when the range of Δf is more than 700Hz, axial resolutions that were smaller than 0.2m were obtained. Then, it seems that the axial resolution that is higher than the theory value is obtained when the Δf is small, because the images calculated by using a stacking method of reflected scattered waves.

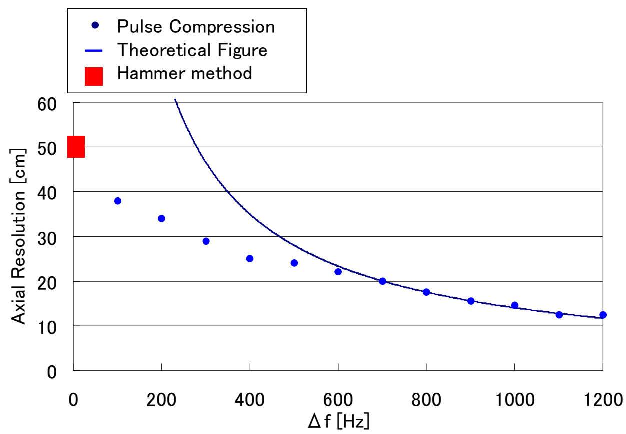

Fig.6 Simulation results.

4 Improvement of lateral resolution by dynamic focusing

4.1 Measurement method

To improve the lateral resolution, we employed the method of controlling the directivity by using a lot of vibration sources in a method similar to the ultrasonic diagnostic equipment in medical field. This method should match the timing of each focus points that all the sound sources drive. However, it is difficult to control the drive of each vibrator at each focus points. And, we have only one sound source. Therefore, the time of received waveforms in our usual method was calculated as if all sound source drive at the same time. Twelve receivers were arranged in a line at 0.5m intervals on the ground. The sound sources are set between all the receivers. The virtual reflection point was horizontally set at intervals of 0.1m as is shown in Fig.7. The down chirp wave was used that oscillates from 600 to 300 Hz (duration 100ms, applied k-flat function) as the output wave.

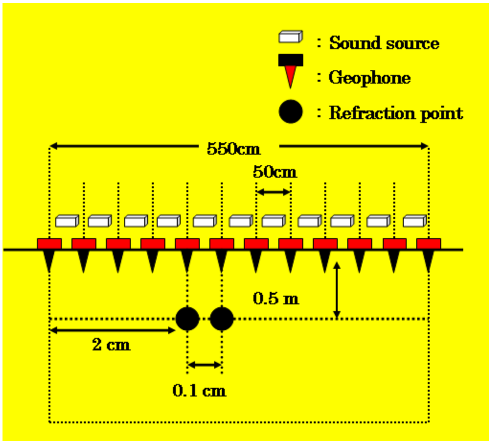

Fig.7 Simulation method.

4.2 Simulation result

The image made by our usual method is shown in Fig.8 (a) and the image made by dynamic focus is shown in Fig.8 (b). In the image by our usual method, two reflection points are overlapped. On the other hand, image by dynamic focus can separate the two reflection points. In these figure, it was confirmed that using the dynamic focus was effective for the horizontal resolution improvement.

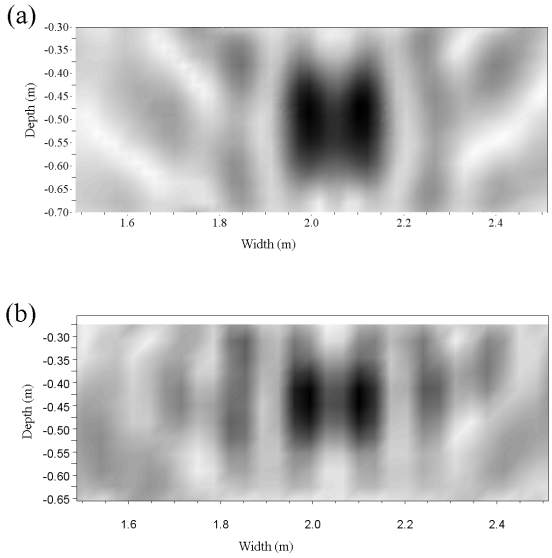

Fig.8 Simulation results.

5 Exploration experiment

5.1 Experimental set-up

To confirm the underground image's resolution, exploration experiments are carried out at Hitachi-shi, Ibaraki-prefecture. The experimental setup is the same as the simulation experiment. The super-magnetostriction vibrator (Moritex Corp, AA140J013-MS1) is used as a sound source and twelve geophones are used for receivers. The output wave is a down chirp wave that oscillates from 800 to 300Hz (duration 100ms, applied k-flat function). The image's axial resolution of this wave is about 0.2m according to the result of the simulation.

We made three exploration lines as is shown in Fig.9. The first line, object was buried the center (2.75m in width) of the exploration line. The second line, two objects were buried at intervals of 0.2m horizontally. The third line, two objects were buried at intervals of 0.1m horizontally. Depths of all buried objects are 0.5m. The buried object is hollow plastic containers (width 13cm, height 12cm, depth 5cm). We experiment three months after the object buried.

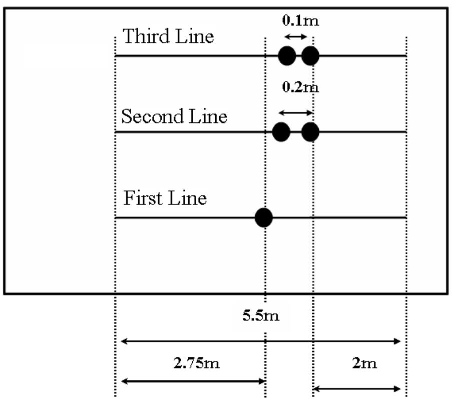

Fig.9 Experimental Lines.

5.2 Experimental results

The received wave, the filtered wave and the wave that applied pulse compression of 6 channel's data in the first line is shown in Fig.10 as a sample. (a) is received wave, (b) is filtered wave (300-800Hz), (c) is pulse compression result. We produced two underground images in the first exploration line; one by applied pulse compression and another by hammer method. Those images are shown in Fig.11. (a) is underground image by Pulse compression, (b) is Hammer method. A boundary rectangle is the buried position (2.75m in width, 0.5m in depth). In the image the signal appeared the position that the object had been buried. It seems that the resolution seen from the image by the pulse compression is much higher than that of by the hammer method. Axial resolution is about 0.2m by almost the same as the result of the simulation.

Then, we produced underground images in the second and the third line by the pulse compression as is shown in Fig.12. (a) is underground image of second line, (b) is third line. The boundary rectangles in the images are the buried positions. In the image by the second line, the signal appeared the position that shifts from buried position lateral by about 0.2m (2.3m and 2.5m in width). In the image by the third line, the signal was overlapped. In these results, we confirm that the lateral resolution of down chirp wave that oscillated 800 to 300Hz (duration 100ms, applied k-flat function) is about 0.2m in actual exploration experiment.

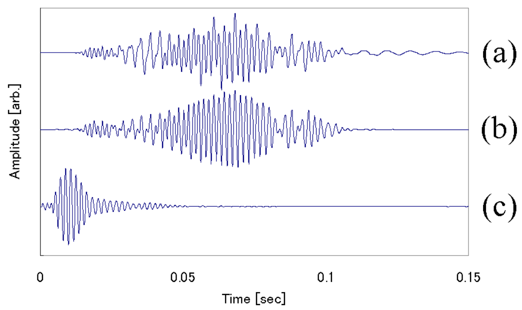

Fig.10 Received waves.
(a) Received wave, (b) Filtered wave (800-300Hz),
(c) Pulse compression result.

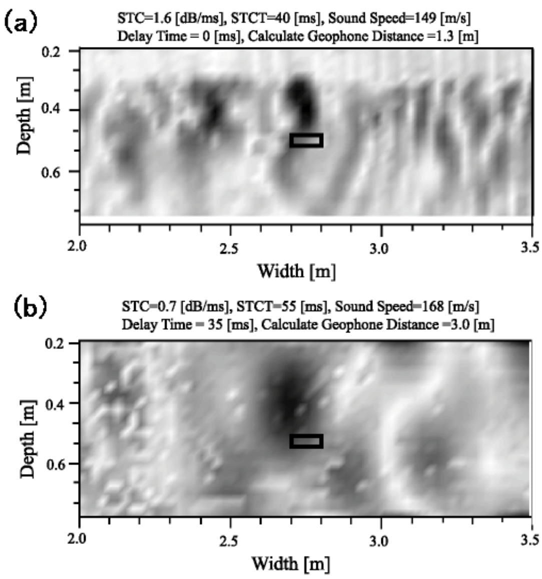

Fig.11 Underground Images of single buried object.
(a) Pulse compression (800-300Hz), (b) Hammer method.

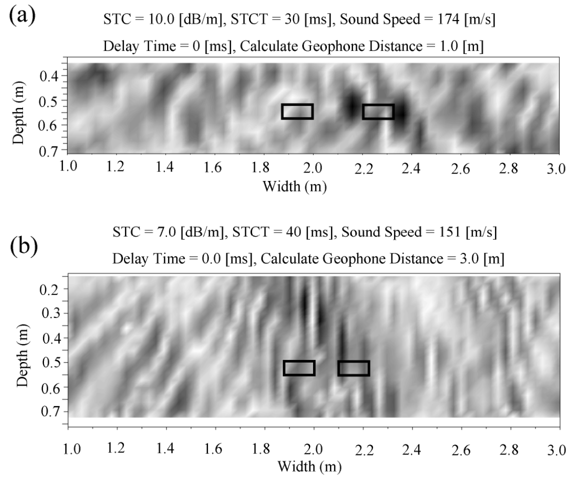

Fig.12 Underground Images of two buried objects.
(a) Image of second line, (b) Image of third line.

5 Conclusion

We confirm that the validity of the pulse compression method for resolution improvement of underground image. From the simulation and exploration experiment results, the axial resolution of pulse compression method is higher than the hammer method. Then, when the range of Δf (between the stop frequency and the start frequency) is more than 700Hz, the obtained axial resolutions is smaller than 0.2m. Then, in the exploration experiment, almost the same axial resolution is obtained as a result of the simulation. Then, it was confirmed that lateral resolution when the down chirp wave that oscillated 800 to 300Hz (duration 100ms, applied k-flat function) is 0.2m in the actual exploration experiment.

Next, dynamic focus will apply to the image made by exploration experiment. Then, it will be solved the problem that the appearing signal shifts horizontally by about 0.2m than the buried position, in the image by pulse compression.

Acknowledgments

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References

[1] T.Sugimoto, M.Okujima, Jpn.J.Appl.Phys.35, 3105-3108 (1996)

[2] T.Sugimoto, H.Saitou, M.Okujima, "Archaeological Prospection", Vp1.7 No.4, 249-261 [in Japanese] (March, 20000)

[3] M.Moriya, T.Sugimoto, Jpn.J.Appl.Phys.41 3501-3502 Part 1, No.5B (2002)

[4] Earth Remote Sensing Data Analysis Center (ERSDAC), "SAR processing algorithm description", [in Japanese] (2005) http://www.palsar.ersdac.or.jp/guide/pdf/sar_algorithm.pdf.