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EXPRESS LETTER

A new seismic survey technology using underwater speaker detected a low-velocity zone near the seafloor: an implication of methane gas accumulation in Tokyo Bay

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Abstract

Owing to the strict restrictions on the use of air guns in marine seismic surveys due to concerns about their potential impact on the marine ecosystem, there have been several cases where seismic surveys were not permitted. This tendency has been particularly significant in coastal waters where fishing activity is flourishing, which creates blank zones in seismic surveys. The authors, therefore, adopted underwater speakers as environment-friendly seismic sources that can be used under such restrictions. In December 2017, the applicability of underwater speakers as a seismic source was tested in a seismic reflection experiment in the northern part of Tokyo Bay. As a result, shallow subsurface structures were successfully imaged, and a low-velocity zone was detected 7–8 m below the seafloor. In this paper, the concept of environment-friendly seismic survey using underwater speakers is reported. In addition, the potential presence of a methane gas layer that was detected in the low-velocity zone is discussed. If the methane gas is widely distributed near the seafloor in the northern part of Tokyo Bay, a large amount of gas might be released into the water and then into the air when, for example, a large-scale earthquake occurs directly underneath the Tokyo Bay area. Given the high flammability of methane, the features and volume of its distribution must be precisely investigated from the perspective of earthquake occurrences in the metropolitan area.

Keywords: Seismic survey, Underwater speaker, Environment-friendly, Non-explosive source, Methane gas, Near seafloor, Tokyo Bay

Introduction

Seismic reflection technology has developed as a method to image subsurface structures, especially in the oil and gas exploration industry. It is possible to identify sedimentary structures from the reflection configuration and faults by offsetting the reflections on the seismic reflection profiles (e.g., Tsuru et al. 2018). At present, the use of seismic reflection technology has expanded into other areas, including crustal studies in seismogenic zones for earthquake disaster prevention (e.g., Park et al. 2002; Tsuru et al. 2002) and carbon capture and storage (Tsuji et al. 2014).

Recently, the use of explosive type of energy sources such as air guns was restricted because of its potential impacts on marine mammal and fish species (IOGP 2017). This restriction is particularly severe in coastal waters such as Tokyo Bay, where detailed geological structures are still unknown because of a lack of seismic data. Therefore, we are developing an environment-friendly seismic survey system that uses underwater speakers (UWSs) as a non-explosive type of energy source. Explosive sources instantly generate impulsive waves with high sound pressure, whereas non-explosive sources generate non-impulsive waves with low sound pressure over a certain period of time. Using an energy source with low sound pressure, it is possible to conduct

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seismic surveys with a relatively low environmental impact on marine ecosystems.

Seismic surveys in Tokyo Bay are also important for modeling the structures in the surrounding Kanto basin (e.g., Koketsu et al. 2009). Recent seismological studies revealed that shallow geological structures control long-period ground motions (e.g., Takemura et al. 2015), which may cause severe damages to large-scale man-made structures such as high-rise buildings, oil tanks and suspension bridges (Koketsu and Miyake 2008).

In December 2017, a seismic reflection experiment was conducted to evaluate the exploration ability of UWSs as a seismic energy source in the northern part of Tokyo Bay. In this paper, we report the results of the experiment and show the applicability of UWS technology as a next generation seismic source that is environment friendly. In addition, we discuss the presence of a methane gas layer, which was detected near the seafloor, from the perspective of earthquake disaster prevention in metropolitan areas.

Method

Compared to explosive sources that instantly shoot an impulsive wave with a considerably higher level of sound pressure (Fig. 1a, d), non-explosive sources generate non-impulsive waves with relatively smaller level of sound pressure for a certain period of time (Fig. 1b, d). By taking the cross-correlation between the non-impulsive wave and an observed record that includes a series of reflections originating from the non-impulsive wave source, the observed record is converted into a series of impulsive reflections (Fig. 1c). In this survey, it is possible to obtain high-resolution subsurface structural images using the non-impulsive source, which are as good as those obtained using an explosive source. This data processing method is the same as that used in onshore vibroseis surveys (Yilmaz and Doherty 1987).

The sound pressure levels (SPLs) of both explosive and non-explosive sources are compared in Fig. 1d. The former has an SPL of more than 160 dB in the frequency range below 400 Hz, which is greater than the pressure level that threatens aquatic mammals and fish (Hatakeyama et al. 1997). Conversely, the latter has an SPL of about 130 dB in the frequency range of 100–1000 Hz, which is significantly less threatening. This shows that non-explosive sources have less impact on marine ecosystems.

Here, we consider the effect of increasing the signal-to-noise (S/N) ratio by cross-correlation processing. Based on a numerical experiment in which it is assumed that the UWS oscillates the source wavelet shown in Fig. 1b for 10 s and the S/N ratio of observed wave is 1, the S/N ratio increases by about 20 times with cross-correlation processing. Namely, the increase in the S/N ratio due to cross-correlation processing of UWS source wave used in this study is about 26 dB. Since the increase in the S/N ratio is equivalent to the effect of increasing the SPL of a source wave, the SPL of the UWS used in this study becomes larger by about 26 dB after cross-correlation processing. As a result, the SPL of the UWSs becomes larger than that of an air gun in the frequency range greater than about

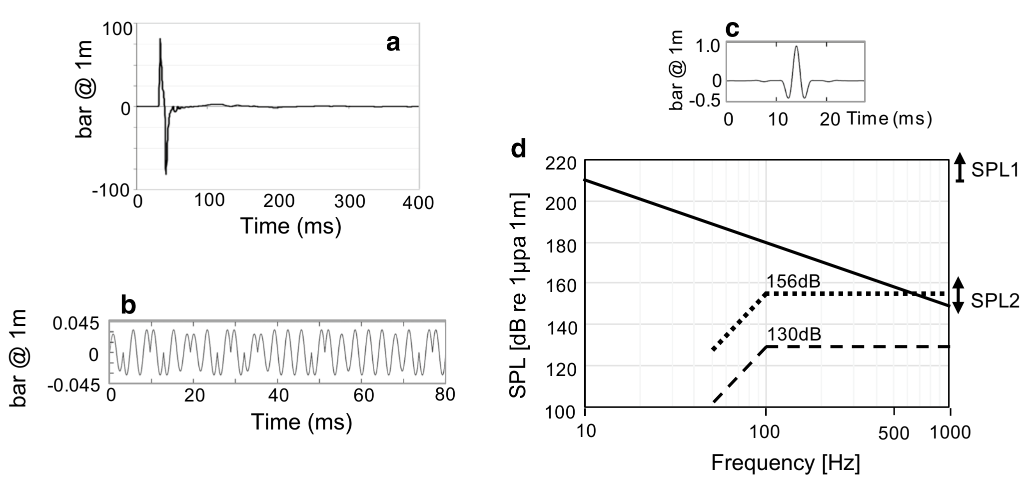

Fig. 1 **a** An example of source wavelet of the air gun (IAGC 2002), which instantly shoots an impulsive wave. **b** An example of source wavelet of the UWS, which generates a non-impulsive wave for a certain period. **c** An example of cross-correlated wavelet between the UWS source wave and an observed wave. **d** The sound pressure levels (SPLs) of the air gun and the UWS. The solid line shows the SPL of the air gun (IAGC 2002). The broken line and dotted line represent the SPLs of the UWS (provided by UETAX Corporation) before and after cross-correlation processing, respectively. SPL1 and SPL2 are the SPLs that harm fish and pose a threat to fish, respectively (Hatakeyama et al. 1997)

650 Hz. Thus, UWSs can provide high-resolution images for shallow structures.

Experiment

In December 2017, a seismic experiment using a UWS was conducted by T/V *Hiyodori* of the Tokyo University of Marine Science and Technology in the northern part of Tokyo Bay. The seismic line was set in the WNW–ESE direction at a water depth of 8–9 m, as shown in Fig. 2a. The northern part of the Tokyo Bay is known to be a sea area with active fishery and busy marine traffic (e.g., Inaishi et al. 2006; Japan Coast Guard 2012). Although a few seismic surveys have been conducted in this region for the purpose of research on earthquake disaster prevention (e.g., Iwabuchi et al. 1995; Sato et al. 2005), no seismic survey has been performed since 2004.

During the experiment, seismic reflection data for a length of around 540 m were collected using a UWS. The shooting was conducted with a shot point interval of 10 s, which corresponds to a shot point spacing of 10 m with a boat speed of 2 knots, which was the standard used in the present experiment. The recording was done using an eight-channel streamer cable with a group spacing of 3.125 m. The sampling rate and record length (after cross-correlation) were 1 ms and 1 s, respectively. For the source waveform, a pseudorandom wave generated using the Mersenne Twister method (Matsumoto and Nishimura 1998), which is one of the random number generator algorithms used in MATLAB, was used.

Results and discussion

Figure 2b shows the seismic profile obtained from the experiment. Continuous reflections from the seafloor are visible at about 11 ms in two-way travel time. Beneath the seafloor reflections, several continuous reflections can be observed clearly, including a continuous reflection with a significantly high amplitude (Ref. A) and a somewhat continuous reflection with a low amplitude (Ref. B). Beneath those reflections, a continuous reflection with somewhat low amplitude (Ref. C) is visible.

First, we discuss the depth of penetration in the present survey using the UWS. The deepest signal reflection that is reflected from a subsurface geological formation can be identified (Ref. C) based on its continuity over the entire seismic profile. Since no continuous reflections are reliably recognized below Ref. C, the penetration depth of the UWS survey system used in this study area was at least 50 ms, which corresponds to 37.5 m when we assume that the average velocity is 1500 m/s.

Next, Ref. A is considered. As shown in Fig. 2b, Ref. A has conspicuous characteristics: significantly high amplitude and reverse polarity. These characteristics are supported by the results of the velocity analysis. As shown in Fig. 3, the three velocity models were tested: one-layer velocity model with 1500 m/s velocity (Fig. 3a), two-layer model with velocities of 1500 m/s and 1100 m/s (Fig. 3b) and two-layer model with velocities of 1500 m/s and 1600 m/s (Fig. 3c). Based on the flatness of the reflections of the model shown in Fig. 3b, the existence of a low-velocity zone immediately below Ref. A can be confirmed. According to the theory of reflection coefficient (e.g., Sheriff and Geldart 1995), the large velocity gap at

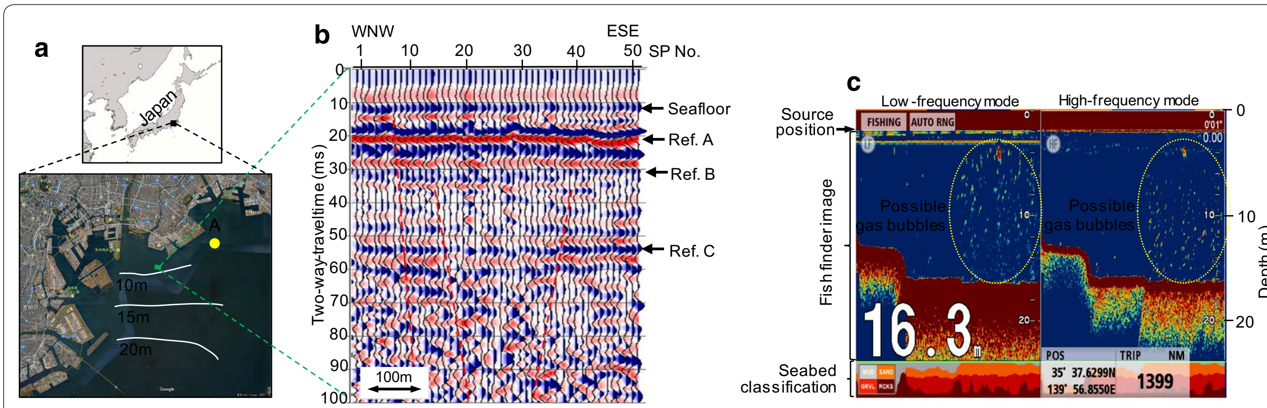

Fig. 2 **a** Location map of the seismic experiment conducted in December 2017. The survey area is located at the northernmost part of Tokyo Bay. The white contour lines and two-digit numbers represent water depths. **b** Resulting seismic reflection profile, which was stacked by a constant velocity of 1500 m/s. Blue color indicates positive amplitude and red color indicates negative amplitude. **c** Fish finder images that suggest the presence of a gas foaming phenomenon, observed at location A (see **a**) by T/V *Hiyodori* in the spring of 2017. The colors in the fish finder images represent the reflection strength of either the fish or seabed: Warmer colors indicate higher strength and colder colors indicate lower strength. The colors in the seabed classification section represent lithology: Gray, orange, red and brown colors show mud, sand, gravel and rock facies, respectively

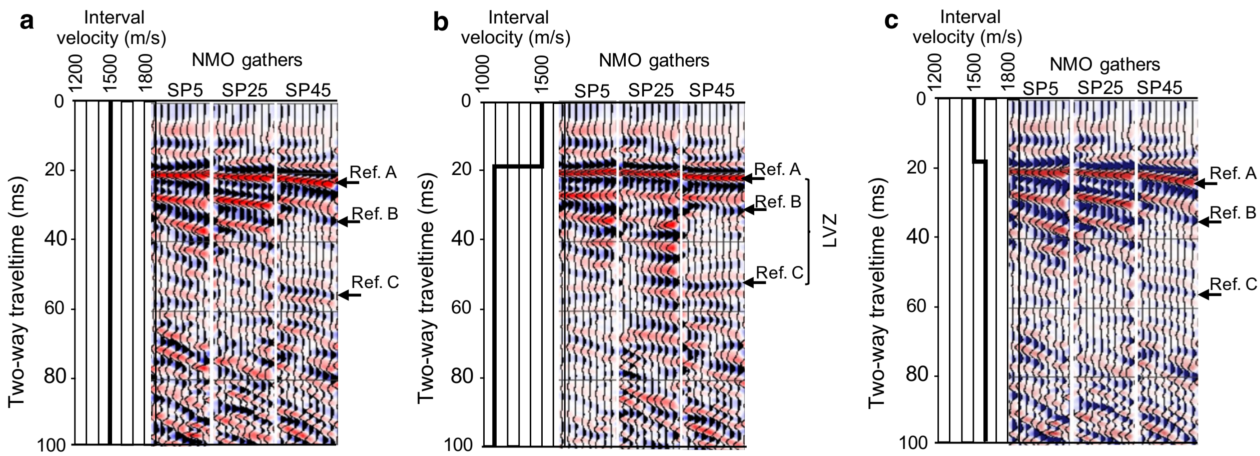

Fig. 3 Results of velocity analyses. **a** One-layer velocity model with 1500 m/s velocity. **b** Two-layer model with velocities of 1500 m/s and 1100 m/s. **c** Two-layer model with velocities of 1500 m/s and 1600 m/s. Based on the flatness of Ref. B and Ref. C, the low-velocity zone (LVZ) was specified immediately below Ref. A

the interface in this model well explains the significantly high amplitude of Ref. A, whereas the low velocity that is detected is consistent with its reverse polarity. Since the estimated velocity of the low-velocity zone is 1100 m/s, which is considerably less than 1500 m/s (the water velocity), the zone must contain gas. In the oil and gas exploration industry, these conspicuous characteristics are well known as the Bright Spot phenomenon and are typically used to identify gas reservoirs (Sheriff and Geldart 1995).

However, the depth of the detected gas layer is about 7–8 m below the seafloor when the velocity above Ref. A is 1500 m/s, which indicates that there is only a 7–8-m-thick sediment acting as a vertical seal over the gas. Compared with the general thickness of vertical seals over hydrocarbon reservoirs, which is larger than several 100 m, the thickness of 7–8 m for the seal would be unreliable to prevent the release of hydrocarbons for millions of years or more. Although it is difficult to clarify why the gas has potentially accumulated below such a thin seal layer, the gas may dynamically or temporally accumulate for a certain period of time due to the balance between supply from a deeper layer and upward leakage.

The evidence of methane gas in the northern part of Tokyo Bay has been reported in previous studies (Furota 1987; Iwabuchi et al. 1995). However, such an extremely shallow methane layer has never been observed. If the low-velocity zone contains methane, the present study suggests that the gas is distributed near the seafloor in the northern part of Tokyo Bay. In addition, fish finder images suggest the presence of a gas foaming phenomenon on the dredged seafloor near the study area (provided by Mr. Takeuchi K., the Captain of T/V *Hiyodori*), as shown in Fig. 2c. Interestingly, this phenomenon can be seen only on the most deeply dredged seafloor, where there are only little mud deposits. Given that vertical sealability is proportional to the thickness of the seal in an environment with uniform seal material (mud deposits in the study area), this possible gas foaming phenomenon "visible on the seafloor with the thinnest seal" may be consistent with our interpretation of "dynamic or temporal accumulation of gas under the balance between supply from a deeper layer and upward leakage".

Here, we consider where the gas comes from. As for the methane gas foaming from the seafloor, it may be thought that the methane is produced by biological decomposition from the sludge deposited over the seafloor. However, according to a previous study (Takii et al. 2001) in the northern part of Tokyo Bay, the methane produced by biological decomposition from the sludge was observed only at depressed topographies such as dredged shipping lanes and sand mining sites, but not on undredged natural seafloor. The low-velocity zone was discovered in the natural seafloor (Fig. 2a, b); therefore, the biological decomposition from the sludge is not a likely candidate for the cause of methane accumulation.

As another candidate, the natural gas dissolved in water (NGDW) may be related to the methane accumulation causing the low-velocity zone. It is well known that NGDW is distributed widely under the metropolitan area in Japan, which includes the northern part of Tokyo Bay. A portion of the gas leaks out to the surface via faults and is utilized for household purposes in areas near Tokyo Bay (Sawaki and Kaneko 2010). However, the gas has caused some explosion accidents during civil engineering works in and around Tokyo (MLIT 2007). Considering that some faults near the seafloor have been discovered in previous seismic reflection studies (e.g., Kato 1984), there is a possibility that the low-velocity zone contains methane gas that migrated from deeper regions via such faults. If so, a large volume of methane could be distributed widely over the northern part of Tokyo Bay.

The northern part of Tokyo Bay has a potential risk of near-field earthquakes such as the 1855 Ansei Edo earthquake (e.g., Usami 1996; Bakun 2005). If an earthquake occurs, the faults would be activated, and a significant volume of methane gas might be released into the air. Methane not only causes a significant greenhouse effect, but is also highly flammable; therefore, it is important to identify the features and volume of its distribution. Hence, further seismic surveys are strongly required in the northern part of Tokyo Bay, even though the area appears as a blank zone in seismic surveys because of the active fishery and busy marine traffic.

Conclusions

The applicability of UWSs as an environment-friendly seismic source was tested in the northern part of Tokyo Bay. As a result, the shallow geological structures were clearly imaged down to at least 37.5 m below the seafloor. In addition, a low-velocity zone, suggesting methane gas accumulation, was discovered about 7–8 m below the seafloor. Considering both the high level of greenhouse effects and flammability of methane, the features and volume of its accumulation must be investigated from the perspective of environmental conservation and earthquake disaster prevention.

Additional file

Additional file 1. Seismic reflection data shown in Fig. 2b are available as the additional file with CSV format.

Authors' contributions

TT is responsible for the entire manuscript. KA contributed to the data acquisition in the seismic experiment. J-OP contributed to the design of the study and the interpretation of seismic data. JS contributed to the design of the data acquisition system. MT contributed to the data analysis for source wavelet optimization. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

Seismic reflection data after stacking were provided as a Additional file 1 with csv format.

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