Development of directional drilling system and measurement method in the borehole -Application of seismic tomography between surface and the borehole-

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Abstract

Preliminary investigations in site selection for High Level Waste disposal require evaluation of geological characteristics from the ground surface and/or several boreholes, and seismic reflection is one investigation method used. To obtain a more precise reflection profile, it is necessary to obtain a highly accurate P-wave velocity profile. The Central Research Institute of Electric Power Industry has investigated directional borehole drilling and technologies for logging and measurement. Seismic tomography can be conducted using boreholes and the ground surface, resulting in P-wave velocity profiles and more precise reflection profiles. In an in-situ test we drilled a 1000 m borehole, drilling horizontally at lengths exceeding 700 m. Hydrophones were installed every 10 m at drilling lengths of 100 m to 785 m. Vibrator points were installed every 20 m at the ground surface above the borehole. We acquired waveform data by hydrophones when the vibrator oscillated a seismic wave. We obtained a P-wave velocity profile between the ground surface and the borehole by 2-D tomographic inversion. Using this P-wave velocity profile, we recalculate the reflection profile obtained at the ground surface to be the same as at the vibrator points. The results demonstrated that we could interpret geological structures from the reflection profile more accurately than before.

Keywords: High Level Waste disposal, directional drilling, seismic tomography, MDRS method

1. Introduction

In site selection for High Level Waste disposal, preliminary investigations are conducted to assess the geological characteristics from the ground surface and/or several boreholes. The seismic reflection method is one methods used in such investigations, but to obtain more precise reflection profiles and evaluate the geological characteristics in detail, it is necessary to obtain the P-wave velocity profiles with high accuracy.

Central Research Institute of Electric Power Industry (CRIEPI) has investigated directional borehole drilling and technologies for logging and measurement, and has developed drilling technologies for fault zone drilling, horizontal drilling, gentle slope drilling, coring, and locality detection, and applications of these methods have been verified in in-situ tests (Kiho et al., 2015). Seismic tomography can be conducted using borehole and ground surface data. More precise P-wave velocity profiles can be obtained from the seismic tomography results. Furthermore, the reflection profile will be improved by using this P-wave velocity profile. In this study, we conducted seismic tomography using a borehole drilled in an in-situ test.

2. Directional drilling

2.1 Study area

The study area, Horonobe town, is located about 50 km south of Wakkanai, the northernmost city in Japan. The geology around the study area mainly consists of the Koetoi and Wakkanai formations of the Neogene. Rock facies of these formations are mainly diatomaceous mudstone (Koetoi Formation) and hard shale (Wakkanai Formation). Each formation is more than several hundred meters thick (Fukusawa, 1985). The Horonobe area is characterized by the prevalence of folded structures and reverse Omagari faults. Fold axes have a north-northwest trend, dipping to the north at the northern part of Horonobe. The Omagari fault has a similar trend and a length of 25 km. It intersects through the town center, with the fault outcrop clearer in the southern part of the town (Ishii et. al., 2006). The porosity of the diatomaceous mudstone of the Koetoi and Wakkanai formations are respectively about 60% and 30%, and their uniaxial strengths are respectively about 6 MPa and 15 MPa.

2.2 In-situ directional drilling test

In the directional drilling project, a 1000 m borehole was drilled with horizontal drilling at lengths of 700 m and beyond. Casing was set at drilling lengths of 200 m and shallower. The borehole passed the Omagari fault at drilling lengths of about 330 m to 450 m,.

3. Seismic tomography

3.1 Equipment for the measurements

There are generally two types of receiver used in boreholes, those that crimp to the borehole wall (geophones) and those that do not (hydrophones). Geophones can reduce the influence of tube waves, but it is necessary to install the unit to crimp to the borehole wall, making multiple installations difficult and measurements time-consuming. In contrast, hydrophones do not require crimping, so it is easy to install multiple units. In this study, we used a hydrophone array for the seismic tomography. Figure 1 shows a schematic layout of the hydrophone array. We used 24 hydrophones (HTI-96-MIN/V 5/8, High Tech, Inc.) installed at 10 m intervals. The array tools can be inserted into the borehole by self-weight, but must be inserted at horizontal drilling depths by a driving force. We therefore installed a feeding apparatus at the bottom end of the hydrophone array tools.

We used Enviro VIB / Minibuggy (IVI, Inc.) for the seismic source from the surface and the GDAPS-4A digital telemetry system (JGI, Inc.) for data acquisition.

3.2 Layout and measurement conditions

Figure 2 shows a location map of the hydrophones and vibrator points. Hydrophone array positions were divided into three sections (section 1: 555–785 m; section 2: 340–570 m; section 3: 110–330 m). Vibrator points (VP) were installed at odd-numbered points (20 m intervals) from VP 15 (near the HCD-3 well head) to VP 117 (about 1000 m from the well head). Table 1 shows the vibration parameters, and Table 2 shows the recording parameters.

The cable was suspended and not crimped when hydrophones were set in section 3, so the waveform S/N was very low and we could not distinguish the initial shock. Therefore, we did not use analysis data from this section.

We also conducted a seismic refraction method at the ground surface to obtain the P-wave velocity profile in shallow areas and conduct full waveform inversion.

3.3 2-D tomographic inversion

We conducted 2-D tomographic inversion between the surface and the borehole. First, a P-wave velocity profile was calculated using the results of seismic tomography between the surface and the borehole, and then the profile was updated by full waveform inversion using the results of the seismic refraction method at the ground surface. The analysis procedure was as follows:

(1) The initial velocity profile was updated using the recorded travel time. The back-projection method was used for tomographic inversion.

(2) The refraction ray path was calculated using the updated velocity profile calculated in (1). The

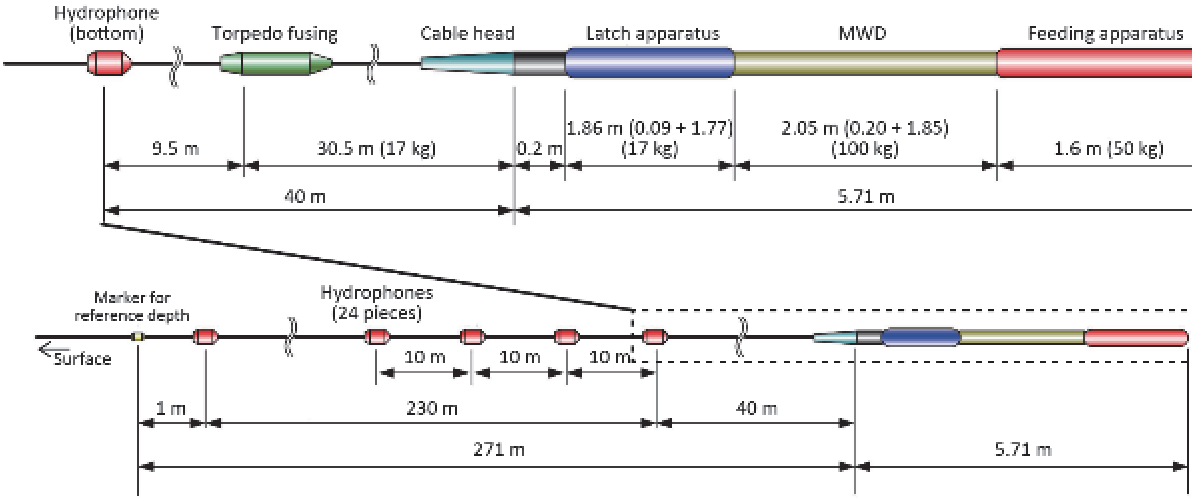

Fig. 1 Schematic layout of the hydrophone array.

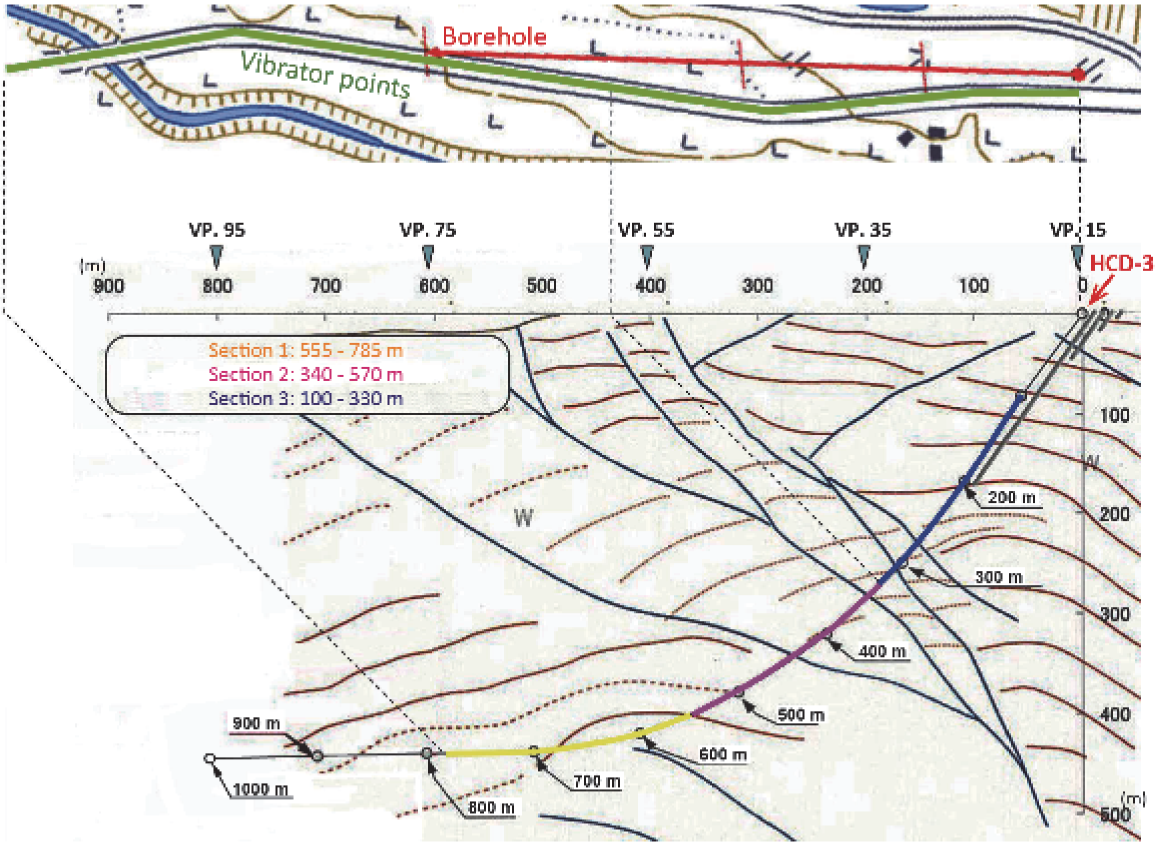

Fig. 2 Hydrophone and vibrator point locations.

Table 1 Vibration parameters.

Item	Parameter
Sweep length	12 s
Frequency	8 to 80 Hz
Stacking	10
Sweep wave	Linear up sweep

Table 2 Recording parameters.

Item	Parameter
Sampling interval	1 ms
Recording length	3 s
Number of channels	24
Preamplifier gain	18 dB
Noise edit	Factor 2, Gate 15 s

linear travel-time interpolation (LTI) method was used for the calculation.

(3) The velocity profile was updated using the refraction waveform calculated in (2). The conjugate gradient method was used for the tomographic inversion.

(4) Using the velocity profile calculated in (3), the velocity profile was updated by frequency domain full-waveform inversion. We used TOY2DAC software (SEISCOPE Consortium, http://seiscope2.osug.fr/?lang=en) for full-waveform inversion.

3.4 P-wave velocity profile from seismic tomography

Figure 3 shows the P-wave velocity profile from seismic tomography. To verify the effectiveness of the velocity profile from seismic tomography, we compared the P-wave velocity from seismic tomography with that from laboratory experiments using rock samples from the borehole. Figure 4 shows a comparison of P-wave velocities from seismic tomography and rock samples. As that figure shows, the measurements are highly consistent. On the other hand, there was a difference at drilling lengths between about 300 m and about 400 m. The borehole passed through the Omagari fault at this drilling length, and these fractures may have caused the observed decrease in velocity. Note that laboratory experiments were conducted using intact rocks, so any velocity decrease caused by fractures would not have been reproduced, making P-wave velocities from seismic tomography lower than that from rock samples. The results of laboratory experiments demonstrated that the rapid decrease in velocity occurred at drilling lengths around 850 m. Rock facies changed (from Wakkanai to Koetoi formations) at this drilling length, so there is a possibility that this velocity change occurred due to the change of rock facies. However, no velocity change was obtained in the seismic tomography

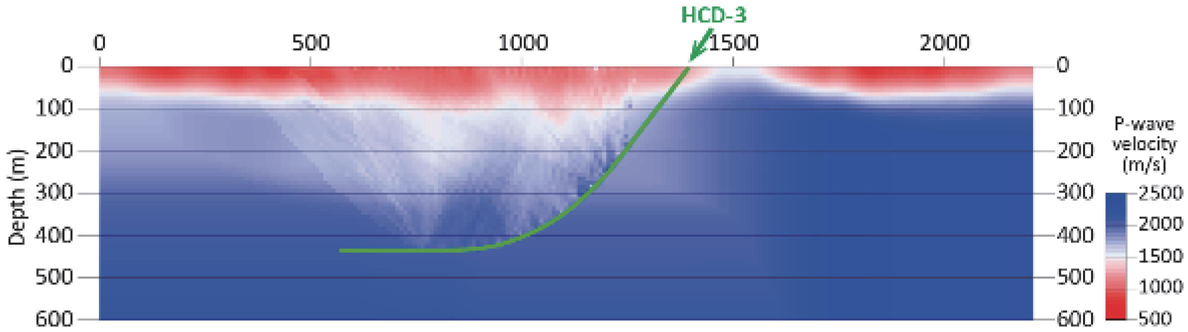

Fig. 3 P-wave velocity profile from seismic tomography.

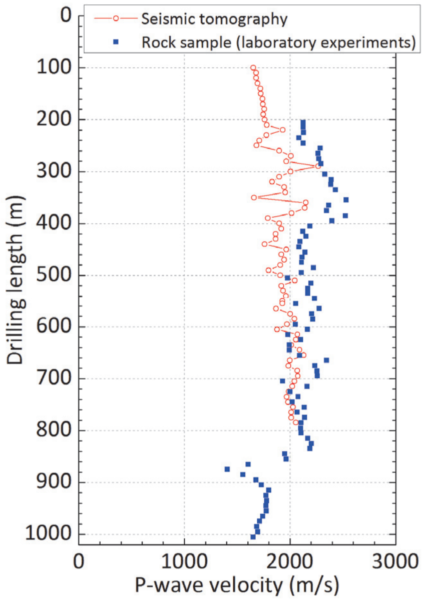

Fig. 4 Comparison of P-wave velocity from seismic tomography (open circles) and rock samples (filled squares).

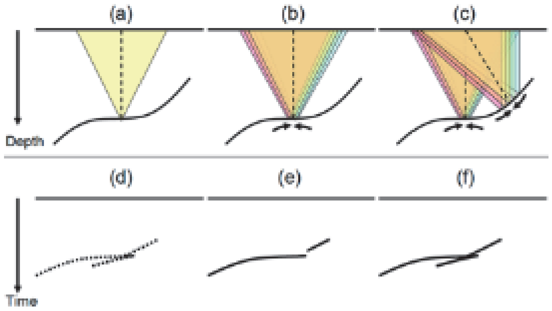

Fig. 5 Schematic representation of three stacking methods (a–c) and their zero-offset sections (d–f) (Aoki et al., 2011).

results, because hydrophones were not set at this boundary (the deepest hydrophone was at 785 m).

4. Recalculation of the reflection profile using P-wave velocity profile

4.1 Outline of the recalculation

We recalculate the reflection profile obtained at the ground surface in the same way as the vibrator points, using a P-wave velocity profile obtained from seismic tomography between the surface and the borehole. In this study, the multi-dip reflection surface (MDRS) method (Aoki et al., 2011), an improvement on the common reflection surface (CRS) stack method (Jager et al., 2001; Mann et al., 2007; Schleicher et al., 1993), was used for the inversion to derive a more precise reflection profile.

Figure 5 shows a schematic representation of the MDRS method (Aoki et al., 2011). The top figures show stacking methods such as common midpoint (CMP) (Fig. 5a), CRS (Fig. 5b), and MDRS (Fig. 5c). Each triangle represents rays from a CMP gather. The CRS method utilizes several CMP gathers by considering the slope and curvature of a reflection surface (Fig. 5b). MDRS acts the same way, except that it simultaneously considers reflections from different surfaces. The bottom figures show zero-offset sections. The CMP section (Fig. 5d) suffers from noise (dashed line). The CRS section (Fig. 5e) obtains enhanced events (bold lines), but loses an event at a conflicting dip part. The MDRS section (Fig. 5f) achieves not only enhanced events but also a higher fidelity wave field representation.

4.2 Reflection profile

Figure 6 shows the reflection profile calculated by conventional CMP stacking (Fig. 6a) and the MDRS method (Fig. 6b). In comparison with CMP stacking, the MDRS method improved in the continuity of reflection events, making it easier to distinguish the boundary of rock facies. We therefore conclude that a reflection profile can be acquired with high accuracy and that the geological structure is easily interpreted by using the highly accurate P-wave velocity profile calculated by the MDRS method.

Figure 7 shows the geological section estimated from surface geology and rock samples. The amplitude and continuity of reflection events decreased at drilling lengths of about 300–400 m (Fig. 6). The decrease occurred because fault

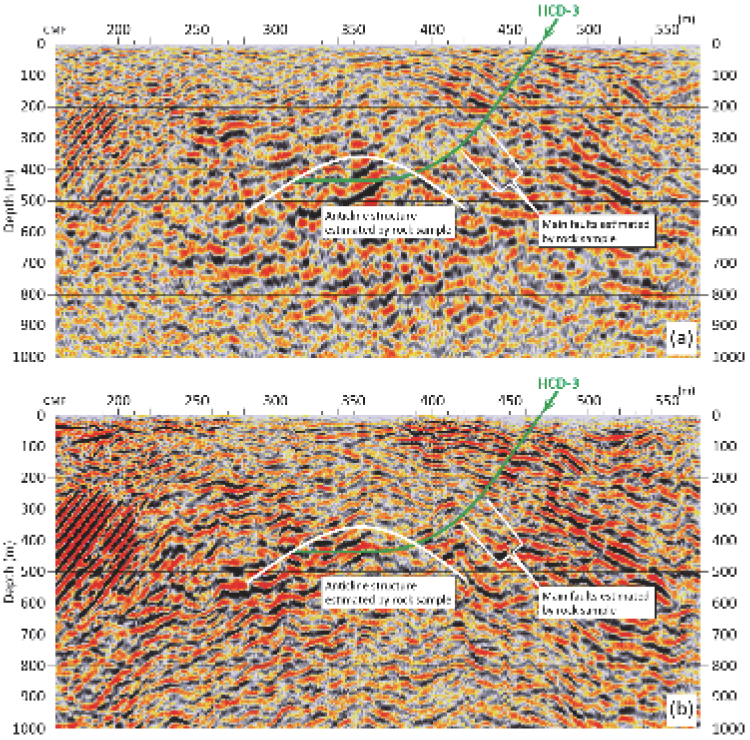

Fig. 6. Reflection profiles: (a) conventional CMP stacking, (b) MDRS method.

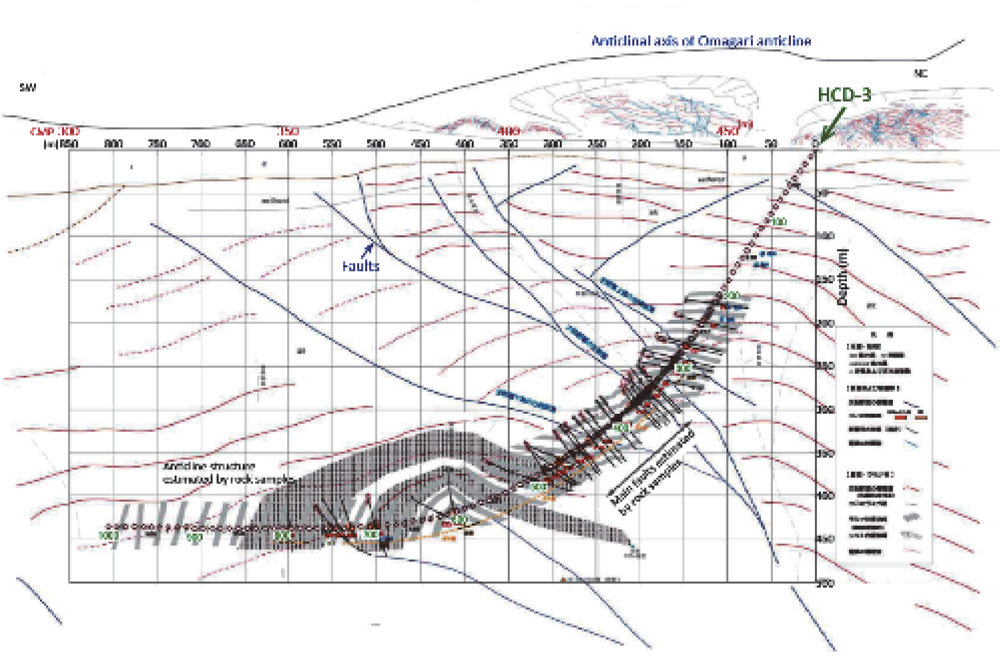

Fig. 7 Geological section estimated from surface geology and rock samples.

fractures scattered the reflected waves. Using the profile calculated by the MDRS method made this decreased zone easier to distinguish. High-amplitude reflection events appeared at depths of 300–500 m, CMP distances of 280–400 m in MDRS method (Fig. 6b). This zone was consistent with the underlying anticline. This high-amplitude event (the anticline) did not appear in the reflection profile from CMP stacking (Fig. 6a), suggesting that a more precise reflection profile than conventional CMP stacking can be obtained by using the P-wave velocity profile obtained from seismic tomography between the surface and the borehole in directional drilling.

5. Conclusions

We conducted seismic tomography between the surface and a borehole, and calculated the reflection profile using the obtained P-wave velocity profile and the MDRS method. The results demonstrated that a reflection profile could be obtained more precisely than when using the conventional stacking method. This suggests that it becomes easier to evaluate geological characteristics by seismic tomography using a directional drilling borehole and the MDRS method.

Acknowledgements

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