Small-diameter directional borehole radar system with 3D sensing capability

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***Abstract*—This paper describes a new directional borehole radar system and its field testing. The system uses a thin radar probe (57 mm diameter) and a circular dipole array directive antenna. The radar is of the step frequency type with a network analyzer. Through careful antenna design, we were able to achieve the compact radar probe and precise measurement at frequencies between 5 and 500 MHz. All the associated surface electronics for the radar system can be fit into a small carrying case. The radar probe includes a triaxial accelerometer, a triaxial compass, an angular velocity sensor and a thermometer. Data from these sensors can be used to compensate for the rotation and inclination of the radar probe, and this enables us to locate reflection points in 3-D space correctly. All the data acquired by the radar probe were sent to the processing electronics via an optical link, and the data was updated in real time. Our field testing confirmed that system accuracy for determining arrival directions was better than 10 degrees between 30 and 180 MHz in wet soil. We demonstrated 3-D location of a buried cylindrical conducting object, which was set 2 m from the radar in wet soil. After system calibration and signal processing, we were able to estimate the reflection point position with an accuracy of 41 cm.**

***Index Terms*—Directional borehole radar system, pile location.**

I. Introduction

Many reconstruction projects for earthquake-resistant buildings, public facilities, and infrastructure have been undertaken in densely populated alluvial plain areas, such as the city of Tokyo. Detecting existing buried structural objects such as foundation piles and sheet metal piling walls is an early-stage exploration target in those projects. Ground penetrating radar (GPR) sounding has provided valuable information on objects buried in the subsoil up to several meters below the ground surface. Due to the sounding depth limitation of GPR, conventional commercially available non-directional borehole radar has started to be utilized at such construction sites [1]. However, radar operators are often faced with difficulties in data interpretation, caused by a lack of directional information for buried objects.

Ebihara et al. [2] developed a directional borehole radar system to estimate the three dimensional features of fractures and/or faults in hard rock. We have developed a new directional borehole system based on the Ebihara system concept, attaching MEMS sensors for 3D attitude radar probe sensing and strengthening the system's 3D visualizing applications for locating buried objects in the field. Moreover, we have added new applications for automatic parameter setting, and horizontal distance scanning using the modified Semblance method (Taner and Koehler) [3] to compute arrival angles and the distances traveled by the reflected wave from buried objects to the system operators. A field study using the system was carried out at our test site, evaluating the results for single and crosshole measurements.

II. Design of The Directional Borehole Radar

A. Radar system

Our target borehole diameter is 67 mm, equivalent to the inner diameter of polyvinyl chloride pipe widely used in geotechnical fields (VP65, Japanese Industrial Standards). In this case, considering the thickness of the fiber reinforced plastic (FRP) vessel used for housing the antennas and allowing a gap between the vessel and the borehole wall sufficient to avoid getting the radar probe stuck, the diameter of the radar probe should be smaller than about 60 mm. For this type of thin radar probe, we may consider adopting an array antenna for the directive antenna. The dipole array antenna fed by coaxial cables was recently proposed for directional borehole radar in [4], and this antenna has been used for 3-D imaging of a fault [2]. Recently, researchers succeeded in reducing the bore size of the antenna through the addition of ferrite cores [5]. With such a dipole array antenna, one may measure the arrival time difference of the array signals to estimate the signals' directions of arrival (DOA). Based on this prior work, we carefully designed the size of the dipole array antenna to be appropriate for use in a borehole. We determined all the antenna parameters theoretically, avoiding any mutual coupling among antenna elements, feeding lines, and the chassis, including the other sensors. In this theoretical analysis, the borehole effects, which comprise the influence of the borehole on radar signals, were considered. Although the antennas are mounted on an acrylic resin cylinder whose diameter is about 4 cm, we may ignore all the electromagnetic mutual coupling.

The type of the radar used in this study was a step frequency radar. In the frequency band between 5 and 500 MHz, precise measurement was carried out with a vector network analyzer (VNA). This tool enabled us to calibrate all the cables' delay and attenuation in the radar system. This leads to precise estimation of the azimuth direction of the arriving wave, exploiting arrival time difference in the time domain in the dipole array antenna. All the data acquired by the radar probe were transmitted to the surface equipment immediately after measurement using optical links. The surface equipment consisted of a carrying case, a personal computer, and a portable VNA as shown in Fig. 1. The carrying case held the system electronics, including a microcomputer, amplifiers, laser dipoles, photodiodes, and batteries. The entire system, including the surface equipment and radar probe, was designed to work with rechargeable batteries.

B. Technical data

The following is a summary of the radar system's specifications.

Radar probe diameter 57 mm

Radar probe length
Up to 4.5 m, including the transmitter and receiver

Radar probe weight 20 kg

Type of radar Step frequency radar

Operating frequency 5 – 500 MHz

Dynamic range between transmitter/receiver
140 dB

Maximum Pressure
200 m in a vertical water-filled borehole

Carrying case, including electronics
W 480 mm, D 385 mm, H 190 mm, 12 kg

Data transmission between probe and surface equipment
Optical link with single mode optical fibers

Antenna set-up Bistatic

Transmitting antenna Dipole antenna

Receiving antenna Dipole array antenna (directional) Dipole antenna (non-directional)

Avg. angle accuracy Better than 10 degree (30-180 MHz)

Sensors included in the probe
Triaxial compass, triaxial accelerometer, triaxial gyroscope, thermometer.

Battery run time More than 5 hours.

Fig. 1. Carrying case including ground surface electronics, portable VNA, and laptop computer (top). Transmitter and directional probes with a diameter of 57 mm (bottom).

III. Data Processing and Object Detection

A. 3-D location of radar target

Dipole array data was acquired at each depth of the radar probe. At the same time, the data from all the sensors such as the triaxial compass were also acquired. The frequency domain data of the radar was transformed to time domain signals after an optimal filtering on the ground surface. We may pick an arrival time of the wave of interest in the time domain, and track the arrival times of the wave with the radar probe depths. At each depth, we can estimate the azimuth directions of arrival waves with the arrival time difference recorded by the dipole array antenna. The distance from the borehole and the depth of the radar target can also be estimated from measurements collected at only two narrowly separated depths of the radar probe. The reflection point on the radar target can be displayed in 3-D figures. All the signals described below were processed automatically on a laptop personal computer.

B. Compensation for rotation and inclination of probe

The radar probe inside the borehole can be inclined and rotated. The rotation and the inclination of the radar probe can be compensated in the 3-D location, exploiting the output data of the triaxial compass and the accelerometer. All the data of these sensors were digitized in the radar probe, and transmitted from the radar probe to the surface equipment. The radar probe's rotation and inclination may be monitored continuously, and used to compensate the 3-D location of the radar target.

IV. Field Experiment

In order to test the developed radar system, we conducted the following two experiments with the directional borehole radar. Borehole-1 and Borehole-2 were drilled in the Neyagawa campus in Osaka Electro-Communication University. The test site is composed of wet clay. The estimated relative permittivity of the medium is about 25, and we may interpret the medium as high loss one. The field data were collected below the water table, whose depth is 90 cm.

A. Crosshole Measurement

We set the receiving array antenna at a depth of 2.42 m in borehole-1. Another dipole antenna serving as the transmitter was set at the same depth as the receiver in borehole-2, which was 2 m away from borehole-1. The two boreholes were filled with water.

Figure 2 shows the received signals of the dipole array antenna. These time domain signals were obtained after the inverse Fourier transformation. The direct wave arrived at about 40 ns. We may observe arrival time differences among the dipole array signals. This corresponds to the azimuth direction of the transmitting antenna.

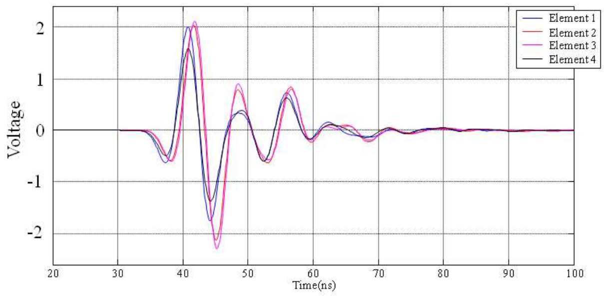


Fig. 2. The array signals in the crosshole measurement

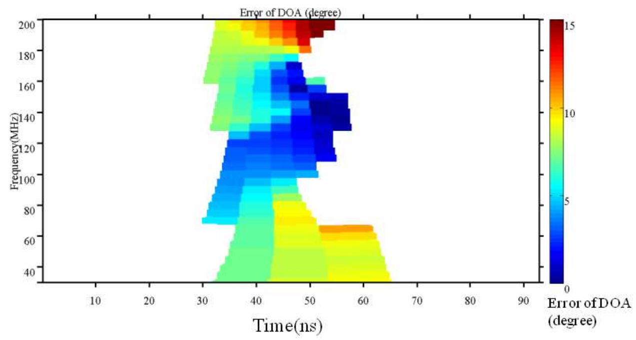


Fig. 3. DOA estimation error of the direct wave in the crosshole measurement in time-frequency plane.

Figure 3 shows the DOA estimation results. In this estimation, we used the algorithm in [4]. In order to obtain frequency resolution, we applied bandpass windowing to the frequency domain data. It seems that the estimation error is below about 10 degrees at frequencies below about 180 MHz. This implies that the compensation of the probe rotation and the calibration of the cable time delay did not introduce significant errors. The solid line in Fig. 4 shows the averaged error angles of Fig. 3. We may confirm that the estimation error of the DOA is less than 10 degrees below about 180 MHz.

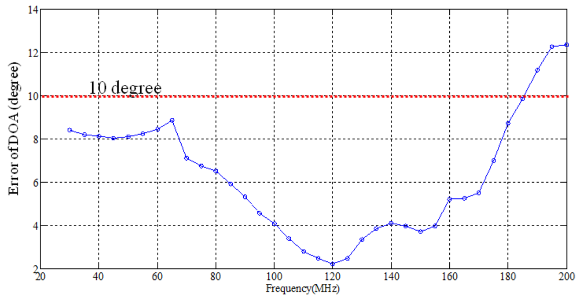


Fig. 4. DOA estimation error of the direct wave in the crosshole measurement. Averaged error of DOA at each frequency.

B. Singlehole Measurement

We scanned the radar probe including both the transmitting and the receiving antenna at a depth of around 4 m in borehole-1. We inserted a conducting cylinder inside borehole-2 for a reflector. This is a kind of semi-infinite conducting cylinder, and we expect a scattered wave from the bottom of borehole-2. In order to evaluate the accuracy of the 3-D location with the radar, we tried to estimate the borehole-2 bottom position with only the radar output.

Figure 5 shows the received time domain signals of the first element of the dipole array antenna. We are sure that the reflected waves, which are indicated by the red broken line, arrived from the borehole-2. This is because we confirmed that removal of the conducting cylinder leads to change of the waveform. At each location, the receiving dipole array data may be analyzed using the array signal processing.

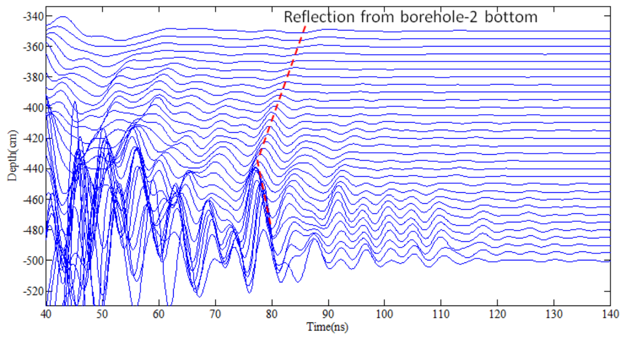


Fig. 5. Time domain signals acquired at the first element. Signals were bandpass filtered with the center frequency, 150 MHz, and the frequency bandwidth, 300 MHz.

Figure 6 shows the estimated reflection point positions. In this estimation, we used the algorithm in [2]. Note that there are multiple estimated points in the figure, since we may locate the reflection point at each depth of the radar probe. The estimated reflection points are near the bottom of borehole-2. This implies that the radar located the borehole-2 bottom successfully. In order to evaluate accuracy of the location, we projected all the estimated reflection points on the *x-y, x-z,* and *y-z* planes in Fig. 7. It can be seen that almost all the distances between the estimated reflection points and the borehole-2 bottom are less than 50 cm. Averaging the distances, we find that the accuracy of the 3-D location is 41 cm. Since the accuracy of the arrival time estimation is better than that of angle estimation, the estimated reflection points are distributed on an ellipsoid.

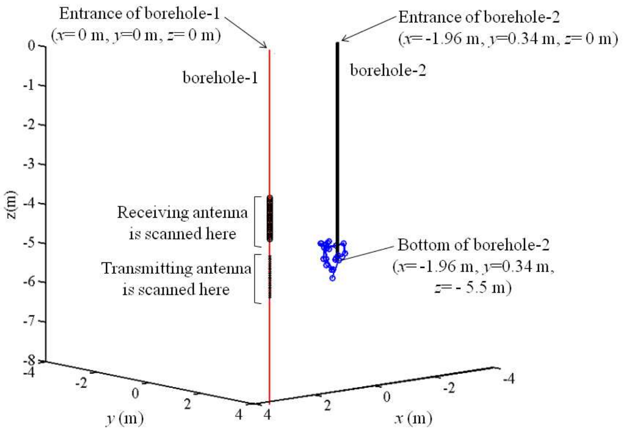
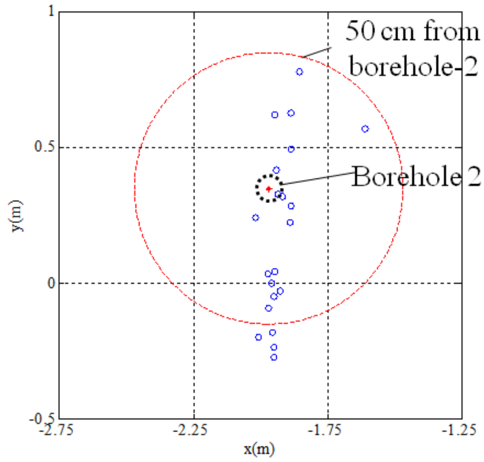


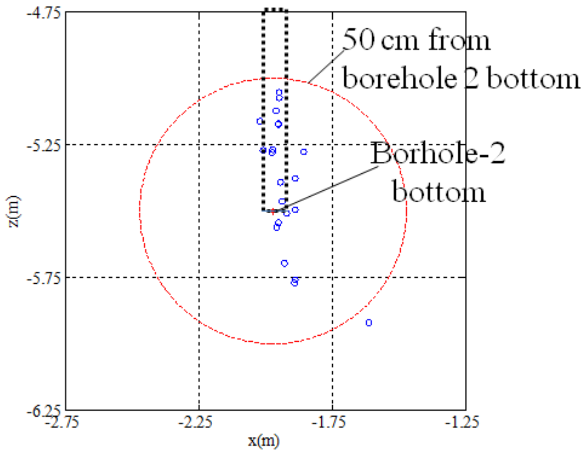
Fig. 6. The 3-D estimation results from field experiments. The blue circles represent the estimated reflection points.

Considering drilling operations at actual construction sites, we can assume that buried structural objects are typically oriented perpendicular to the ground surface. We can, therefore, expect that most of the energy of reflection waves from the buried objects will arrive in a horizontal direction towards nearly a vertical measuring borehole. Monitoring the arrival direction of such radar reflection waves at each measuring depth can provide on-site information regarding buried objects surrounding the borehole in the soil.

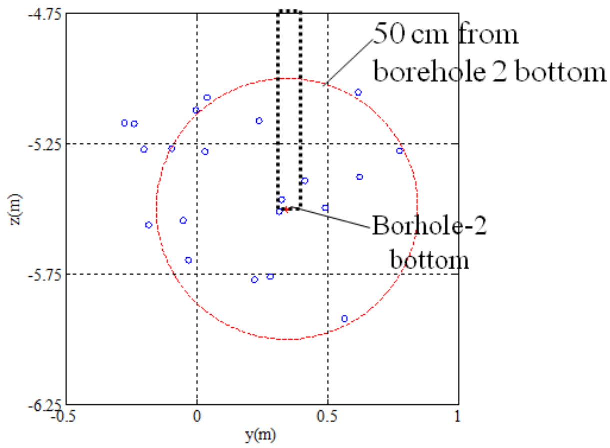
Since the dipole array antenna is housed in an acrylic tube with a diameter of 4cm, the arrival reflection wave can be treated as a plane wave, compared with the distance to the reflector. Taner and Koehler [3] first defined conventional Semblance, a normalized coherency coefficient. We newly defined a modified semblance and applied it to evaluate the similarity of the radar wave forms. In order to calculate Semblance, we first shifted radar wave trace in selected time range by estimated arrival delay times for each antenna, varying direction angle of arrival by 8 degree per step, and calculated Semblance mapping with distances to reflection point estimated from the central time of the selected time range. Furthermore, we modified the original Semblance mapping, multiplying the original Semblances by a difference of maximum and minimum Semblance values in the time range and squared them for both suppressing direct wave and noise and emphasizing reflected wave, and then converted the modified Semblance mapping to radar chart for the horizontal scan view.



(a) Projection on *x-y* plane



(b) Projection on *x-z* plane



(c) Projection on *y-z* plane

Fig. 7. Projection of the 3-D estimation results in Fig. 4 on each plane.

Figure 8 shows an example of the modified semblance map in a radar chart at the depth of 4.55m. The radial axis is the radial distance from the center of the borehole and the angular axis is the angle in relation to magnetic north. The figure shows the strong signal from the reflector at an angle of 190 degrees in relation to magnetic north and at a radial distance of 2.1 meters from the borehole center proving the excellent directionality of the system. Yellow lines represent local peaks of the normalized semblance map.

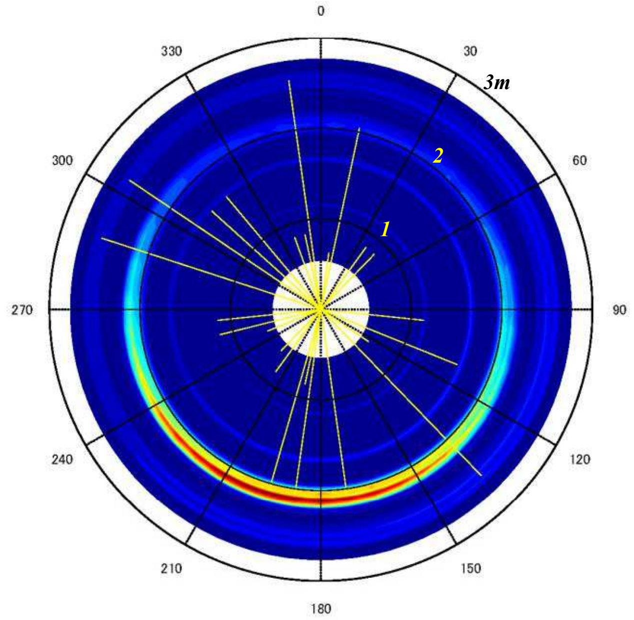


Fig. 8. Horizontal scan view by modified semblance.

V. CONCLUSIONS

We built and tested a prototype of the 3D Directional Borehole Radar system in order to detect buried objects in subsoil from a borehole. The system consists of two (non-directional and directional) receiver and transmitter probes and a control unit with VNA. The main characteristic of the system are:

- Directional borehole radar
- 3D attitude sensing of directional Rx probe
- Small caliber probe with a diameter of 57 mm
- Application for 3D estimation of buried objects
- Application for on-site horizontal scanning view
- Separable transmitter and receiver probes for both single-hole and cross-hole measurements
- Easy operation

The system was applied to single-hole and cross-hole experimental measurements for the estimation of a 3D artificial reflector's location. The test results showed the system's high precision estimation abilities. Future studies are planned to conduct more realistic experimental measurements in several actual geotechnical and rock engineering fields, with the goal of refining the equipment and methods described here.

ACKNOWLEDGMENT

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REFERENCES

[1] Y. Yamashita and T. Toshioka, "Application of Borehole Radar to Buried Object Survey for Civil Engineering Purpose", EAGE 64th Conference & Exhibition, Florence, Italy, May 30, 2002.

[2] S. Ebihara, H. Kawai and K. Wada, "Estimating 3-D Position and Inclination of a Planar Interface with Directional Borehole Radar," Near Surface Geophysics, vol. 11, pp. 185-195, 2013.

[3] M. T. Taner and F. Koehler, "Velocity spectra - digital computer derivation and applications of velocity functions", Geophysics, 34, 859–881, 1969.

[4] S. Ebihara, H. Hanaoka, T. Okumura and Y. Wada, "Interference Criterion for Coaxial-Fed Circular Dipole Array Antenna in a Borehole," IEEE Trans. Geosci. Remote Sens, vol. 50, no. 9, pp. 3510 – 3526, Sep. 2012.

[5] S. Ebihara, Y. Kimura, T. Shimomura and R. Uchimura, "Singlehole Borehole Radar Measurement with a Thin Directional Borehole Radar Sonde," Proceedings of the 7th International Workshop on Advanced Ground-Penetrating Radar (IWAGPR2013), Nantes, France, July 2-5 2013.