Foundation pile and cavity detection by the 3D directional borehole radar system, ReflexTracker

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Abstract* – In order to evaluate our developing 3D directional borehole radar system, ReflexTracker®, we carried out experimental studies on its capability to detect foundation piles in poor subsoil in the Tokyo area, and cavities beside a housing complex in Aichi Prefecture, central Japan. To evaluate foundation pile detectability, we took omni-directional and the directional borehole radar measurements in two boreholes (vertical and tilted at 60 degrees) near known concrete piles. We utilized existing drawings and specifications that well described the piles at the site such as their materials, structures, locations and depths, and conducted GPR and vertical differential magnetic surveys to confirm the exact locations of the pile heads. The measurements were successfully taken for both boreholes. The estimated 3D locations of the reflected points were in good agreement with the known pile locations, with an accuracy of 0.14 to 0.20 m from the pile for measurements with the vertical and the titled boreholes, respectively. For the cavity detectability evaluation, we collected core samples to check geological conditions and existing cavities estimated by drilling operations and N-values by SPT. The directional borehole radar measurements showed several significant reflected phases in a radargram and revealed the existence of the cavities corresponding to the drilling results obtained from 3D reflected points. As a result of the two experimental studies for foundation piles and cavity detectability of the ReflexTracker, we concluded that the system could be applied to civil-engineering issues in poor subsoil ground.

Index Terms—Directional borehole radar system, ReflexTracker, foundation pile location, cavity detection

I. Introduction

Borehole radar systems have been widely used for evaluating the presence and the bottom depth of existing foundation piles when rebuilding and for detecting cavities causing buildings to tilt or cracks to form in walls. Against a backdrop of insufficient construction management of foundation piles for apartment buildings in Japan, the borehole radar approach has been approved by the Japanese government as an appropriate technique to check the bottom features of existing piles.

We have been developing a new directional borehole radar system by attaching MEMS sensors for 3D attitude radar probe sensing and strengthening the system's 3D visualizing applications for locating buried objects in the field [1][2]. We used our 3D directional borehole radar system, ReflexTracker (hereafter, RT), to evaluate the system's ability to detect foundation piles and cavities in an alluvial plain.

To evaluate the ability of RT to detect 3D features of foundation piles, we conducted an experimental study at an old factory site on soft ground in an alluvial plain in the Tokyo area (Site A). Ground Penetrating Radar (GPR) and Overhauser magnetic gradiometer surveys conducted on the ground surface with existing work design drawings and documents revealed the exact locations of the tops of the three foundation piles at a depth of 0.9 m. Two drill holes (vertical and tilted at 60 degrees) were prepared to evaluate the system. The precision of the 3D reflected points was 0.14 m and 0.20 m from the foundation pile's surface for the vertical and the tilted borehole tests, respectively.

The other experimental study area was located on silty soil in Aichi prefecture in central Japan, where ground depressions had formed due to underground cavities created by old-time excavations of a peat layer (Site B). Two vertical boreholes were drilled close to the apartment building to detect surrounding cavities and to investigate geological conditions. The results showed that the estimated 3D reflection points were located at the self-settling depths revealed at the check-drilling sites, and some buried objects were detected in other directions.

This paper describes the high capability of the 3D directional borehole radar system to detect foundation piles and cavities through the two experimental studies at soft ground sites A and B.

II. The Directional Borehole Radar System

A. Radar system

We used the RT, a small (57mm) diameter directional borehole radar system with 3D sensing capability, in the experimental studies. The RT is a step-frequency radar system with a frequency band of between 5k and 500 MHz, which enabled us to calibrate the delay and attenuation of all cables in the radar system with a vector network analyzer (VNA). The directional-antenna probe was equipped with "Micro Electro Mechanical Systems" (MEMS) sensors to monitor the rotation, tilt angles and temperature of the probe.

This led to a precise estimation of the azimuth direction of the arriving waves, based on the arrival time difference in the time domain by six dipole array antennas. All the datasets acquired by the radar probe were transmitted to the surface equipment instantaneously via optical cable links. The surface equipment consisted of a surface control device, a personal computer and a portable VNA [1]. We also used a non-directional antenna probe in this system to observe relative permittivity.

III. FIELD EXPERIMENTS

In order to evaluate the RT, we conducted the following two experiments for foundation pile and cavity detection with the directional borehole radar. Both of the test sites (A and B) were underlain by wet clay and silty sand. The following is a description of the results of the experimental studies.

A. Foundation pile detection (site-A)

Site A is a flat, asphalt-covered site of a demolished factory in the Tokyo metropolitan area. The design drawings for the dismantled factory buildings show that there were 350mm-diameter precast concrete piles, made in 1985, existing to a depth of 22 m at the test site. We prepared several drill holes with polyvinyl chloride pipe casing with an inner diameter of 67 mm at the site. The test site is located in poor subsoil composed of silty clay and sandy gravel layers with a water level of GL-1.1 m whose N-values were shown by the Standard Penetration Test (SPT) to be less than 5 to a depth of 21.5m. The soil basement at the depth of 22 m is a gravel layer with N-values of more than 30.

GPR and magnetic gradiometer surveys

We conducted a GPR survey using the GSSI's DF utility scan with two central frequencies of 300 MHz and 800 MHz and a magnetic survey using a GEM GSM-19 Overhauser magnetic gradiometer with vertical gradient spacing of 1m and a magnetic resolution of 0.01nT in order to confirm the locations of the tops of the foundation piles. Gradiometers can offer a high degree of immunity from diurnal and minor magnetic storm activity in ambient magnetic fields; they can also enhance near-surface, small or weakly magnetic anomalies due to the vertical gradient of the magnetic field.

The GPR measurements were carried out along orthogonal survey profiles in a rectangular zone of 10 m by 20 m. The intervals of the survey profiles were mainly 0.5 m at the site and 0.25 m around the foundation piles shown in the design drawings of the dismantled factory buildings. Fig. 1 shows the strength distribution of reflected radar waves from depths ranging from 0.8 to 0.9 m in the western part of the site. The white circle shows the location of the targeting foundation pile shown in the design drawings. We can see a strong reflection showing a red spot 0.15 m away from the white circle.

Figure 2 shows magnetic anomalies estimated by the analytic signal processing using a gradiometer measurement dataset along the same profiles of the GPR survey. Nabighian [3][4] developed the notion of analytic signals or energy envelopes of magnetic anomalies. An important characteristic of these analytic signals is that they are independent of the direction of magnetization of the source. The amplitude of the analytic signals is simply related to the strength of magnetization. The significant magnetic anomaly shown as the large red spot by the white circle in Fig. 2 corresponds to the top of the foundation pile.

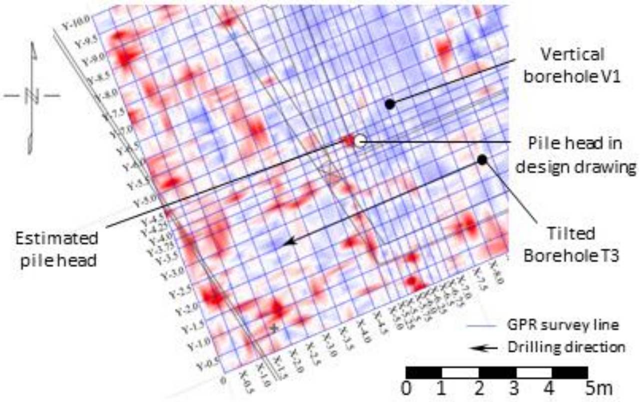

Fig. 1. Strength distribution of radar waves reflected from depths of 0.8 to 0.9m.

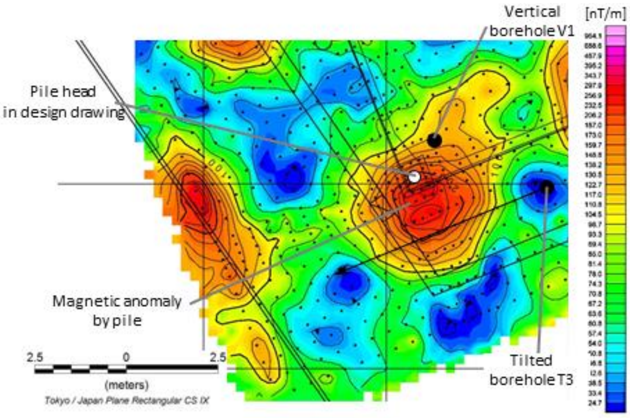

Fig. 2. Analytic signal of vertical gradient of the magnetic field.

RT application to a vertical borehole V1

We took RT measurements of the vertical borehole V1 at a depth of 27 m located 1.2 m away from the foundation pile. The measurement depth interval was 0.1 m.

First, a non-directional antenna probe was used to estimate relative permittivities and to check reflected waves from the pile. Observed signals were normalized by the maximum amplitude at each depth (Fig.3), and the depths are shown at feeding points of the receiver antenna (Rx). The distance between the transmitter antenna (Tx) and Rx was 1.89 m for the non-directional borehole probe. We can see similar phases around 40 ns to a depth of about 22 m. The turbulent direct waves appeared near the bottom of the borehole whose direct wave arrive earlier than those of the similar phase are affected by gravel basement layer with lower relative permittivity.

We assumed that the similar phases were waves reflected from a buried pile that was parallel to borehole V1. The estimated average relative permittivity was 24, and was used to calculate 3D reflected points.

Then, we used the directional borehole radar data to estimate 3D reflected points from the foundation piles. The estimated 3D reflected points are shown with the actual foundation positions in Fig.4. The reflected points occur close to the pile's position to a depth of around 22 m in the 3D view of Fig.4 (right). Since the other reflected points near the bottom were located away from the pile, the bottom depth of the pile was estimated to be about 22 m, corresponding to the description in the design drawings for the dismantled factory building. The averaged error distance from the pile's surface to the reflected points was 0.14m.

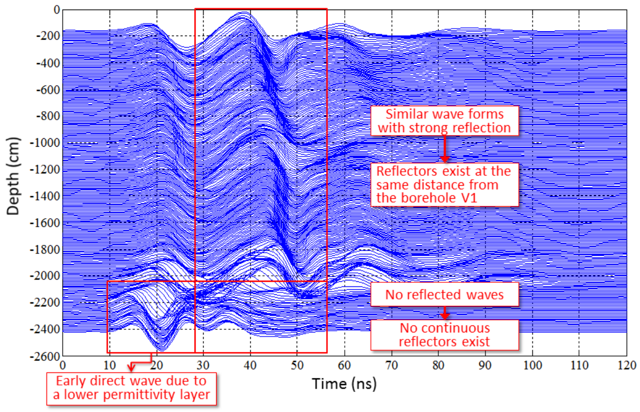

Fig.3 Similar reflected waves down to a depth of about 22 m and turbulent waves around the bottom.

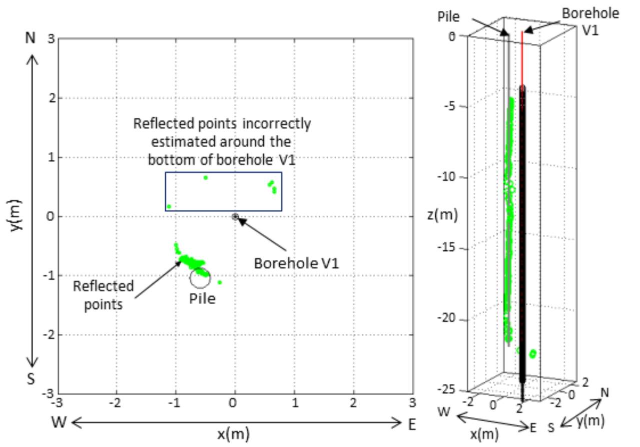

Fig. 4. The 3-D reflected points with the pile's actual position estimated from RT measurements of the vertical borehole V1.

RT application to a tilted borehole T3

We took measurements for the RT data in the tilted borehole with an inclination of 60 degrees and a length of 12 m, which was located at 1.7 m away from the foundation pile. The measurements for the borehole radar dataset were taken at intervals of 0.1 m.

Figure 5 shows the amplitudes of a normalized radargram of the borehole T3 after Auto Gain Control (AGC) processing. The phase with a large amplitude around 20 ns is a direct wave. Another significant phase is a wave group showing hyperbolic curves at times ranging from 75 to 80 ns. The measurement configurations of the tilted measurement borehole T3 and vertical pile were twisted around each other, when the centers of the Rx and Tx antennas' feeding points were closest to the foundation pile at a depth of around 4.0 m. Since the arrival time to the antennas was fastest at 4.0 m and slower above and below that depth, the farther the distance was between the center of the feeding points and the pile, the more hyperbolic were the shapes of the phase of the reflected waves. This indicates that the phase would be waves reflected from the pile.

Calculated 3D reflection points plotted by small green dots with the pile's position in a planar view and a 3D view are shown in Fig.6. The estimated reflected points occur near the green circle in the planar view and the cylinder in the 3D view representing the pile. The average error distance between the pile's surface and the obtained reflected points is about 0.2 m.

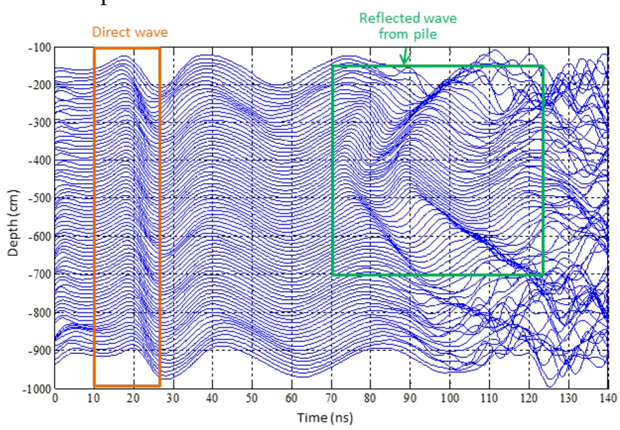

Fig. 5. Strong reflection obtained at tilted measurement borehole T3 (central frequency of bandpass filter: 100MHz; bandwidth: 100MHz).

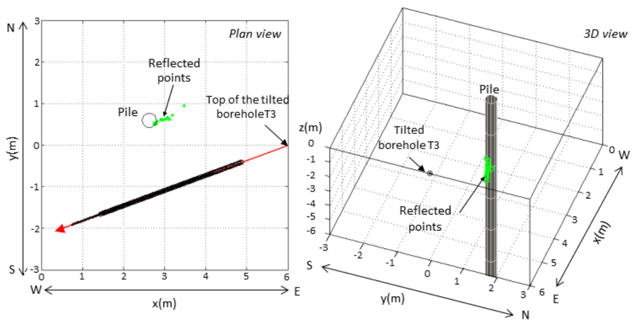

Fig. 6. The 3-D reflected points with the pile's actual position estimated from RT measurements in the tilted borehole T3.

B. Cavity detection (Site B)

Site B is located on silty soil in Aichi prefecture, on a ground depression caused by underground cavities created by the old-time excavation of a peat layer [5]. A vertical drill hole N1 for measurement was made beside the apartment building to explore surrounding cavities. The N1 borehole was drilled to 16m with a casing inner diameter of 67 mm. Site B was located in poor subsoil composed of silt, silty sand and some lignite with a water level of GL-8 m whose N-values were shown to be less than 5 by the SPT to a depth of 12.2m of the borehole N1. The N-values jumped up to > 15 at a depth of 13m. Another core-sampling borehole, S1, was drilled 1m south of the borehole N1 (Fig.7).

Fig. 7. Study Site B for cavity detection in Aichi Prefecture, Japan.

RT application for cavity detection

A radargram detected by the dipole antenna element 1 of the directional array antennas (Fig. 8) shows complex features. Also in this case, the depth axis is shown at feeding points of the receiver antenna. At depths of 6 to 7 m, the direct waves arrived earlier than those of other depths, suggesting that there may exist a cavity with lower relative permittivity. Since the length between Tx and Rx was 1.48 m for the directional borehole probe, it would improve the accuracy of the depth of the arriving direct waves by adding half of that length, 0.74 m, to the depths. We could estimate that the earlier direct waves arrived at a depth range of 6.7 to 7.7 m, and were located just above the water level.

Several interesting phases labeled from Ph1 to Ph3 can be seen in the radargram. Ph1, showing a hyperbolic shape, appears in the depths corresponding to the earliest direct wave's arrival. The other two phases, Ph2 and Ph3, appear at levels lower than the water level.

Figure 9 presents the 3D reflection points estimated from the phases Ph1, Ph2 and Ph3 on the E-W and S-N sections. The reflection points of Ph1 exist above the water level, corresponding to the self-settling zone in borehole N1. The other reflection points, i.e., Ph2 and Ph3, were below the water level.

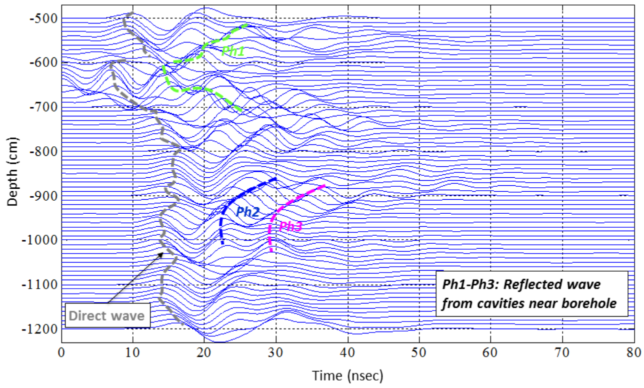

Fig. 8. Complicated radargram with several reflection waves.

The 3D reflection points are plotted on a planar view with the geological column of the core-sampling borehole S1 in Fig.10. The reflected points of Ph3 concentrate near borehole S1 and the depths correspond to the self-settling zone of S1. On the other hand, the plotted Ph1 reflector is located near borehole N1. Since the distribution pattern is linear, it suggests that the phases of Ph2 was wave reflected from buried objects or one of the building's foundation piles and were not from unknown cavities.

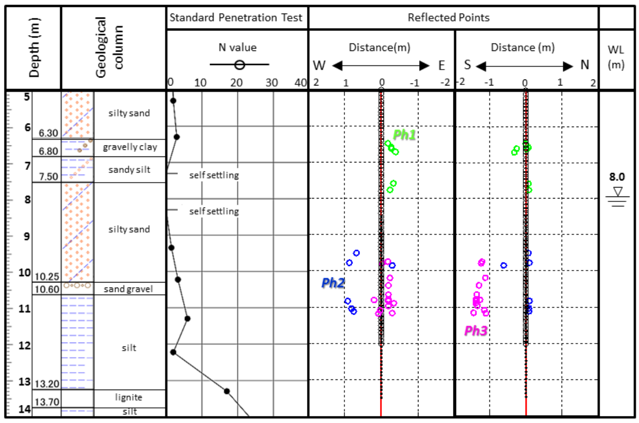

Fig. 9. Reflected points on two sections and geological column with N-values of the measurement borehole N1.

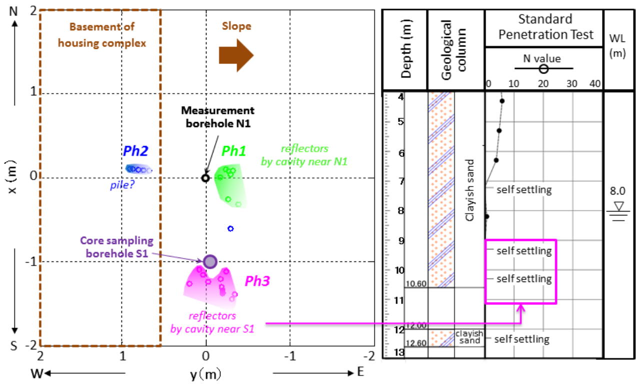

Fig. 10. Planar view of reflected points with geological column and N-values of the core sampling borehole S1.

IV. Conclusions

We conducted experimental studies for the 3D Directional Borehole Radar system, ReflexTracker (RT), to evaluate its ability to detect buried objects and cavities in subsoil.

For foundation pile detection, we conducted RT surveys in two boreholes (vertical and tilted at 60 degrees) that were 1.2 to 1.7 m, respectively, away from the pile at Site A. Directional borehole measurements taken with an interval of 0.1m revealed that the average error distance between the estimated 3D reflected points and the actual pile position was 0.14 for the vertical borehole (parallel configuration with the target) and 0.2m for the tilted borehole (twisted configuration). This experimental study showed that the 3D directional borehole radar system, RT, has a high capability for detecting foundation piles.

For cavity detection, the RT survey was carried out on silty and silty-sandy soil, containing some lignite, on a ground depression caused by underground cavities that were created by old-time excavation of a peat layer. A vertical drill hole close to an apartment building was used to detect cavities around the drill hole. Some of the estimated reflectors occurred close to the self-settling layers existing in the boreholes, suggesting that it may be possible to detect cavities. In future, we will continue to conduct experimental studies and modelling to bring this method into practical use.

Acknowledgment

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