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GROUND SURVEY BASED ON THE DISTRIBUTION OF SURFACE WAVE VELOCITY AND ELECTRICAL RESISTIBILITY

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ABSTRACT: Geophysical exploration, which can explore the distribution of material properties underground, has, for less than the last half a century, been applied for prospecting groundwater and bedrock. Though simulation techniques have improved with greater sophistication of the constitutive model for soil material, comprehension of current soil conditions is important for accurately predicting the behavior of earth structures. Therefore, the importance of geophysical exploration is growing. Soil parameters are indirectly identified from physical parameters, such as wave velocity, electric conductivity and so on. In geophysical exploration, calibrating physical parameters with necessary soil parameters is required for individual soil material and has thus prevented the application of geophysical exploration at the site level. In this study, surface wave and electric prospecting were conducted at a site first investigated circumstantially by borings and other soundings. Then, the applicability of surface wave and electric prospecting were validated through their comparison. Next, geophysical explorations were conducted on a large-size embankment. Consequently, the applicable scope of this type of exploration was demonstrated, proving its applicability for geotechnical engineering sites.

Keywords: Geophysical Exploration, Surface Wave Velocity, Electrical Resistibility, Embankment

1. INTRODUCTION

Recently, a constitutive model for soil has improved, and numerical computing techniques have become more sophisticated (e.g. Sugiyama et al., 2016, Noda et al. 2016 and Oka et al., 2019). Therewith, numerical simulation has become more reliable in geotechnical engineering and has been used for designing and maintaining earth structures. When we conduct numerical simulation, the initial condition is needed. In the case of an existing earth structure, the current condition within the earth structure is the initial condition for simulation. Therefore, ground surveys, such as borings and soundings, are important. However, these ground surveys cannot be conducted at a fine scale due to economic constraints. Geophysical exploration is effective for knowing material properties of the ground through non-destructive inspection to develop in-depth cross-sectional information. On the other hand, in geophysical exploration, necessary soil parameters, such as the N-value and soil moisture, have to be converted from elastic wave velocity and electric resistibility. These material properties are influenced by other soil parameters. Consequently, geophysical exploration is only used as a supplement.

In this study, surface wave and electric prospecting were conducted in ground first surveyed by borings and various soundings for calibration. Based on the calibration, geophysical exploration techniques were applied to a large-size embankment.

2. GEOPHYSICAL EXPLORATION

2.1 Surface wave prospecting

When the ground is hit by a hammer, the surface wave, called a Rayleigh wave, is transmitted along the ground surface. A Rayleigh wave has more vertical vibration and 0.9 to 0.95 times velocity of a

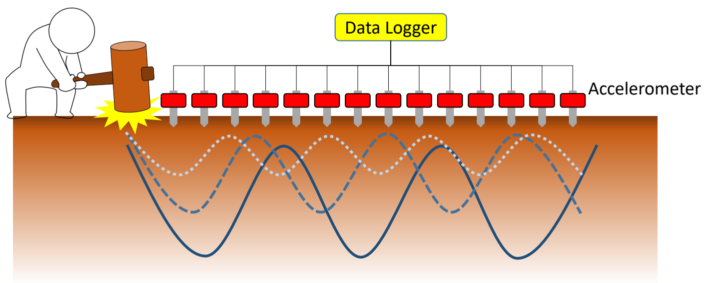


Fig.1 Surface wave prospecting

Photo 1 Surface wave prospecting

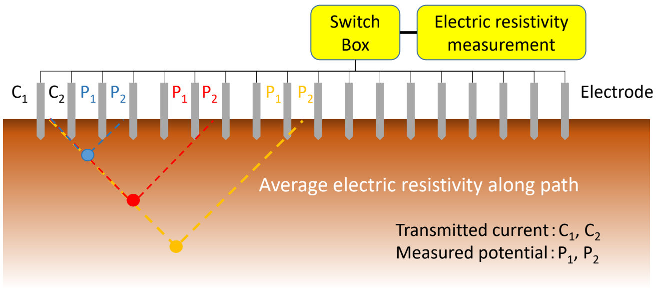


Fig.2 Electric prospecting

Photo 2 Electric prospecting

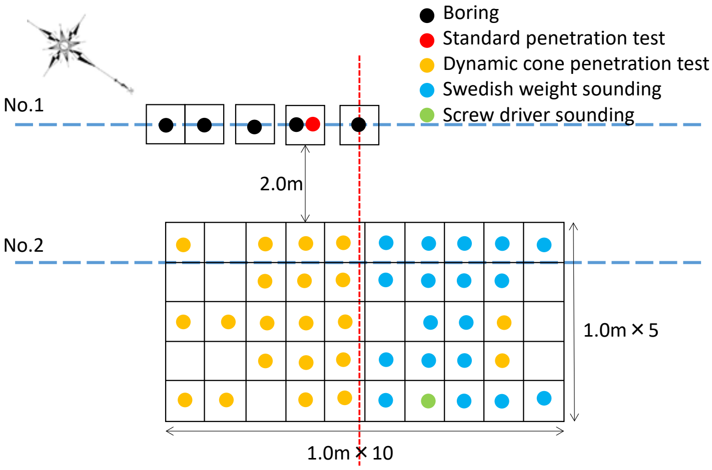


Fig.3 Location of borings and soundings

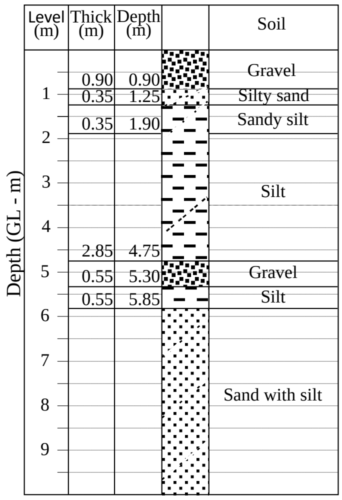


Fig.4 Stratigraphic column

shear wave. Since the energy of vibration occurs mostly at the ground surface and dampens with depth, shear wave in shallower depth than wavelength can be measured. With surface wave prospecting, we can know the distribution of shear wave velocity within the ground by catching waves with accelerometers aligned on the ground surface (as in Figure 1 and Photo 1). All wave shapes measured by each accelerometer are applied to frequency analysis, and the relationship between phase velocity and frequency are obtained (Park, 1999). It is said that the shear wave velocity correlates well with the stiffness of soil material and that it is applicable for estimating ground properties. Various correlation equations between the shear wave velocity and N-value have been proposed (Japan Road Association, 2012). Imai and Tonouchi (1982) proposed the following equation.

$$N = \left(\frac{V_s}{97}\right)^{\frac{1}{0.314}} \tag{1}$$

Here, N is the N-value obtained from the standard penetration test, and V_s is shear wave velocity (m/s).

2.2 Electric prospecting

The potential response on the ground surface is generated by passing an electric current through the ground. In electric prospecting, the distribution of electric resistibility can be identified from this potential response (as in Figure 2 and Photo 2). The apparent electric resistibility can be calculated by attenuation from the potential difference between transmission electrodes (C_m, C_n) to the potential difference between receipt electrodes (P_m, P_n). Here, apparent electric resistibility means average electric resistibility along the path from transmission electrodes to receipt electrodes. The distribution of true electric resistibility can be obtained by back analysis (Shima, 1997). The finer electrodes are aligned, the higher the resolution of the electric resistibility distribution that can be obtained. There are some methods to align electrodes (The Japanese Geotechnical Society, 2018) and we have to select according to the intended use. The obtained electric resistibility reflects porosity, soil moisture, mineral content, temperature and so on. Electric resistibility is said to correlate to soil moisture in homogeneous material ground.

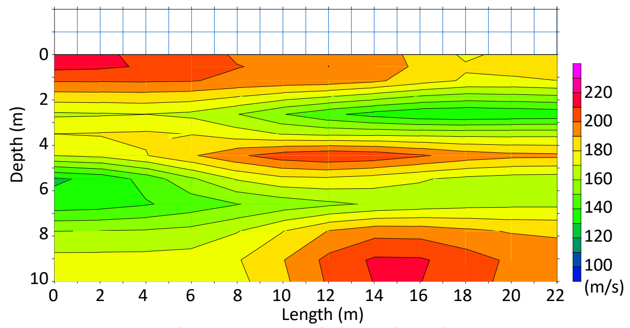


Fig.5 Shear wave velocity distribution (Line No.2)

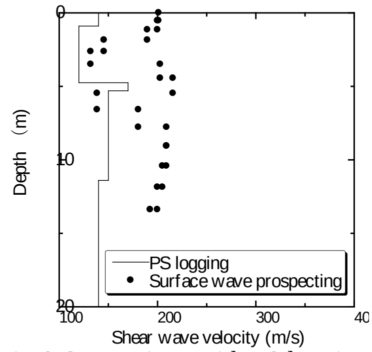


Fig.6 Comparison with PS logging

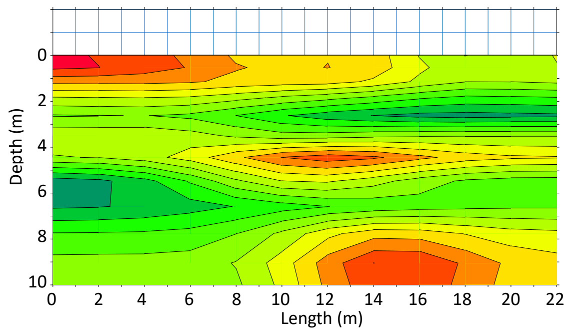


Fig.7 N-value distribution (Line No.2)

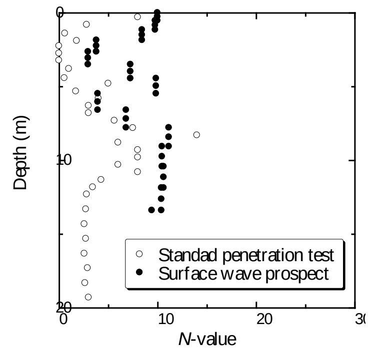


Fig.8 Comparison with a standard penetration test

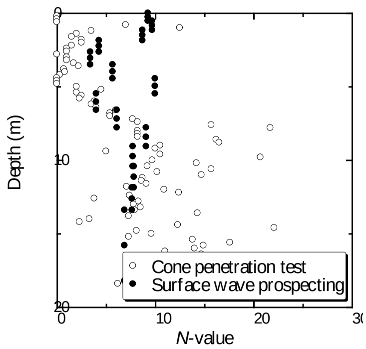


Fig.9 Comparison with a cone penetration test

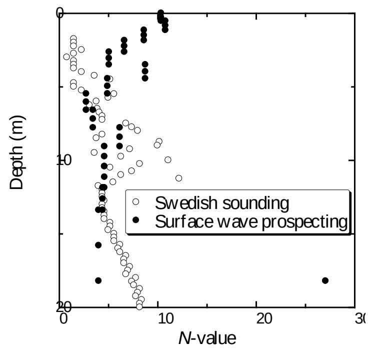


Fig.10 Comparison with Swedish sounding

3. COMPARISONS OF GEOPHYSICAL EXPLORATION WITH BORINGS AND SOUNDINGS

To verify the results from geophysical exploration, surface wave and electric prospecting explorations were conducted at a centrally located site in Osaka city. There, detailed ground surveys, including five borings and various soundings, were conducted. Figure 3 shows the locations of the ground surveys. Here, the dynamic cone developed by some companies was included and their specifications are various. Both the surface wave and the electric prospecting were conducted along survey Lines No.1 and No.2 shown in Figure 3. Figure 4 shows the stratigraphic column obtained from one boring. It indicates a thick alluvial clayey soil layer under an alluvial sandy soil layer near the ground surface. Diluvial sand and clay layers repeatedly appear under the alluvial layer, and this ground exhibits West Osaka's typical plain stratigraphy. The groundwater level appears around 2.0m deep.

Figure 5 shows shear wave velocity distribution obtained from surface wave prospecting along Line No.2. The green areas indicate small wave velocity and low stiffness. On the other hand, red areas indicate relatively higher stiffness. In this site, PS logging was conducted at one boring hole. The results of PS logging and surface wave prospecting are

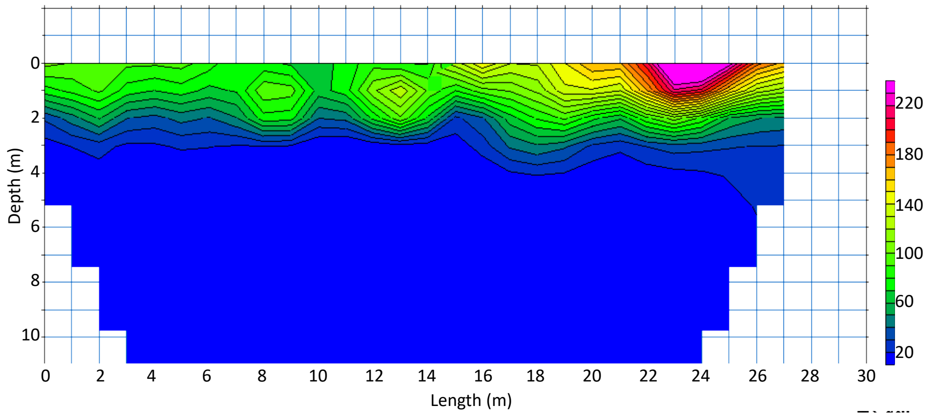


Fig.11 Electric resistibility distribution with Pole-Pole Array (Line No.2)

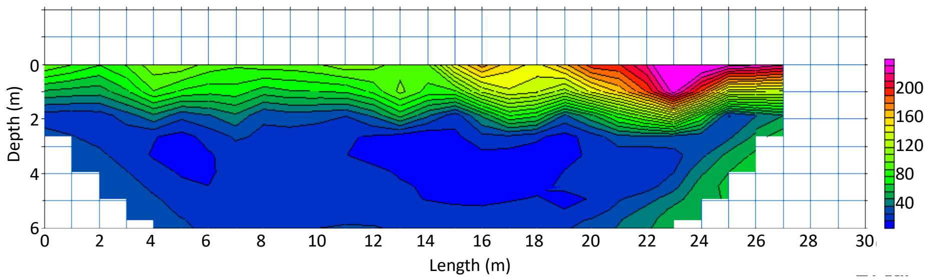


Fig.12 Electric resistibility distribution with Dipole-Dipole Array (Line No.2)

compared in Figure 6. A similar tendency can be seen near the ground surface. It is generally said that surface wave prospecting is applicable until 15m deep. Moreover, the results from PS logging show 2 to 3 times of the results from surface wave prospecting. This is because the shear wave velocity can be directly obtained from PS logging, while shear wave velocity is converted from Rayleigh wave velocity in surface wave prospecting. In soundings, the ground stiffness is expressed by the N-value. Figure 7 shows N-value distribution calculated from Figure 5 by equation (1). Figures 8, 9 and 10 show comparisons of the N-value expressed in Figure 7 with the N-value obtained by each of the soundings. They show good agreement. However, as seen in the comparison with PS logging, some difference between surface wave prospecting and soundings appear, and surface wave prospecting is applicable only at depths shallower than 10m.

In electric prospecting, measurable area and resolution is dependent not only on electrode separation but also on the array of transmission and receipt electrodes. Here, electrodes were placed 1.0m apart. Both the two-electrode method (Pole-Pole Array) and the four-electrode method (Dipole-Dipole Array) were applied as electrode alignment. It is said that relatively deeper ground can be explored with Pole-Pole Arrays and that Dipole-Dipole Arrays show higher resolution. Moreover, when we apply a Pole-Pole Array, two reference potential points are needed, and two electrodes are placed at 5 times the maximum measurement length apart from the measurement line. Figures 11 and 12 show the electrical resistibility distribution obtained from the Pole-Pole Array and the Dipole-Dipole Array, respectively. The bluer area shows lower electrical resistibility. In this site, the groundwater level is about 2.0m deep. The contour of 40Ω•m electrical resistibility corresponds to the groundwater level. As detailed before, the electrical resistibility depends not only on soil moisture but also on mineral and ionic contents. However, differences in soil properties apparent deeper than the groundwater level in Figure 4 cannot be identified. We can say that soil moisture is a dominant factor for electrical resistibility in this site. Moreover, though the water pressure distribution, indicating existence of perched groundwater, was found in borings, it cannot be found in the electrical resistibility distribution. The difference between Figures 11 and 12 is not large, and both arrays are applicable for the site condition.

Though geophysical explorations, surface wave and electric prospecting exhibit some differences from soundings, they show good agreement qualitatively. Because of this, we can say that they are effective for comprehensively characterizing

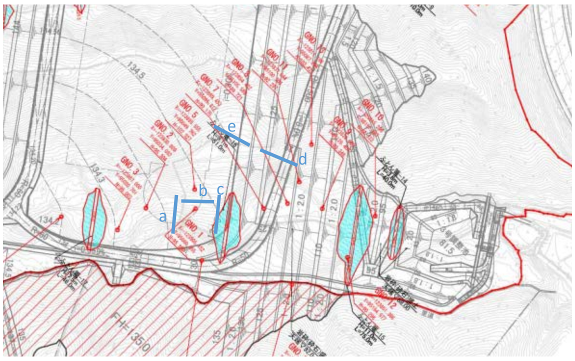


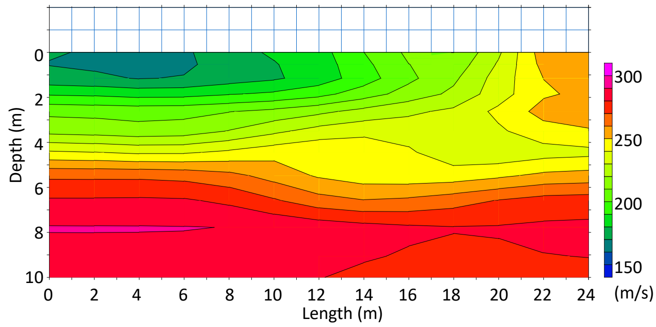
Fig.13 Construction site and exploration lines

relatively shallow ground.

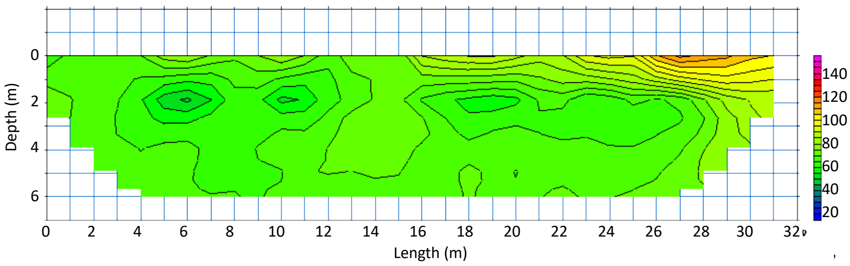
4. APPLICATION OF GEOPHYSICAL EXPLORATION FOR EMBANKMENT

To test the applicability of geophysical exploration to embankment, surface wave and electrical prospecting were conducted at a large earthmoving construction site. Figure 13 shows the geography of the site and the locations of geophysical exploration. Lines a, b and c are located in what was originally a valley area and surrounding a sand basin for construction. In this area, a 40m high embankment was constructed. Lines d and e are in a cut area and on the construction site access road. The surface wave prospecting was conducted in September 2018, and the electric prospecting was conducted in November 2018. The embankment was built up to 5m high around the sand basin at the time of the surface wave prospecting. As the construction progressed afterwards, the embankment had reached 10m high at the time of the electric prospecting. Figures 14 and 15 show results of geophysical exploration in Line a and c, respectively. Redder areas indicate that higher shear wave velocity and higher stiffness exists at depth. A shear wave velocity of 250m/s can be converted to an N-value of 20. If this is regarded as the boundary between embankment material and original ground, then it corresponds to about 5m depth for both Lines a and c, showing good agreement with the actual construction process. Moreover, in this site, the valley is inclined from the left to the right side of Figure 13. Therefore, the embankment of Line a is thicker than that of Line c, and this difference is captured in the results of surface wave prospecting. Considering the construction process, the exploration area for the electric prospecting, shown in Figure 14 (b) and 15 (b), indicate an embankment area. Kawai et al. (2017) monitored soil moisture distribution of embankment and clarified seepage behavior within embankment. They said that water contained in embankment material redistributes due to potential head difference within embankment after construction and that it finally forms the phreatic surface at the bottom of the embankment. The electrical resistibility shown here indicates the redistribution process of water within embankment. The difference in electric resistibility between Lines a and c can be regarded as the difference in time elapsed during construction.

Figure 16 shows the results of geophysical exploration conducted in Lines d and e. This area is a cut slope. Therefore, fairly high shear wave velocity

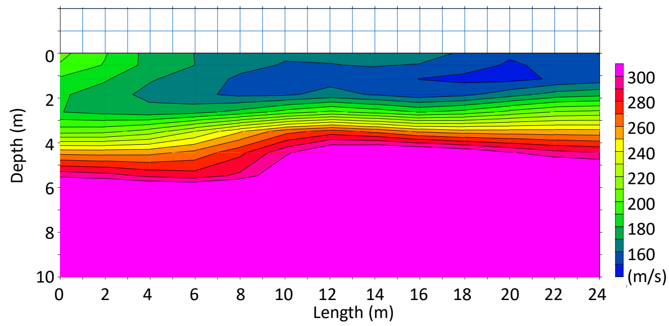


(a) Shear wave velocity distribution

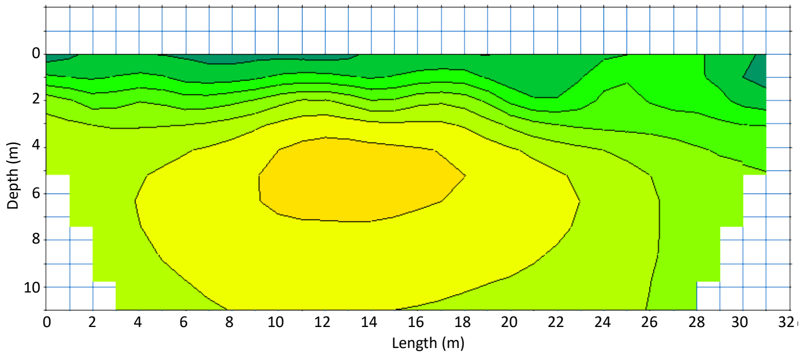


(b) Electrical resistibility distribution

Fig.14 Geophysical exploration (Line a)

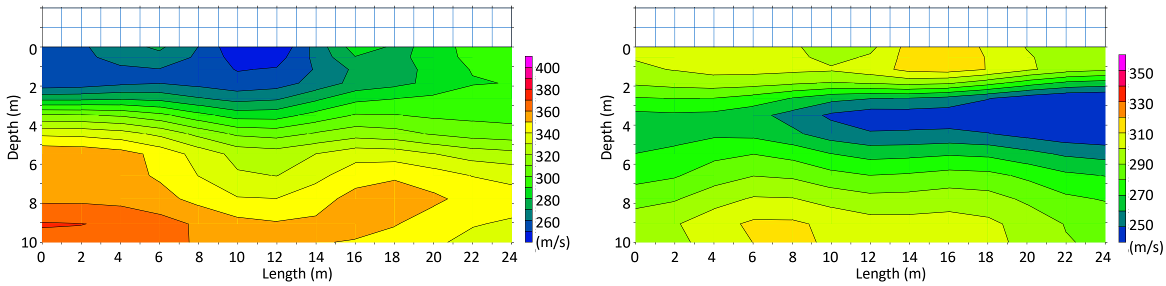


(a) Shear wave velocity distribution

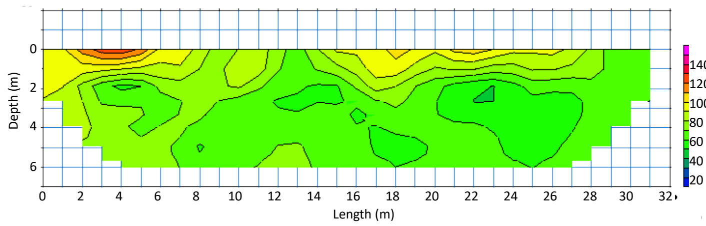


(b) Electrical resistibility distribution

Fig.15 Geophysical exploration (Line c)



(a) Shear wave velocity distribution



(b) Electrical resistibility distribution

Fig.16 Geophysical exploration (Line e: left and d: right)

distributions are seen. The minimum shear wave velocity in the exploration area is 250m/s, and this corresponds to the boundary between embankment and original ground, as shown in Figure 14 and 15. The results of electric prospecting illustrate the tendency of higher electrical resistibility at depth. This tendency is more apparent than in Lines a and c.

Consequently, it appears that geophysical exploration can express the ground conditions of the construction process well, and it is applicable for ground surveys.

5. CONCLUSIONS

In this study, investigating the applicability of geophysical explorations to embankment, surface wave and electric prospecting were conducted at a site investigated in detail by borings and various soundings. In addition, applicability was also investigated at a huge earth moving construction site.

Consequently, the following conclusions were determined:

(1) Comparing the results of geophysical exploration with borings and soundings found good agreement. However, limits in the measurable area of the geophysical exploration were discovered. In the case of surface wave prospecting, the applicable limit is about 10m depth from the ground surface.
(2) Electric prospecting shows good agreement with the groundwater level. However, it only indicates soil moisture and cannot resolve pressure differences within saturated ground, such as those caused by perched groundwater.
(3) Geophysical exploration can express the process of embankment construction.

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