Case study of three-dimensional geotechnical evaluations for tunnel design and construction by helicopter-borne geophysical survey

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SUMMARY

Helicopter-borne electromagnetic surveys using a grounded electric dipole source was conducted to delineate resistivity structures in deeper parts of a tunnel construction site in Hokkaido pref., Japan. The survey area is mainly composed of Cretaceous sedimentary rocks, with serpentinite dykes intruded into the sedimentary rocks. The surveys covered the tunnel site and its surroundings, as the three-dimensional information, to estimate the distribution of sediment rocks and serpentinite. As a result, the resistivity structure of deep sections delineated the serpentinite and their distribution, which are useful in understanding potential geotechnical issues when excavating a tunnel.

Keywords: case study, civil engineering, tunnel construction, helicopter-borne geophysical survey

INTRODUCTION

Refractive seismic explorations are frequently used for the survey of tunnel sites in Japan. However, the penetration depth is not always sufficient when the overburden is large. In such situations, two-dimensional electric resistivity sounding and the controlled source magneto-telluric method are more suitable to detecting rock types, groundwater distributions and alternate zones. However, it is difficult to perform these surveys on steep slopes and in deep forests in mountainous areas due to safety and environmental issues.

On the other hands, airborne geophysical surveys, such as the helicopter-borne electromagnetic (HEM), method, gives us three-dimensional subsurface structures in large and inaccessible areas. Therefore, they have been used recently to investigate large-scale landslides (Nakazato and Konishi, 2005) and in monitoring active volcanoes (Kaieda et al., 2005), as well as in mineral explorations (Smith et al., 2005).

We carried out a grounded electrical source airborne transient electromagnetics (GREATEM) survey to delineate resistivity structures at a long tunnel construction site and discussed in the issues encounter tunnel construction planning. GREATEM has been first proposed by Mogi et al., (1998) and developed to apply survey in volcano (Mogi et al., 2009). These HEM surveys are useful to obtain data three dimensionally at equal spacing sites. This feature is good condition to construct three-dimensional structures accurately.

OUTLINE

The survey area is situated in a mountainous region of northern Hokkaido pref., Japan. A new national highway road has been planned in this area to avoid slope disasters on the present route. The total length of the planned tunnel is 2.7 km, and the maximum overburden is estimated at 380 m. The survey area is mainly composed of Cretaceous sedimentary rocks extending north to south and is penetrated by serpentinite. The serpentinite is mostly distributed in the central part of the tunnel route, and mudstone and sandstone are distributed in the eastern and western sides, respectively. Excavating through the serpentinite zone would raise various geotechnical issues. Squeezing is one of the most serious risks involved in tunnel construction in serpentinite zones. Therefore, it is very important, for safe and efficient tunnel construction, that the distribution of serpentinite be detected.

We carried out a GREATEM survey to delineate a resistivity structure and interpreted the geological structures of the tunnel construction site. We also measured electrical resistivity of some types of rocks which were sampled from drilled core, and compared these data with electrical logging results. This paper describes the feasibility and effectiveness of this survey to provide geotechnical information for tunnel sites.

METHOD

The total length measured using GREATEM was approximately 50 km. With this technique, a timevarying current was transmitted to the ground as the signal source via a linear cable set on the ground surface, and three components of the secondary magnetic field induced in accordance with the ground resistivity were recorded using helicopter-mounted devices in called bird. The magnetic field responses were recorded for both the current 'off' as well as the current 'on' time. The waveforms were digitized through a 24-bit AD converter at a rate of 80 μs, and 10,000 sets of data were recorded during one cycle (0.8 (s)) in this survey. The sensor altitude was monitored using a GPS device attached to the bird, and the sensor height above the ground was obtained by taking the difference between the sensor altitude and the topographic elevation reading from a 50-m-grid digital elevation map.

The data processing and its descriptions are movement correction, coordinate transformation, removing local noise, data stacking and inversion. A movement correction that minimizes the noise due to movement of the magnetic sensor in the geomagnetic field was made using a response function relating to variations in the recorded magnetic field and magnetometer movement, as monitored by a gyro. The transformation of magnetic field components from bird-based coordinates to geographical coordinates was based on directional sensor data. The correction was made using a tri-axis orthogonal coordinate transformation. To cancel out stationary commercial noise with frequencies of 50 Hz or 60 Hz, two transient curves induced by opposing current directions were stacked in the reverse direction. The helicopter moved at 54 km/h (15 m/s) and 97 km/h (27m/s) along the southern lines and the northern lines in this survey. Six cycles of stacked data (4.8 (s) data), covering 72 m and 130 m, respectively, were used as one data set for the inversion.

After the above corrections were made, the transient response was inverted to a resistivity structure, assuming a horizontally layered structure. The inversion was made by comparing field data with theoretical responses. The inversions were made at 860 sites where we obtained clear transient responses after the above processing. The RMS errors in the inversions were within 10%.

RESULTS

Electrical resistivity of rocks

Figure 1 shows the electrical resistivity of some rock types sampled by drilled core under normal conditions. Among the serpentinites, the massive type showed the highest resistivity value, followed by foliated and clayey types in this order. Regarding sedimentary rocks, the resistivity values of sandstone and green stone were higher than those of mudstone. The difference in electrical resistivity between hard massive serpentinites and other rocks including clay minerals was estimated to be approximately ten-fold.

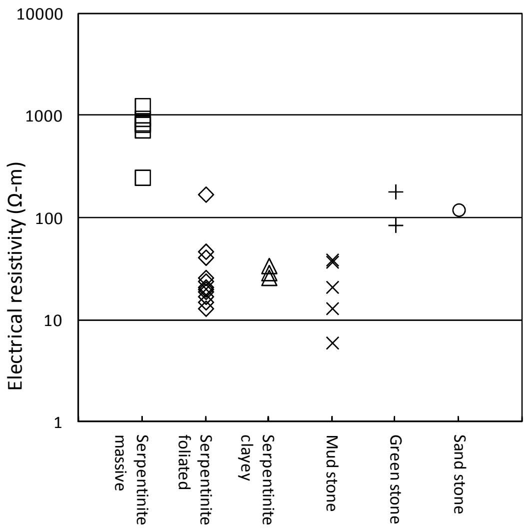

Figure 1. Electrical resistivity of rocks.

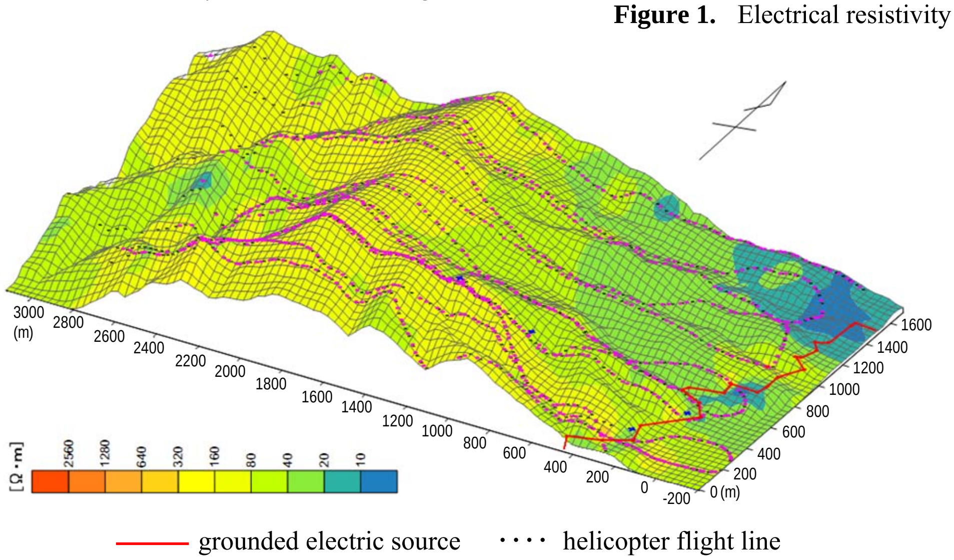

Figure 2. Electrical resistivity distribution of tunnel site surface.

Electrical resistivity distribution

Figure 2 shows the electrical resistivity distribution along the flight lines of tunnel site surface. The resistivity structures were obtained by one-dimensional inversion assuming a horizontal multi-layered structure at each point. The one-dimensional resistivity structures were combined into a two-dimensional structure along the section. The plan views of the resistivity distribution at depths of surface and tunnel line were plotted by interpolation of the resistivity structure. Relatively low-resistivity zones were seen in the shallower sections of the north-eastern part of the survey area.

Figure 3(a) shows the electrical resistivity slice of depth 300 m. The relatively low-resistivity zones were seen in the sections of the eastern part, they also appeared in the shallower sections in the north-eastern part as shown in figure 2. On the other hand, relatively high-resistivity zones were distributed on the western side and extended from north to south in the central part of the of the tunnel elevation.

Figure 3(b) shows the electrical resistivity profile of tunnel line. The electrical resistivity in this profile includes information on the electrical resistivity along the surrounding as the three-dimensional information. Relatively high-resistivity zones were mainly seen from the surface layer to a depth of 100 m. Although relatively low-resistivity zones were seen in the deeper section of profile of tunnel line, they also appeared in the deeper sections in the western side of tunnel line.

The survey area is formed mainly of mudstone, sandstone and serpentinites. It is thought that the distribution of relatively low-resistivity zones on the eastern side of the survey area suggests the presence of wet mudstone and clayey soil and that the distribution of relatively high-resistivity zones in the central and western parts indicates the presence of sandstone and massive serpentinite. The tendency to such as electrical resistivity is similar to the tendency to the electrical resistivity of the bore-core rock samples.

Comparison of geological properties and resistivities

Figure 4 shows the result of electrical logging by tunnel constructor. Relatively high-resistivity are distributed in the shallower section at depths of surface to 50 m and that relatively low-resistivity zones are distributed in the deeper section at depths of 50 m to 295 m. As a result of geological drilling in the central part of the tunnel, shown in Figure 3, two types of serpentinite were confirmed: one type that consists mainly of massive and brecciated forms, documented as shallower part and a second type that shows high ratio of the foliated form

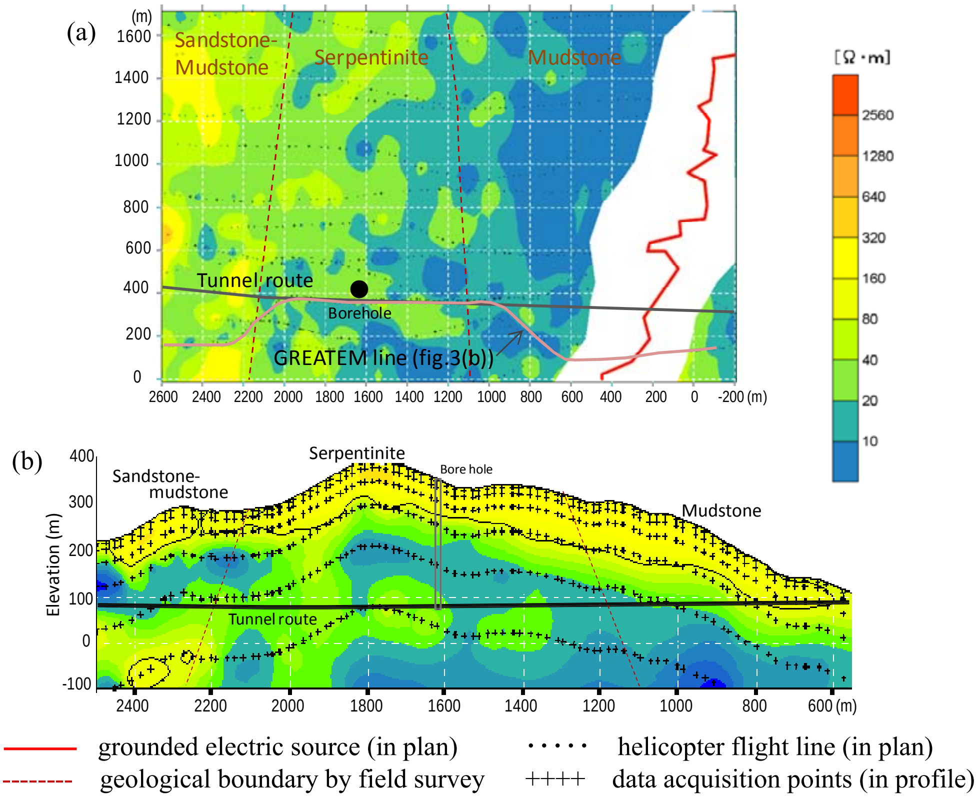

Figure 3. Electrical resistivity slice of depth 300 m (a) and profile of tunnel line (b).

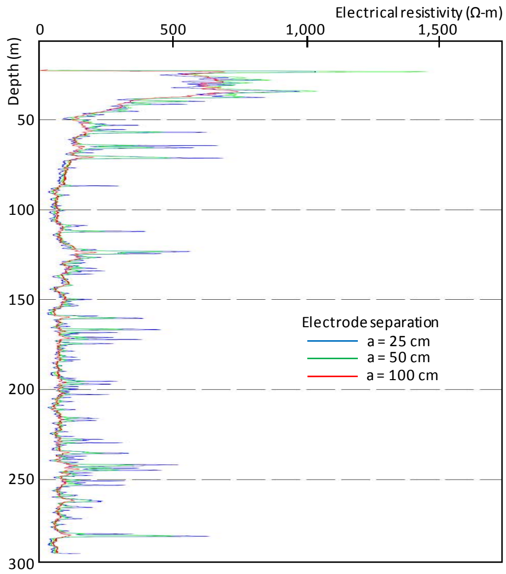

Figure 4. Results of electrical logging.

(partially clayey), documented as deeper part. The results of these surveys revealed that the electrical resistivity corresponds to the distribution of the type of rocks. This tendency is also similar to results of electrical resistivity of the bore-core rock samples. The cause with a high resistivity along shallow is not only influence of type of rocks but also could be presumed existence of many cracks and an unsaturated zone.

DISCCUSIONS

Based on the GREATEM results, shown in Figure 3, the 80 ohm-m layer is distributed at depths of 50 m to 100 m from the surface. At the tunnel level, low-resistivity zones cover the area from the survey point to between 600 m and approximately 1,300 m, and from there to the west, high- and low-resistivity mixed layer zones are present. At a survey point of at least 1,900 m to 2,100 m, relatively high-resistivity zones are present. It is estimated that low-resistivity zones consist of a clayey layer, weak foliated serpentinite, mudstone, and alternating layers of sandstone and sandstone-mudstone. The massive and foliated serpentinites are probably distributed in relatively high-resistivity zones. The geological conditions change at depths where low-resistivity zones, resistivity-changing zones or high- and low-resistivity mixed layer zones were found in the GREATEM survey. When drilling a tunnel in these areas, one must pay attention to faults, fracture zones, unsymmetrical pressure zones due to geological condition changes, flowing groundwater, and similar factors. The resistivity structure of deep sections determined by GREATEM survey is effective for the acquisition of basic data to predict potential geotechnical issues when excavating a tunnel.

CONCLUSIONS

The results of this survey and the applicability of the GREATEM survey are summarized as follows:

1) When the electrical resistivity results of the measuring bore-core samples and electrical logging were compared with those obtained by the GREATEM survey, the tendency of these resistivity showed similar features suggesting that resistivity in the tunnel site is high in the shallower parts and low in the deeper parts.

2) The resistivity structure obtained in this study identified the distribution of two types of serpentinite. It is very important, for the sake of safe and efficient tunnel construction design.

The result showed in this paper was based on stitched 1D structure. We will construct accurate three-dimensional structure bringing out the three dimensional GREATEM data.

ACKNOWLEDGMENTS

The authors thank for the Ministry of Education, Culture, Sports, Science and Technology, Japan for supporting development of airborne survey system. We would also like to express our special thanks to the staff of the Ministry of Land, Infrastructure, Transport and Tourisms Hokkaido Regional Development Bureau; and The Field Science Center for Northern Biosphere of Hokkaido University for allowing us to enter and carry out surveys in their field.

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