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Helicopter-borne electromagnetic surveys for civil engineering in Japan

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Abstract: Helicopter-borne electromagnetic (HEM) systems were originally developed for the exploration of mineral deposits. The frequency range of a conventional HEM system for mineral exploration, however, is relatively low and so not invariably suitable for its application to the fields of civil engineering because of its poor resolution in the shallower part of the earth. A DIGHEM HEM system was acquired by Nippon Engineering with the frequencies chosen by the senior author. The five frequencies range from 220 Hz (the lowest) to 137,500 Hz (the highest). These frequencies improve the resolution of materials in the shallower part while maintaining a depth of investigation of greater than 100 m.

This paper describes six case histories of geological and geotechnical surveys for civil engineering using HEM. These case histories include HEM surveys for investigating landslide, an alluvial area, root selection of road construction areas related to dam and tunnel construction, and the simultaneous joint inversion of HEM and CSAMT data for a deep tunnel. These survey results show that HEM has sufficient resolution in both horizontal and vertical directins to contribute significantly to outlining the regional geology and its engineering problems.

KEY WORDS: HEM, application to civil engineering, three-dimensional survey

1. Introduction

Well informed persons have pointed out on occasion that we should grasp the whole geotechnical problems in a survey area by investigating a wide area and then focus the points for the follow-up survey to avoid the useless surveys and to reduce the total cost from the plan to the maintenance after beginning a service. They have also insisted on the importance of the three-dimensional survey. Ground geophysical methods have only line or spot coverage which are not suitable for a wide area and often result in incomplete data sets because of difficult access to steep terrains. Such methods are also slow and expensive, and are susceptible to serious terrain effects (i.e., data artifacts), especially on slopes. On the other hand, HEM is suitable for the coverage of wide areas and provides the three dimensional information. HEM data are densely sampled, are very uniform over a survey area, and are not likely to suffer from topographic effects since the HEM "footprint" is relatively small compared with terrain changes. These factors make HEM measurements suitable for detecting the small resistivity changes caused by geotechnically weak portions.

2. Survey methodolgy

The schematic view of NE's HEM system is shown in Figure 2.1. This system is the DIGHEM-V type, which has five frequencies from 220 to 137,500 Hz with a five-fold increase in each successive frequency.

To preserve the quality of data during the measurement, 1) the flight line is arranged approximately orthogonal to the contour lines of the topography, rather than parallel to them, 2) the helicopter flies lines in only one direction from the bottom to the top of the steep slope, and 3) the bird height is kept between 30 m and 60 m with a flight speed of 20 to 40 km/h. The spacing of flight lines is usually 100 m. A differential GPS system is used for navigation and for flight path recovery.

The height of the EM bird above the earth is the importan factor for the interpretation of data. This height may be obtained from the radar altimeter in the helicopter, but the data of a radar altimeter typically includes many errors because of severe terrains and dense tree covers. Fortunately, the apparent height, obtained from the data of the highest frequency, tends to yield the true height within a range of 5 m in most cases(Figure 2.2). Therefore, the data measured at 137,500 Hz are very useful for bird height estimation as well as for improving the resolution in the shallower part of the earth.

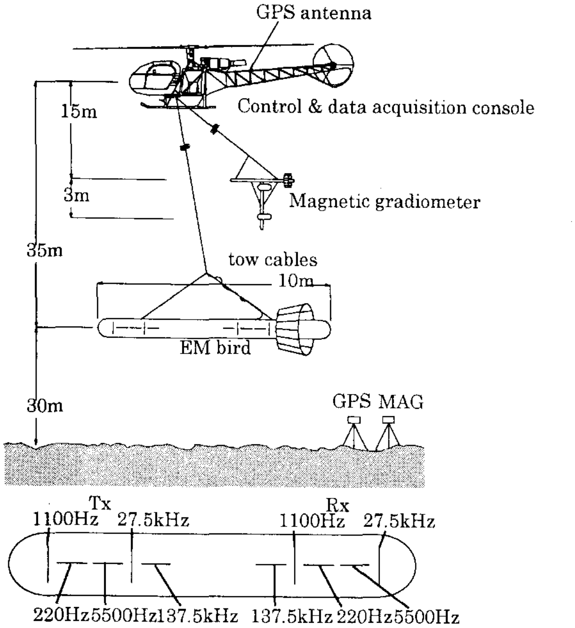

Figure 2.1. The Nippon Engineering HEM system configuration.

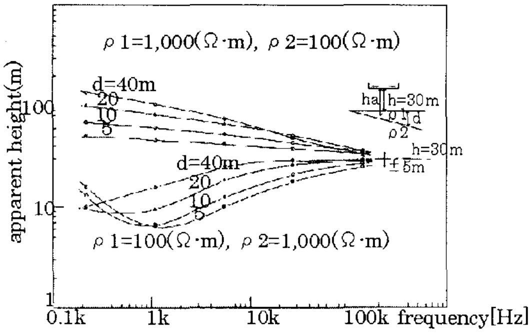

Figure 2.2. The relationship between frequency and apparent height for a two-layer model. The apparent height (ha) of the EM bird approaches the true height (h) as the frequency of measurement increases. In cases where the resistivities are lower than those shown here, the apparent height at 137,500 Hz is very close to the true height.

3. HEM case histories

3.1 The HEM survey result of Sumikawa Landslide

The Sumikawa Landslide, which occurred on May 2, 1977 in the Hachimantai national park of northern Japan, caused a debris flow on a scale of 6,000,000 m^3. This landslide hit National Road 341 and resulted in a disaster downstream. This landslide, located on an active geothermal alteration slope in a Quaternary volcano area, is composed largely of tuff and andesite lava with an underlying strongly altered zone.

As shown in Figure 3.1-1(a)~(c), low resistivity zones are widely distributed. There are many reasons for low resistivity zones in the survey area, such as vigorous hot springs, fumarole manifestations and montmorillonite zones. Even in the wide low resistivity distribution, a markedly lower resistivity spreads out around the recent landslide, entirely covering it and spreading to the west. This low resistivity zone is considered to indicate the present and potential landslide area. In fact, according to a newspaper dated October 17, 1997, there have been several indications that another new landslide has begun to move at 400 m west of this landslide.

Figure 3.1-2(a) shows an apparent resistivity section along a center of the landslide in which the upheaval pattern of low resistivity is recognized. The markedly lower resistivity zone at the foot part corresponds to outcrops of altered clay zones. The moving mass, on which trees still stand, corresponds to a relatively high resistivity because of a tuff not saturated by groundwater.Figure 3.1-2(b) shows the result of a two-layer inversion.

Figure 3.1-2(c) shows the landslide section obtained from drillings along the same line, the result of which shows good correspondence with the result of the HEM two-layer inversion.

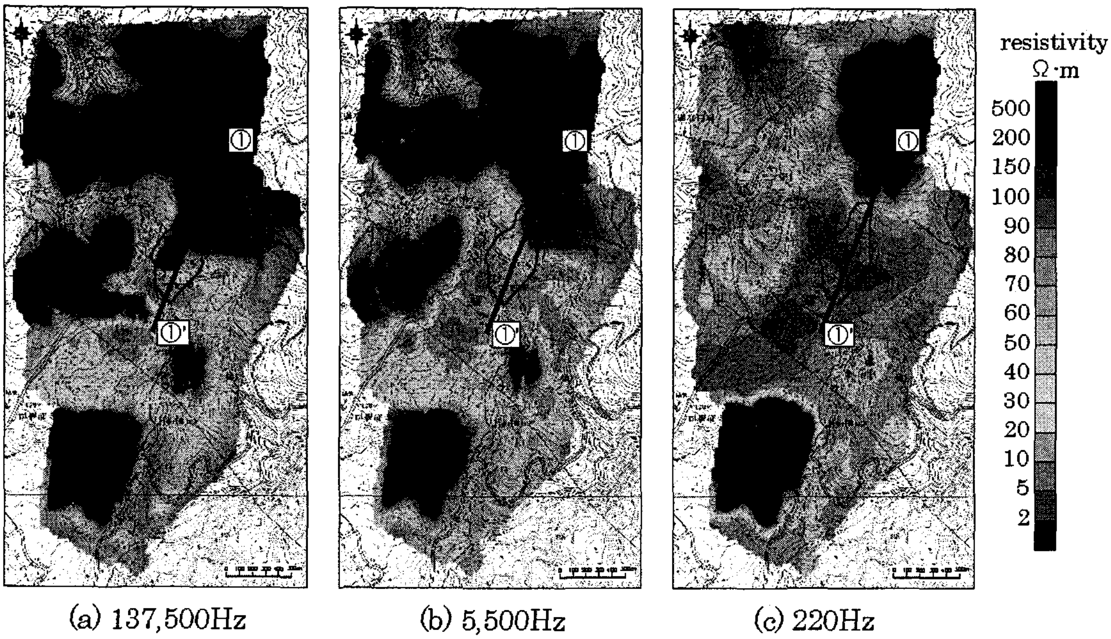

Figure 3.1-1 Apparent resistivity at three frequencies (panels a, b and c) in the Sumikawa Landslide. The actual landslide lies in the outlined area between ① and ①'. Note the zone of low resistivity enclosing the landslide and the lobe of low resistivity extending to the west.

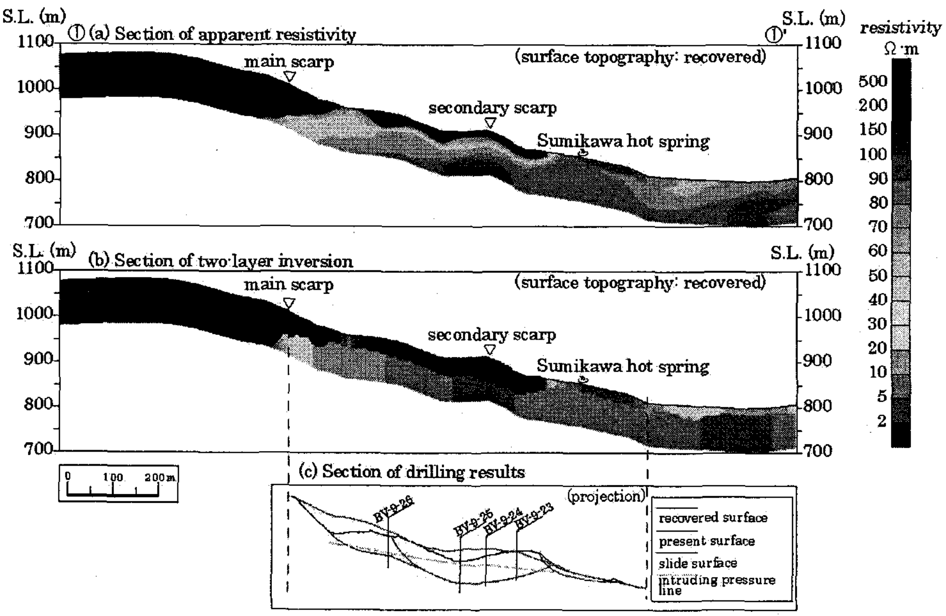

Figure 3.1-2 Apparent resistivity section (a), two layer inversion (b), and drilling results (c) in the Sumikawa Landslide along profile ①-①', as shown in Figure 3.1-1.

3.2 The HEM survey results of an alluvial area along the Mogami River

The survey area is located in the Shonai alluvial plain, Yamagata Prefecture, Northern Japan, which is composed of mud, sand, gravel and their interbeds. This survey was conducted to detect the old river channels and to delineate the distribution of soft ground.

Figure 3.2-1(a)~(c) shows the apparent resistivity distribution at 137,500 Hz, 5,500 Hz and 220 Hz, the depth of exploration of which is roughly estimated to be 5~10 m, 20~40 m and 40~70 m respectively according to the concept of a centroid depth (Sengpiel, 1988).

The high resistivity distribution shown in Figure 3.2-1(a) reflects the existence of the gravel and the gravel-sand mixed layer. The low resistivity distribution in Figure 3.2-1(a) reflects the existence of the clay, silt and clayey sand. The low resistivity distribution at the western side in Figure 3.2-1(a) correlates with the old delta, and the other low resistivity zones correlate with the back sloughs. The medium resistivity distribution in Figure 3.2-1(b) and (c) reflects the mud-sand interbeds.

Figure 3.2-2 shows the contrast between the apparent resistivity at 137,500 Hz and the old topographical map made in 1913. The natural levees correlate with the high resistivity. The medium resistivity zones, extending linearly along the natural levees, reflect the old river channels which are composed of silt and silty sand embedded in the gravel layer. The natural levees over the old delta do not correlate with the high resistivity in Figure 3.2-2, but correlate with the slightly high resistivity in Figure 3.2-1(a) and (b).

Figure 3.2-3 shows the resistivity section along the left bank of the present Mogami river. The high resistivity of the upper layer reflects the gravel layer and the medium resistivity of the lower layer reflects the mud-sand interbeds. The boundary between the upper- and the lower layer coincides with the one recognized by drillings within an accuracy of ±90 %.

As a result of this survey, it is recognized that HEM is expected to have sufficient resolution in both horizontal and vertical directions to define the outline of an alluvium.

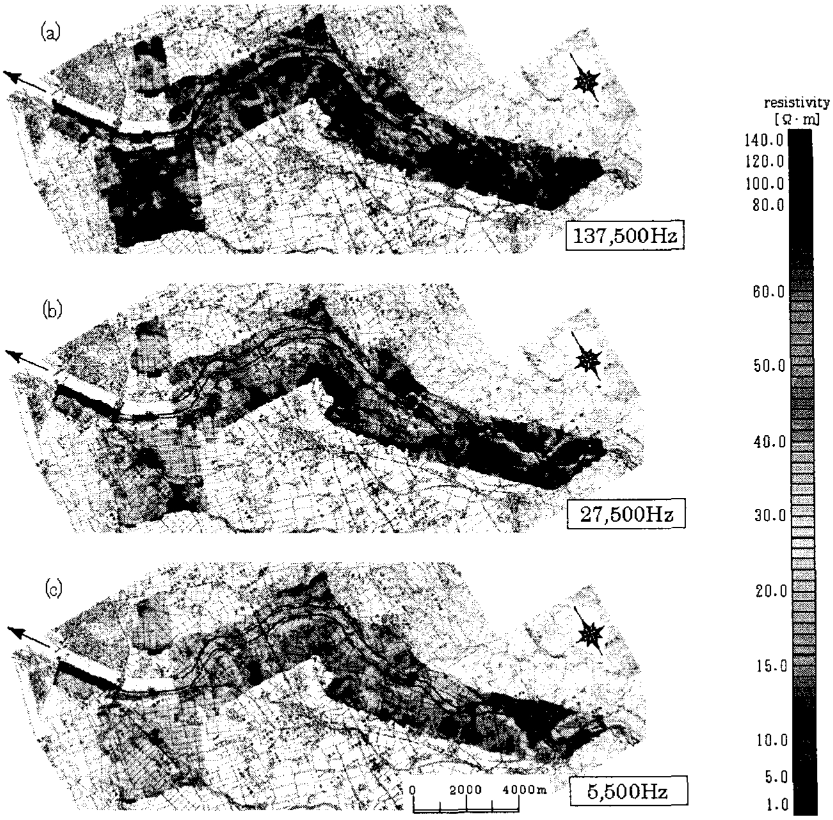

Figure 3.2-1 Apparent resistivity at three frequencies in an Alluvium along the Mogami river.

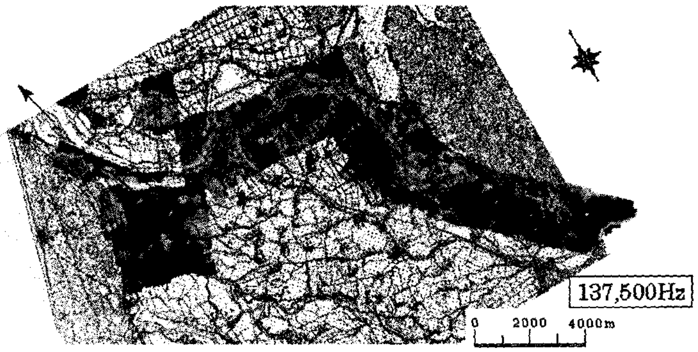

Figure 3.2-2 The contrast between the apparent resistivity at 137,500 Hz and the old topographical map made in 1913.

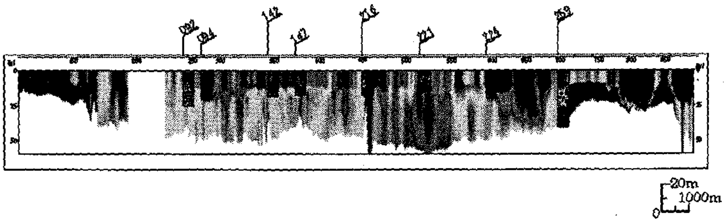

Figure 3.2-3 The resistivity section along the left bank of the present Mogami rivrer and drilling results.

3.3 Verifications of validity of HEM by comparison with an another method

3.3-1 The comparison of HEM result with electrical logging

Figure 3.3-1 show the apparent resistivity section by HEM along a planned road tunnel and the enlarged figure of the gateway portion. The gateway portion of the tunnel correlates with the low resistivity distribution of 20～35 Ω-m which reflects the argillaceous sandstone layer. The central portion of the tunnel correlates with the high resistivity distribution which reflects the andesite lava.

Figure 3.3-2 shows the result of electrical loggings drilled at BV-2 and BV-3 after the HEM survey (cf. Figure 3.3-1). The parallel lines on logging data in Figure 3.3-2 show the resistivity ranges of HEM interpretation at well sites. As for the BV-2 position, the resistivity ranges of HEM coincide well with the result of electrical logging. As for the BV-3 position, the resistivity ranges of HEM show slightly higher values than those of the electrical logging in the upper part of BV-3, but both coincide well in the lower part of BV-3.

As a result of this investigation, it is concluded that the resistivity distribution obtained from the HEM data shows a good correlation with the actual resistivity of ground.

3.3-2 Comparison of HEM result with the ground resistivity method

Figure 3.3-3(a) shows the resistivity section on a planned quarry for a dam construction, obtained from the two dimensional interpretation of ground resistivity measurements.

Figure 3.3-3(b) shows the HEM resistivity section on almost the same line of Figure 3.3-3(a), derived from the three dimensional resistivity distribution obtained by the HEM survey. Both ground and airborne resistivity sections show similar resistivity distributions. However, several discrete anomalies of low resistivity are recognized on the section of ground resistivity method and they are probably artifacts caused by the effects of terrains and the process of interpretation.

The target rock is the andesite. The fresh andesite is suitable for rock quarrying and should show a resistivity higher than 300～500 Ω-m. The resistivity value of 100～150 Ω-m in Figure 3.3-3(a) is too low for fresh andesite, which suggests that the andesite must be deeply weathered or altered and not suitable for rock quarrying. However, Figure 3.3-3(b) shows a resistivity more than 500～700 Ω-m, which suggests the existence of a fresh andesite. The result of drilling investigations shows the consistence of the HEM result more than the ground resistivity result.

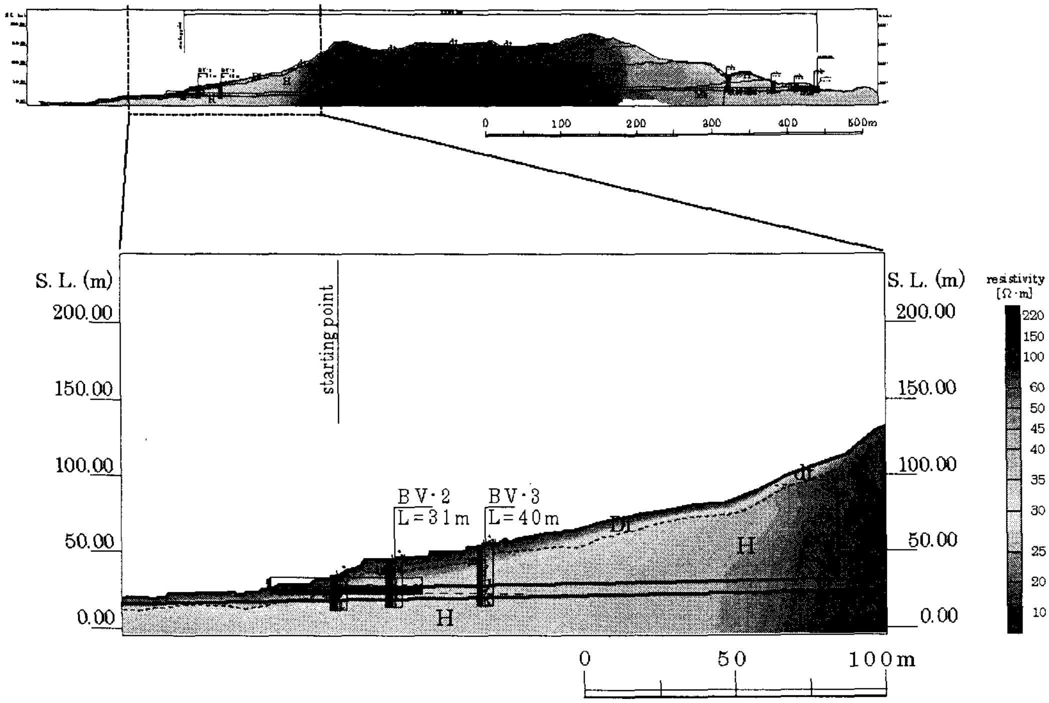

Figure 3.3-1 The apparent resistivity section along a planned road tunnel and the enlarged figure of gateway portion.

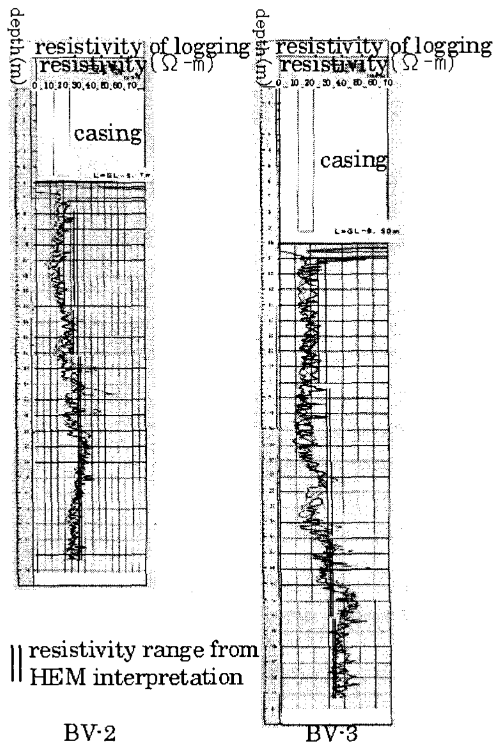

Figure 3.3-2. The result of electrical loggings and the resistivity range from HEM interpretation.

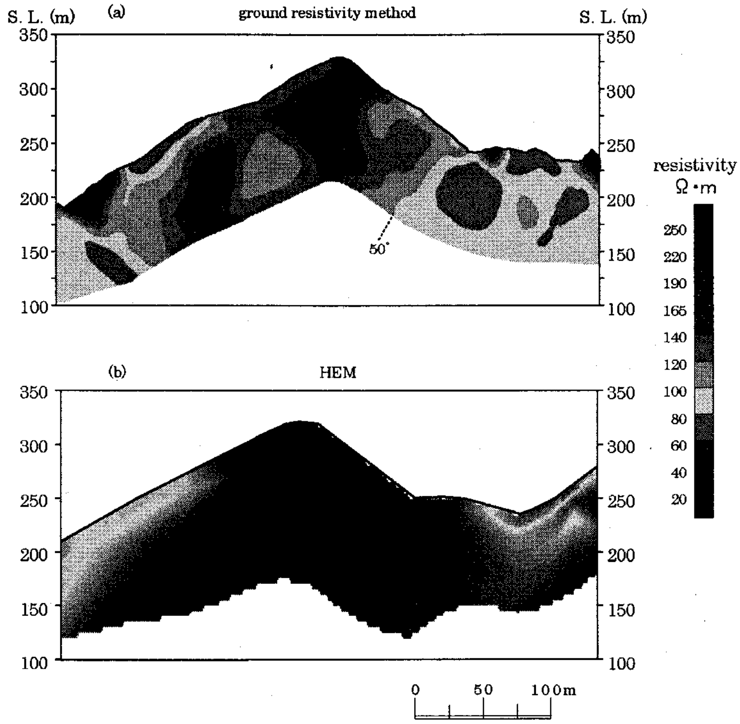

Figure 3.3-3 The resistivity section obtained from the two dimensional interpretation of ground resistivity measurements (a) and the resistivity section derived from HEM (b) at a planned quarry.

3.4 HEM survey results of active faults

This article is quoted and extracted from Takakura et al. (1996). This HEM survey was conducted to map resistivity anomalies due to active faults after the Kobe earthquake in 1995.

Figure 3.4-1(a)～(c) show the apparent resistivity distribution of 137,500 Hz, 27,500 Hz and 5,500 Hz in the northern region of the Awaji Island, Japan. In comparison with the geological map, the high resistivity zones of more than 200 Ω-m correlate with the granites of the Cretaceous. The relatively low resistivity zones of 10～100 Ω-m correlate with Tertiary and Quaternary sediments. The sea area shows the low resistivity of less than 1 Ω-m. Thus, the resistivity distribution obtained by HEM shows good correspondence with the known geological distribution.

Figure 3.4-2 shows the comparison between the apparent resistivity of 5,500 Hz and the active fault traces extracted from geological maps made by GSJ. Most of the faults in this area appear along the boundaries of resistive and conductive zones, by reason of which most faults are located near the boundaries between granites and sediments. On the other hand, some faults, such as Kusumoto Fault (2) and Nodao Fault (10), which exist in granite areas, show relatively low resistivity anomalies with a linear structure. This means that the faults themselves may show relatively low resistivity anomalies. The low resistivity anomalies may be due to fractures associated with the faults. Other resistivity anomalies with a linear structure, which have do not correlated with the faults on the known geological maps, may show the potential faults.

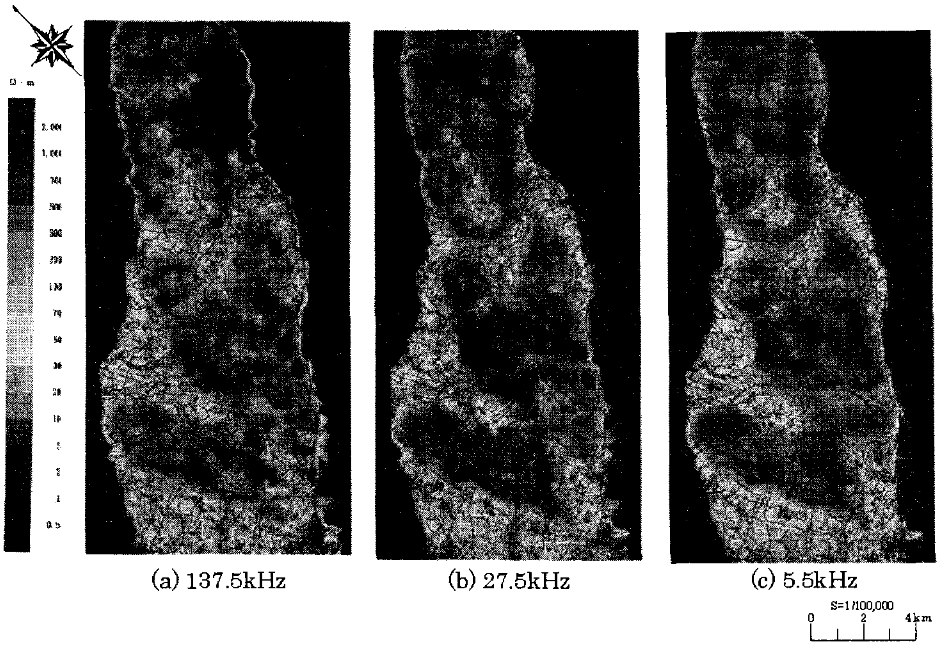

Figure 3.4-1 The apparent resistivity at three frequencies in the northern region of the Awaji Island, Japan

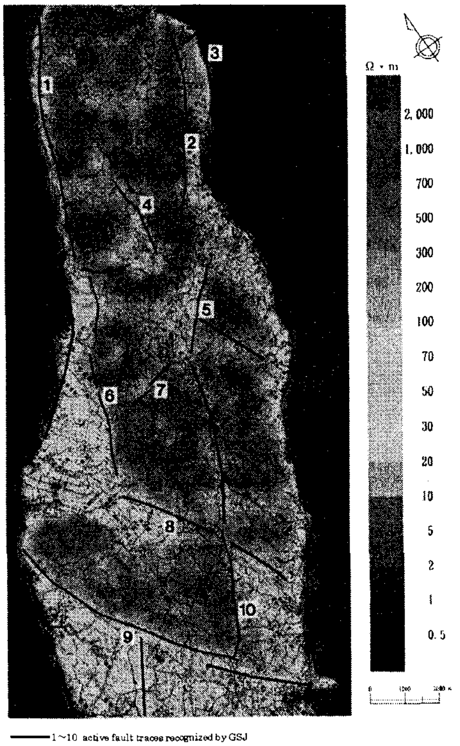

Figure 3.4-2 The contrast between the apparent resistivity of 137,500 Hz and active fault traces recognized by GSJ.

3.5 The result of a simultaneous inversion of HEM and CSAMT

The depth of exploration in geophysical prospecting methods has a reciprocal relation with the resolution. The effect of shallower portions of the earth should be correctly estimated to investigate a deeper part. The depth of exploration of HEM and CSAMT is roughly 100～150 m and 500～700 m respectively, whereas the resolution of HEM is substantially better than that of CSAMT in the shallow part. The simultaneous inversion of HEM and CSAMT is expected to correct the reciprocal relation between the depth of exploration and the resolution and to improve the accuracy of interpretation.

This case history describes the result of a simultaneous inversion of HEM and CSAMT data for the survey of a deep tunnel. Figure 3.5-1 shows the result of two dimensional interpretation using only CSAMT data, in which a low resistivity zone appears in the shallow part. This is probably an artifact caused by static shift. Static shift is a problem peculiar to some EM methods such as MT and CSAMT, whereupon the resistivity in the deeper part shows the lower value than the actual distribution caused by small-scale low resistivity inhomoegeneities at the near surface. This should be corrected by other means.

Figure 3.5-2 shows the result of a simultaneous inversion of HEM and CSAMT, in which the low resistivity in the shallow part of Figure 3.5-1 disappears and the relatively low resistivity wholly shifts to the deeper part. Figure 3.5-3 shows the comparison between the result of an electrical logging and the resistivity ranges of HEM/CSAMT inversion, in which a good correspondence is recognized between the both. This means that the simultaneous inversion of HEM and CSAMT is useful for obtaining an accurate resistivity distribution in the deep part.

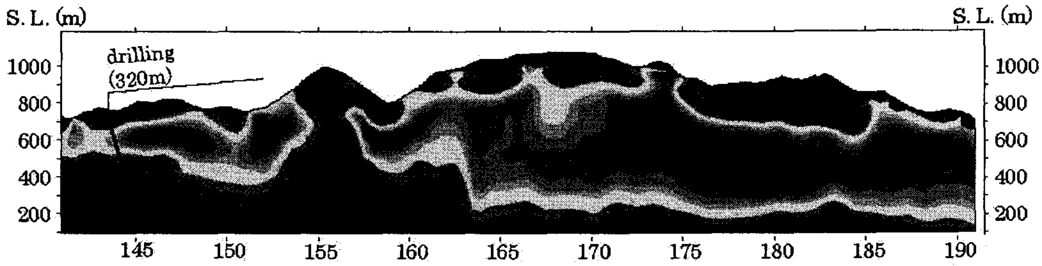

Figure 3.5-1 The result of a two dimensional interpretation using only CSAMT data (100 m spacings)

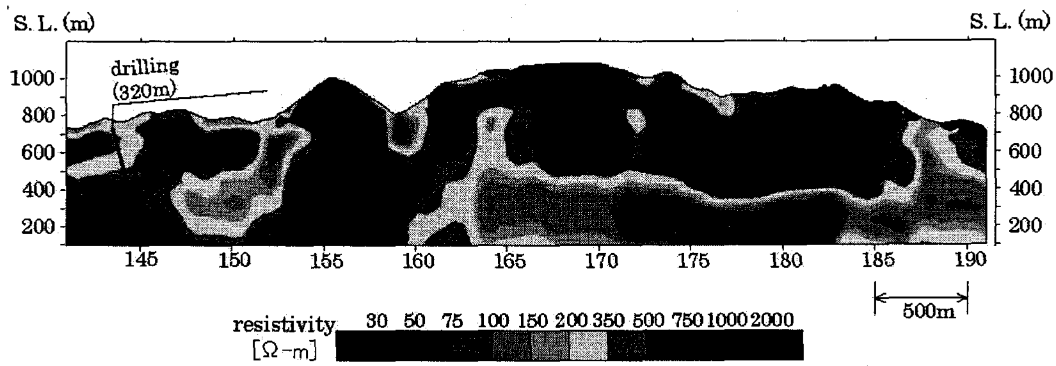

Figure 3.5-2 The result of a simultaneous inversion of HEM and CSAMT.

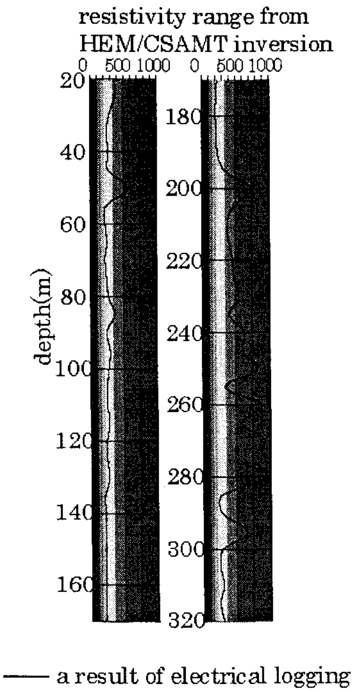

Figure 3.5-3 The contrast between the result of an electrical logging and the resistivity range of HEM/CSAMT inversion.

4. Conclusions

The principal aim of the interpretation of resistivity data is to confirm and or modify the geological/geotechnical maps obtained from other surveys and to detect the objective informations such as geotechnically weak portions and a groundwater. Therefore, we need to get accurate three-dimensional resistivity distributions and to know the dominant factors which affect the resistivity in a survey area.

The HEM method, utilizing a wide range of frequency, has been demonstrated in this paper to be useful for the detection and delineation of the geological /geotechnical problems, owing to

1) its excellent ability to detect low resistivity zones,
2) its high data acquisition density and broad uniform coverage,
3) its reduced sensitivity to terrain effects in comparison with other geophysical methods,
4) its high survey speed and relativity low cost, and

its ability to point out a potential geotechnical weakness such as landslides, even those which are difficult to recognize from ground prospecting.

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