Mitsuhata, Y., Uchida, T., Application of electromagnetic methods to the investigation of seawater intrusion into coastal aquifer – A case study in the Hasunuma area, Chiba Prefecture, Japan.
International Symposium on the Fusion Technology of Geosystem Engineering, Rock Engineering and Geophysical Exploration
Seoul, Korea, Nov. 18-19, 2003

Application of electromagnetic methods to the investigation of seawater intrusion into coastal aquifer – A case study in the Hasunuma area, Chiba Prefecture, Japan

Yuji Mitsuhata, Toshihiro Uchida
Exploration Geophysics Research Group, Institute for Geo-Resources and Environment, AIST, Tsukuba, Japan

Abstract: The estimation of seawater intrusion into deep aquifers has been becoming an important subject in terms of site characterization for geological disposal of radioactive waste. Conventional direct-current resistivity methods have been used for ground water explorations and recently have been applied to environmental problems. However, electromagnetic methods are more practical and useful for such a deep investigation. We consider audio-frequency magnetotelluric (AMT) and surface-to-borehole electromagnetic (EM) tomography methods as promising tools for the investigation of deep aquifer. These methods were tested in the Hasunuma area, Chiba Prefecture, Japan. Although the study area is in an urban area, high-quality AMT data were acquired, which was mainly accomplished by night-time data recording and remote-reference data processing. One-dimensional inversion results of the AMT data revealed two extremely conductive zones, which is consistent with the electrical conductivity profile of pore water in core samples. It can be interpreted as the seawater intrusions into both zones. However, the chemical analysis of the groundwater sampled in the deep zone suggests that this groundwater must be fossil seawater that had been confined during sedimentation processes. In addition, the permeability coefficient of the deep layer is very low. Thus the deep conductive zone corresponds to the fossil seawater regarded as being difficult to flow.

1. Introduction

The investigation of seawater intrusion into deep coastal aquifers is demanded to evaluate the stability and site selection for radioactive-waste disposal. In coastal areas, fresh groundwater goes up along a salt-fresh water interface and flows out at the bottom of the sea (Marui and Hayashi, 2001). It means that if some chemical contaminants leak out from disposal sites, they can be transported by groundwater and finally spread out into ocean. Therefore, without the investigation of subsurface structure respecting hydraulics, we cannot select a proper site and evaluate the stability of geological disposal. The direct-current resistivity (DC) method is commonly applied to groundwater exploration, and it has began to be used for the investigations of seawater intrusion (e.g. Ushijima, 1997; Hwang et al., 2003) and the variation in a salt-fresh water interface due to a tide (Tang et al., 2000). The DC method is usually employed for shallow explorations less than 100 m. For deep explorations, electromagnetic (EM) methods utilizing alternative electrical current must be more convenient and effective. In terms of radioactive-waste disposal, facilities are planned to be constructed at the depth less than 1 km in hard rock such as granite or at the depth less than 500 m in soft rock such as the Neogene (Shimizu, 2000).

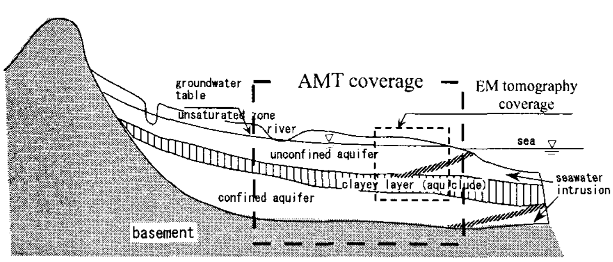

Fig. 1. Coverage of AMT and EM tomography methods in the investigation of shallow and deep seawater intrusions.

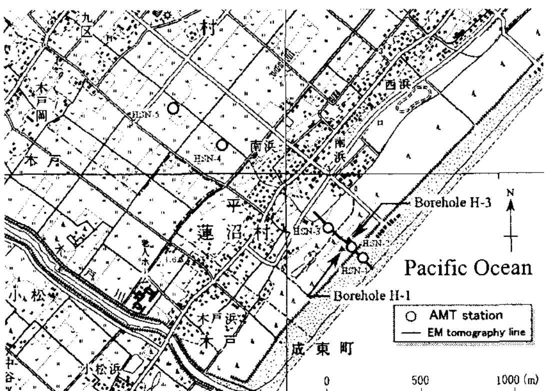

Fig. 2. Location map of AMT stations and EM tomography measurements line in the Hasunuma test area (after Geographical Survey Institute of Japan).

We have started the research project to grasp the distribution of seawater intrusion. In this project, we use the audio-frequency magnetotelluric (AMT) method for a large-scale investigation (about 3 km 3 km × 1 km) and apply surface-to-borehole EM tomography for a more detailed survey (Fig. 1). In this paper, we report a preliminary result of the AMT and EM tomography measurements in a Hasunuma area, Chiba Pref., Japan, which lies on the coast of the Pacific Ocean (Fig. 2).

2. Study area

In the Hasunuma area, three boreholes has already been drilled, and well logging, chemical analysis of groundwater (Marui et al., 1999) and resistivity tomography (Takahashi, et al., 2001) have been performed in them. Fig.3 shows the profile of conductivity of groundwater samples in borehole H-1 (Kiyama and Marui, 1999). Since the conductivity of surrounding seawater is 4500 mS/m, it is estimated that the seawater intrudes into a shallow part around the depth of 30 m and into a part deeper than 160 m. The area is underlain by horizontal sediments which is divided into an alluvial unconsolidated sandy formation upper than 22 m and a lower diluvial clayey formation, the Kokumoto Formation. The average permeability coefficient of the clayey formation is 3×10^{-8} cm/s (Kiyama and Marui, 1999) which corresponds to an aquiclude.

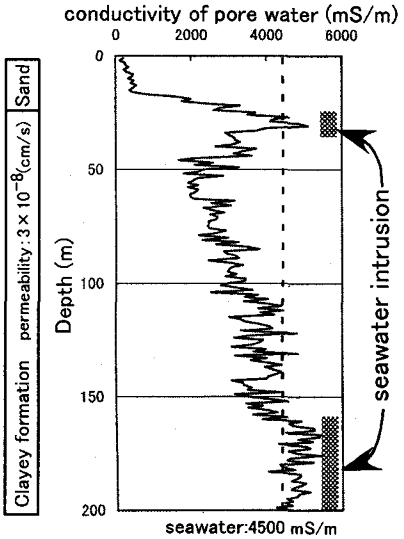

Fig. 3. Conductivity profile of cores sampled in Borehole H-1 (after Kiyama and Marui, 1999).

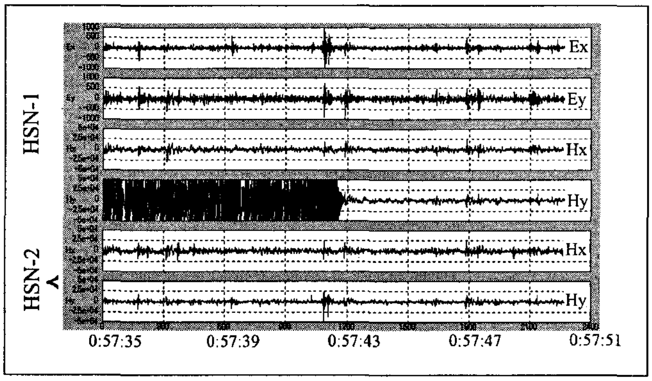

Fig. 4. An example of time-series AMT data recoded from 0:57:35 a.m. to 0:57:51 a.m. at stations, HSN-1 and HSN-2.

3. AMT data acquisition

The AMT method has been applied to mineral explorations and the investigations of shallow parts of geothermal areas. Unfortunately, the quality of acquired data was poor, in particular, around 1 kHz, because the power of natural geomagnetic field is weak in this frequency range. However, owing to recent improvements of AMT instruments such as synchronization by the GPS system, small-size and large-capacity memory cards, automatic data acquisition at night when artificial noise decreases and the data reprocessing with remote reference data have been realized. In addition, the employment of high-speed 24 bit A/D boards makes recording tiny signals overlain by large noise possible. Thanks to these recent advances, the quality of acquired AMT data has been significantly improved (Takayama et al., 2002).

In the Hasunuma area, the AMT measurements were carried out at five stations as shown in Fig. 2. It seemed impossible to obtain good-quality data at first because these stations were near human habitations. We used the Phoenix Geophysics MTU-5A systems that measure at 54 frequencies, 10 kHz to 1 Hz, and the data acquisition was done from 8 p.m. to 5 a.m. for nine hours per day. A remote-reference station was placed at a quiet site about 15 km far from the Hasunuma area. Fig. 4 shows an example of time-series data recorded with the sampling frequency of 150 Hz at stations HSN-1 and HSN-2. The distance between these two stations was only about 100 m. Nevertheless, the *Hy* component of magnetic field at HSN-1 station was noisy until 0:57:43 a.m., and this noise suddenly disappeared at about 0:57:43 a.m. We can recognize that each component exhibit good correlation with the other components after that. Such noise could not be recognized in the data at HSN-2 station. The HSN-1 station was closest to the coastline. As a possible cause of the noise, we guess that a cable through which some EM signal is sent is embedded along the coastline and that it generates magnetic field perpendicular to the coastline, which corresponds to the *Hy* component. Avoiding using such noisy data and applying the remote-reference reprocessing, we have finally obtained good-quality AMT parameters: apparent resistivity and phase as shown in Fig. 5.

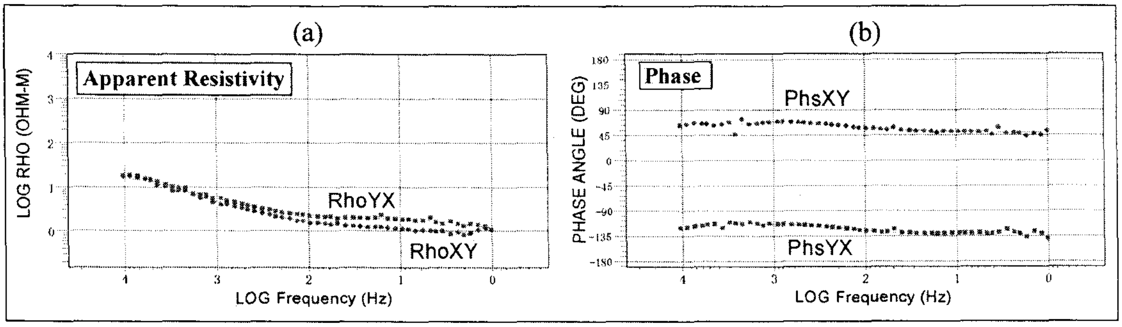

Fig. 5. AMT parameters at HSN-1 station evaluated through the remote-reference processing.
(a) Apparent resistivity and (b) Phase data. Rhoxy and Phsxy means the TE mode in which electric field is parallel with the coastline, and Rhoyx and Phsyx means the TM mode in which electric field is perpendicular to the coastline.

Since the anisotropy of AMT parameters is not very large, one-dimensional inversion has been applied to the analysis of the TE-mode data at each station. By sticking together each inversion result, a resistivity image is constructed in Fig. 6. The estimated resistivity image is consistent with the conductivity profile of Fig. 3. Two conductive zones can be recognized. One is clearly delineated around the depth of 30 m. In contrast, the other exists below about 100 m and is not very clear. Since the shallow one is around the unconsolidated sandy formation which seems to be very permeable, it must be a seawater-intrusion zone. The depth of groundwater table is 0.7 m to 1.5 m (Marui and Hayashi, 2001). Therefore, an unsaturated fresh-water zone lies over the shallow seawater-intrusion zone. In terms of the deep conductive zone, it is very thick and the clear delineation of its figure is impossible. In addition, it is in the almost impermeable formation. According to chemical analysis of groundwater samples in the boreholes (AIST, 2003), the groundwater sampled in this zone exhibits the lack of SO4, which suggests that this groundwater must be fossil seawater that had been confined during the sedimentation process of Kokumoto formation. Thus the deep conductive zone corresponds to the fossil seawater regarded as being difficult to flow.

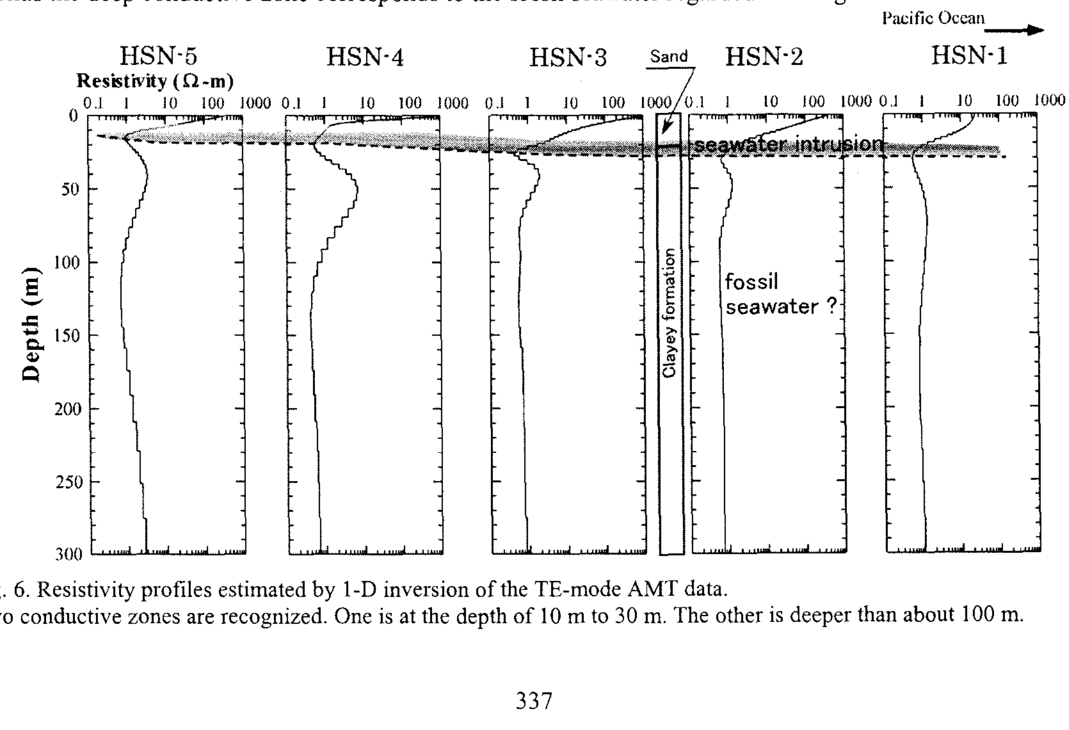

Fig. 6. Resistivity profiles estimated by 1-D inversion of the TE-mode AMT data.
Two conductive zones are recognized. One is at the depth of 10 m to 30 m. The other is deeper than about 100 m.

4. Surface-to-borehole EM tomography

Our objective of the application of the surface to borehole EM tomography is realizing the improvement of resolving power by placing receivers into the borehole in addition to receivers at the surface, which is illustrated in Fig. 7.

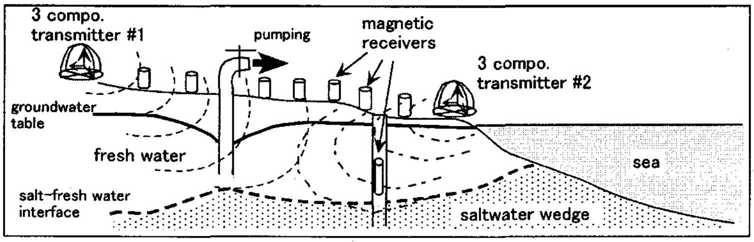

Fig. 7. A schematic diagram of the application of the surface to borehole EM tomography to detect the change of salt-fresh water interface due to a pumping test.

In this study, we used the EM tomography system developed by the Metal Mining Agency of Japan (MMAJ) (ANRE, 2000; Osato and Katayama, 1999). Magnetic sensors for the vertical magnetic component were placed on the measurements line (Fig. 2) whose length was 430 m and into Borehole H-3. Three-component transmitters were set at four different places (Fig. 8), and EM signals from 14 kHz to 8 Hz were transmitted from each transmitter. To investigate the effects of a pumping test, we performed the EM tomography measurements during and after the pumping test in Borehole H-1.

In Borehole H-1, significat changes in the amplitude of vertical magnetic field generated by transmitters TxB and TxC are recognized. The profiles of the amplitude difference, ΔBz, beteween after and during the pumping test along the depth are shown in Fig. 9. We can find the changes due to the pumping test above 100 m.

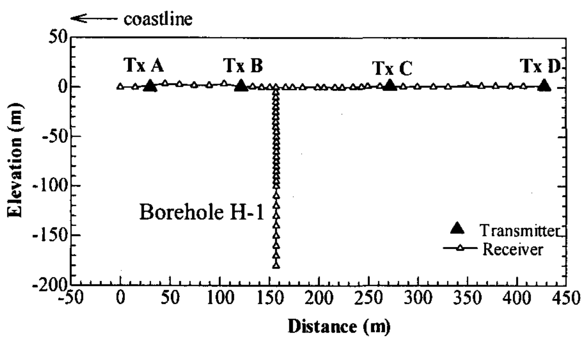

Fig. 8. A section view of the layout of surface t borehole EM tomography.

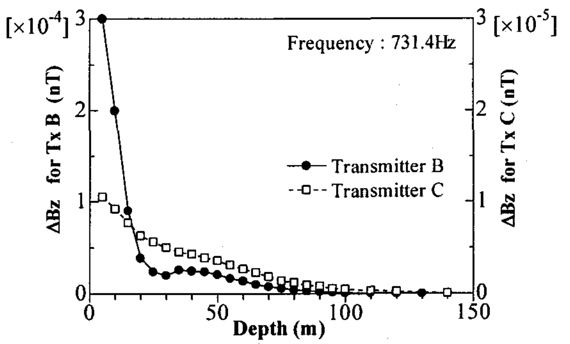

Fig. 9. Profiles of the changes in the amplitud of vertical magnetic field due to the pumpin test along the depth in Borehole H-1.

5. Conclusions

The AMT and surface-to-borehole EM tomography measurements were conducted in the Hasunuma area. It seemed impossible to obtain good-quality data at first because human habitations were around this area. Nevertheless, the good-quality AMT data were acquired. The one-dimensional inversion results of AMT data revealed the existence of two conductive zones. The shallow conductive zone is deemed to be a seawater intrusion zone in the permeable sandy formation, and the deep conductive zone must be caused by the fossil seawater confined in the impermeable clayey formation. In terms of the EM tomography data, the change due to the pumping test was recognized. For the quantitative interpretation on it, a further data analysis is necessary.

Acknowledgements

We would like to acknowledge MMAJ for permitting the use of the EM tomography system, and we are grateful to Atsunao Marui and Kinichiro Kusunose of AIST for their support to continue this study.

References

Agency for Natural Resource and Energy (ANRE), 2000, Report on geophysical exploration methods in the research and developments of mineral resources explorations in fiscal year 1999, ANRE, Japan.

Hwang, S., Shin, J., Park, I., Lee, S., and Yang, S., 2003, Assessment of seawater intrusion using geophysical well logging and surface geophysics in a coastal aquifer, Youngkwang-gun, Korea, *Proc. 6th SEGJ Int. Symposium*, 312-315.

Kiyama, T., Marui, A., 1999, Study on groundwater flow and seawater and fresh-water interface in Hasunuma Parkland, Chiba –Part 2; observation of the depth of sea-water and fresh-water interface by using core sample of Well #1-, Chishitu News, No. 539, 55-59 (in Japanese).

Marui, A., Ishii, T., Uchida, Y., Hayashi, T., 1999, Study on groundwater flow and seawater and fresh-water interface in Hasunuma Parkland, Chiba –Part 1; study plan and situation of drilling about Well #1-, Chishitu News, No. 539, 47-54 (in Japanese).

Marui, A., Hayashi, T., 2001, Hydrological research for understanding of 3D shape of the seawater/freshwater interface, Shigen-to-Sozai, Vol. 117, No. 10, 816-821 (in Japanese with English abstract).

National Institute of Advanced Industrial Science and Technology (AIST), 2003, Report on study about the detection of salt-fresh water interface in fiscal year 2002, AIST, Japan.

Osato, K., Katayama, H., 1999, Development of the electromagnetic tomography system –Development of the equipment and results of the field test 2-, Extended abstract of the 100th *SEGJ* conference, 163-167 (in Japanese).

Shimizu, K., 2000, Geological disposal of high-level radioactive waste and site characterization techniques, Buturi-Tansa, Vol. 53, No.6, 532-542 (in Japanese with English abstract).

Takahashi, S., Azuma, H., Imamura, S., Marui, A., 2001, An application of evaluation of saltwater-freshwater boundary on a coast area using geophysical exploration and well logging, Extended abstract of the 105th *SEGJ* conference, 77-80 (in Japanese).

Takayama, J., Kishimoto, M., Yokoi, K., Graham, G., Doods, J., Yamashita, M., 2002, Introduction of time-domain audio magnetotelluric system and report of field test, Extended abstract of the 106th *SEGJ* conference, 217-220 (in Japanese).

Tang, X., Ohtoshi, K., Fujiwara, T., Ishii, M., Oka, T., 2000, Variation of fresh-salt water interface in a coastal aquifer and detection of the interface by electrical prospecting, Jour. of Groundwater Hydrology, Vol. 42, No. 3, 223-233 (in Japanese with English abstract).

Ushijima, K., 1997, Monitoring of ground water aquifer by electrical prospecting, Buturi-Tansa, Vol. 50, No. 6, 632-642 (in Japanese with English abstract).