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Controlled Source Audiofrequency Magnetotelluric method applied in urban area of Central Osaka, Japan

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ABSTRACT

A detailed study was carried out to find out the most suitable time for electromagnetic sounding in order to apply the CSAMT method in the urban area of Central Osaka. The preliminary data collected during the daytime were highly noise-contaminated, which couldn't be attenuated even on increasing the sampling time. Because of this reason, all the soundings were obtained during the nighttime when the electromagnetic noises were drastically reduced. The changes in layer resistivities with depth, as obtained from the 1-D inversion of the observed data, correspond to the different reflectors as seen in the seismic section. It is found that the vicinity of Uemachi Fault, in the western part of the study area, is characterised by high conductivity.

INTRODUCTION

Magnetotelluric (MT) method is the most common type of electromagnetic sounding. In this method, the electric and magnetic field components of the ground current are measured in the broad range of frequencies between about 0.0001 Hz and 100 Hz. In general, naturally occurring electromagnetic fields created due to the disturbances in the magnetosphere are employed as sources. The ratio of horizontal electric field to horizontal magnetic field is measured as a function of frequency to obtain a frequency-dependent apparent resistivity, based on which the geoelectric section can be derived.

Audiofrequency Magnetotelluric (AMT) method is simply an extension of the MT technique and utilises the frequency within the audible range (1 Hz to 20 kHz) band so as to achieve exploration depths up to about 2 km depending on terrain resistivity. Natural source MT method often suffers from low levels of the storms, which make up the signal source. These problems have encouraged the use of a fixed electric dipole as a controlled signal source and hence the technique is called Controlled Source Audiofrequency Magnetotelluric (CSAMT) method. However, the CSAMT method is also based on the same basic principle as the other electromagnetic techniques. This approach was first investigated by Goldstein (1971), and was described by Goldstein and Strangway (1975).

Noise arising from different sources affects the application of electromagnetic methods in industrial and urban areas. In this regard, the most important aspect of the study was to find out a practical way to collect the relatively noise-free data (high S/N ratio) in order to effectively use the CSAMT technique of exploration even in technically difficult environment. Besides, understanding the changes in geoelectrical characteristics around the fault zone together with delineating the deeper subsurface geoelectrical properties in the area was the prime goal of the present study.

In the study area the electromagnetic noise sources are widespread, as it lies in densely populated Central Osaka (Fig. 1). Ward (1990) has summarised the cultural noise sources and grouped them into active (one that generates noise) and passive (that interferes induced current) ones. Some notable sources are power lines, telephone lines, electrified rails, pipelines, and rails. Of these, almost all sources of noise are present in the study area. The suitable sites for the installation of electric dipole source (antennae) as well as the receiving system were restricted only along the Yamato River, which is flowing from east to west. The apparent resistivity was calculated using the measured electric and magnetic field components and the data were further analysed to obtain the resistivity of different layers up to the depth of 1 km.

GEOLOGICAL SETTING OF THE AREA

The Osaka Basin (Fig. 1) is subdivided from top to bottom into the Alluvium (Holocene), Terrace deposits (Upper Pleistocene), Osaka Group (Late Pliocene-Upper Pleistocene), and the Cretaceous Granitic Basement Rocks (Ikebe and Takenaka 1969). Alluvial deposits consist chiefly of unconsolidated clay, sand, and sandy gravels attaining a maximum thickness of 35 m, whereas the terraces (maximum thickness: 85 m) consist of alternating beds of marine clay with sand and non-marine sandy gravel, sand, and clay. The Osaka Group is further subdivided into the Upper, Middle, and Lower Osaka Subgroups (Huzita et al. 1983). The upper and middle Subgroups consist of alternating beds of marine clay with sand and gravel and non-marine sandy gravel,

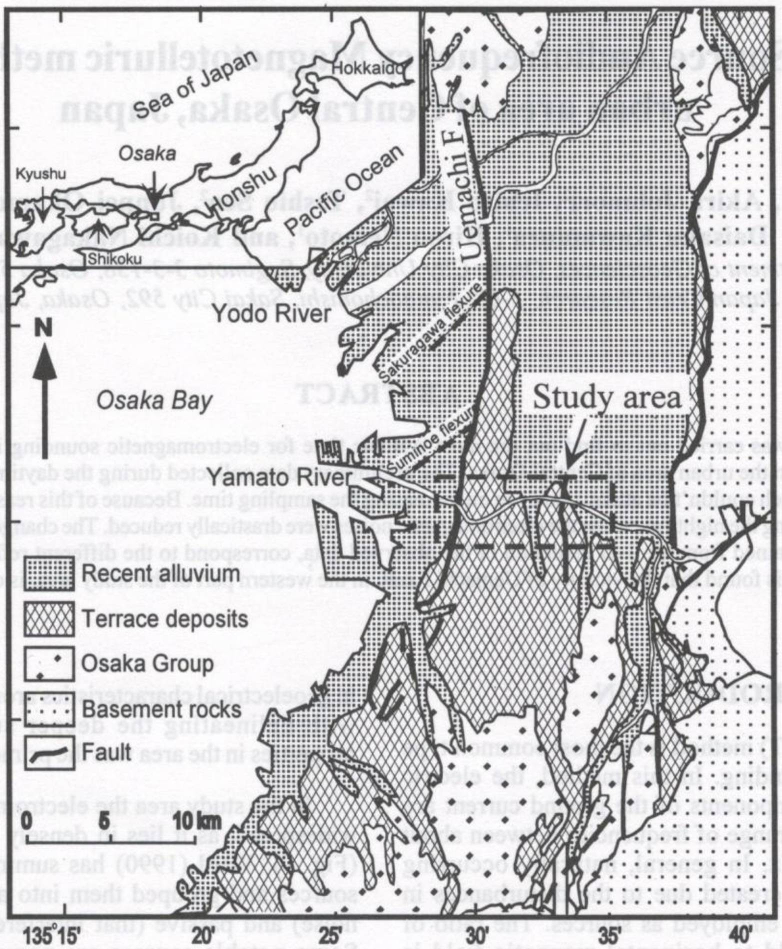

Fig. 1: General geological map of Osaka Basin (Modified after Ikebe et al. 1969) and the position of area in the Basin. Location of Osaka is shown in the inset.

sand, and clay. The Lower Subgroup comprises non-marine clay, sand, and gravel. The major fault in the basin is the Uemachi Fault that runs almost N-S dividing the Osaka City into the eastern and western parts.

PREVIOUS GEOPHYSICAL WORKS IN THE STUDY AREA

The Uemachi Fault lying in the western part of the area was delineated from the seismic reflection survey (Sugiyama 1997). Likewise, flat, slightly eastward-inclined reflectors are reported in the eastern part (Toda et al. 1992; Nishida 1992) of the Yamato River. Most of the seismic reflectors are found to lie within the depth of 700 m. The gravity survey in the Osaka Basin (Inoue et al. 1998; Nakagawa et al. 1991) has revealed that the maximum depth of the basement is about 2 km in the East Osaka region. The dipole-dipole electrical survey along the Yamato River (Ryoki 1995) suggests a high resistive zone at the upper layer while the conductivity is higher at the depth.

CSAMT data acquisition

Field observations were carried out using the transmitter JCR-302T, which is capable to transmit the electric current at 14 different frequencies ranging from 5120 Hz down to 0.625 Hz, and the receiver JCR-95. Mogi et al. (1990) have described the details of the instrument. The power source for the transmitter was a 4.5 kW generator. In order to record the noise for each frequency of transmission, the transmitter synchronously used to cease inducing the electric current for 2 minutes after transmitting the current for that frequency. Thus recorded signals could be used for calculating signal to noise (S/N) ratio for each frequencies. The electric current was induced into the ground by means of a grounded electric dipole, 1.5 km (during the reconnaissance survey), and 3.0 km (during soundings) in length, with 15-20 electrodes at both the ends (Fig. 2). The source antenna was set (further upstream) at a distance of about 5.75 km from the nearest observation point, so as to avoid recording the near field signal. It is to be noted that the CSAMT method is based on the assumption that the source is at the far field so that the plane wave approximation of the inducing electric current could be applied. This can be achieved by making the observations at least at a distance of 3 times the skin depth from the source. Skin depth is the term that is widely used in all types of electromagnetic surveys. It is the criterion for penetration of electromagnetic wave, and is the depth in which the amplitude of the EM fields decreases to 1/e (37 %) of its value at the surface. This is calculated for the inhomogeneous medium by the following formula:

$$\delta = 503\ (\rho/f)^{1/2}$$

where, ρ = apparent resistivity measured at respective frequency, Ωm

f = frequency of transmitted signal, Hz, and

δ = skin depth, m.

The above relationship shows that the resistivity of a medium increases with increasing depth of penetration while it decreases with increase in frequency. The data acquisition methodology followed during the present study is subdivided broadly into the reconnaissance survey (noise monitoring) and the CSAMT sounding.

Reconnaissance survey (noise monitoring)

The purpose of reconnaissance survey was to develop a strategy to carry out the CSAMT sounding in the proposed study area. It was necessary as this area lies in the densely populated Central Osaka City with a high possibility of the presence of electromagnetic noises.

The noise test was carried out at two observation sites using the 1.5 km source antennae (Fig. 2). Initially, the observation was made during the daytime at both sites. It was found that S/N ratio was very low, indicating the presence of a very high noise level in the area (Fig. 3, 4). Based on this preliminary observation, it was decided to increase the sampling time for each transmitted frequency. The increase in sampling time is supposed to enhance the coherent signal and attenuation of the incoherent noise (Fig. 5). The sampling time was as long as 55 minutes for the lowest frequency values (0.625, 1.25 and 2.5 Hz) while it was only 5 minutes for the highest values (5120, 2560 and 1280 Hz). For the rest of the frequencies, it was 15 minutes. The signal strength in terms of induced electric and magnetising field intensities was recorded for different transmitting frequencies at both sites during the daytime.

Likewise, at the successive day, the noise was recorded in each site for the same duration of time and during the same time as the signal was measured previously. Based on the observation of both the signal and noise, it was possible to calculate an approximate S/N ratio in the area. The S/N ratio of the measured electric field intensity, Ex (V/m) to magnetising field intensity at both sites was very low in almost all transmitted frequencies. The representative plots are shown in Fig. 6 and 7.

In view of the above, it was found that increasing the sampling time is not effective to enhance the signal if the noise level is very high in the survey area Then, the observations were made during the nighttime at both sites, with normal sampling time: 15 minutes for the lowest frequencies, 3 minutes for the highest frequencies, and 5 minutes for the intermediate frequencies of transmission. There was no significant improvement in signal strength at site A, where the observation was made between 11 PM and 12:30 PM (Fig. 8). In contrast to site A, there was an improved S/N ratio at site B (Fig. 9), where the observation was made between 2:00 AM and 3:30 AM.

Among all the cultural noise sources in the survey area, the electric trains can be considered as one of the most influencing ones. The increase in signal strength in the data obtained at late night can be correlated to the fact that after 1:00 AM, the trains are not in service. Besides, other anthropogenic activities also become less during that time. Based on the observations, it was concluded that the most suitable time for the data collection was between 1:00 and 5:00 AM.

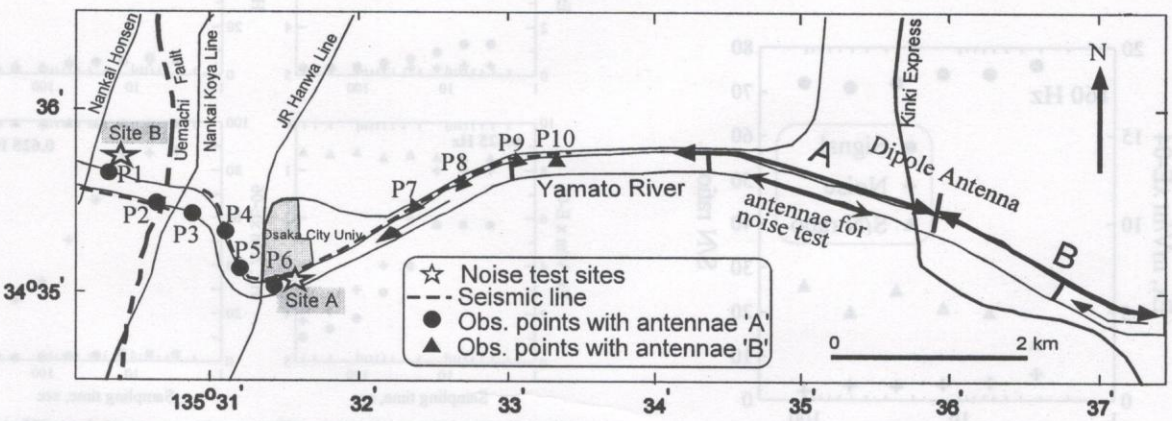

Fig. 2: CSAMT survey layout during the noise test and sounding along the Yamato River, Central Osaka. The noise test carried out with source antennae of 1.5 km in length, while the observations P1 to P6 and P7 to P10 were carried out with the anntenna settings A and B, respectively, both about 3 km in length.

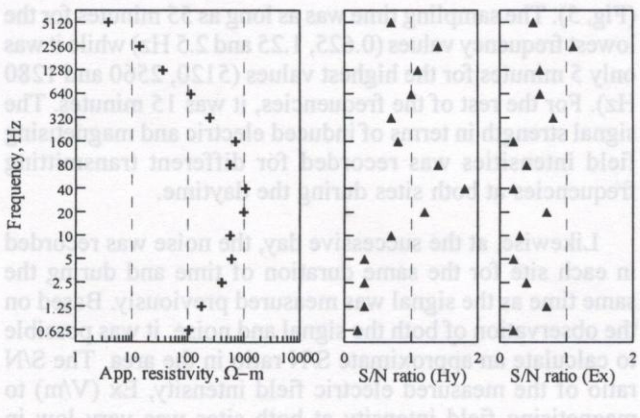

Fig. 3: The very low S/N ratio in both cases of Hy (magnetising field intensity) and Ex (electric field intensity) shows the presence of a very high noise leved at site A during daytime.

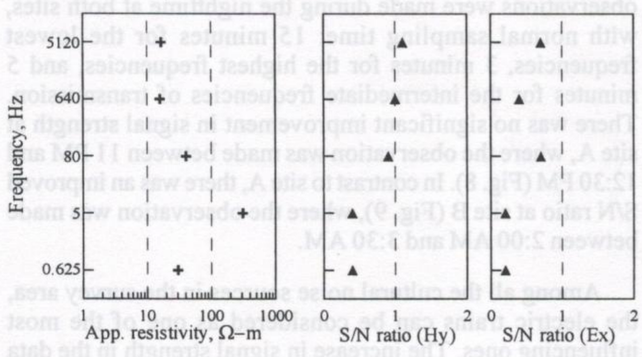

Fig. 4: The very low S/N ratio in both cases of Hy (magnetising field intensity) and Ex (eletric field intensity) shows the presence of a very high noise level at site B during daytime.

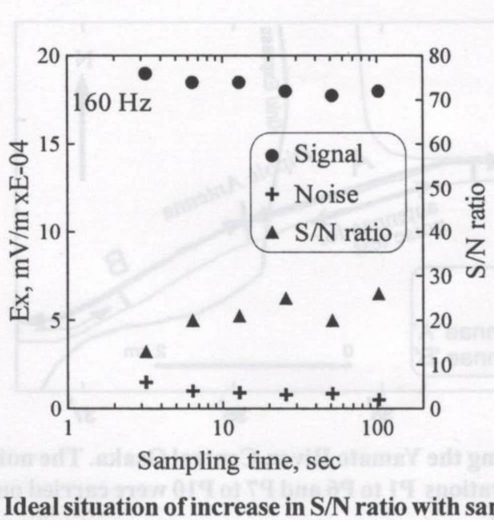

Fig. 5: Ideal situation of increase in S/N ratio with sampling time (Soure: Japan Crust Research)

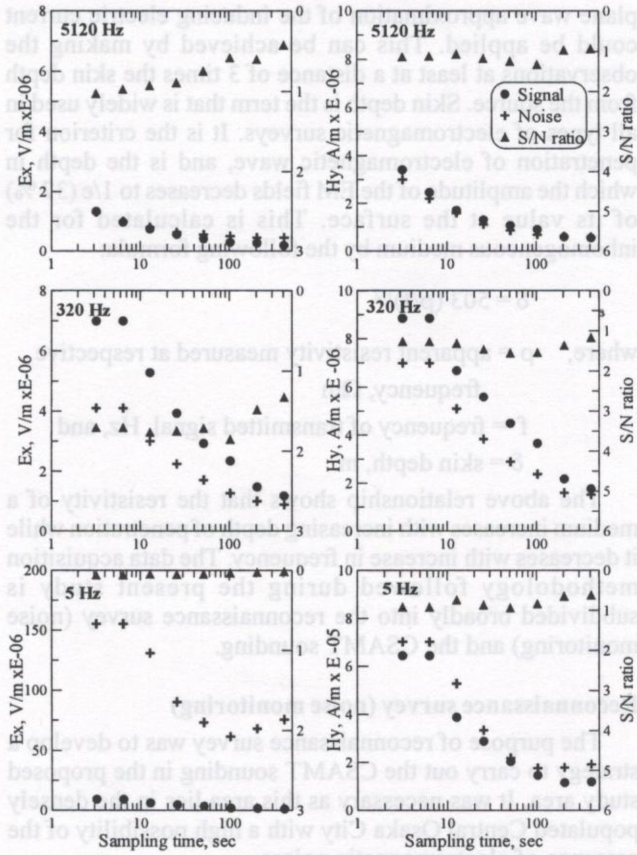

Fig. 6: Daytime electric (Ex) and magnetising (Hy) field intensities for three representative frequencies at site A. The figures clearly show the very low S/N ratio, which was not increases even on increasing the sampling time.

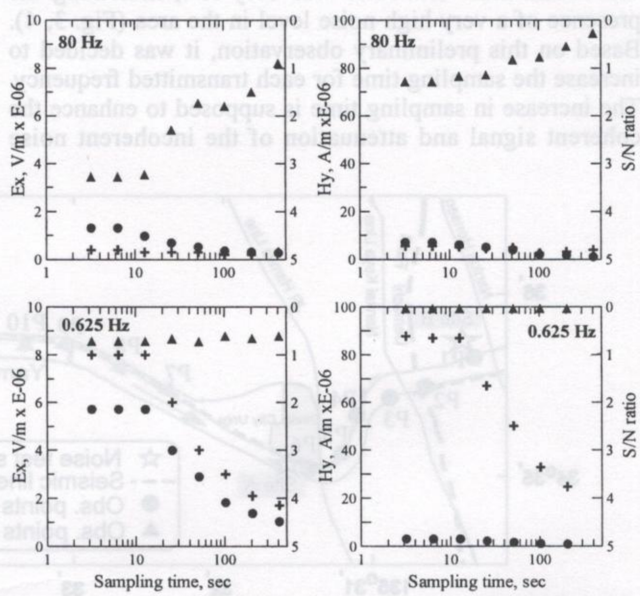

Fig. 7: Daytime electric (Ex) and magnetising (Hy) field intensities for two representative frequncies at site B. The S/N ratio remains too low regardless of increased sampling time.

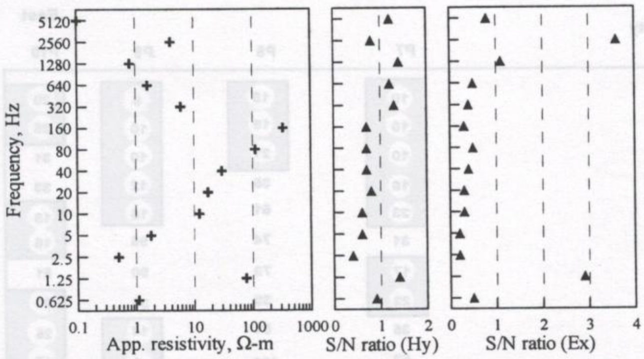

Fig. 8: The S/N ratio at site A was lower in both cases of Hy (magnetising field intensity) and Ex (electric field intensity), when the observation was made at 11:00 PM.

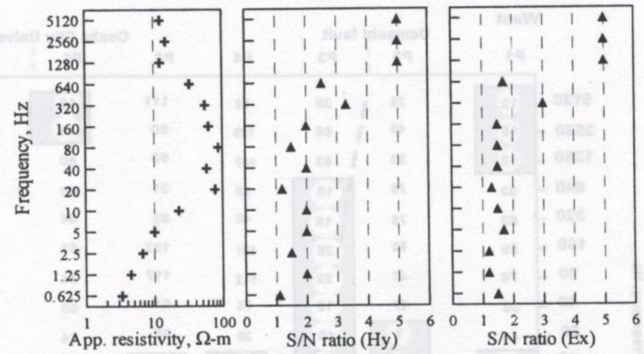

Fig. 9: The S/N ratio at site B was higher in both cases of Hy (magnetising field intensity) and Ex (electric field intensity), when the observation was made at 02:00 AM.

CSAMT sounding

Following the noise test, the CSAMT sounding was performed with two different antenna settings both 3.0 km in length (Fig. 2). All the data were collected between 1:00 AM and 5:00 AM, the most suitable time for soundings as learnt from the results of the reconnaissance survey. Likewise, three receiving electric dipoles were used in each observation sites, and observations were made at two different times with the fixed receiving sets at same sites. These were helpful to remove the effect of very local and intermittent noises arising at particular frequency at particular time.

Altogether 10 observation points were selected for further analysis, which cover a total length of about 5.0 km. The six points, P1 to P6, were acquired with the antenna setting A, while the antenna setting B was used for the remaining four observation points. The minimum distance between the centre of source and the nearest sounding points was 5.8 km and 5.5 km for the sources A and B respectively. It was possible to gather data covering the Uemachi Fault, in the western side of the study area.

DATA ANALYSIS AND INTERPRETATION

The field data were sorted out in order to select the data with high S/N ratio. This was done with two different approaches. One way of sorting was made among the data that were recorded through different receiving electric dipoles in each sounding point. It was necessary in order to avoid the very local noise source in the vicinity of each electrode setting. Secondly, in some sounding points, separate observations were made with the same receiver settings at two different times. This approach was found to be the best one to avoid the effect of intermittent noise, though it is not cost-effective in routine exploration works. Besides, the general trend of the apparent resistivities at different frequencies was considered very carefully.

Observed CSAMT data and 1-D modelling

The ratio of amplitudes of the orthogonal horizontal electric and magnetic field components at the earth's surface were measured in the field. From this ratio the true resistivity of the underlying earth (if the resistivity does not vary with depth) or an apparent resistivity (if the earth is horizontally layered), is calculated using the following relationship (Cagniard 1953):

$$\rho_a = 1/\mu\omega * (|E/H|)^2$$

Where, ρ_a = apparent resistivity, Ωm

$|E|$ = amplitude of horizontal electric field, V/m

$|H|$ = amplitude of horizontal magnetic field, A/m

ω = angular frequency, $2\pi f$ (f = frequency, Hz)

μ = magnetic permeability (considered to be equivalent to magnetic permeability at free space, $\mu_o = 4\pi \times 10^{-7}$ Henry/m)

Here, the ratio $|E/H|$ is also called the Cagniard impedance. The calculation is done either using the ratio Ex/Hy or Ey/Hx.

Thus calculated apparent resistivities for respective frequencies are plotted on an apparent resistivity pseudosection (Fig. 10). It has been observed that the apparent resistivity values are very low at all frequencies the Uemachi Fault in the westernmost part of the area. Similarly, a gradual decrease in apparent resistivity towards the east is observed, particularly at sounding points P9 and P10. Rather high apparent resistivities have been observed at low frequencies, especially at sounding points P2, P4, P7, and P8. Thus, it is clearly observed that there are conductive layers even at deeper levels at the two extremities of the survey area.

The layer resistivities were obtained by using one dimensional inversion package. This package utilises the Marquardt algorithm for least square estimation of nonlinear parameters (Marquardt 1963). Sasaki (1981) has applied this algorithm also for the inversion of direct current electrical resistivity field data. Because of the principle of equivalence, there is a range of values of each resistivity and thickness that will all produce the same sounding curve In view of this, the number of iterations of inversion was decided based

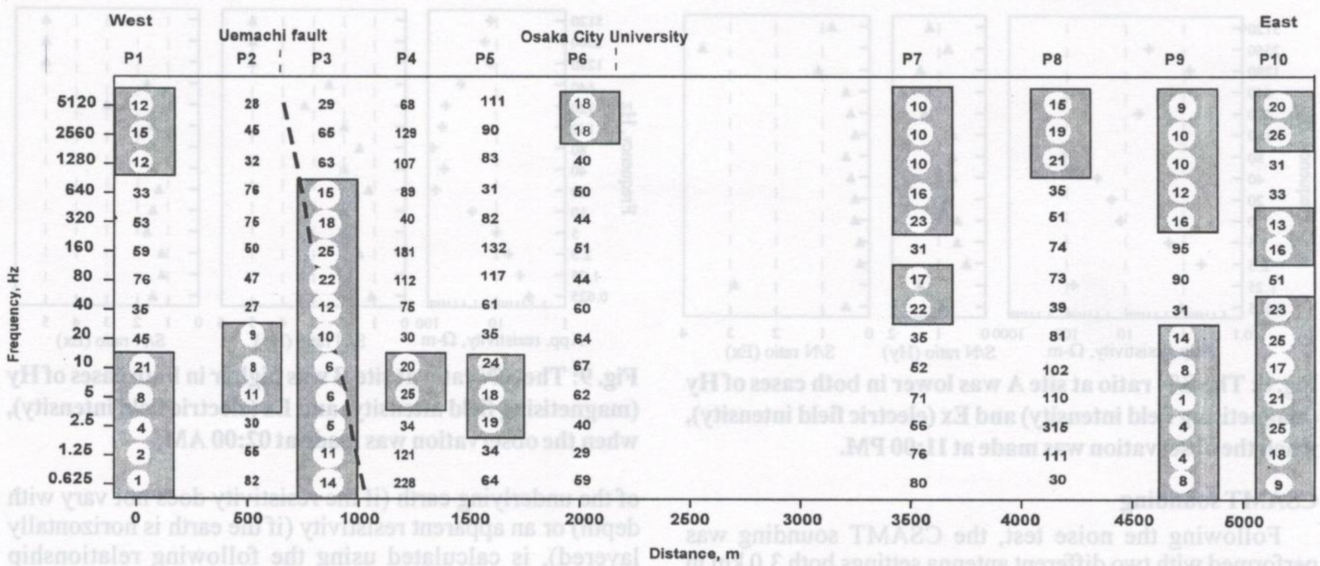

Fig. 10: Apparent resistivity pseudosection along the Yamato River. Shaded zones represent the conductive zone with the apparent resistivity values less than 25 Ωm at respresentative frequencies.

on the lowest error value of the fit. For most of the observation points, the least error was found after 5 iterations. The inversions can be constrained by other geophysical data or by borehole data. However, in present case the inversion was fully automated since no adequate reference data were available in the survey area.

The top few m in almost all sounding points show low resistivities (Fig. 11). It was possible to obtain the resistivity model up to 1 km depth at all observation points except at point P1 where there is a continuous decrease in resistivity at lower frequencies. This is because of the reason that the electromagnetic method is not capable of detecting structure beneath very high conductive overburden (Strangway et al. 1973). The depth of exploration is usually found considerably less than a skin depth in conductive areas (Sandberg et al. 1982).

The resistivity values obtained from the inversion clearly show that the top few m have low resistivity. The presence of a high conductive zone (< 20 Ωm) can also be observed below the depth of 150 m at the westernmost part of the study area, especially near the Uemachi Fault. Similar condition has been observed in easternmost part of the study area. The thick, high resistivity zone (> 100 Ωm) exists below the depth of 600 m at observation point P2 in western part, while in the eastern part, at observation points P7 and P8, it extends further downwards from around the depth of 400 m. In addition, layers with the resistivity values lying between 25 and 100 Ωm are distributed at various depths in all sounding points. These intermediate resistivity zones are lying in between the highest and lowest zones, indicating the absence of very sharp change in resistivity values. The resistivity change at different depths is in good agreement with the seismic reflection pattern as observed in the seismic section.

Resistivity model and geological implications

The subsurface geology of the study area is not known in detail. Almost all the investigation deep borings (OD series) lie farther away from the area. The seismic reflection sections of Sugiyama (1997), Nishida (1992), and Toda et al. (1992), along the Yamato River were compiled. It can be clearly seen that most of the reflectors in the eastern part are flat, slightly inclined towards the east. However, in the western part, the vertical displacement of the strata around the Uemachi Fault is clearly observed. Besides, different geological boundaries have been identified from the seismic section, which facilitated to demarcate the different geological subdivisions in the area. It has been observed that the resistivity change at different depths corresponds to the different seismic reflectors. It is found that the youngest alluvium and terrace deposits have 44 Wm as the average resistivity value, while for the Upper, Middle, and Lower Osaka Subgroups, it is 105 Ωm, 80 Ωm, and 93 Ωm, respectively.

The conductive zone in the westernmost part can be contributed to the effect of Uemachi Fault. The decrease in resistivity values in the vicinity of faults has reported by many authors (Sandberg et al. 1982). In view of the presence of hot springs in the eastern part of the study area as well as in other parts of the Osaka Basin, the conductive zone at depth can be correlated to the effect of hydrothermal solutions. Further, the high chloride content in the groundwater samples (up to 300 m), north of Yamato River in the study area is interpreted as the result of the fossil water (Tsurumaki 1962, 1970). However, there is no additional information whether the fossil water horizon continues around the study area and extends further down.

A comparison of the resistivity values obtained from the present study and that from the borehole logging

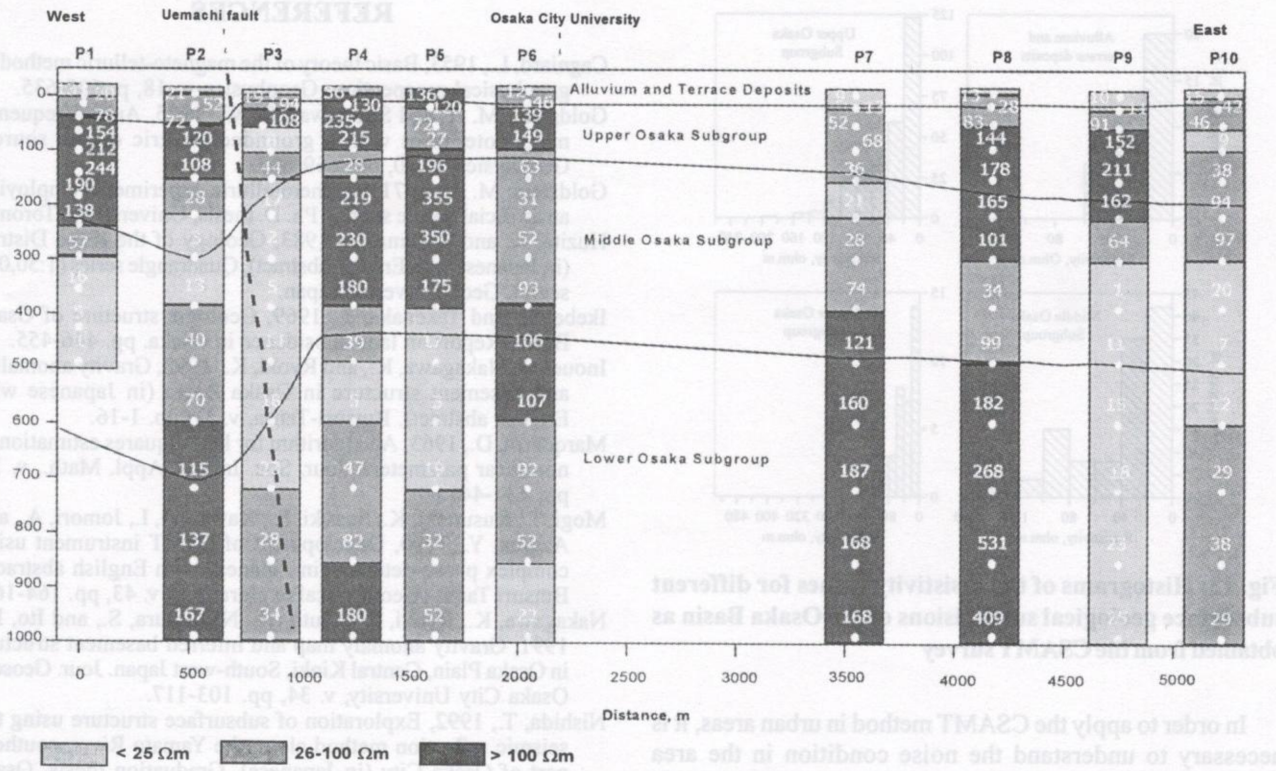

Fig. 11: Layer resistivities obtained from 1-D inversion of CSAMT data. Note that the vicinity of the Uemachi Fault in the west is characterised as a highly conductive zone. The geological boundaries are derived from the different reflectors (referring to the change in density and velocity of the layer) as observed in the seismic section.

(Ikebe et al. 1969) indicated that the resistivity ranges as well as the average values for the youngest sediments (alluvium and terrace deposits) are close in both cases (Fig. 12, 13). Whereas, in case of the entire Osaka Group, the resistivity values obtained by present study are higher in comparison with that obtained from the borehole logging. The upper range of resistivity of the Lower Osaka Subgroup, obtained from the borehole logging is too low (maximum being 60 Ωm). In this connection, the possibility of the presence of fossil water, hydrothermal solution as well as the effect of fluid in borehole can not be ignored. Furthermore, the biased location of the borehole should be taken into account because the fossil water is not distributed throughout the Osaka Basin. Another point worthwhile to be considered is that in case of logging, the probe is in close contact to the formation and the contained fluid. Whereas, in the case of surface exploration, only the impedance in terms of electric and/or magnetic response of the subsurface strata is measured. There is no close contact between the formation and receiving dipoles, and hence it gives comparatively higher resistivity values.

CONCLUSIONS

Since the CSAMT method can overcome the problem of variability of primary field and weak signal strength of the natural source as encountered in the natural source MT method, its application in urban areas has become possible.

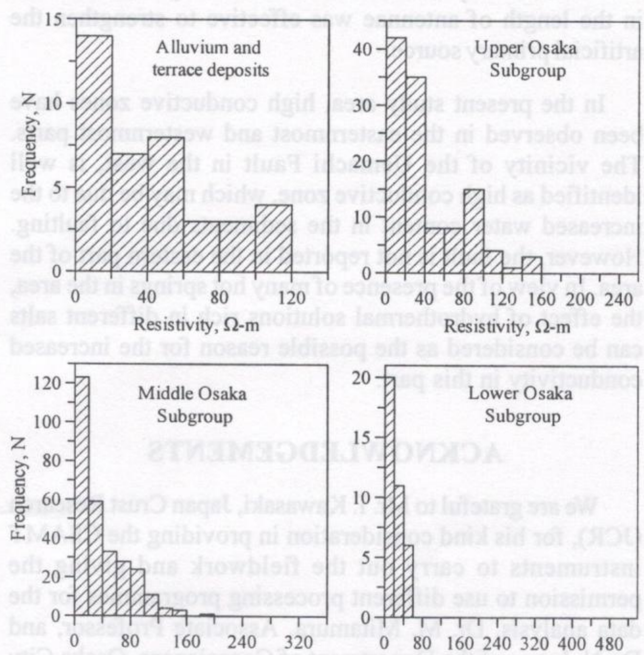

Fig. 12: Histograms of the resistivity values of different subsurface geological subdivisions of the Osaka Basin as obtained from the borehole logging

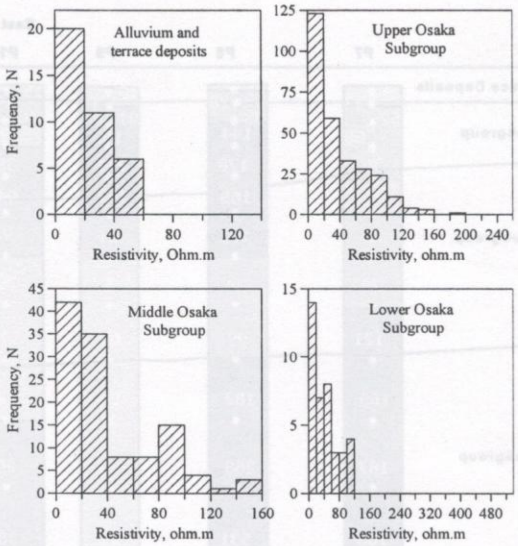

Fig. 13: Histograms of the resistivity values for different subsurface geological subdivisions of the Osaka Basin as obtained from the CSAMT survey

In order to apply the CSAMT method in urban areas, it is necessary to understand the noise condition in the area properly. The increase in sampling time, which is usually effective to enhance the signal by attenuating the noise, is not effective in the area where the noise level is very high. Repeated measurement and use of a couple of receiving electrodes is very effective to sort out noisy data. Increase in the length of antennae was effective to strengthen the artificial primary source.

In the present study area, high conductive zones have been observed in the easternmost and westernmost parts. The vicinity of the Uemachi Fault in the west, is well identified as high conductive zone, which may be due to the increased water content in the sediments due to faulting. However, the fault is not reported in the eastern part of the area. In view of the presence of many hot springs in the area, the effect of hydrothermal solutions rich in different salts can be considered as the possible reason for the increased conductivity in this part.

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REFERENCES

Cagniard, L., 1953, Basic theory of the magneto-telluric method of geophysical prospecting: Geophysics. v. 18, p. 605-635.

Goldstein, M. A. and Strangway, D. W., 1975, Audio-frequency magnetotellurics with a grounded electric dipole source. Geophysics, v. 40, pp. 669-683.

Goldstein, M. A., 1971, Magnetotelluric experiments employing an artificial dipole source. Ph. D. thesis, University of Toronto.

Huzita, K. and Kasama, T., 1983, Geology of the Kobe District (in Japanese with English abstract), Quadrangle series (1:50,000 scale). Geol. Survey of Japan.

Ikebe, N. and Takenaka, J., 1969, Geologic structure of Osaka Basin. Report on land subsidence in Osaka. pp. 446-455.

Inoue, N., Nakagawa, K., and Ryoki, K., 1998, Gravity anomalies and basement structure in Osaka Basin (in Japanese with English abstract). Butsuri-Tansa, v. 51, pp. 1-16.

Marquardt, D., 1963, An algorithm for least-squares estimation of nonlinear parameters. Jour. Soc. Indust. Appl. Math., v. 11, pp. 431-441.

Mogi, T., Kusunoki, K., Suzuki, K., Kawasaki, I., Jomori, A., and Azuma, Y., 1990, Development of CSMT instrument using complex phase-detector (in Japanese with English abstract): Butsuri Tansa (Geophysical exploration). v. 43, pp. 164-169.

Nakagawa, K., Ryoki, K., Muto, N., Nishimura, S., and Ito, K., 1991, Gravity anomaly map and inferred basement structure in Osaka Plain, Central Kinki, South-west Japan. Jour. Geosci., Osaka City University, v. 34, pp. 103-117.

Nishida, T., 1992, Exploration of subsurface structure using the seismic reflection method along the Yamato River, southern part of Osaka City (in Japanese). Graduation thesis, Osaka City University, 111 p.

Ryoki, K., 1995, A electrical prospecting system for inferring basement structure in the urbanized area (in Japanese with English abstract). Jour. Osaka Polytechnic college, v. 3, pp. 13-22.

Sasaki, Y., 1981, Automatic interpretation of resistivity sounding data over two-dimensional structures (I) (in Japanese with English abstract): Butsuri Tanko (Geophysical exploration). v. 34, pp. 15-24.

Sandberg, S. K. and Hohmann, G. W., 1982, Controlled-source audiomagnetotellurics in geothermal exploration, Geophysics. v. 47, pp. 100-116.

Strangway, D. W., Swift, C. M., and Holmer, R. C., 1973, The application of audio-frequency magnetotellurics (AMT) to mineral exploration: Geophysics. v. 38, pp. 1159-1175.

Sugiyama, Y., 1997, Seismic reflection survey of the Uemachi fault system (in Japanese).(*in* outline of active fault investigation during the fiscal year 1996). Geological Survey of Japan investigation report No. 303.

Toda, S., Nakagawa, K., Mitamura, M., Nishida, T., Yamamoto, E., Terada, Y., Uda, H., and Yokota, H., 1992, Seismic reflection method at the Central Osaka Plain (in Japanese): Yamato River (Oriono-Yata line). Japan Soc. Engg. Geol., Abstract, x, pp. 189-192.

Tsurumaki, M., 1962, Quality of ground water in Western Osaka, Japan - with special reference to the genesis of high-chloride zone. Jour. Geosci., Osaka City University, v. 6, pp. 145-186.

Tsurumaki, M., 1970, Quality of groundwater in Eastern Osaka, Japan, and its hydrogeological interpretation. Jour. Geosci., Osaka City University, v. 13, pp. 149-178.

Ward, S. H., 1990, Resistivity and induced polarization methods. In: Ward, S. H. (ed.), Geotechnical and environmental geophysics. Society of Exploration Geophysicists (SEG). v. I, sp. publ., pp. 147-189.