Conceptual and Predictive Design for Geophysical Information Measurements and Evaluation by Electrical Methods**

By

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Abstract

In the recent geophysical information measurements by electrical methods, it is worth special mention that conceptual and preliminary/predictive design for the performance of methods applied to practical problems have become more important to investigate than ever. Since geoelectrical resistivity interpretation techniques have become very useful tools for high accuracy geophysical information measurements, it may be exceedingly important for their practical application to design preliminary/predictive models and methods using computer 2D-3D or 3D simulation and visualization.

In this paper, first, the significance of conceptual and preliminary/predictive design for evaluating geophysical information measurements is described, with the problems and the characteristics of geophysical target inhomogneities, fundamental research and application activities, extraction and enhancement of desired geophysical information, modeling, sensitivity analysis, standard curves catalogs, and interpretive design of models, for reliable geophysical information measurement.

Next, the author reviews the three-dimensional (3D) sensitivity analysis technique and its extended method. Finally, sensitivity analysis for the improvement of accuracy of geophysical information measurements by the electrical method, the development of differential sensitivity distribution analysis technique and the examples of computerized clear image models are discussed.

1. Introduction

Recent advances in research on geophysical information measurements include improvement of borehole geophysical methods, clear geophysical imaging techniques, high density computer simulation and visualization, subsurface information prediction, target-oriented interpretation, high-resolution analysis, system and modeling optimizations, evaluation methods, integrated geophysical interpretation and inter- or multi-disciplinary studies and applications. The increase of activity in geophysics and geology has led to the assessment of geophysical

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information measurements for detecting, propsecting, mapping, monitoring and evaluating natural mineral and energy resources, groundwater reserves, engineering/conservation of environments and also rock and other materials testing. Geophysical information measurement by electrical methods can assist in prospecting target inhomogeneities and in the detailed characterization of their surrounding geological structures.1-2)50)54)

In geophysical information measurements, electrical resistivity tomography (ERT) becomes a conventional tool, as described by Daily and Owen (1991)11), for detecting the electrical resistivity distribution in the various subsurface structures from discrete borehole information measurements. Furthermore, Yorkey (1986)32) has already developed a reconstruction technique for electrical impedance tomography in which no prior knowledge of the subsurface resistivity need be assumed. Yorkey's algorithm provides a flexible method if inverting electrical data taken in a variety of solid array configurations, including crossborehole, or borehole-to-surface. At present, however a complete effective ERT algorithm based on an effective forward solution of Laplace's equation has not been constructed. Asch and Morrison (1989)3) investigated mapping and monitoring electrical resistivity with surface and subsurface electrode arrays and Le Masne and Poirmeur (1988)6) and Poirmeur and Vasseur (1988)7) studied the three-dimensional model results for an electrical hole-to-surface and hole-to-hole method from the view point of electrical 3D surveys. As a theoretical study, it is worth special mention that Lytle (1982)10) already developed resistivity and induced-polarization probing in the vicinity of a spherical anomaly, which was reported in the paper, IEEE Trans. Geosci. Remote Sensing. And also, a practical study on preliminary design for the multi-array borehole electrical method by Green and Ward (1986)13) is significant research supporting cost-effective development of fracture controlled (or other complex) geothermal reservoirs and the environment. Recently, as a high accuracy modeling technique, Lowry, Allen and Shive (1989)46) proposed singularity removal: a refinement of the resistivity modeling method, in which the primary component of the partial equation may be reduced and secondary component can be calculated by the discrete algorithm. And the inversion of pole-pole data for 3D resistivity structures beneath arrays of electrodes studied by Park and Van (1991)12) has proved an efficient research activity. Sugano and Sassa (1989)14) and Sugano (1989, 1990a)26-27) conducted the computer simulation and the theoretical studies to evaluate response due to target inhomogeneities and to evaluate the solid electrode array (three-dimensional) effects in the computerized section construction procedure for resistivity interpretation. Sugano (1991a, 1991b)50-51) has investigated the evaluation of reliability in the computerized geotomographic image model selection by electrical methods.

Today, geophysical/geological information measurements can provide more reliable and stable subsurface estimation procedures, including effective monitoring and evaluating elements for the improvement of selection of electrical clear image model. Systematical and integrated evaluation methods have been fundamentally investigated for a more successful and reliable geophysical measurement system of subsurface information due to various target inhomogeneities. In recent geophysical information measurements by electrical methods, new conceptual and preliminary design for the performance of methods applied to practical problems have become more important to investigate than ever. Also, as solid electrode array (three-dimensional) resistivity interpretation techniques have become very useful tools for high accuracy geophysical information measurement, it may be especially useful for practical applications to design preliminary models and methods using computer simulation and visualization of subsurface geophysical information.28-29)50)54)

First, in Section 2, the significance of conceptual and preliminary design for evaluating geophysical information measurements are described, with the problems of the characteristics of geophysical target inhomogeneities, fundamental research and application activities, extraction and enhancement of desired geophysical information, three-dimensional modeling and sensitivity analysis, standard curve catalogs, and basic concepts of computerized image models for reliable geophysical information measurements. And then, in Section 3, the author reviews three-dimensional sensitivity analysis for the improvement of accuracy of geophysical information measurements by the electrical methods, and the development of a differential sensitivity distribution analysis technique. Section 4 shows examples of computerized clear image models made by the three-dimensional extended differential sensitivity analysis method. Finally, in Section 5, discussions and conclusions are described.

2. Significance of preliminary design for geophysical information measurements and evaluation by the three-dimensional and the extended sensitivity analyses

2.1 Category of geophysical information measurements by electrical techniques

Table 1 shows the systematical concept of geophysical information measurements by surface and solid (hole-to-surface, tunnel-to-surface or crosshole) using surface and subsurface electrodes. The recent tools are the computer modeling technique, sensitivity analysis of electrical methods, catalogs of standard master curves and subsurface image reconstruction techniques including computerized tomography and extended geophysical visualization.

Table 1 Conceptual design for geophysical information measurements by electrical methods

CONCEPTUAL DESIGN

MODELING
FORWARD & INVERSE PROBLEMS

SINGLE-BOREHOLE
GEOPHYSICAL
INFORMATION
MEASUREMENTS

SENSITIVITY
ANALYSIS

2D-3D & 3D
ALGORITHM
COMPUTER
SIMULATION

SOLID ARRAY
ELECTRICAL METHODS
GEOPHYSICAL
INFORMATION
MEASUREMENTS

STANDARD
CATALOG
CURVES

VISUALIZATION
IMAGING
GEOTOMOGRAPHIC
MODEL RECONSTRUCTION

CASE HISTORIES

MULTI-DISCIPLINARY
WELL-BALANCED
INTERPRETATION

HIGH-ACCURACY
HIGH-RESOLUTION
RELIABLE
DESIRED INFORMATION
AND KNOWLEDGE

2.2 Electrical characteristics of geophysical target inhomogeneities

Generally speaking, all of the electrical resistivity target inhomogeneities are classfied into three groups. The resistivity of the first group, conducting target inhomogeneities called conductors, is less than 10^{-7} ohm-m. The resistivity of the second group, called semi-conductors, ranges from 10^{-7} ohm-m to 10^5 ohm-m, and of the third group, insulating target inhomogeneities, is greater than 10^5 ohm-m. In geophysical information measurements, mineral, clay and seawater have low resistivity, and rock materials have high resistivity. Also, soil or rock materials with a high water content have lower resistivity. Archie's law is as follows:

$$\rho_a/\rho_w = a\varphi^{-m} \qquad (1)$$

where ρ_a is the resistivity of the target inhomogeneities or the geological structure formation which is saturated by groundwater with a resistivity ρ_w, and φ and m

are the porosity and cementation factors, respectively. Therefore, the electrical resistivity classification is very useful for the evaluation of geophysical target inhomogeneities, for example, rock characterization or investigation of hydrogeological targets. Table 2 shows the applications of geophysical information measurements by electrical methods.[50)]

Table 2 An example of application activities in the author's database of geophysical information measurements.

	Target	Application Research Activity	Keywords, Electrode Array Design
1	Geological Structure, Mineral Deposit	Yanahara Mine	Using Tunnel, Mise-a-la-Masse, C(pilot borehole)P(tunnel) Electrical Monitoring Resistivity, Anisotropy, IP
2	Rock, Fracture, Fault	Yahagi Dam (M.C.) Kisenyama Underground Power Plant Tail Race Tunnel	Before and After Grouting CPPC(borehole), Cross-section Monitoring, Grouting Effects Low and High Pressure Groutings C(DH-1)P(DH-2)P(DH-3)C(DH-4), C(DH-1)C(DH-2)P(DH-3)P(DH-4) Electrode Rotating Array
3	Environment Engineering	Toa Fuel Shimizu Industry, Tank Foundation Poor Subsoil	Improvement Effect,C(surface)P(DH-1)P(DH-2)C(surface),C(DH-1)P(DH-2)P(DH-3)C(DH-4)Solid Array
4	Groundwater	Musashino JR Ikuta Tunnel	Borehole-to-Surface, C(subsurface)PP(surface) Groundwater Flow Direction Resistivity Measurement
5	Tunnel Underground Cave,Space and etc.	Sanyo-Shinkansen Rokko Tunnel Chuo-Expressway Ena Tunnel	Fault Prediction Using Tunnel and Surface Topography Effects Mise-a-la-Masse, C(surface)P(tunnel),CC(surface)PP(tunnel)Solid Array

2.3 Three-dimensional modeling and the standard resistivity curves

In practical problems, both controlled current sources and earth structures deal with three-dimensional elements. And also, the response due to target inhomogeneities in the geophysical information measurements must be interpreted as three-dimensional problems. However, as the high level computer model simulation has been conducted at the same level as the complex field problems, one can not interpret and evaluate the results of the computer modeling by three-dimensional methods. Therefore, as a tool for the reliable evaluation of the computer complex results calculated with difficulty, it is necessary to provide the standard curve catalogs for the typical target inhomogeneities.

Figure 1 shows an example of 3D resistivity modeling[55)] (Sugano, Arai and Sassa, 1991). The 3D earth structure model shown in Figure 1a has been simulated by newly developed three-dimensional electric resistance network. Figure 1b

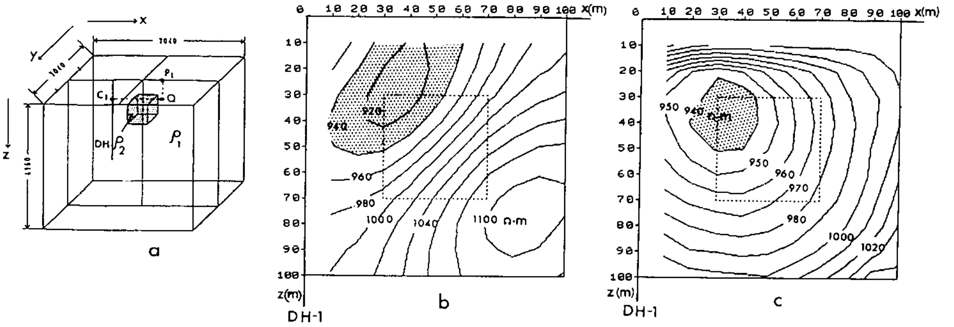

Fig. 1 An example of three-dimensional modeling.[55]
(a) Target inhomogeneity modeled by three-dimensional electric resistance network,
(b) Resistivity standard curve expressed by onepoint plotting pseudosection for C(subsurface, borehole DH-1)P(surface) pole-pole solid array system,
(c) Multi-plotting resistivity pseudosection for the same solid array system as the case shown in Figure 1b.

shows the result of the resistivity modeling, which consists of the current source C_1 (subsurface, borehole DH-1) (See Fig. 1a) and the potential electrode P_1 (surface) (See Fig. 1a) which is the so-called hole-to-surface solid electrode array system, and a unit cubic conducting structure (mineral body, fractured zone or hydrogeological formation with high water content) with a resistivity of 100 ohm-m, in a homogeneous background (rocks or fresh geological formation) with a resistivity of 1000 ohm-m. The standard curve shown in Figure 1b has been expressed by the onepoint plotting resistivity pseudosection method. Figure 1c indicates an expression of the resistivity information calculated by the multi-plotting pseudosection technique in the preliminary interpretation procedure.

2.4 Basic concept of computerized subsurface image model based on sensitivity analysis

As is well known, it is very efficient to investigate the sensitivity analysis of electrical methods. Sensitivity analysis for the arbitrary solid array system is significantly useful for the evaluation of interpreted field measurement data or three-dimensional complex computational results.

Figure 2 shows examples of the three-dimensional sensitivity distributions in the vertical section and the horizontal sections for the CC(subsurface, vertical borehole DH-1)PP(subsurface, vertical borehole the DH-2) dipole-dipole solid

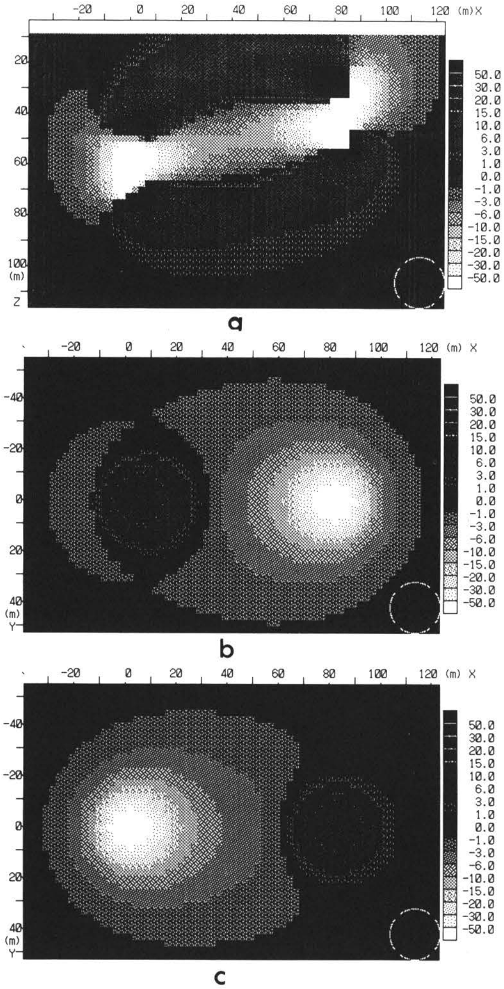

Fig. 2 Examples of the three-dimensional sensitivity analysis of electrical method.

(a) Sensitivity distribution at the vertical section with the electrodes for CC(subsurface, borehole DH-1)PP(subsurface, borehole DH-2) solid array system,

(b) Sensitivity distribution at the horizontal section in the depth of 40 m for the same electrode array as the case shown in Figure 2a,

(c) Sensitivity distribution at the horizontal section in the depth of 60 m for the same electrode array as the case shown in Figure 2a.

array system. Figure 2a shows a vertical section of the three-dimensional sensitivity distribution. Figures 2b and 2c show the horizontal sections of the three-dimensional sensitivity distributions at the depths of 40 m and 60 m for the same CC(borehole DH-1)PP(borehole DH-2) crosshole system.

Usually or, in the interpretation procedure, at first, the potential distribution due to the target inhomogeneities by electrical array configuration must be calculated. The forward problem is: given the following relation under the equations,

$$\nabla\cdot(1/\rho)\nabla V=0 \qquad (2) \qquad \text{in the domain of interest,}$$

$$(1/\rho)(\partial V/dn)=\gamma \qquad (3) \qquad \text{on the boundary of the domain,}$$

where ρ is the resistivity distribution, which is everywhere real and positive, V the potential distribution, n the outward normal, and γ the applied flux, what is any potential distribution or any apparent resistivity distribution? And at the next stage, the inverse problem is: given the apparent resistivities based on potential or potential difference data, ρ_{af}, what is the resistivity distribution? To solve the inverse problem, generally a least-squares error is defined,

$$\varepsilon=(1/2)(\rho_{af}-\rho_{ac})^T(\rho_{af}-\rho_{ac}) \qquad (4)$$

where ρ_{ac} is calculated by the computer model. The optimum resistivity distribution must be selected minimizing ε. The theoretical apparent resistivity can be obtained by the two (2D) and three-dimensional (so-called 2D-3D) finite element method or the three-dimensional (3D) electric resistance network solution, and also, by using the FEM 2D-3D or the resistance network solution. Furthermore, using the FEM 2D-3D or the network 3D algorithms, apparent resistivity or sensitivity distributions can be easily obtained.

For the image model selection, the following sensitivity equations have been used,

$$I_{k.ij}=\Sigma w^{ij}{}_{k,n}\cdot R_{ak,n} \qquad (5)$$

$$w^{ij}{}_{k,n}=S^{ij}{}_{k,n} \qquad (6)$$

where $S^{ij}{}_{k,n}$ is the sensitivity due to the target inhomogeneity locating i,j for arbitrary electrode array, $w^{ij}{}_{k,n}$ the filter coefficient at the location of target, $I_{k,ij}$ the initial resistivity information after filtering by the equation (5), and $R_{ak,n}$ the apparent resistivity data to be inverted with number of data n. In order to analyze the resistivity distribution of ρ_k, the following relation has been introduced,

$$\begin{bmatrix} S_{11}\ S_{12}\ \cdots\cdots\ S_{1n} \\ \cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots \\ S_{k1}\ S_{k2}\ \cdots\cdots\ S_{kn} \\ \cdots\cdots\cdots\cdots \\ S_{n1}\ \cdots\cdots\cdots\ S_{mn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \cdot \\ I_k \\ \cdot \\ I_n \end{bmatrix} = \begin{bmatrix} R_{a1} \\ R_{a2} \\ \cdot \\ R_{ak} \\ \cdot \\ R_{an} \end{bmatrix} \qquad (7)$$

where $R_{ak}(k=1,2,3,...,n)$ are input data and $[S]$ is the sensitivity matrix

$$[I]=[R_a]\ \ [S]^{-1} \qquad (8)$$

The resistivity information I_k $(k=1,2,3,\cdots,n)$ can be easily obtained by the above back projection equation (8). Therefore, the relation (7) or (8) provides the resistivity initial information for each cell of the target inhomogeneities in the domain of interest for the vertical or horizontal sections of computerized images.

2.5 Some problems in the fundamental research and the application activities

The increase of activity in geophysics and geology has led to the assessment of geophysical information measurements for detecting, prospecting, mapping, monitoring and evaluating mineral and energy resources, groundwater reserves, engineering, environments and also rock and other materials testing.

As shown in Table 1, modeling, forward and inverse problems, 2D-3D or 3D algorithm computer simulation, sensitivity analysis and standard catalog curves are very important fundamental elements. After them, resistivity measurements using single-borehole or solid array electrical methods, imaging, and subsurface visualization including geotomographic model reconstruction are the second level tools. And finally case histories, multi-disciplinary and well-balanced interpretation high-accuracy, high-resolution, reliable information and desired information and knowledge are found in the application research activities.

3. Sensitivity analysis for the improvement of accuracy of geoelectrical information measurements

3.1 Sensitivity analysis for the improvement of accuracy of geoelectrical information measurements

As is well known, the generalized solid electrode array system does not always have a constant configuration factor but often zero or infinite value. Figure 3 illustrates the examples of the discontinuity of geometric interference for solid

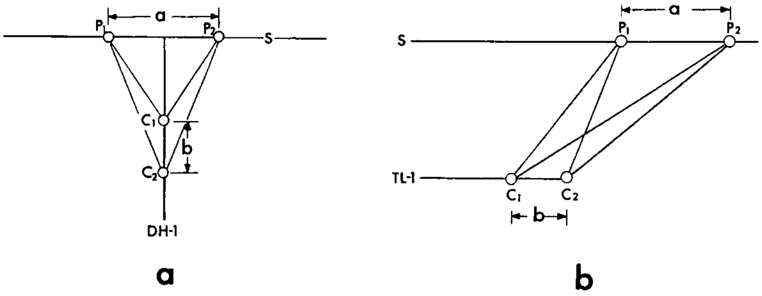

Fig. 3 Examples of differential solid electrode arrays.
(a) CC(borehole DH-1)PP(surface)hole-to-surface configuration as the pure differential system,
(b) CC(tunnel TL-1)PP(surface)tunnel-to-surface configuration as the extended differential system.

array systems: (a) CC(subsurface, borehole)PP(surface), and (b) CC(subsurface, tunnel)PP(surface). For example, in the case of zero value of the geometric factor G shown in Figure 3a, the apparent resistivity method can not be applied to all of the data obtained by their solid array systems because of discontinuity. In general, the conventional apparent resistivity method has been conducted in the condition of no presence of the discontinuity data or reduction of these data. Therefore, using subsurface image model construction by the conventional apparent resistivity method. It is very important that the perfect use of the data can not be performed for the arbitrary subsurface or solid electrode array system.

3.2 Development of the differential sensitivity and the extended differential sensitivity analysis techniques

As above mentioned, in arbitrary electrode array systems, the sensitivity distribution method expressed can not always cover the resistivity interpretation. Removal of the discontinuity shown such as in Figures 3a and 3b of the geometric interference is a very important problem for the development of clear image model construction techniques. The conventional method, which often includes discontinuities of resistivity geometric interference, has been applied after reducing the discontinuity data aquired by the system.

However there are many discontinuity cases in electrical array systems. In this study, the differential sensitivity distribution method has been developed, by which all the electrical measurement data can be used for resistivity image model construction. It is especially effective for solid electrode array configurations. In this new analysis, the differential sensitivity $S_k{}^E$ can be newly defined as follows,

$$S_k{}^E = S_{k1}{}^E - S_{k2}{}^E \qquad (9)$$

where $S_{k1}{}^E$ is the sensitivity difference between the sensitivity S_{k11} for C_1P_1 pole-pole electrode system (domain of apparent resistivity ρ_{ak11}) and the sensitivity S_{k12} for C_1P_2 system (domain of apparent resistivity ρ_{ak12}), and $S_{k2}{}^E$ is the sensitivity difference between the sensitivity S_{k21} for C_2P_1 pole-pole electrode system (domain of apparent resistivity ρ_{ak21}) and the sensitivity S_{k22} for C_2P_2 system (domain of apparent resistivity ρ_{ak22}).

$$\left.\begin{aligned} S_{k1}{}^E &= S_{k11} - S_{k12} \\ S_{k2}{}^E &= S_{k21} - S_{k22} \end{aligned}\right\} \qquad (10)$$

where the sensitivities S_{k11}, S_{k12}, S_{k21} and S_{k22} are $(\rho_{ak11} - \rho_{akN})/\rho_{akN}(\rho_{akN}$: apparent resistivity of the background inhomogeneities $\rho_N)$, $(\rho_{ak12} - \rho_{akN}/\rho_{akN}$, $(\rho_{ak21} - \rho_{akN})/\rho_{akN}$ and $(\rho_{ak22} - \rho_{akN})/\rho_{akN}$.

Extensively, the definition of the differential sensitivity $S_k{}^E$ can integrate the formula for the composition and separation of the sensitivity distribution as in the following equation,

$$S_k{}^E = \sum_{i,j}^{2} (-1)^{i+j} S_{kij}. \qquad (11)$$

The differential sensitivity with the relation of $S_k{}^E \leqslant 0$ in the case of $\rho_k \leqslant \rho_N(\rho_k$ is the resistivity of the target inhomogeneity, and ρ_N is the resistivity of the background inhomogeneities) is called the normal differential sensitivity, and the one with the relation of $S_k{}^E \geqslant 0$ in the case of $\rho_k \geqslant \rho_N$ is called the reverse differential sensitivity.

From equation (11), the extended differential sensitivity distribution analysis can be conducted by a procedure similar to the conventional sensitivity analysis.

3.3 Three-dimensional sensitivity and the extended differential sensitivity distributions

Figures 4a, 4b and 4c are the three-dimensional differential sensitivity distributions for CC(borehole DH-1, C_1(40,0,60)C_2(40,0,80), electrode spacing of 20 m)PP(surface, P_1(20,0,0)P_2(60,0,0)) solid array configurations, which are in the vertical section, and in the horizontal sections at the depths of 60 m and 70 m. These differential sensitivity distributions are constructed by the equation (9) newly defined. Figures 5a and 5b show the extended differential sensitivity distribution and the sensitivity distribution for the CC (borehole DH-1,

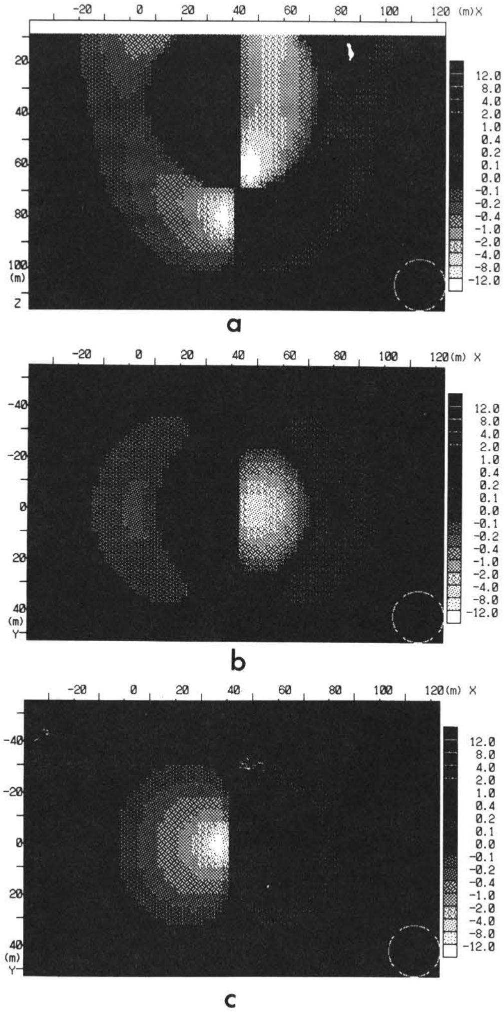

Fig. 4 Examples of the three-dimensional differential sensitivity analysis of electrical method.

(a) Differential sensitivity distribution at the vertical section with the electrodes for CC(subsurface, borehole DH-1)PP(surface)solid array system,

(b) Differential sensitivity distribution at the horizontal section in the depth of 60 m for the same electrode array as the case shown in Figure 4a,

(c) Differential sensitivity distribution at the horizontal section in the depth of 80 m for the same electrode array as the case shown in Figure 4a.

$C_1(40,0,60)C_2(40,0,80)$ electrode spacing of 20 m) PP(surface, $P_1(50,0,0)P_2(70,0,0)$) solid array configuration.

Of course, the pure differential sensitivity case shown in Figure 4a can not be constructed by the so-called sensitivity distribution method. Comparing Figures 5a with 5b, the distribution patterns are similar, in which the white zones are high normal differential and pure sensitivities, and the black zones near the current electrodes in the borehole DH-1 are distinct reverse differential and pure sensitivities. It is important that equation (10) and the extended relation expressed by equation (11) provide new sensitivity information in the case of the domain of apparent resistivity discontinuity.

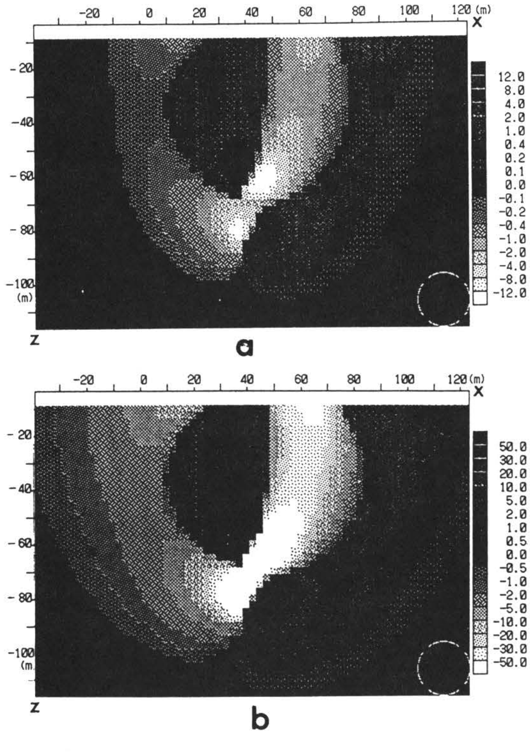

Fig. 5 Examples of the three-dimensional extended differential sensitivity analysis of electrical method.

(a) Extended differential sensitivity distribution at the vertical section with the electrodes for CC(subsurface, borehole DH-1)PP(surface) solid array system,

(b) Sensitivity distribution at the same vertical section as the case shown in Figure 5a.

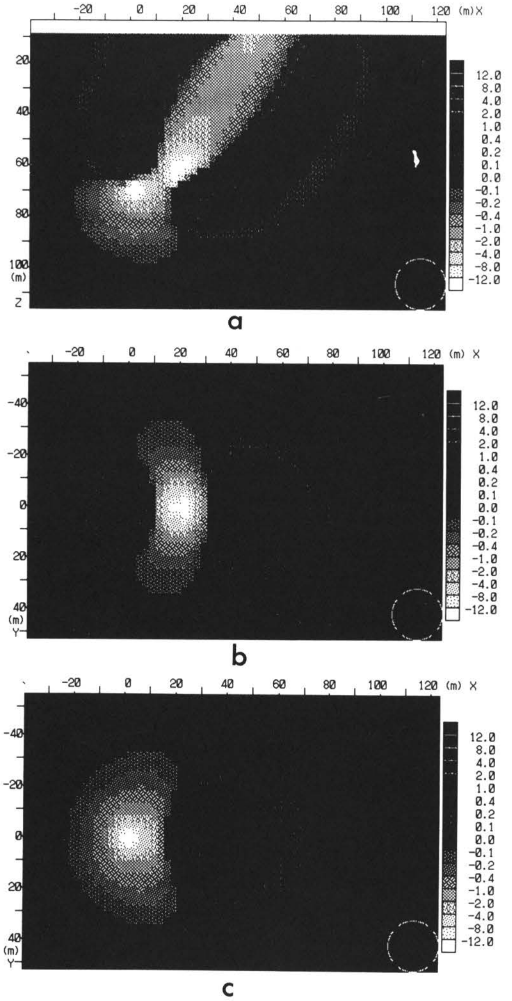

Fig. 6 Examples of the three-dimensional extended differential sensitivity analysis of electrical method.

(a) Extended differential sensitivity distribution at the vertical section with the electrodes for CC(subsurface, tunnel TL-1)PP(surface) solid array system,

(b) Extended differential sensitivity distribution at the horizontal section in the depth of 60 m for the same electrode array as the case shown in Figure 6a,

(c) Extended differential sensitivity distribution at the horizontal section in the depth of 80 m for the same electrode array as the case shown in Figure 6a.

Figures 6a, 6b and 6c show the extended differential sensitivity distributions for CC(tunnel TL-1)PP(surface)solid array configurations, which are in the vertical section, and in the horizontal sections at the depths of 80 m and 100 m. The normal differential sensitivities are distributed in the area between the tunnel TL-1 and the surface.

4. Computerized geotomographic image model by the three-dimensional differential sensitivity distribution techniques

Figure 7 shows an electrode combination pattern of CC(borehole DH-1, spacing 20 m)PP(surface, expanded spacing) hole-to-surface expanding array configuration as a differential data aquisition system. As the spacings of the surface expanded electrodes PP are 20,40,... and 240 m, differential data of one hundred and twenty are obtained. The target inhomogeneity is a perfectly conducting sphere in a homogeneous environment with a resistivity of 100 ohm-*m* and a radius of 10 m. The depth of the sphere center is 60 m from the surface. A point of the analysis is the pattern excited by the target anomaly. Figures 8a and 8b show the computerized horizontal sections reconstructed by the three-dimensional differential sensitivity distribution technique. The differential sensitivity distributions shown in Figures 4a and 4b have been referred in order to reconstruct the subsurface images. These differential sensitivity analyses

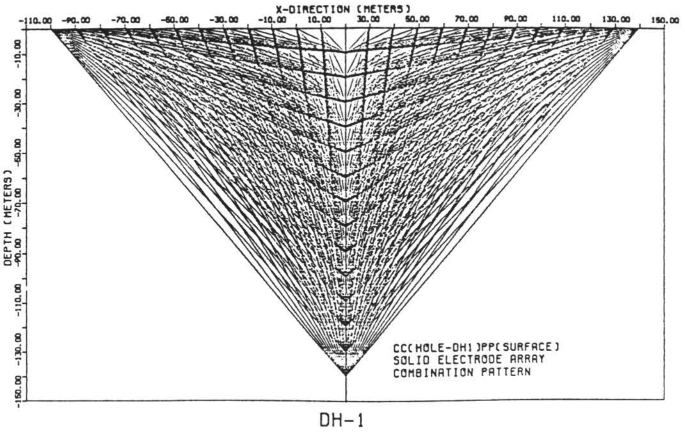

Fig. 7 An example of electrode combination pattern of geophysical information measurements by CC(borehole DH-1)PP (surface) extending hole-to-surface differential array system.

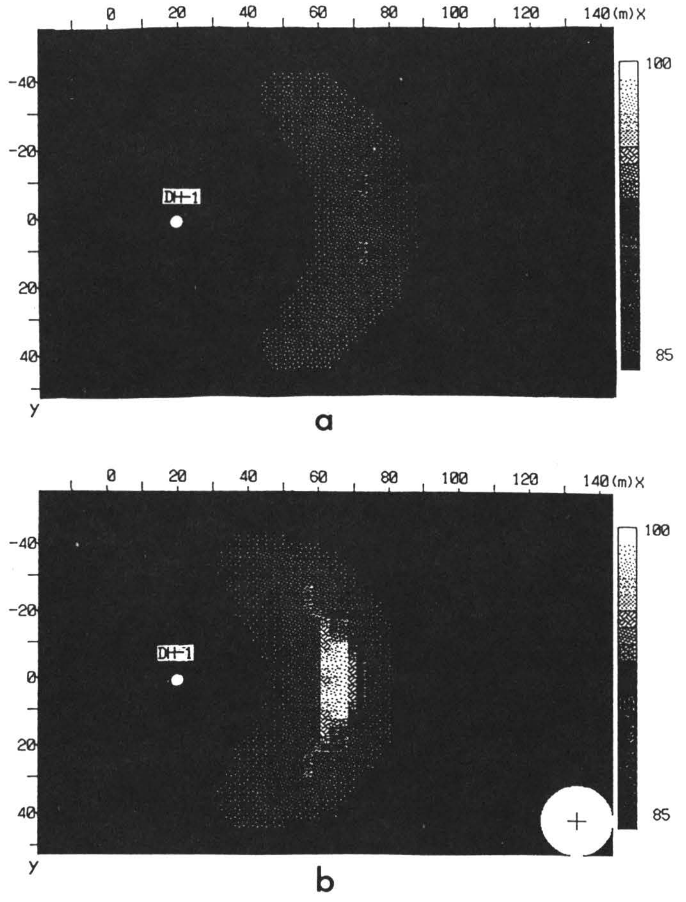

Fig. 8 Three-dimensional computerized horizontal sections for solid array geophysical information measurements.
(a) Computerized horizontal image section reconstructed by differential sensitivity distribution technique for solid array system in the depth of 50 m shown in Figure 7,
(b) Computerized horizontal image section reconstructed by differential sensitivity distribution technique for solid array system in the depth of 60 m shown in Figure 7.

indicate normal differential sensitivity zones and reverse differential sensitivity zones one by one at the right side of the borehole DH-1, and indicate the reverse differential sensitivity zones and $S_k^E(S_k^E<0)$ or the normal differential sensitivity zones in order at the left side of the DH-1. The computerized sections of the subsurface images shown in Figures 8a and 8b are displayed by a variable density shading as an expression of the probability of target inhomogeneities. High probability zone percentages appear near the center of the target spherical body. The size of target inhomogeneity is shown at the lower right corner of the display. Figure 8a shows the section at a depth of 50 m from the surface, and Figure 8b shows the section at a depth of 60 m from the surface including the center of the sphere. It is very interesting that the subsurface image shown in Figure 8a is affected by the weak response due to the target inhomogeneity. And next, Figures 9a, 9b and 9c show the vertical image sections reconstructed by the three-dimensional differential sensitivity distribution technique. Figure 9a shows the section at a distance of 30 m from the center of the sphere, Figure 9b shows the section at a distance of 15 m from the center of the sphere, and Figure 9c shows the section including the center of the sphere and the boreholes DH-1 and DH-2. The subsurface images shown in Figures 9a and 9b, in which the target body does not exist, are affected by the response due to the target inhomogeneity.

It is also significant and very important that any computerized resistivity section of a subsurface image can not be constructed by the conventional resistivity sensitivity technique in this typical differential electrical data aquisition system.

5. Conclusions

This study has clarified the significance of conceptual and preliminary design for evaluating geophysical information measurements with the problems of the characteristics of resistivity target inhomogeneities, fundamental research and application activities, extraction and enhancement of desired geophysical information, 2D-3D and 3D modelings, three-dimensional sensitivity analyses, and standard curve catalogs. Next, the author has demonstrated the applied sensitivity analysis technique with the extended method using several examples. Also, the three-dimensional sensitivity analysis for the improvement of accuracy of geophysical information measurements by the electrical method has been discussed by using examples of computerized clear image models.

The increase of activity in geophysics and geology has led to the assessment of geophysical information measurements for detecting, prospecting, mapping, monitoring, testing and evaluating, in which target inhomogeneities are natural mineral and energy resources, groundwater reserves, engineering and environmenal targets, and also rock and other materials testing. Geophysical information measurements by electrical methods can assist in prospecting target inhomogeneities and in the detailed characterization of their surrounding geological structures.

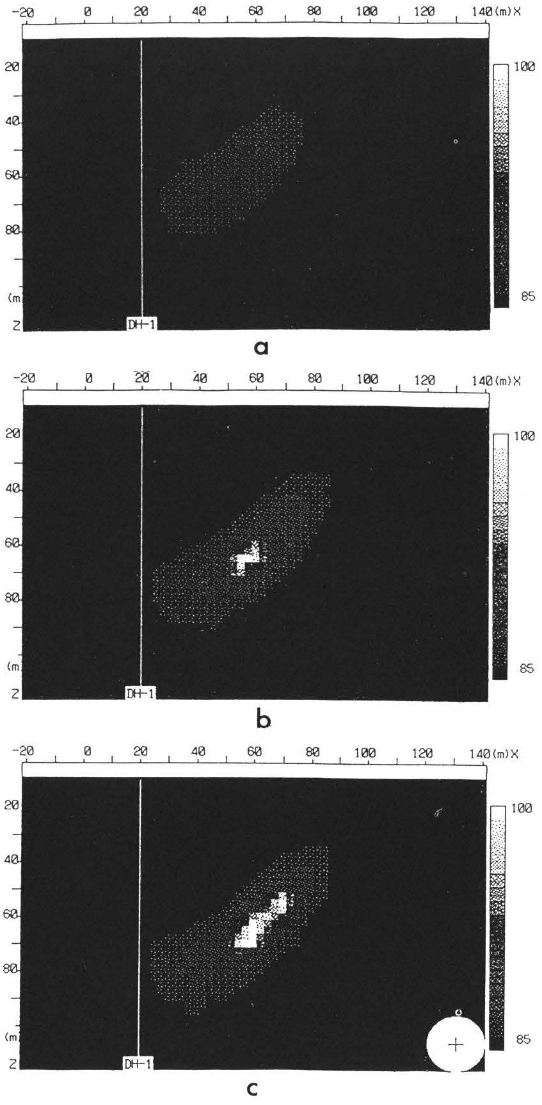

Fig. 9 Three-dimensional computerized vertical sections reconstructed by the differential sensitivity distribution technique for the same solid array system as the case shown in Figure 7.

(a) Computerized vertical image section at the distance of 30 m from the center of the sphere,

(b) Computerized vertical image section at the distance of 15 m from the center of the sphere.

(c) Computerized vertical image section including the center of the sphere, the borehole DH-1 and DH-2.

Today, geophysical/geological information measurements can provide more reliable and stable subsurface estimation procedures, including effective monitoring and evaluating elements for the improvement of the electrical clear image model selection. Integrated evaluation methods have been systematically performed for a more successful, reliable and powerful geophysical measurement system of subsurface information due to various kinds of target inhomogeneities under the various environmental earth structures.

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