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by

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Abstract

Using pole-dipole array, electrical resistivity survey was conducted to investigate the subsurface under a subsiding building located in Kita Kyushu area, Japan. The resistivity measurements were acquired along two traverse lines and interpreted using a graphical procedure known as Bristow's method. Moreover, a vertical electrical sounding (VES) was acquired and interpreted using 1-D inversion technique. Integrated interpretation of the resistivity data reveals a presence of some weak zones (shows high resistivity anomalies) in the surveyed area. The shallower weak zone (cavity) is located between 11 to 16 meters depth under the building. This cavity elongated in N-S direction with maximum diameter of about 10 meters. This interpretation agrees well with the boring results that ascertain a presence of very loose silt formation between 8 and 19 meters depth. It is concluded that, the presence of this cavity (very loose zone) is the main reason of the subsidence of the building.

Keywords: Pole-dipole, Resistivity, Cavity

Introduction

Detection and delineation of subsurface cavities and abandoned tunnels using geophysical methods have gained wide interest in the last few decades. The most widely used surface methods include electrical resistivity, electromagnetic, gravimetric, seismic techniques and recently GPR method. Of these methods, the electrical resistivity has been the most extensively used. An early application of the resistivity method is described by Palmer[1] in reference to the location of subterranean caves. This method employed a symmetrical four-electrode configuration in which the half-array electrode spacing ratio was held constant as the array was expanded to provide depth sounding. Bristow[2] modified the pole-dipole electrode array in a manner which allowed direct graphical interpretation of the cavity

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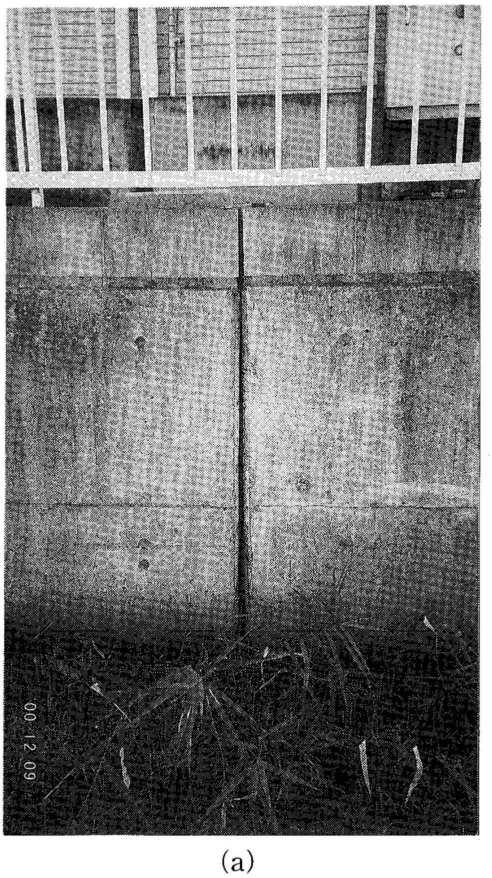
targets in approximate depth, position and size. Using this method in field studies, Bristow was able to describe the approximate position of several known passages over karst terrains. Moreover, he discovered two cavities and verified their existence through boring and excavation.

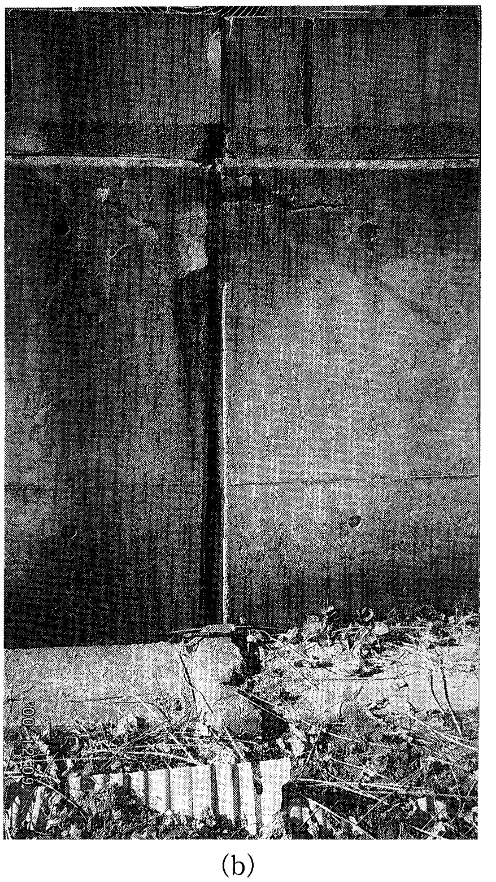
Bates[3] has applied Bristow's method to delineate a number of known cavities. After making some slight modifications, he was also able to locate a relatively small target cavity. Several field examinations of Bristow's method have been conducted with various degrees of success. Fountain et al.[4] Were able to detect both air-filled and mud-filled cavities, Smith[5] located a solution-filled cavity, and Ushijima et al.[6] Successfully delineated air-filled cavities, all of which are confirmed by drilling.

Kirk and Werner[7] claim a success rate for the method of just over 50 percent, based on their own experiences and published accounts of other investigations. The method of intersecting arcs used to interpret the data, however, has drawn criticism from some researchers[8,9], who argue that it is based on faulty assumptions and that many of the positive results reported using Bristow's method may well be serendipitous. Ushijima[10] has evaluated the accuracy of graphical interpretation of the pole-dipole measurements based on numerical simulation for various cavities by Finite Element method. Lowry and Shive[11] evaluated Bristow method in comparison with various electrode arrays using numerically modeled resistivity traverse over spherical and cylindrical cavities. They concluded that, the Bristow method is a legitimate tool not just for detection, but also for delineation of cavities and it is probably the most sensitive electrical resistivity technique advanced for those purposes to date.

This paper describes the data acquisition and interpretation of the resistivity measure-



(a)



(b)

Fig. 1 Photographs showing the wideness in the joints of the outer fence due to the subsidence of the building (a) at the eastern side, (b) at the southern side.

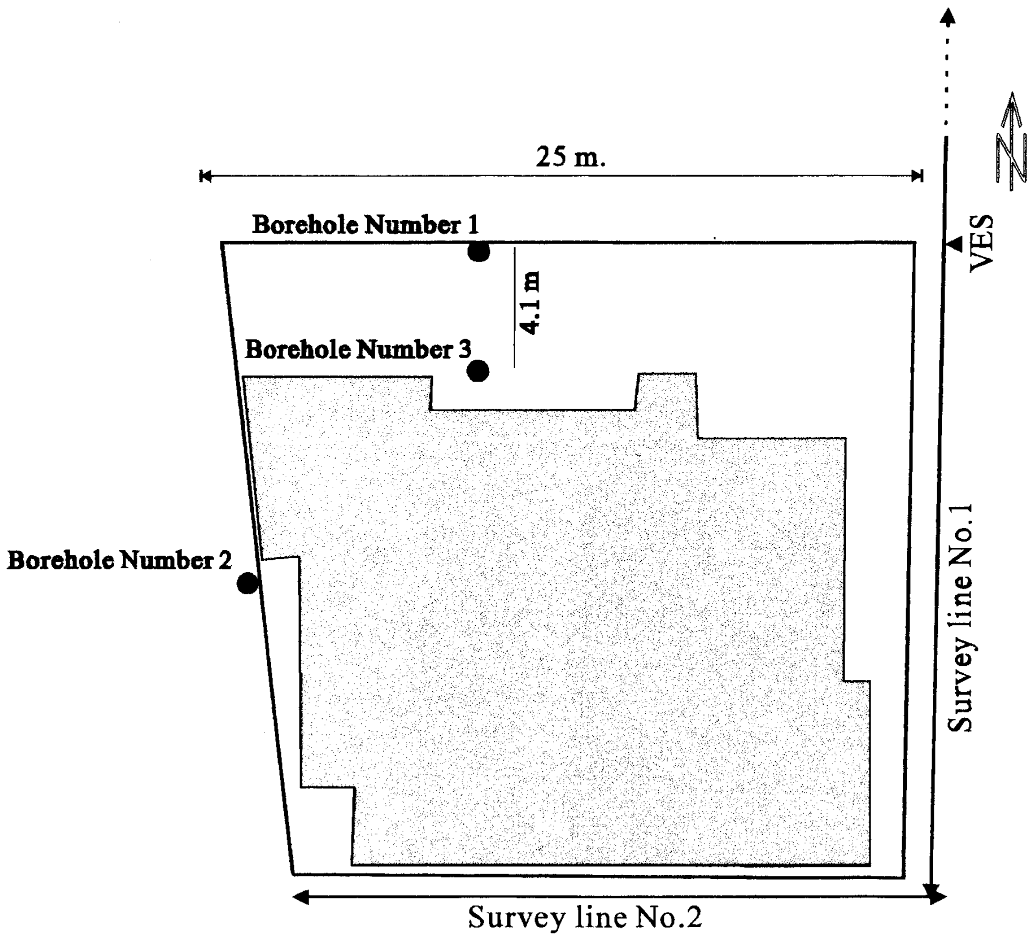


Fig. 2 Sketch showing locations of the geophysical survey lines and boreholes arround the subsiding building.

ments conducted, using pole-dipole and Schlumberger arrays, around a building in Kita Kyushu area. This building has been subjected to noticeable ground subsidence that affects its safety. **Figures 1a & 1b** show the influence of the subsidence on the outer fence of the building at the eastern and southern sides. This work aims to investigate the subsurface conditions under the building in order to locate and delineate any week zones (voids and/or cavities), that might be the cause of the subsidence of the building, as a guide for further drilling and safety maintenance processes.

Resistivity techniques

1. Pole-dipole resistivity method

The pole-dipole electrode array (**Fig. 3**) incorporates two current and two potential electrodes arranged linearly. One current electrode is placed at "an effective infinity" (greater than five to ten times the length of the survey line). Potential difference is measured between two potential electrodes located at a fixed separation a and moved incrementally ($n=1,2,...$) over interval of a for a distance equal to $10a$ on either side of the local current electrode along a survey line. The voltage measurements are then expressed as apparent resistivities-in essence, the resistivity indicated by the measured voltage given the relative positions of the electrodes and assuming the ground has invariant electrical properties throughout[11].

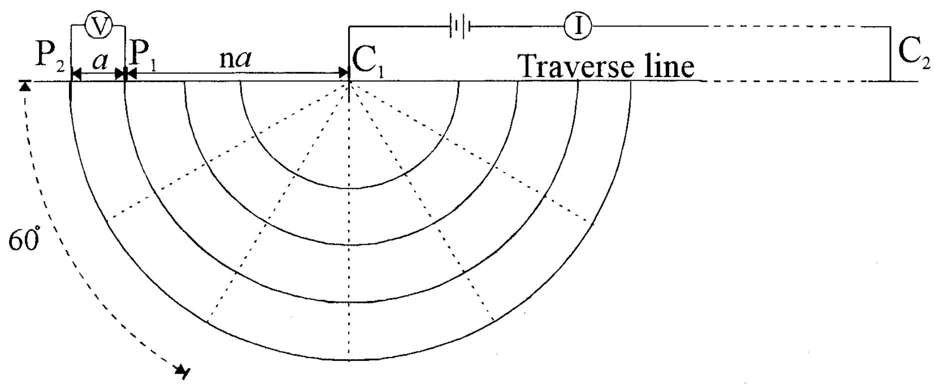


Fig. 3 Geometry of the pole-dipole array for resistivity measurements.

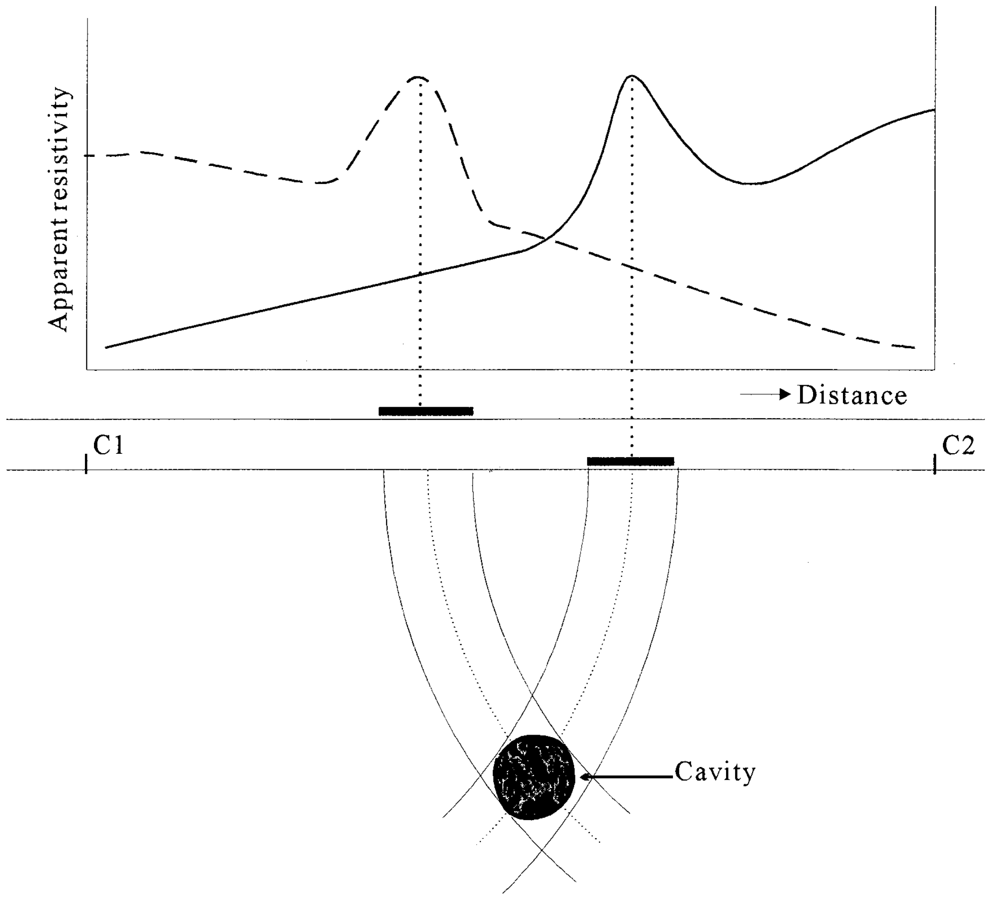


Fig. 4 Graphic interpretation procedure of pole-dipole resistivity data.

The apparent resistivity at the point midway between the potential electrodes, denoted ρ_a, is given by

$$\rho_a = \frac{2\pi V}{I}\left(\frac{1}{\frac{1}{P_1C_1} - \frac{1}{P_1C_2} - \frac{1}{P_2C_1} + \frac{1}{P_2C_2}}\right), \tag{1}$$

in which V is the voltage, I is the current, P_1C_1 and P_2C_1 are the distances from the potential electrodes (P_1 and P_2) to the local current electrode (C_1), and P_1C_2 and P_2C_2 refer to their distances from the remote current electrode (C_2). Equating the distances to the remote current electrode to infinity, the resistivity of a pole-dipole system is

$$\rho_a = \frac{2\pi V}{I}\left[\frac{P_1C_1 \times P_2C_1}{P_2C_1 - P_1C_1}\right]. \tag{2}$$

In terms of array parameters, this equation can be written as;

$$\rho_a = 2\pi n(n+1)aR, \tag{3}$$

where R is the measured resistance, a is the potential electrode separation, and n is the dipole separation factor.

By moving the current source location along the traverse at incremental distances, the measured resistivity profiles will overlap. The apparent resistivity values are plotted against the potential electrodes mid-point position (**Fig. 4**). On a scale drawing of the vertical section along the survey line, intersection of two or more equipotential hemispherical shells having radii corresponding to the current-to-potential electrode separation distance at which resistivity anomalies are observed will locate the subsurface cavity. When this method is applied with sufficient overlap of the resistivity profiles, the subsurface zone of intersection can provide reasonably good indication of cavity target cross-sectional size and depth[12].

2. Schlumberger VES survey

Schlumberger array is one of the most common electrode configurations used in resistivity survey since 1920's. Unlike the pole-dipole, the current and potential electrodes in the Schlumberger array are separated symmetrically around the central point (**Fig. 5**). The potential electrodes are usually kept with fixed separation l, while the current electrode spacing L is expanded in logarithmic interval maintaining the relation AB>5MN. With very large values of L it may, however, be necessary to increase l also in order to maintain a measurable potential.

The apparent resistivity at the central point between the potential electrodes is given by:

$$\rho_a = \pi \frac{L^2 - l^2}{4l} \cdot R \tag{4}$$

where R is the measured resistance, L and l are the current and potential electrodes separations respectively. The vertical electrical sounding data is always presented as curve expressing the variation of the apparent resistivity with increasing the electrode separation. This curve represents, qualitatively, the variation of the resistivity with depth. Quantitative interpretation of apparent resistivity curves is difficult task because of the wide variation in the resistivity possessed by geological materials and the difficulty in developing theoretical expression for apparent resistivities of all but the simplest geometries. The traditional interpretation of the resistivity measurements relied primarily on curve matching procedure. This technique involves a comparison of the measured apparent resistivity curve with a set of standard master curves. With the advent of fast digital computers, the interpretation of the resistivity data has progressed fast from curve matching using the computer to forward

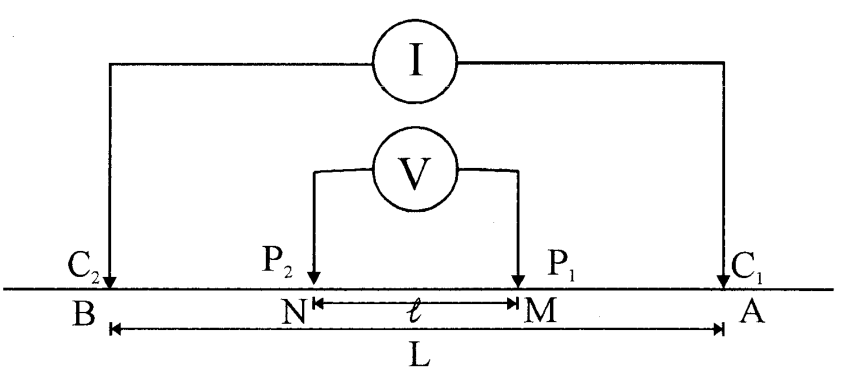


Fig. 5 Geometry of the Schlumberger array for resistivity measurements.

and inverse modeling in one, two and three dimensions. However, these modeling techniques are suffering of inherent ambiguous and non-unique solution.

Field measurements

Using the pole-dipole array, resistivity measurements have been acquired along two traverse lines directed NS and EW, parallel to the eastern and southern sides of the building, respectively (**Fig. 2**). Current electrodes were planted along the survey line No.1 with 20 meter separation and the potential differences were measured with two meter interval potential electrodes, moving incrementally over intervals of 2 meters. On the survey line No. 2, the multiple current electrode separations are reduced to be 5 meters, with potential electrode separation of 2 meters and horizontal shift of 1 meter. Current electrodes were laid out along the survey line and the potential differences at a given location corresponding to each current electrode are measured. Moreover, vertical electrical sounding (VES) measurements were acquired using Schlumberger array, in a selected location according to the preliminary interpretation of the pole-dipole measurements (**Fig. 2**). Schlumberger array was selected, because of its high vertical sounding ability, to provide the resistivity structure underneath the observed area in integration with the pole-dipole measurements. The half current electrode spacing AB/2 starts from 0.5 up to 90 meters in successive steps. For both measurements arrays, we used the (McOHM) electrical resistivity meter for data acquisition with manual switching system to select the excited current electrode in the pole-dipole survey.

Interpretation

The pole-dipole apparent resistivity measurements are presented as "pseudo-sections" to show lateral as well as vertical variations of resistivity with depth (**Figs. 6a** and **7a**). The "pseudo section", however, is not a true resistivity cross-section because the vertical scale is not a true depth. The pseudo-sections depict anomalous high resistivity regions that considered as indication of weak zones. The actual size and location of these weak zones can be delineated by the graphical interpretation of the resistivity profiles using the Bristow's method.

Graphical interpretation of the pole-dipole data acquired along the profile No.1 revealed a presence of five high resistivity zones (**Fig. 6b**). Four shallow zones are aligned horizontally between 16 and 24 meters depth with approximated diameters of about 5 meters. Those high resistivity zones could be interpreted as cavities (weak zones) filled with soft sediments partially mixed with water. The deeper interpreted high resistivity zone located at depth from 42 to 56 meters with a diameter of about 10 m. This zone may be reflects one of the old coal mine tunnels that encountered in many places in Kyushu area representing serious problems to the major engineering projects such as highways and subway tunnels. However, the accurate interpretation of this zone requires further measurements along longer traverse lines with wider array specifications.

Interpretation of the data acquired along the profile No.2 shows a high resistivity zone with approximately circular cross-section located between 11 to 16 m depth below the ground surface (**Fig. 7b**). This zone can be interpreted as a cavity filled with loose sediments partially mixed with water, and can be considered as the main reason of the subsidence of the building. Referring to the interpretation of the profile No.1, the interpreted shallow high resistivity zones are suggested to be the extension of this main cavity.

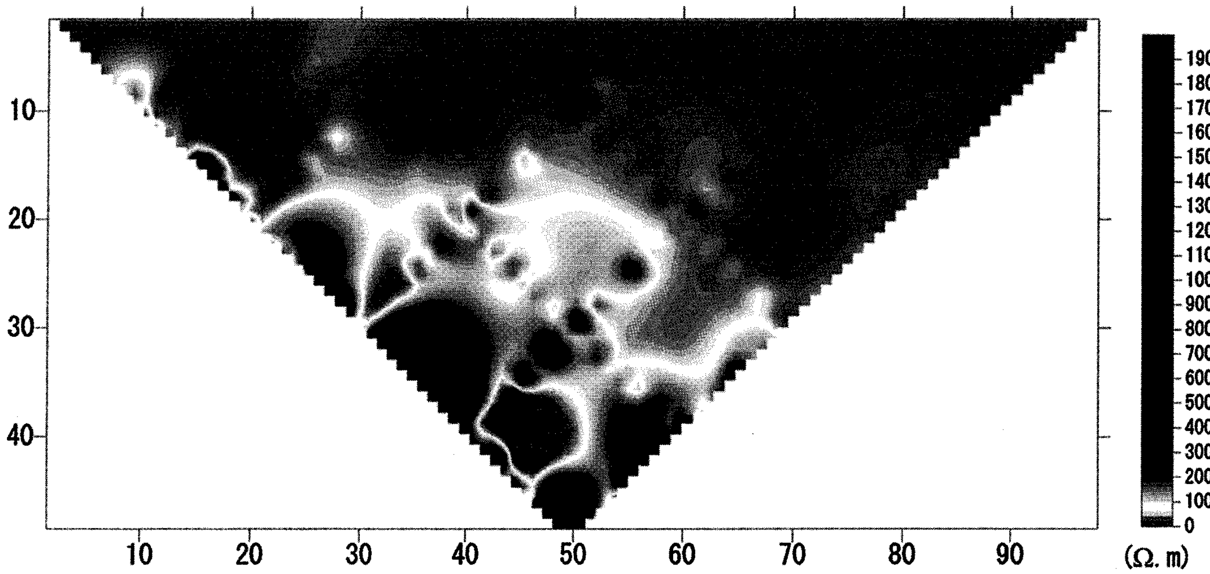


Fig. 6a Apparent resistivity pseudosection under the survey line No.1.

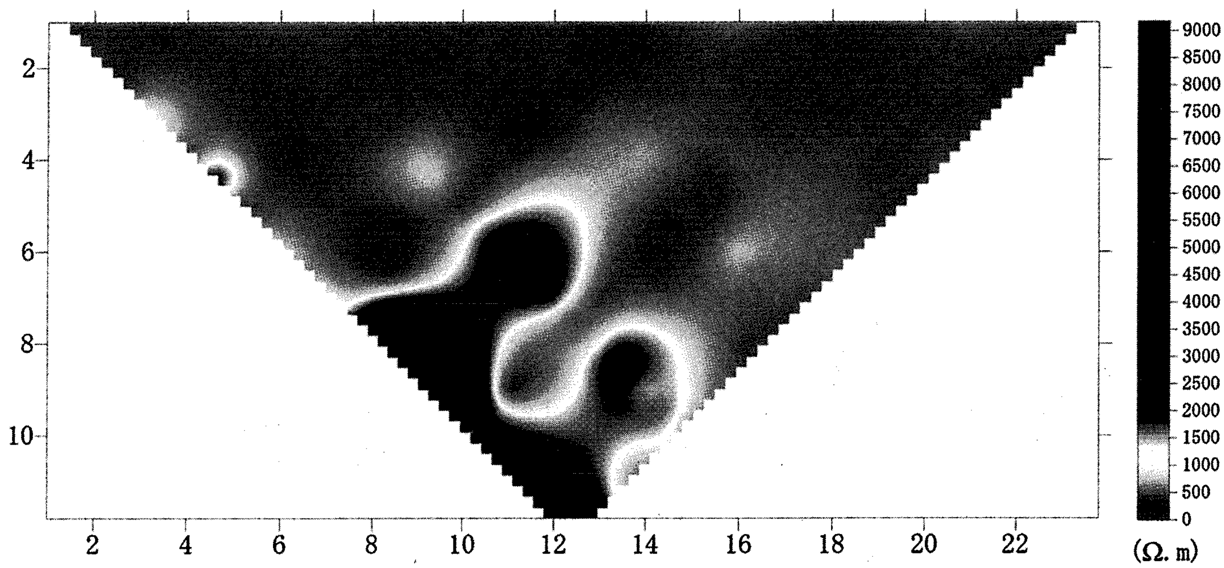


Fig. 7a Apparent resistivity pseudosection under the survey line No.2.

The VES data are plotted and inverted using the RESIX software that creates 1-D model for the sounding data by two inversion techniques (**Figs. 8a** and **8b**).

1) Occam's inversion that enables automatic interpretation of the resistivity data in terms of smooth model. In this method, the depths to the bottom of each layer are logarithmically spaced between the minimum and maximum depth; and then the resistivities are initialized to the average value and adapted using Occam's inversion to produce the smoothest model that fits the data.
2) Standard inversion method facilitates obtaining interpreted model in a least square sense. In this method, the initial model parameters (provided by the author) are adjusted iteratively using a ridge regression[13] to a best fitted model.

The inverted smooth model (**Fig. 8a**) reveals the presence of high resistivity zone deeper than 10 meter. The model obtained using ridge regression technique emphasizes the presence of this zone, with resistivity 21 Ω.m, between 10 and 22 m depth. This interpretation agrees

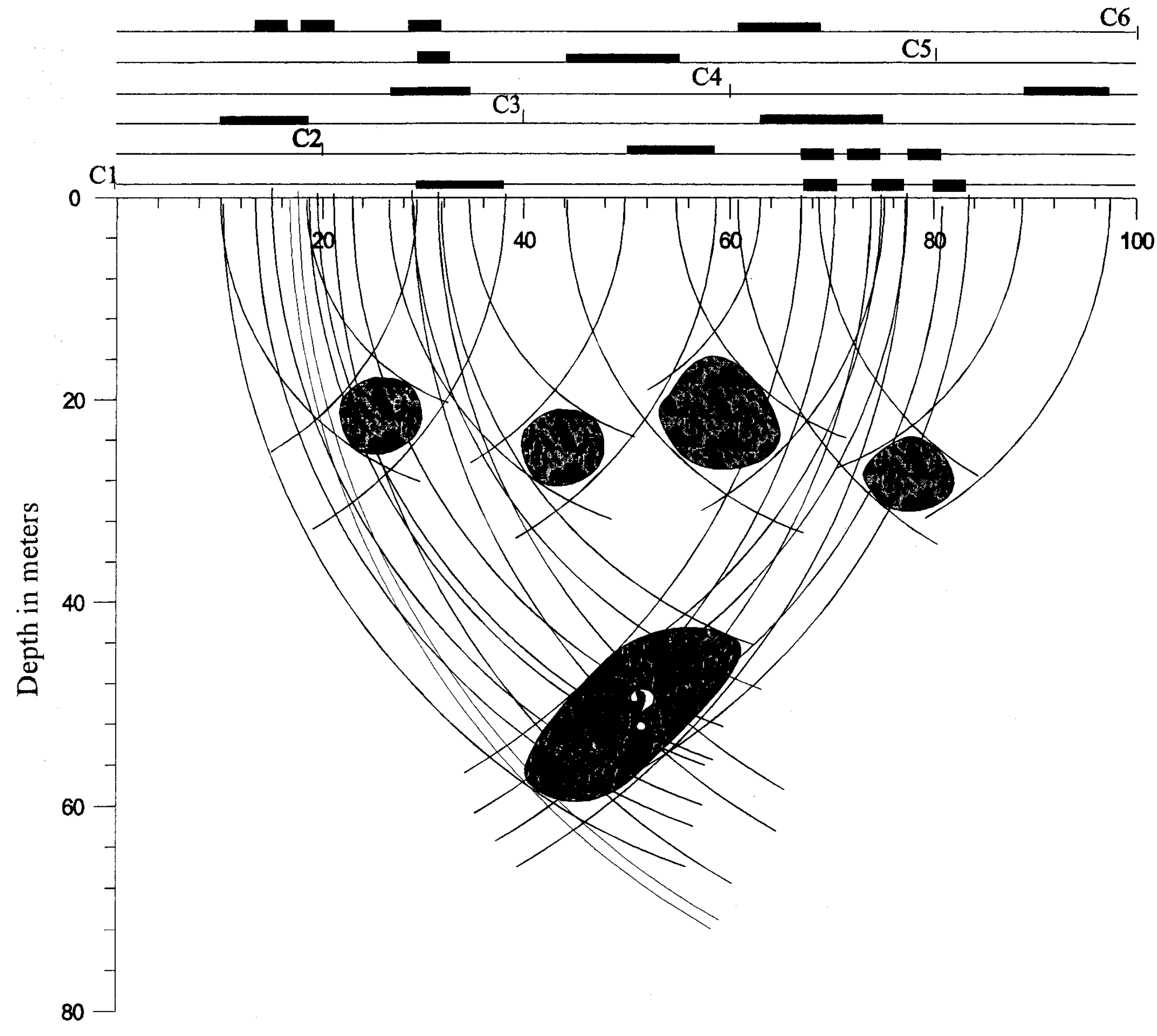


Fig. 6b Intersecting arcs and interpreted anomaly location for pole-dipole resistivity data measured on the survey line No.1.

well with the interpretation of the pole-dipole profile of line No.1.

Three boreholes were drilled in the surveyed area with maximum depth of 25 meters (**Fig. 2**). Continuous core samples were collected from the borehole number one to probe the composition of soils and rocks. Meanwhile, Standard Penetration Test (SPT) was applied during the drilling of the boreholes No.2 and No.3. In the SPT test, a number of blows are applied by a drop hammer to the sampler to complete 30 cm penetration. The number of blows, known as N-value, is an indication to the hardness of the formation.

Investigation of the core samples, of the borehole No.1, shows that the succession under the surveyed area can be divided into three main units. The shallower unit (up to about 4 m depth) is composed of surface soils and shale. The middle unit extends from 4 m to about 20 m and is composed mainly of silt, shale, and clay. The third unit extends deeper to more than 25 m and is composed of solid sandstone. The SPT test of the borehole No.2 (**Fig. 9**) shows that the middle unit (from 4 to 20 m depth) is composed of soft materials with small N-values range up to 4. A very loose zone was encountered between depth of 19.15 and 19.65 meters in which the N-value reaches zero. The presence of this zone agrees with the interpretation of the resistivity data that suggests a presence of very weak zone at depth of 20 meters under the survey line No.1.

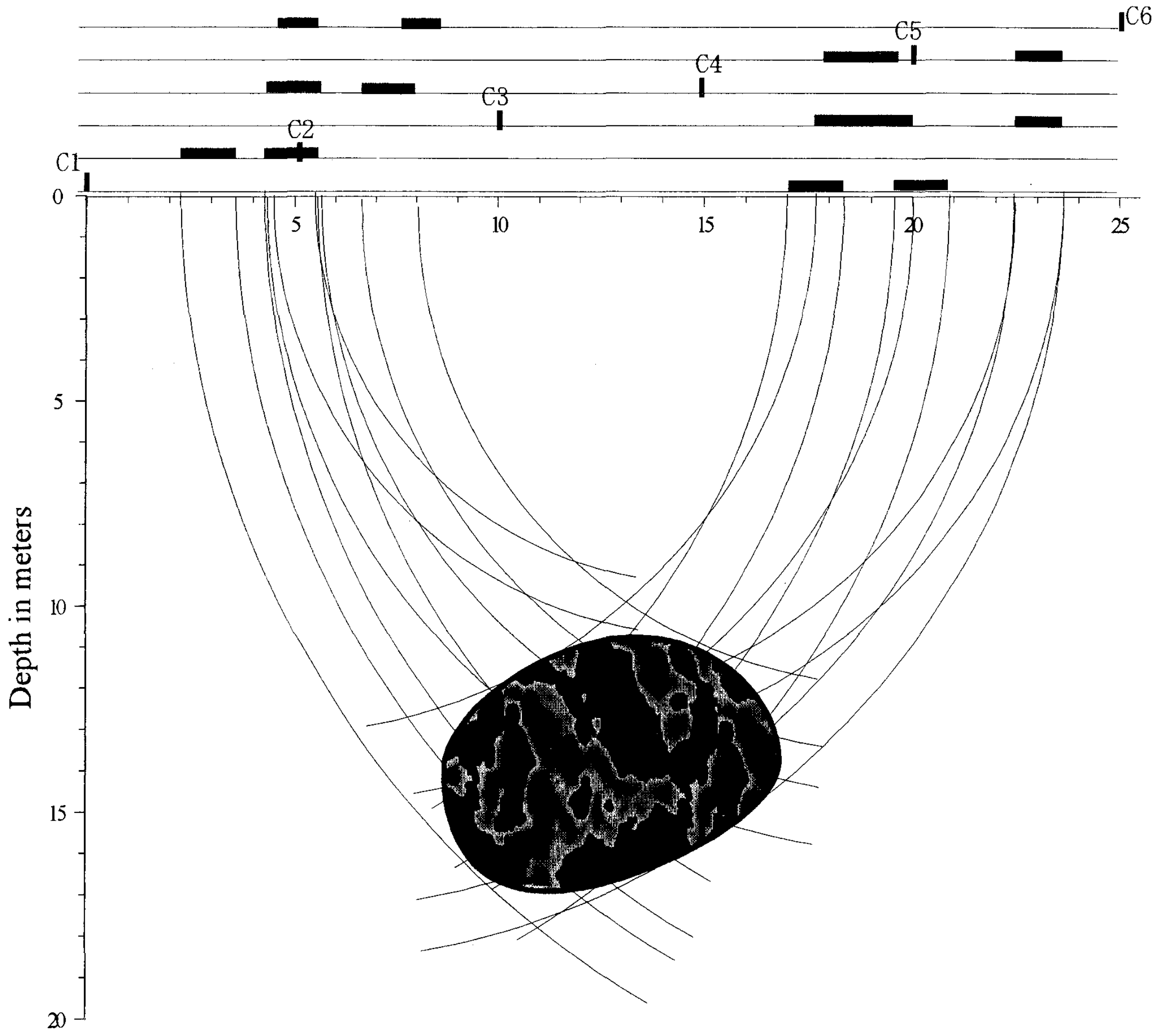


Fig. 7b Intersecting arcs and interpreted anomaly location for pole-dipole resistivity data measured on the survey line No.2.

The SPT measurements acquired in the borehole No.3, reveals a very loose zone (N-value=0) at depth of 8 to 19 meters (**Fig. 9**). This result harmonizes with the interpretation of the resistivity data of the traverse No.2 that delineate a weak zone between 11 to 16 meters depth. Integration of the resistivity interpretation and the drilling information suggests that the subsidence of the building is due to shallow cavity (void) located at depth from 8 to 19 meters. This void is elongated in N-S direction under the building with approximated width of about 10 meters. The positive resistivity response of this void supports the idea that the void is filled with very loose sediments partially saturated by water.

Conclusion

The pole-dipole electrical resistivity and Schlumberger VES surveys have been applied to investigate the subsurface structure on a subsidence area located in Kita Kyushu city. This investigation aimed to delineate any weak zones (cavities or voids), that might be responsible for the ground subsidence occurred under the building, as a guide for further safety maintenance processes.

Interpretation of the pole-dipole and VES resistivity data of the survey line No.1 revealed a presence of high resistivity anomalous zones between 16 and 24 meters depth. This

Layer Number	Resistivity (Ω.m)	Thickness (m)
1	27.99	0.2
2	30.91	0.109
3	40.11	0.16
4	40.25	0.26
5	26.33	0.4
6	17.33	0.62
7	16.15	0.96
8	13.43	1.5
9	5.11	2.32
10	1.89	3.59
11	2.3	5.55
12	5.83	8.59
13	8.51	13.29
14	6.61	20.57
15	4.8	

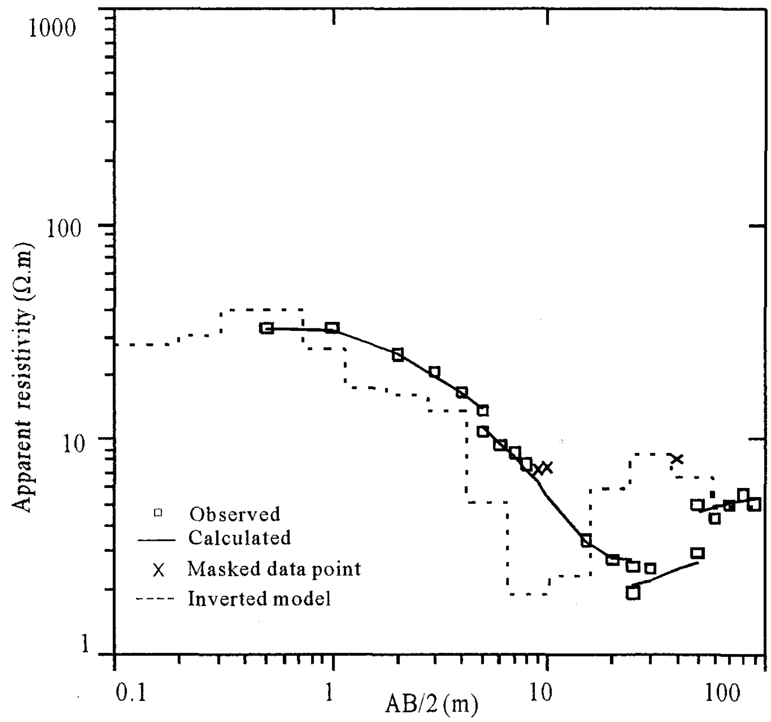


Fig. 8a Results of 1-D inversion of the vertical electrical sounding (VES) data, using Occam's inversion.

Layer Number	Resistivity (Ω.m)	Thickness (m)
2	13.2	4.36
3	0.95	5.32
4	21.07	12.82
5	1.41	20.67
6	5.93	

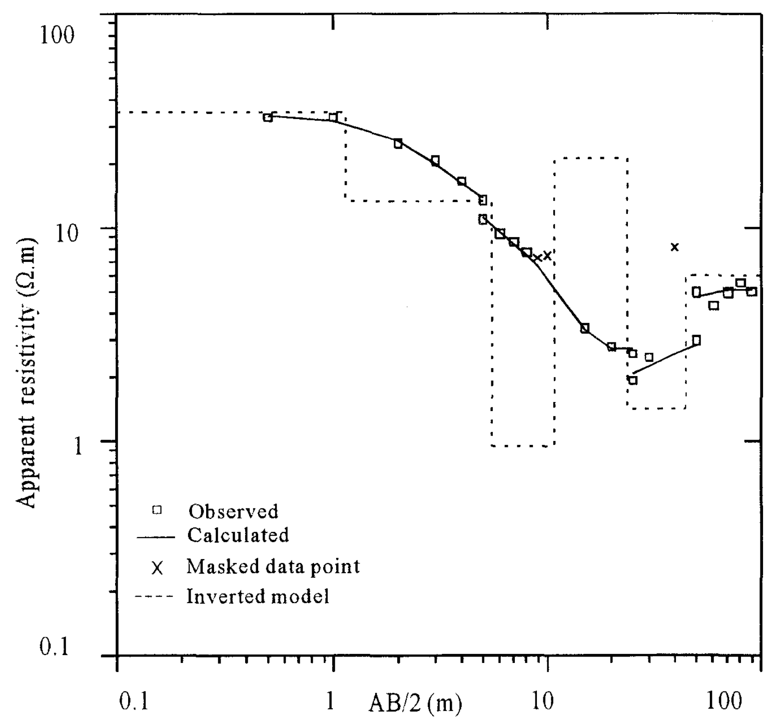


Fig. 8b Results of 1-D inversion of the vertical electrical sounding (VES) data, using ridge regression inversion.

interpretation is confirmed by the extremely low N-value acquired in the borehole No.2 that encountered a very loose zone between 19.15 to 19.65 meters depth. Interpretation of the resistivity data of the survey line No.2 revealed a presence of a cavity located from 11 to 16 meter depth. Borehole No.3 encountered a very loose formation (N=0) between 8 and 19 meters depth.

Integration of the electrical resistivity interpretation supported by drilling results enabled delineation of the most dangerous weak zone under the building. A cavity (very loose

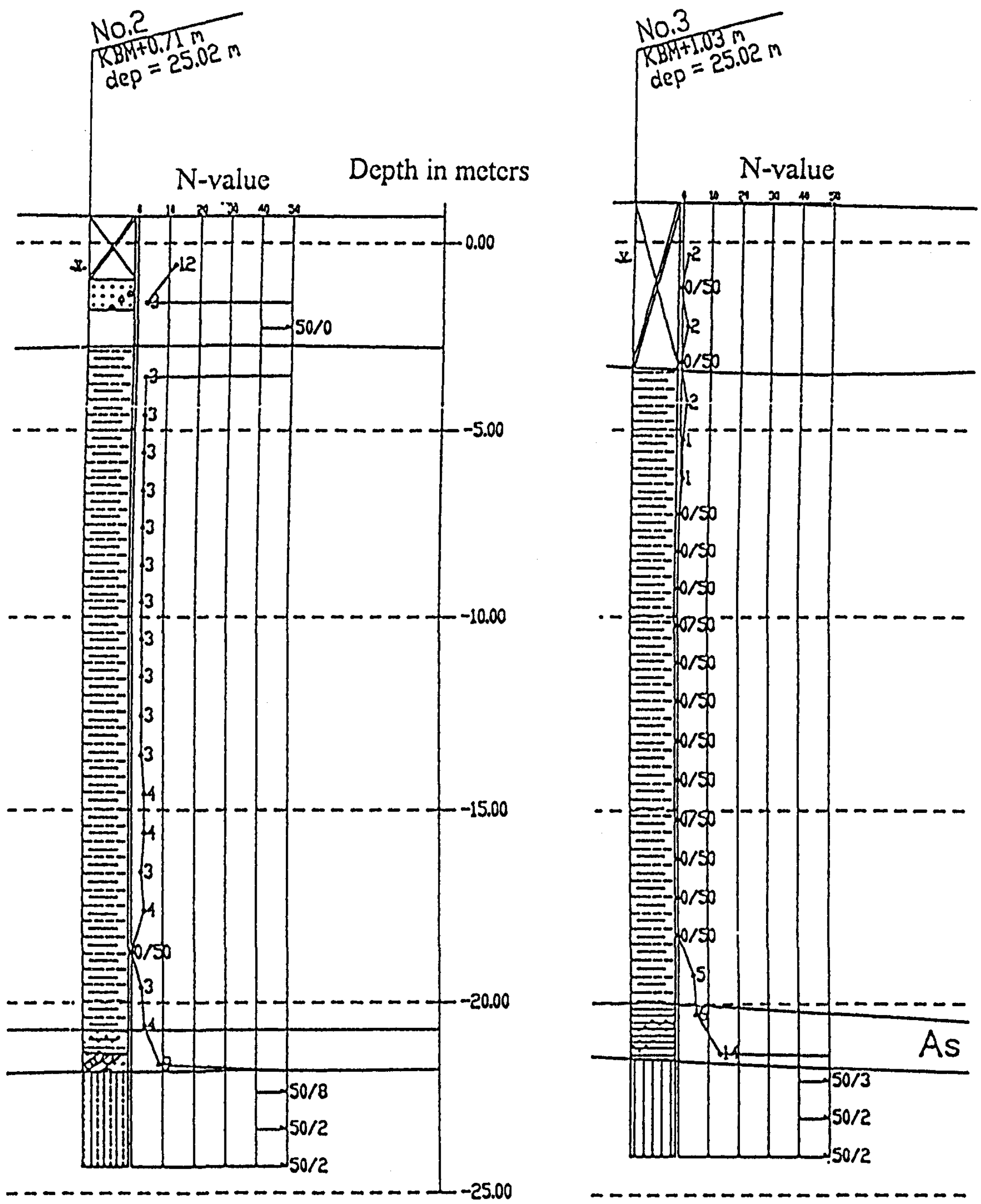


Fig. 9 A graph showing results of the Standard Penetration Test (N-value) carried out in the borehole No.2 and No.3.

zone), elongated in N-S direction is located under the building between 8 to 19 meters depth. The subsidence of the building can be referred directly to the presence of this cavity.

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