APPLICATION OF AN INTEGRATED GEOPHYSICAL METHOD TO LEVEE EVALUATION

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We proposed an integrated geophysical method which can non-invasively estimate soil condition of levees in order to evaluate the vulnerability of levee to seepage and erosion. The geophysical method mainly consists of a surface-wave method using a land streamer and a capacitively-coupled resistivity method. The method is mainly performed along levees at crest or levee toe in order to delineate lateral variation of soil condition. The effective performance of field measurements using these methods is assured because sensors are not fixed on the levee surface. The geophysical properties, S-wave velocity and resistivity, obtained through these methods are very important to evaluate the stiffness and permeability of the levee body and base. We have also developed a cross-plot analysis of the measured geophysical properties in order to estimate soil type in body and base of levees. We have applied the method to many levees in Japan and evaluated the applicability of the method. In conclusion, the cross-plot analysis using S-wave velocity and resistivity obtained through the surface-wave method and the capacitively-coupled resistivity method provides reliable soil information of levee body and base. This paper presents the outline of the geophysical methods, the cross-plot analysis and the application example of the method to a levee in Japan.

Key Words : *levee, geophysical method, surface-wave method, resistivity method, S-wave velocity*

1. INTRODUCTION

Levees have served for centuries as flood-control structures along surface-water systems such as rivers and lakes. Key for building a reliable levee is the construction of a strong, impervious levee body and base and understanding and consideration of the underlying geology. In practice, levees are constructed with locally available materials, which can vary in quality and suitability. Over time, physical and hydrologic processes including seasonal water fluctuations, flood events, differential settlement, external and internal removal of levee matrix (piping), etc., can adversely affect levee structures, thereby increasing the chances for levee failure during high-water events.

Recent severe flooding caused by typhoons, hurricanes, and torrential rains illustrate the need to periodically assess, test, and monitor levee conditions. Conventional levee assessments use invasive borings, which provide extremely useful and detailed information of levees. However, borings

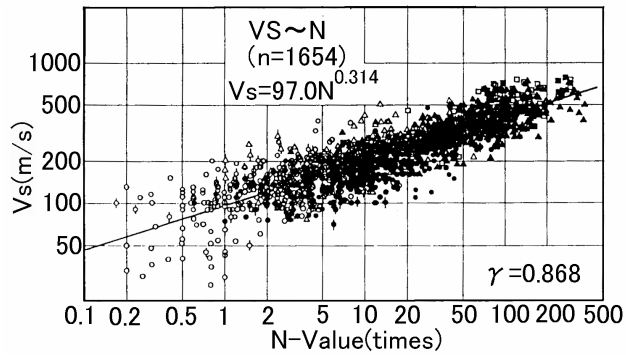


Fig. 1 Correlation between N-value and S-wave velocity (from Imai and Tonouchi, 1982)[1].

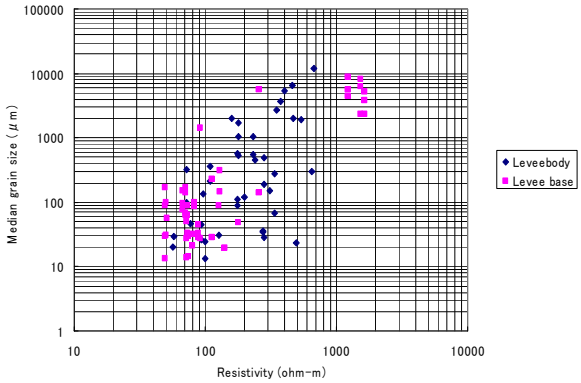


Fig. 2 Correlation between resistivity and median grain size (from Tanaka et al., 2008)[2].

are expensive and cannot provide continuous information along a levee in heterogeneous environments. Non-invasive, rapid, and spatially continuous investigation methods are needed to support traditional investigation techniques. Recently, many geophysical methods have made remarkable progress associated with the evolution of computer and electronics. Considering such progress, geophysical methods can play important role in levee investigations.

2. S-WAVE VELOCITY AND RESISTIVITY IN LEVEE EVALUATION

In order to evaluate the vulnerability of levee to seepage and erosion, shear strength and permeability are two important factors. It is well known that S-wave velocity well correlates with shear strength. Fig. 1 shows a correlation between N-value (blow counts) obtained from SPT tests and S-wave velocity[1]. S-wave velocity is also directly related to shear modulus which is particularly important to levee assessment. Small strain shear modulus (G_0) is a function of S-wave velocity (Vs), according to:

$$G_0 = Vs^2 \rho \qquad (1)$$

where ρ is material density.

Most of us would accept the permeability mainly relates to grain size distribution, such as clay or sand, and degree of compaction. It seems that the degree of compaction relates to shear modulus and can be qualitatively estimated from S-wave velocity. There is no disagreement on this point that resistivity well relates to the grain size distribution or clay contents. Fig. 2 shows the example of correlation between resistivity and median grain size[2]. It follows from what has been said that we can estimate soil condition, such as shear strength and permeability, of levee body and base in terms of S-wave velocity and resistivity obtained through the surface-wave method and the resistivity method.

3. SURFACE-WAVE METHOD

Surface-waves (Rayleigh wave) are elastic waves propagating along the ground surface and their energy concentrate beneath the ground surface. The velocity of surface-wave propagation strongly depends on S-wave velocity of the ground. If a subsurface S-wave velocity varies with the depth, a propagating velocity varies with its frequency or its wavelength. This character is called dispersion. A surface-wave method is a seismic method in which sub-surface S-wave velocity structure is estimated by the analysis of dispersion character of the surface-waves.

The principle of the surface-wave method and instruments used in data acquisition are schematically illustrated in Fig. 3.

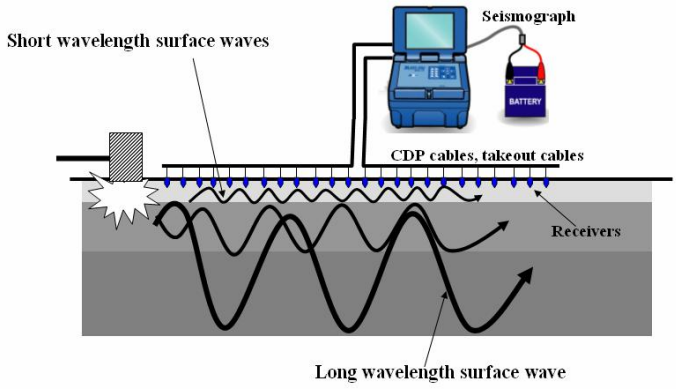


Fig. 3 Schematic diagram of a surface-wave method.

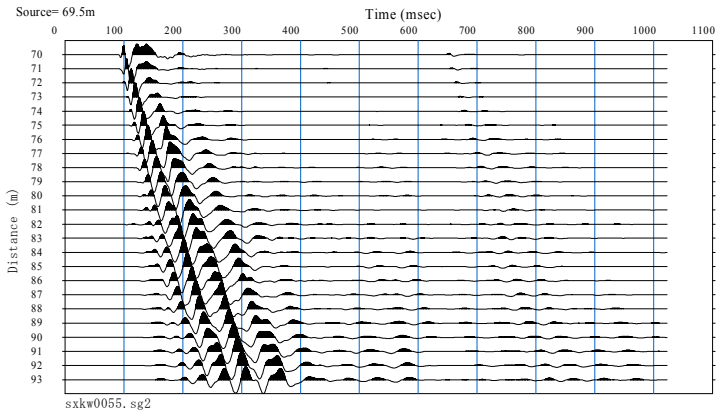


Fig. 4 Example of observed waveform data in a surface-wave method.

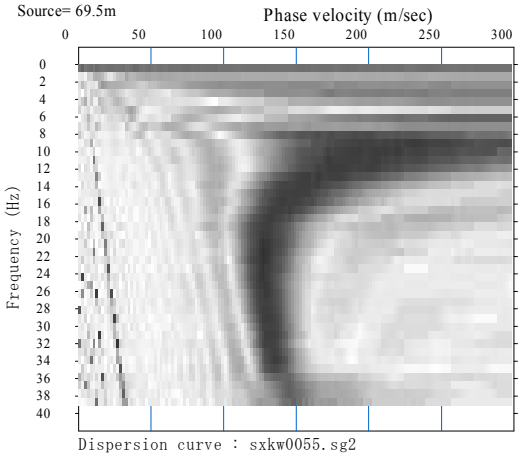


Fig. 5 Example of a phase-velocity image in frequency domain.

In order to move receivers quickly, we use a land streamer[3] comprising 24 geophones on aluminum plates, respectively, aligned in series at 1m intervals by two parallel ropes on the ground surface. Example of observed waveform data (shot gather) is shown in Fig. 4.

In the analysis of the surface-wave method, a CMP cross-correlation (CMPCC)[4] analysis is applied to waveform data firstly and a multi-channel analysis of surface-waves (MASW)[5] is applied to secondly. The CMPCC analysis was applied to raw shot gathers and CMPCC gathers are calculated in order to improve lateral resolution of S-wave velocity profiles. The MASW was applied to each CMPCC gather and a phase-velocity image in frequency domain was obtained. The MASW enables us to calculate multi-modal dispersion curves directly from multi traces or cross-correlations. A typical example of the phase-velocity images is shown in Fig. 5. Phase-velocities are determined as the maximum amplitude in each frequency so that the dispersion curve (relationship between the phase velocity and the frequency) is constructed. Low and high frequencies corresponded to the deep and shallow regions of the soil layer, respectively. A non-linear least square method was applied to each dispersion curve for reconstructing an 1D S-wave velocity model. An initial model was generated by a simple wavelength-depth conversion[6]. The number of layers is fixed as 10 to 15 and only S-wave velocities are changed throughout reconstruction. P-wave velocities and densities are automatically changed based on empirical relationships[7][8]. Theoretical dispersion curves are calculated by a matrix method[9]. We obtain a 2D S-wave velocity section by aligning the 1D S-wave velocity models. Because the shear modulus is proportional to the square of the S-wave velocity, as shown in equation (1), an S-wave velocity section represents the soil stiffness structure.

4.CAPACITIVELY-COUPLED RESISTIVITY METHOD

A capacitively-coupled resistivity (CCR) method is a new resistivity method in which capacitors are used as electrodes. Unlike a conventional resistivity method, the CCR method does not use metalic stakes and enables us to measure the resistivity of the ground very quickly. The fundamental principle of capacitive coupling is that AC current will pass through a capacitor[10]. In a CCR instrument, a cable (or metal plate) acts as one half of a capacitor, while the earth functions as the other half. This cable-earth capacitor (Fig. 6) has a variable capacitance depending on the earth conditions, but an AC current generated by the transmitter will pass from the cable into the ground. At the receiver, the transmitter-generated ground current will generate an AC voltage that is coupled into the CCR receiver and measured. The CCR receiver is conceptually equivalent to an AC Volt meter. The OhmMapper is used as a CCR instrument in the development. The OhmMapper uses shielded twisted-pair cables as line sources and receivers (Fig. 6) in contrast with a traditional galvanic resistivity method uses metallic stakes as point sources and receivers. A dipole-dipole array is used in the OhmMapper as shown in Fig 7. The transmitter drives a 16.5 kHz signal onto the cable shield and that signal is “lost” to the ground through the capacitance of the cable.

In order to evaluate the applicability and reliability of the CCR method using the OhmMapper, we have performed comparative

measurement of the CCR and a traditional galvanic resistivity method. Two different length dipole cables were used in the CCR measurement. Equivalent dipole lengths are 2.5m and 5.0m

respectively. We used a 4 receiver system that could measure 4 different dipole spacings simultaneously. Consequently, resistivity data were obtained for 8 different dipole spacings. A conventional galvanic resistivity method using metallic stakes was also performed with the dipole-dipole array. Apparent resistivity data obtained through these methods were processed by a non-linear least square method and sub-surface resistivity sections were obtained. Fig. 8 shows the comparison of resistivity sections obtained by the CCR and the galvanic resistivity methods. Although the resolution of the CCR method is lower than one of the galvanic method, we can say that almost identical resistivity sections were obtained through two methods.

5. CROSS-PLOT ANALYSIS USING S-WAVE VELOCITY AND RESISTIVITY

Both S-wave velocity and resistivity reflect many physical properties and do not directly relate to engineering properties such as cohesion, internal friction angle, grain size distribution, and permeability. Therefore, we propose an analysis method in which soil type and shear strength are estimated using the cross-plot of S-wave velocity and resistivity obtained through the surface-wave method and the CCR method respectively.

Resistivity is a function of many physical properties such as porosity, pore fluid resistivity, water saturation, and grain size distribution. It is well known that the conductivity (inverse of resistivity) of porous medium is expressed by an equation as follows[11]:

$$\sigma_R = \frac{1}{a} \cdot \phi^m \cdot S^n \cdot \sigma_W + \sigma_C \qquad (2)$$

where, σ_R is conductivity of medium, σ_W is pore fluid conductivity, σ_C is conductivity due to clay mineral, ϕ is porosity, S is water saturation, a, m and n are constants. A first term of right-hand of equation (2) is

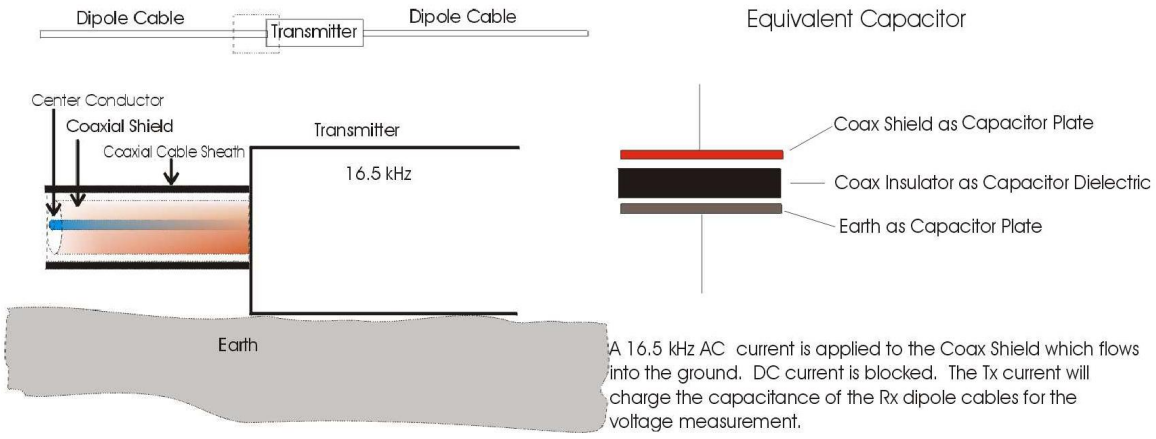


Fig. 6 Equivalence of the cable-ground capacitor to a traditional capacitor (from Groom, 2008)[10].

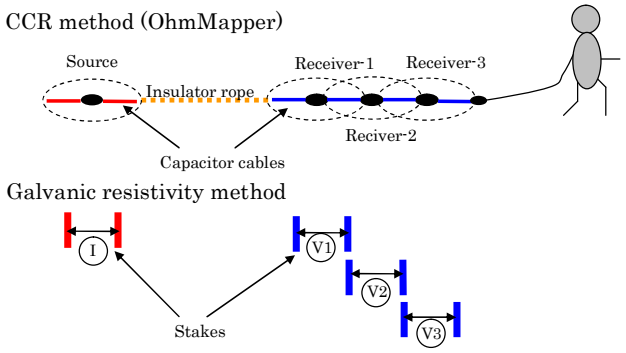


Fig. 7 Dipole-dipole array used in a CCR method (top) and equivalent galvanic resistivity method (bottom).

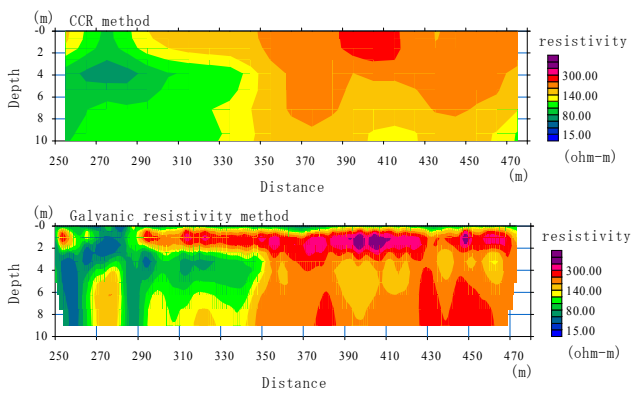


Fig. 8 Comparison of resistivity sections obtained through a CCR method (top) and a galvanic resistivity method (bottom).

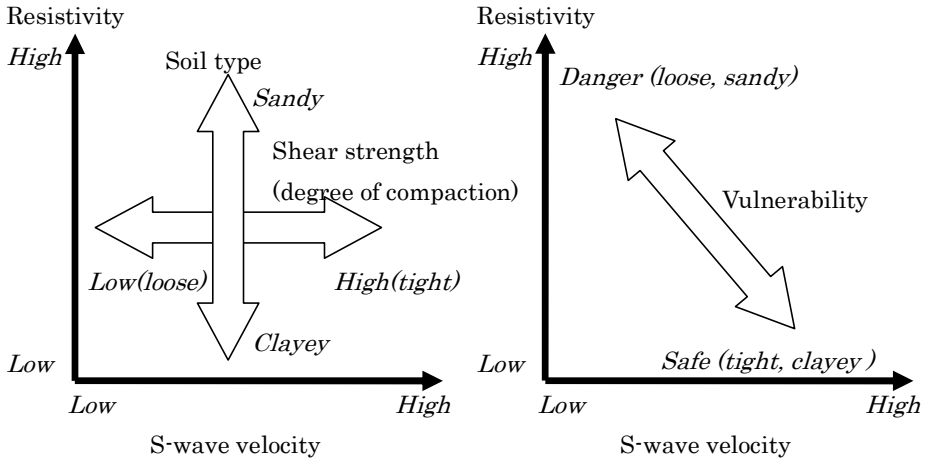


Fig. 9 Schematic relationship between geophysical properties and soil condition (left) and levee vulnerability (right).

known as the Archie's equation and if fluid resistivity and water saturation are identical, resistivity is a function of porosity and resistivity decrease as porosity increase. A second term of right-hand of equation (2) is the effect of clay mineral included in soil. It is well known that the effect of the second term can not be neglected and may be dominant in saturated clayey unconsolidated soil. We may, therefore, reasonably conclude that the resistivity of soil mainly indicates soil type.

On the other hand, it is well known that S-wave velocity is mainly affected by shear strength or porosity. Fig. 9 (a) shows a schematic relationship between resistivity and S-wave velocity. S-wave velocity indicates shear strength or degree of compaction and resistivity indicates soil type or clay contents. Fig. 9b shows a schematic relationship between geophysical properties, such as S-wave velocity and resistivity, and the vulnerability of levees. Loose and sandy levees are more dangerous to tight and clayey levees. Fig. 9 implies that the effectiveness of a cross-plot of S-wave velocity and resistivity on levee vulnerability evaluation.

6. APPLICATION TO KUWANO-RIVER

We have applied the integrated geophysical method to many levees in Japan. Here, we will show the application of the method to the investigation of soil type of levee base[12]. An investigation site was a levee of "Kuwano" river located at Shikoku area in Japan. The levee is constructed in 1950s-60s, and the precise history of the construction was not revealed. According to existing borings, it was considered that alluvial clay, sand and gravel were deposited beneath the levee body (Fig. 10a). The CCR method and the surface-wave method were performed along the river from 6.0 km to 7.8 km Mile Post. A survey line was placed at the riverside of levee toe.

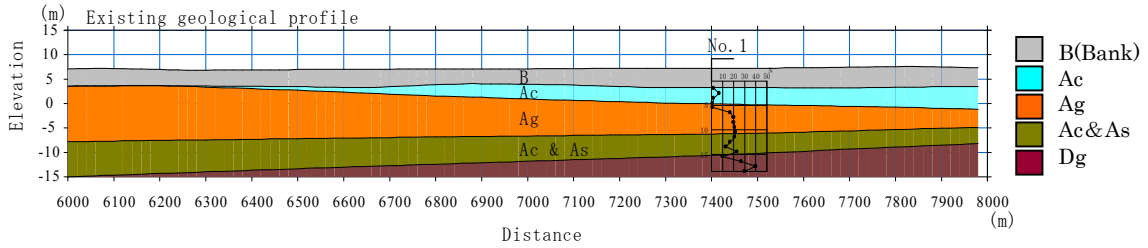
An S-wave velocity and a resistivity sections, obtained through the surface-wave method and the CCR method respectively, are shown in Fig. 10b and 10c. Based on the comparison of geophysical properties obtained by the surface-wave method and the CCR method and geologic column obtained by existing borings, we defined soil type as shown in Table 1. Fig. 11 shows a cross-plot of S-wave velocity and resistivity with classified soil type using Table 1. Each circle in Fig. 11 keeps information about S-wave velocity, resistivity and location in a section so that classified soil type could be projected on the section. Fig. 10d shows the classified soil type projected from Fig. 11. Fig. 10e shows the revised geological section based on the soil type classification shown in Fig. 10d. We can recognize from Fig. 10e that a loose sand layer exits beneath the levee body at the distance between 6000 and 6800m. It is clear that a revised geological section (Fig. 10e) is more useful compared with an original geological section (Fig. 10a).

Table 1 Geological properties and soil type definition.

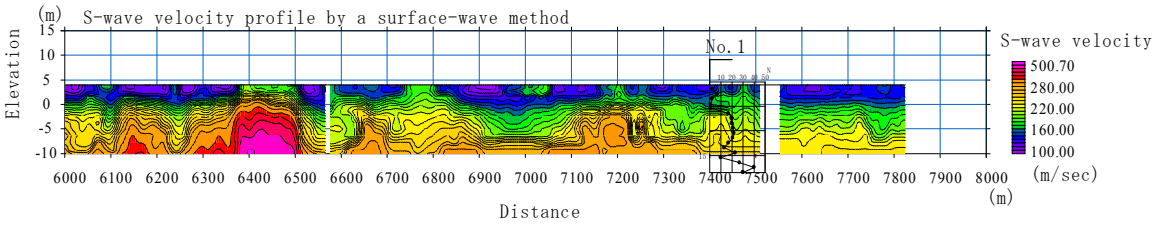
		S-wave velocity (m/s)		
		< 200	200 to 240	240 <
Resistivity (Ohm-m)	250 <	Alluvial gravel (Ag)	Diluvial gravel (Dg)	
	80 to 250	Alluvial sand (As)	Alluvial gravel (Ag)	
	< 80	Alluvial clay (Ac)		

7. CONCLUSIONS

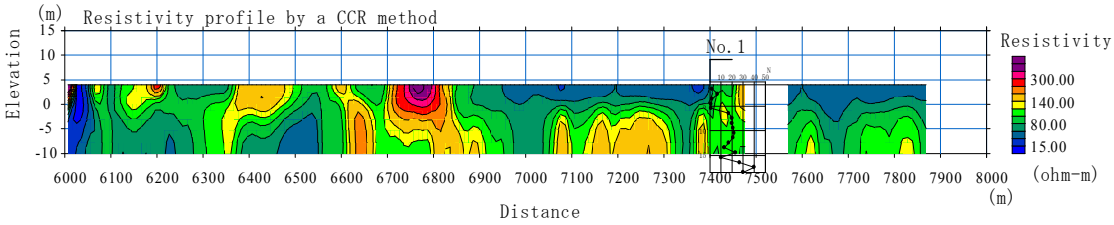
This paper summarized the application of the integrated geophysical method to vulnerability assessment of levees. Introduced geophysical methods, the surface-wave method and resistivity method, can delineate soil condition of levee body and base continuously and non-invasively. Geo-technical properties, such as, soil type, permeability and stiffness of soil can be estimated from the cross-plot of geo-physical properties. Considering that the demand for rapid, non-invasive and continuous investigations is increasing in levee assessment, the method presented here can play a very important role increasingly for such investigations.



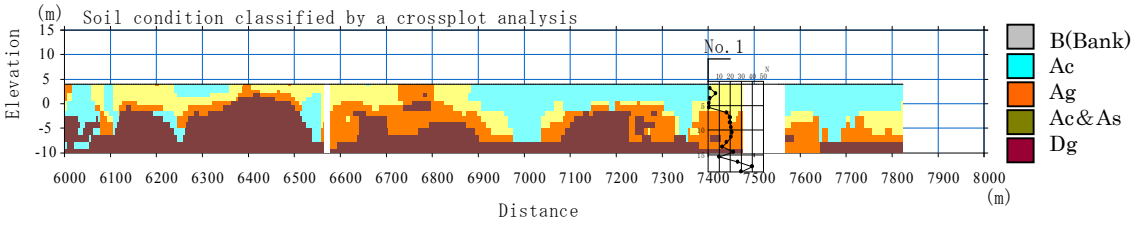
(a) Existing geological profile.



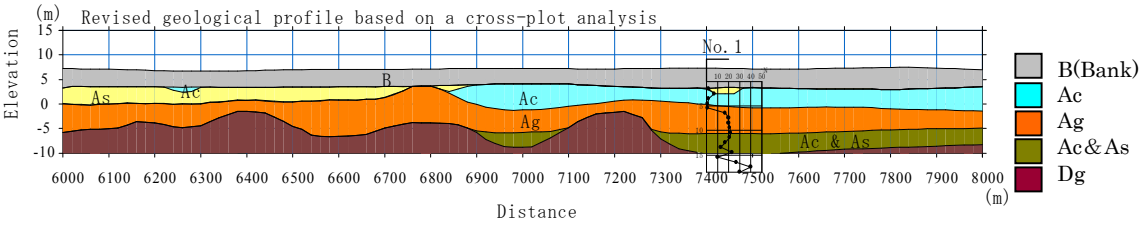
(b) S-wave velocity profile by a surface-wave method.



(c) Resistivity profile by a CCR method.



(d) Soil condition classified by a cross-plot analysis.



(e) Revised geological profile based on a cross-plot analysis.

Fig. 10 Revision of an existing geological profile based on a cross-plot analysis using S-wave velocity and resistivity sections obtained through a surface-wave method and a CCR method (from Konishi et al., 2007)[12].

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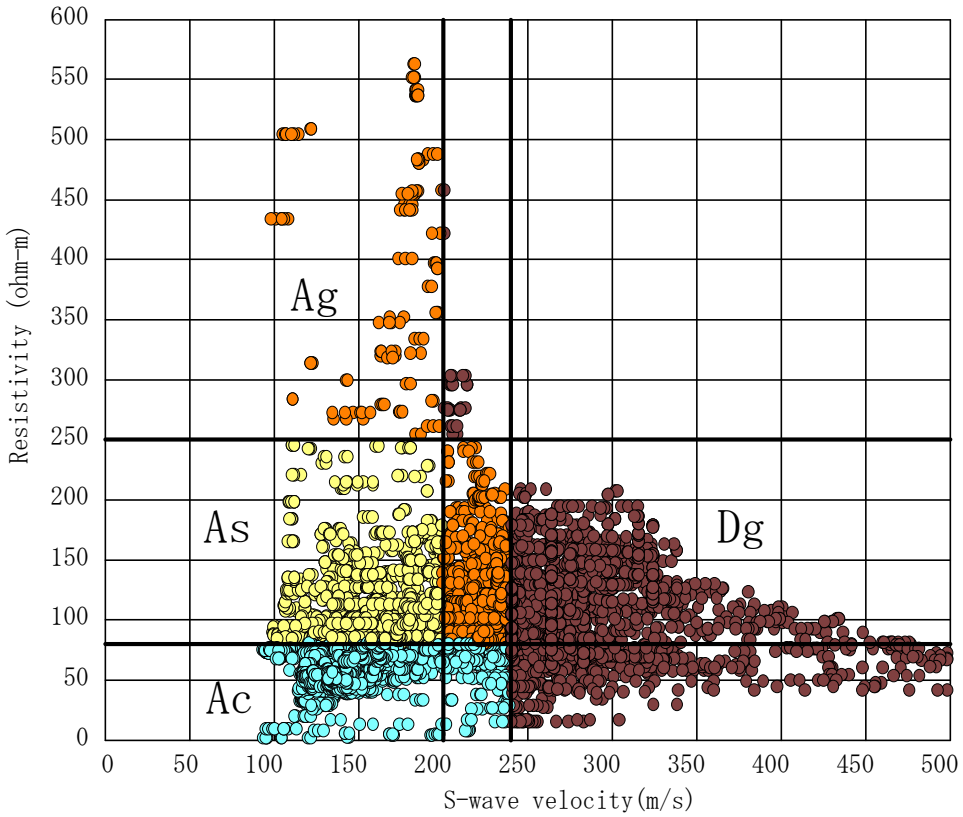

Fig. 11 Cross-plot of S-wave velocity and resistivity with classified soil type (from Konishi et al., 2007)[12].