STATISTICAL ESTIMATION OF SOIL TYPE USING CROSS-PLOTS OF S-WAVE VELOCITY AND RESISTIVITY IN JAPANESE LEVEES

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Abstract

Soil type of levee body and foundation is statistically estimated using cross-plots of S-wave velocity and resistivity in Japanese levees. S-wave velocity and resistivity are collected from surface wave methods and resistivity methods. Total survey line length of the geophysical methods is about 600km on 37 rivers in Japan. Relationship between S-wave velocity, resistivity, blow counts (N-value) and soil type is collected and stored in a database. The blow counts and soil types are collected from about 400 boring logs carried out on geophysical survey lines. S-wave velocity and resistivity at the depth of the blow counts were extracted from geophysical sections. The total number of extracted data is about 4000. Soil type is classified as clay, sand and gravel for the sake of simplicity. The data is grouped in levee body and foundation. A polynomial approximation was used to estimate soil type from S-wave velocity and resistivity. In the approximation, soil type is represented by discontinuous numbers one (clay), two (sand) and three (gravel). Polynomial equations are functions of S-wave velocity and resistivity and yield a continuous number between one and three. Constants of equations are optimized by a least squares method so that the residual between calculated value (from one to three) and actual soil type (one, two and three) is to be minimum. A soil type section can be estimated from S-wave velocity and resistivity sections using the polynomial approximations. Accuracy of estimation can be statistically evaluated by comparing estimated and actual soil types. In this paper, outline of geophysical methods, collected data, polynomial approximations and the accuracy of estimation will be discussed.

Introduction

Conventional levee assessments use invasive borings which provide useful and detailed information of levees. However, borings 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 together with borings.

Many researchers have been trying to apply the geophysical methods to levee investigations (e.g. Dunbar et al., 2007). Surface-wave methods (e.g. Ivanov et al., 2006) and resistivity methods (Liechty, 2010) are often applied to such investigations because S-wave velocity and resistivity obtained through these methods are very valuable to the evaluation of levee safety as follows.

In order to evaluate the safety of levee to seepage and erosion, shear strength and permeability of soils are two important factors. A considerable number of studied have been made on correlation between S-wave velocity and shear strength (e.g. Imai and Tonouchi, 1982). It is well known that blow counts (N-value) increases with the S-wave velocity increases. The S-wave velocity is also directly related to shear modulus which is particularly important to levee assessment. Permeability mainly relates to grain size distribution, such as clay or sand, and degree of compaction (Creager et al., 1944). It seems that the degree of compaction relates to shear modulus and can be qualitatively estimated from S-wave velocity. Resistivity well relates to the grain size distribution or clay contents (Imamura et al., 2007) and grain size increase as resistivity increase. It follows from what has been said that we can estimate soil condition, such as shear strength or permeability, of levee body and foundation in terms of S-wave velocity and resistivity.

Both S-wave velocity and resistivity, however, reflect many physical properties and do not directly relate to engineering properties such as cohesion, internal friction angle, grain size distribution, and permeability. In order to evaluate levee condition quantitatively, integrated geophysical investigations are proposed (Hayashi et al., 2009; Inazaki et al., 2009). The proposed method mainly consists of the surface wave method and the resistivity methods. The cross-plots of S-wave velocity and resistivity are used for evaluating relative safety of levees in the method.

A soil type, such as clay, sand or gravel, or grain size distribution, such as clay contents or D_{20}, is the most important information for levee safety evaluation from an engineering point of view. The soil type or the grain size distribution is used in many engineering analyses such as slope stability, seepage flow, subsidence and liquefaction analyses. In most of such analyses, the soil type or the grain size distribution is obtained by the borings or laboratory tests. Physical properties obtained through the geophysical methods, such as S-wave velocity or resistivity, do not directly relate to the soil type and the grain size distribution. For that reason, the geophysical methods have not been widely used for the levee safety assessment so far. Several researchers have been trying to estimate the soil type theoretically in terms of a rock physics theory that is getting popular in oil and gas explorations. In this paper, we are going to estimate the soil type in terms of a statistical approach using geophysical and geotechnical data collected in Japan. The collected data in this study will play important role in the theoretical study too.

Cross-plot of S-wave velocity and Resistivity

We have collected the results of the surface wave methods and resistivity methods performed at 37 Japanese rivers as well as the results of borings performed on survey lines of geophysical methods. Total survey line length of the surface wave and resistivity methods is about 600km and the number of borings is about 400.

Geophysical methods

In surface wave methods, we generally used a land streamer (Inazaki, 1999) comprising 24 to 48 geophones on aluminum plates, respectively, aligned in series at 1 to 2m intervals by two parallel ropes on the ground surface in order to move receivers quickly. In the land streamer, the geophones are not stuck on ground surface and can be moved quickly. In the analysis of the surface wave method, a CMP (Common Mid Point) cross-correlation (CMPCC) analysis (Hayashi and Suzuki, 2004) was applied to waveform data firstly and a multi-channel analysis of surface-waves (MASW) developed by Park et al. (1999) was applied to secondly.

In resistivity methods, we generally used a capacitively-coupled resistivity (CCR) method (Groom, 2008). The CCR method is a new resistivity method in which capacitors are used as electrodes. Unlike conventional resistivity methods, the CCR method does not use metallic stakes and enables us to measure the resistivity of the ground very quickly. The OhmMapper was used as a CCR instrument in our investigations. The OhmMapper uses shielded twisted-pair cables as line sources and receivers 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. The transmitter drives a 16.5 kHz signal into the cable shield and that signal is "lost" to the ground through the capacitance of the cable. We have applied the method to many site investigations (Yamashita et al., 2004) and have come to the conclusion that the method enables us to delineate precise resistivity image very quickly at least down to a depth of 5m.

The surface wave and the resistivity methods were performed at crest or toe of levees. Analyzed results were saved as a standard XML format defined by SEGJ (Hayashi et al. 2012) and stored in a web-based database for subsequent analyses.

Database of geophysical properties and soil type

Relationship between S-wave velocity, resistivity, blow counts (N-value from the standard penetrating tests) and soil type in Japanese levee is collected and stored in a database. The S-wave velocity and the resistivity at the depth of the blow counts were extracted from geophysical sections. The total number of extracted data is about 4000. The soil type is classified as clay, sand and gravel for the sake of simplicity. Unusual soil types, such as organic clay, loam or weathered rocks etc. were rejected before analysis. The data is grouped to levee body and foundation. The numbers of data in levee body and foundation are 560 and 3485 respectively. The data in levee body can be considered as unsaturated soil above the ground water level. The data in foundation can be considered as saturated soil below ground water level.

Figure 1 shows correlation between S-wave velocity and resistivity with soil classification. Figure 1a shows data in the levee body and Figure 1b shows data in foundation. We can recognize that clayey soil is placed at relatively low velocity and low resistivity area and sandy or gravel soil is placed at high velocity and high resistivity area regardless levee body or foundation. Different soil types are distributed different area and it implies that the soil type can be estimated by S-wave velocity and resistivity. In the next section, the soil type is statistically estimated from S-wave velocity and resistivity based on the correlation between S-wave velocity and resistivity shown in Figure 1.

Statistical Estimation of Soil Type

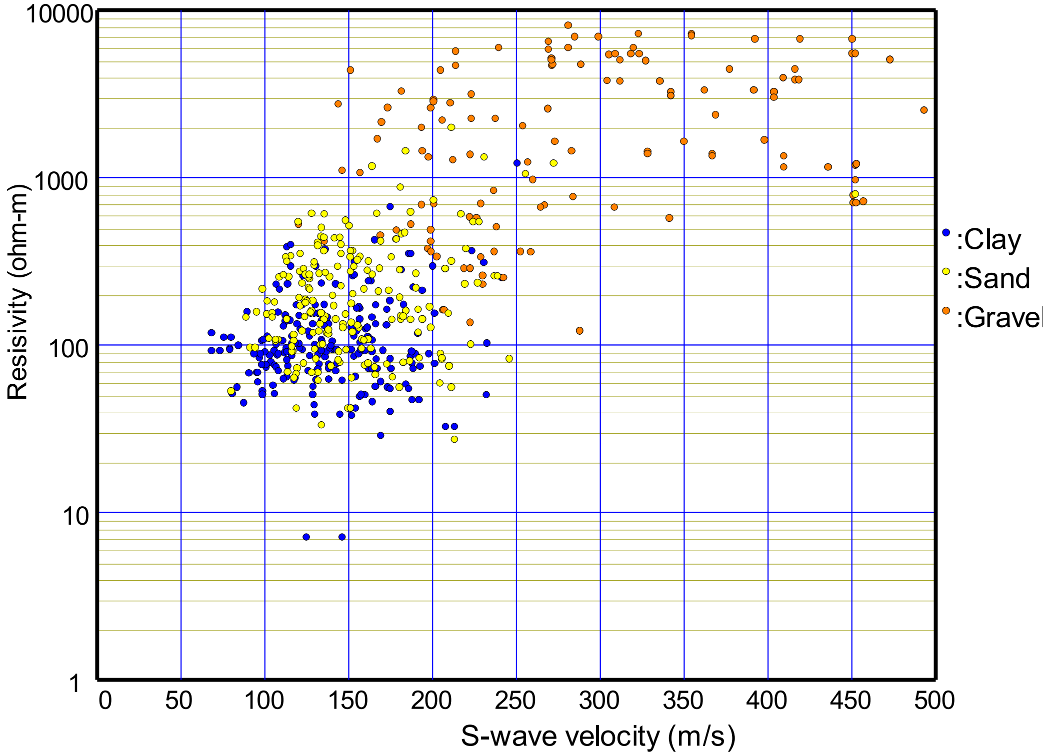
Polynomial approximation of soil type

A polynomial approximation is used to estimate the soil type from the correlation between S-wave velocity and resistivity. In the approximation, the soil type is represented by discontinuous numbers one (clay), two (sand) and three (gravel). Table 1 summarizes a relationship between the soil type and the represented numbers as well as the number of data. A polynomial equation is a function of S-wave velocity (v_s) and resistivity (ρ) and yields a continuous value S between one and three as follows.

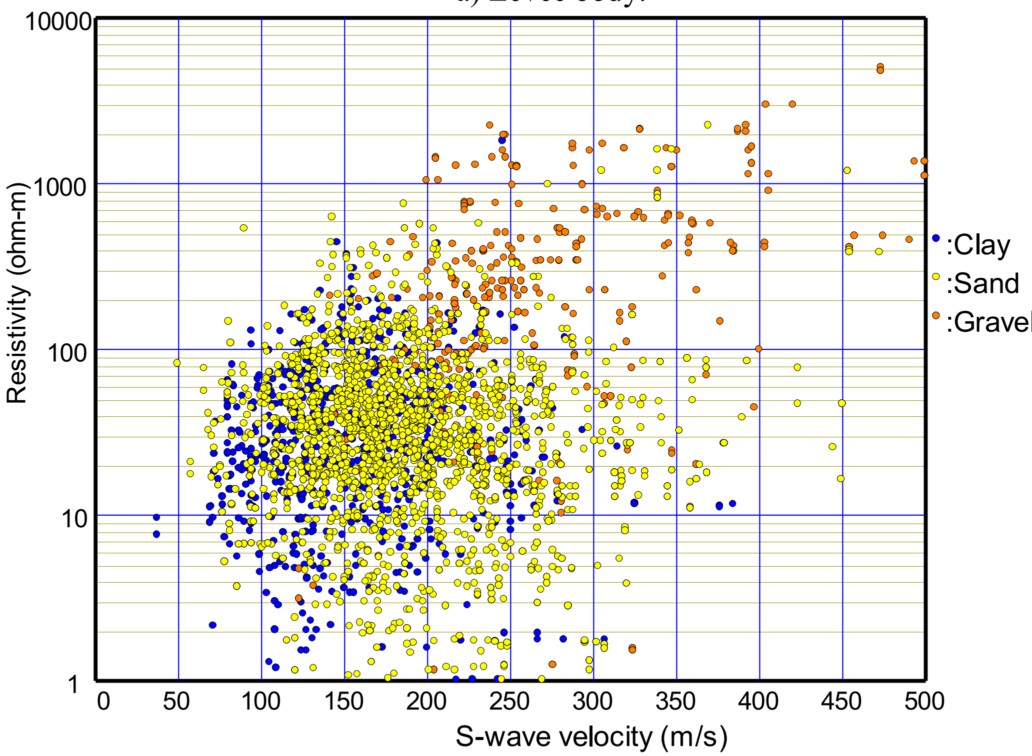
$$S = av_s^2 + bv_s + c\log10(\rho)^2 + d\log10(\rho) + ev_s^2\log10(\rho) + fv_s\log10(\rho)^2 + gv_s\log10(\rho) + h \qquad (1)$$

where, S is defined as a soil parameter and a to h are constants. The constants a to h were obtained by a least squares method so that the residual between calculated soil parameter S (continuous value from one to three) and actual soil type (one, two and three) is to be minimum. The optimized constants for levee body and foundation are summarizes in Table 2.

Figure 2 shows the distribution of the soil parameter S as the function of S-wave velocity and resistivity calculated from the equation (1) with constants shown in Table 2. In Figure 2, color



a) Levee body.



b) Foundation.

Figure 1: correlation between S-wave velocity and resistivity with soil classification.

represents the value of the soil parameter and blue, yellow and orange colors correspond to one (clay), two (sand) and three (gravel) respectively. We can recognize that the soil parameter S changes (increases) from clay (1.0) to gravel (3.0) with S-wave velocity and resistivity increase from left bottom to right top and it agrees with the distribution of collected data shown as color circles. Boundaries of soil types, such as clay to sand or sand to gravel, toward from left top to right bottom. It should be noted that slopes of soil boundaries are gentle in levee body and steep in foundation. It implies that the soil type is more sensitive to resistivity in the levee body and more sensitive to S-wave velocity in the foundation. This tendency is reasonable because the difference of resistivity associated with the soil type is large in unsaturated soil rather than saturated soil.

Table.1 Soil type and represented numbers.

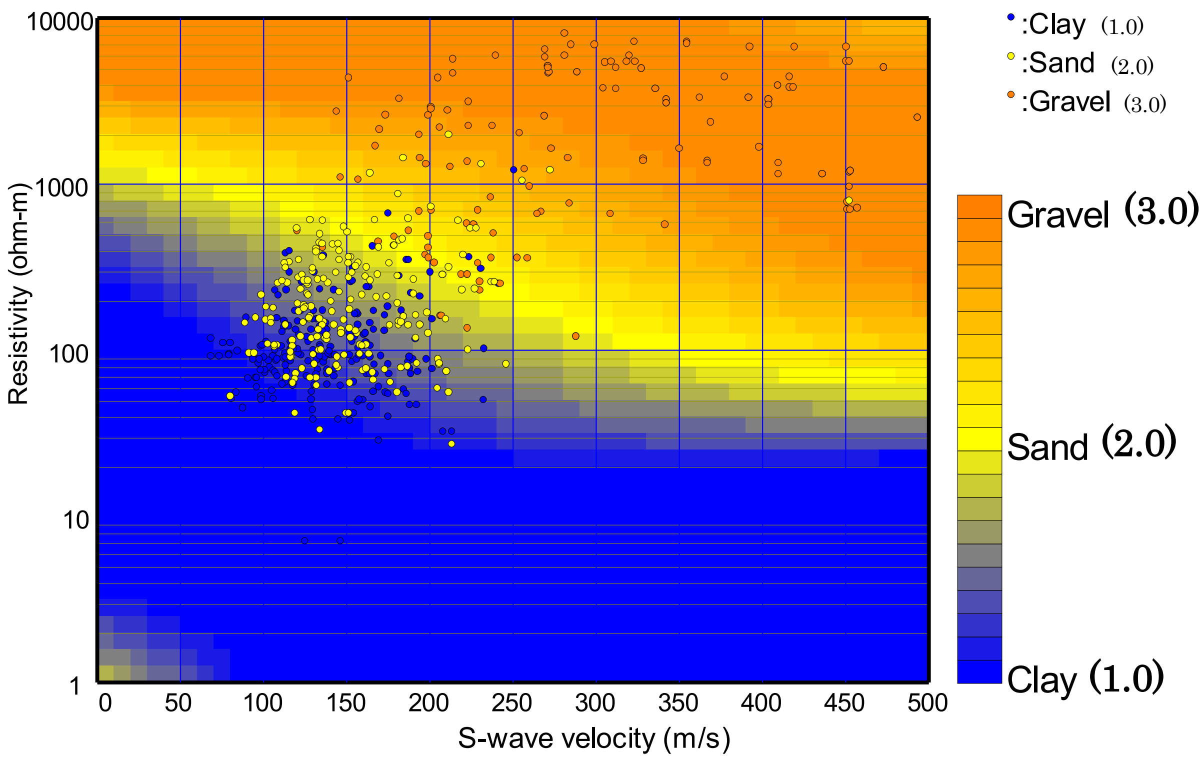
Soil type	Represented number	Number of data	
		Levee body	Foundation
Clay	1.0	221	915
Sand	2.0	199	2145
Gravel	3.0	143	425
Total	-	563	3485

Table.2 Estimated constants of polynomial approximation for levee body and foundation

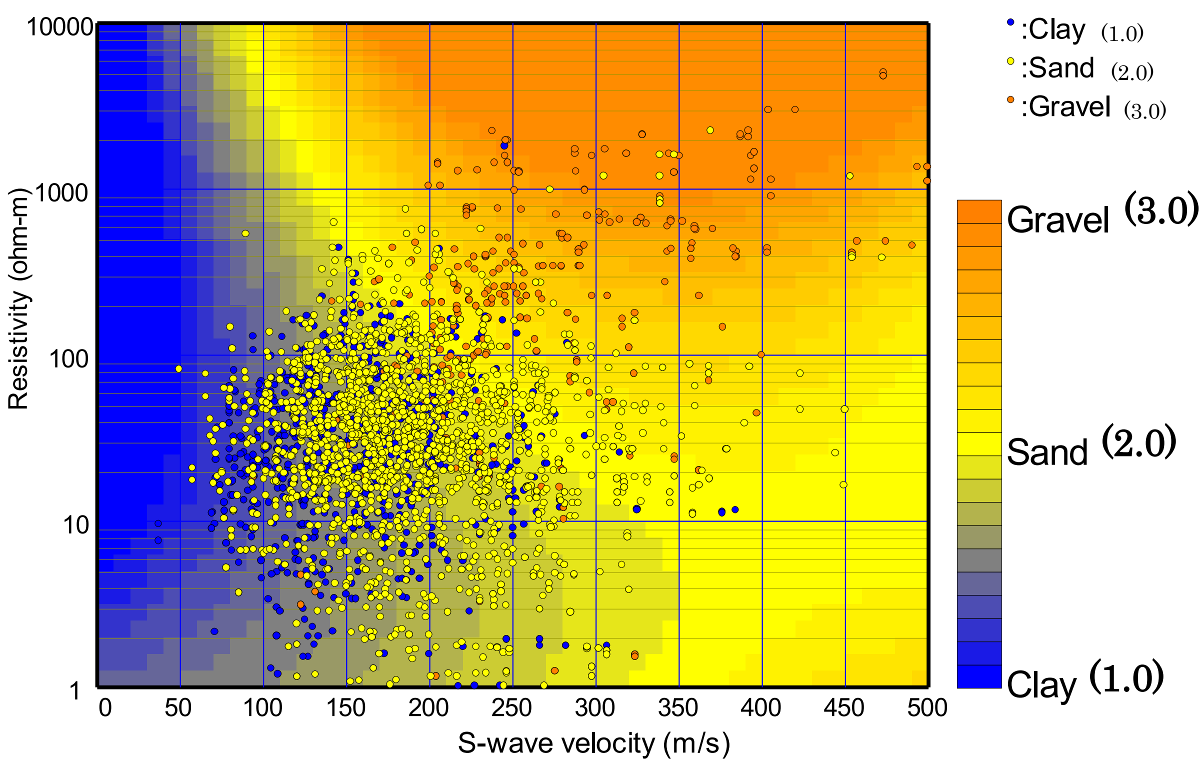
Constant	Levee body	Foundation
a	-0.0000062	-0.0000002
b	-0.0072263	0.0019388
c	0.5333744	0.0938875
d	-1.5275230	-0.5366671
e	0.0000016	-0.0000064
f	-0.0025515	0.0001980
g	0.0111545	0.0032458
h	1.7115340	1.4068120

Example of estimation

Using the polynomial equation (1) with constants in Table 2 or charts shown in Figure 2, the soil type can be estimated from the S-wave velocity and the resistivity in terms of the soil parameter S. In other words, the soil type section can be estimated from S-wave velocity and resistivity sections obtained by the surface wave methods and the resistivity methods respectively. Here is an example of estimation. Figure 3 shows the example of S-wave velocity and resistivity sections. Figure 4a and 4b shows the cross-plots of S-wave velocity and resistivity data shown in Figure 3. Difference of color indicates the soil parameter calculated by the polynomial equation (1) with constants in Table 2. Figure 4c shows an estimated soil type section projected from Figure 4a and 4b. We can recognize that levee body is clayey than foundation. In the foundation, right hand side of the section is sandier than left hand side.

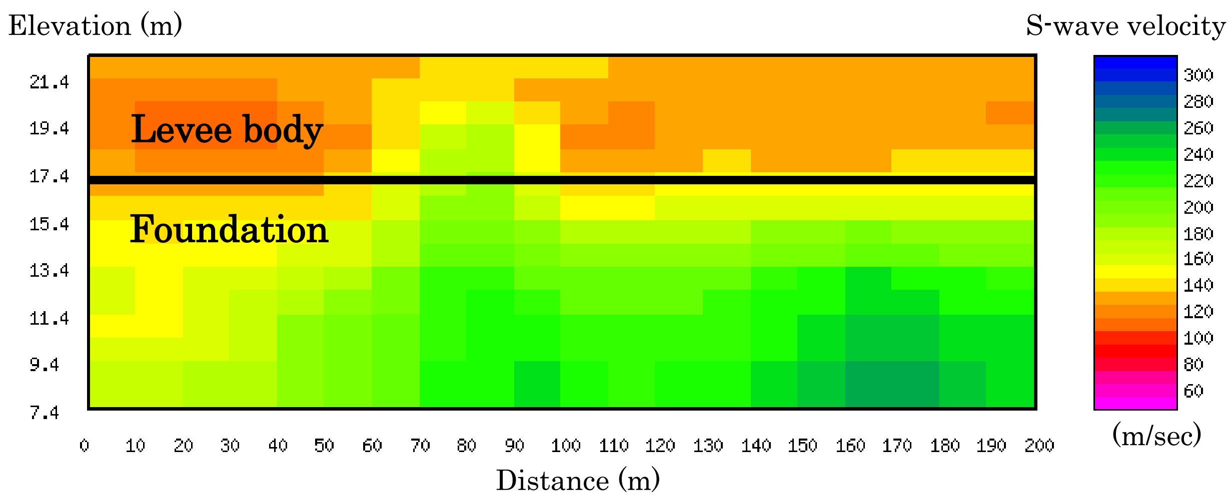


a) Levee body.

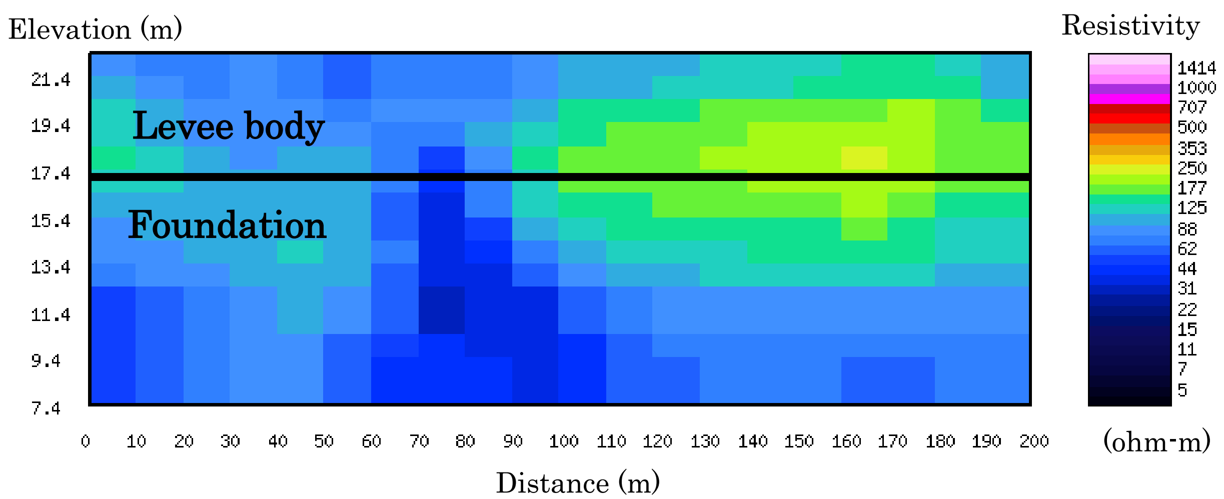


b) Foundation.

Figure 2: Distribution of soil parameter *S* as a function of S-wave velocity and resistivity calculated from a polynomial approximation.



a) S-wave velocity model obtained from surface-wave method.

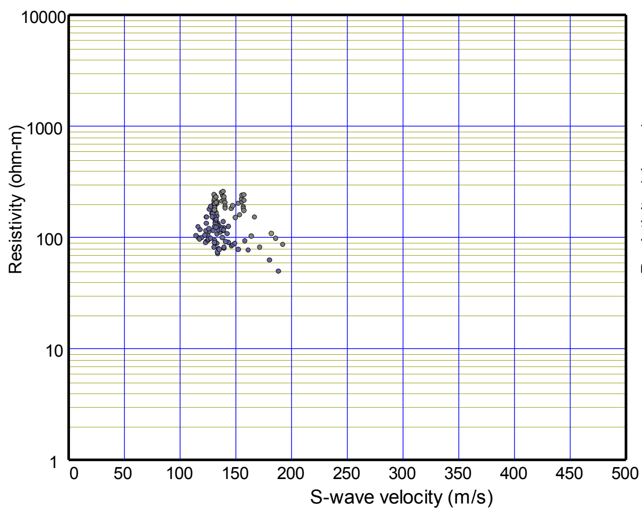


b) Resistivity model.

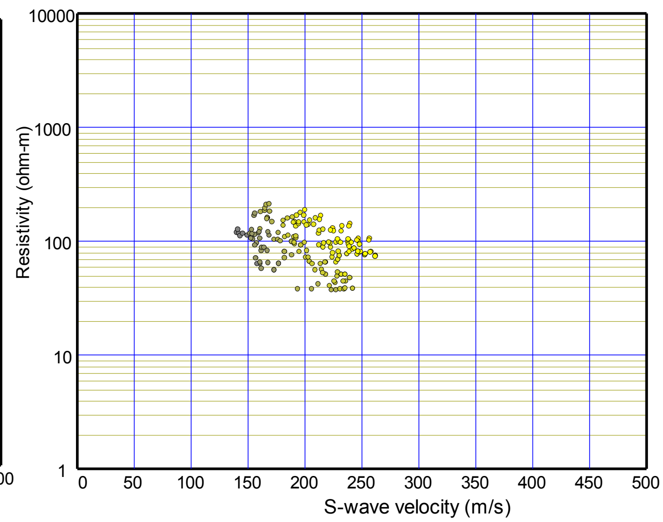
Figure 3: Example of S-wave velocity and resistivity sections.

Accuracy

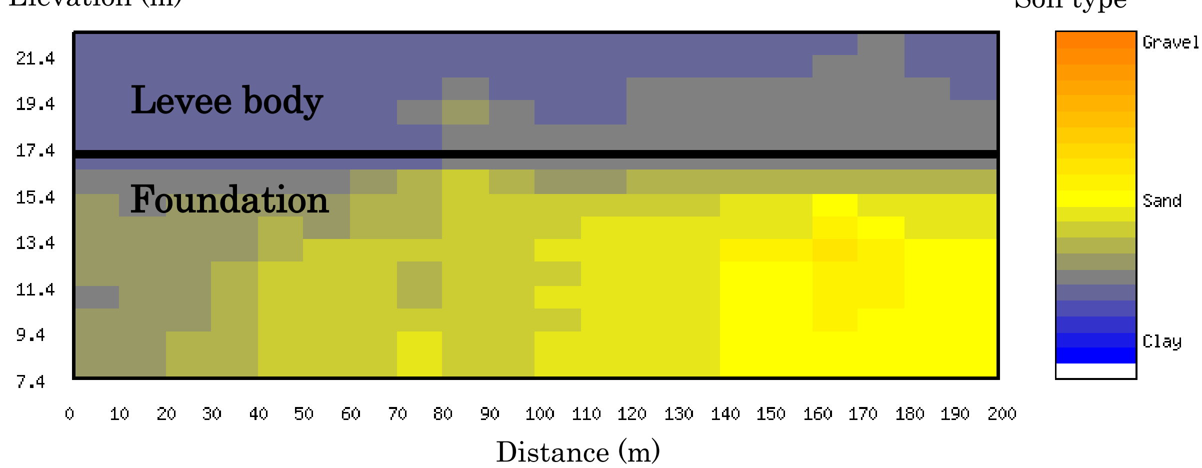
Accuracy of estimation can be statistically evaluated by comparing the estimated soil parameter with actual soil type. Figure 5 shows the summary of comparison. Data were grouped into four groups (1.0 to 1.5, 1.5 to 2.0, 2.0 to 2.5, 3.0 to 3.5) by the estimated soil parameter *S*. In each group, the numbers of actual soil type (clay, sand, gravel) were counted and shown as proportion in Figure 5. For example, if the estimated soil parameter is smaller than 1.5 in levee body, two-thirds of data are classified to be clay and one-third are classified to be sand. If the estimated soil parameter is larger than 2.5, 90% of data are classified to be gravel regardless levee body or foundation. It is clear that as the soil parameter increases, the proportion of sand and gravel increases. Figure 5 shows that the soil type estimation using the cross-plot of S-wave velocity and resistivity gives us approximate soil structure of levee body and foundation.



a) Data in levee body.



b) Data in foundation.

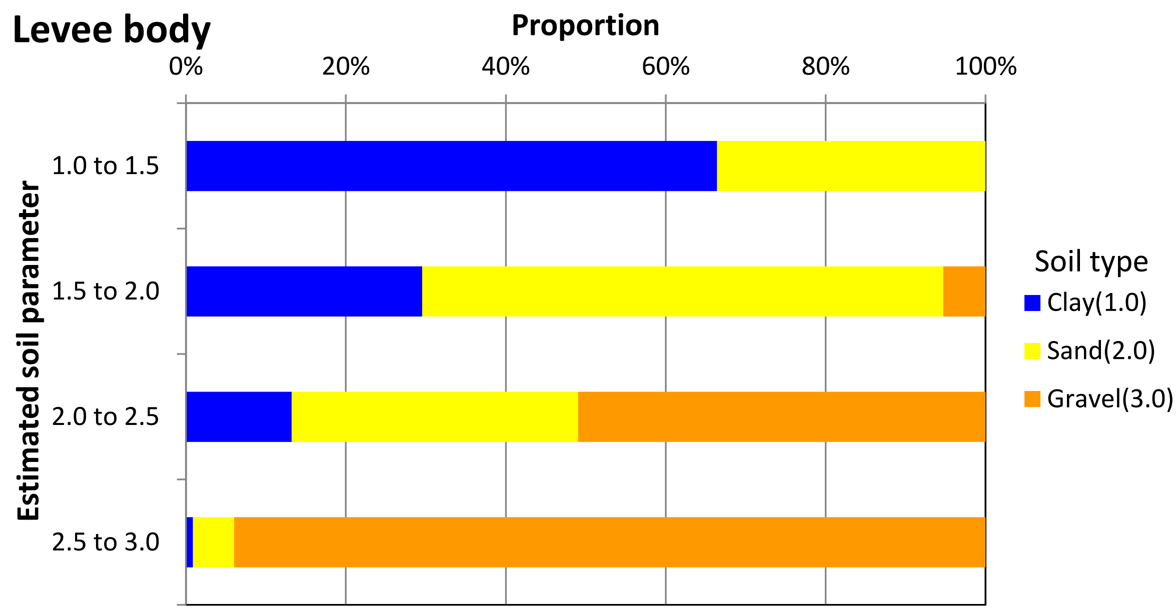


c) Estimated soil type.

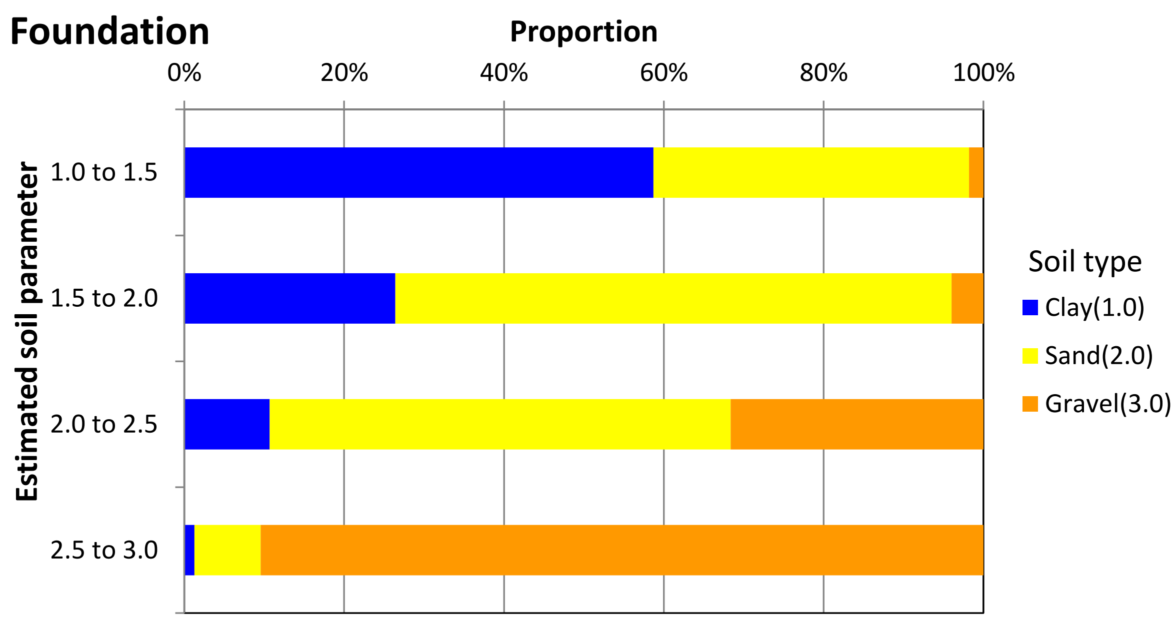
Figure 4: Cross-plot of S-wave velocity and resistivity (a, b) and projected soil type section (c).

Conclusions

The soil type of levee body and foundation was statistically predicted using the cross-plots of S-wave velocity and of resistivity. The results imply that the physical properties obtained by geophysical methods, such as S-wave velocity and resistivity, can be used not only for qualitative interpretation but also quantitative engineering analyses, such as slope stability or liquefaction analyses. Similar approaches can be applied to other purposes besides levee inspection and other countries besides Japan. It is important that any results of geophysical investigations are saved as a standard format and registered in database with adequate geotechnical or geological information.



a) Levee body.



b) Foundation.

Figure 5: Comparison of estimated soil parameter and actual soil type.

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