공학석사 학위논문

3D Geostatistical Integration Based on Site-specific Correlations with Borehole data and Geophysical data

지역적 상관성을 고려한 시추조사자료와 지구물리탐사자료의 3차원 지구통계학적 통합분석

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지도 교수 정 충 기

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김정준의 공학석사 학위논문을 인준함

2015년 8월

위 원 장 ____________________ (인)

부위원장 ____________________ (인)

위　　원 ____________________ (인)

Abstract

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Kim,Jeong Jun
Department of Civil and Environmental Engineering
The Graduate School
Seoul National University

The decision of 3D strata information is necessary in various constructions site. In order to determine the 3D strata information in the site, borehole datasets obtained by borehole tests are mainly used. Borehole data provides relatively clearer geotechnical information compared to other geotechnical investigation methods. However, it has a limitation in the insufficient acquisition of continuous geotechnical information in entire site. In contrast, geophysical tomography covers a larger area and is relatively continuous data due to be investigated by 2D cross section. However, geophysical tomography indicates the geophysical characteristics, which should be transformed into geotechnical information by empirical method. Therefore, it is possible to obtain more reliable strata information by combining borehole data and the geophysical measurements using geo-statistical methods.

The borehole datasets are generally regarded as true value. However, even borehole datasets include outlier because of various uncertainties: the inherent soil variability, the measurement uncertainties, and the transformation uncertainties. Therefore, the borehole datasets have to be optimized to obtain reliable information. In addition, the borehole data and geophysical data have site-specific correlations which it makes difference in each site. Therefore, the site-specific variability must be considered to estimate reliable information.

In this study, the 3D geo-statistical integration method, which combines borehole data and geophysical data, considers site-specific geotechnical variability was proposed. First, the borehole datasets are optimized to obtain reliable information by using outlier analysis based on cross validation. Then, the site-specific geo-layer criteria are determined to transform geophysical data into 3D strata. Finally, 3D strata information considering site-specific correlations in target area is determined by using 3D geo-statistics. In addition, the proposed method was applied to validate applicability on 3 testing sites in Korea.

Keywords: Borehole, Geophysical survey, Electric resistivity, Seismic refraction wave velocity, Outlier analysis, Indicator kriging, 3D geo-statistical integration

Student Number: 2013-23148

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Chapter 1 Introduction

1.1 Background

It is important to estimate reliable 3D strata information in various constructions. The reliable 3D strata information should be estimated by site investigations. In most cases, the subsurface information is investigated based on the boring data which represent 1D soil profiles of each point. Engineers have limitations in the appropriate comprehensions of continuous soil properties (Jaime and Mohan, 1990; Joh et al., 2006). Such a lack of information can be compensated by building 3D spatial geotechnical information structures (Kupfersberger and Deutsch, 1999; Weissmann et al., 1999; Koltermann and Gorelick, 1996).

Geo-statistics is a statistics method used to model the spatial information from discrete data based on spatial interpolation (Deutsch, 2002). Applying the geo-statistical techniques using numerous borehole data, previous researchers attempted to estimate the multi-dimensional distribution of soil properties (Ozturk, 2002; Ryu et al., 2003).

Geophysical surveys such as seismic refraction prospecting and electrical resistivity surveys are conducted to provide soil properties for all locations within a given area. However, geophysical surveys have limitations in the fact that the tomographic results do not guarantee actual soil properties. There are several approaches to integrate inhomogeneous geophysical survey data or borehole data using geo-statistical methods. (Kim et al., 2012a;

Gallerini and Donatis, 2009; Oh et al., 2004; Jaime and Mohan, 1990). Generally, the borehole data are regarded as the actual soil properties. However, even the borehole data have uncertainties because of the inherent soil variability, the measurement uncertainties, and the transformation uncertainties (Kulhway et al., 1992).

Kim (2014) proposed the 3D geo-statistical integration by applying indicator kriging with outlier analysis in order to combine the advantages of both the borehole data and the geophysical survey data. To remove the outliers, the cross validation method was considered. However, the cross validation method did not consider the site-specific geotechnical variability. In addition, this method has a limitation in the fact that it needs existing classification criteria for the geo-layer to determine the 3D strata.

In this study, the optimum outlier thresholds of borehole datasets were proposed to consider site-specific uncertainties of the geo-layer. In addition, the determination method of geo-layer criteria of geophysical survey data considering the site-specific in target area was proposed, and the integrated analysis using indicator kriging was applied in field. The 3D strata were then visualized using a 3D visualization program developed by Seoul National University.

1.2 Objectives

This dissertation deals with the integrated analysis of borehole test and geophysical survey data to estimate 3D strata information. This study primarily focuses on optimization of borehole test data because to calibrate borehole test data, and suggested methods called 3D geo-statistical integration for estimating 3D strata in sites with both borehole test data and geophysical survey data. The specific objectives of this study are as follows:

1. Optimization of borehole dataset: the borehole datasets include errors due to several conditions. Thus, the borehole test data have to be optimized by the standardization of geo-layer boundaries and the optimization of entire datasets based on outlier analysis.
2. Construction of reliable 3D strata : 3D strata is constructed by using 3D geo-statistical integration with \calibrated borehole datasets and geophysical data considering locality :
3. Validation of proposed method : To validate this method, this method are applied at three test site, which have different characteristics respectively, in Korea

1.3 Dissertation Organization

This dissertation documents the development of 3D geo-statistical integration of borehole test and geophysical data.

Chapter 1.Introduction

Introduction includes research background and objectives, and dissertation organization was described.

Chapter 2.Literature Review

Literature review for optimization of borehole datasets and geo-statistical interpolation are described.

Chapter 3.Optimization of Borehole Datasets

To detect and remove outlier of borehole datasets which they will be utilized in 3D geo-statistical integration step, the optimization of borehole datasets were modified and developed.

Chapter 4.Determination of Site-specific Geo-layer Criteria

The geo-layer criteria are utilized to estimate 3D geotechnical strata in 3D geo-statistical integration. These criteria mean relations between geo-layer in borehole datasets and geophysical values. Each site has different site-specific characteristics. Therefore, the determination of site-specific geo-layer criteria must be carried out.

Chapter 5.3D Geo-statistical integration

Currently, various interpolations of geotechnical characteristics were researched and developed. In this study, the 3D geo-statistical integration using both borehole datasets and geophysical data are utilized and described in this chapter.

Chapter 6.Systematic Field Application

The 3D geo-statistical integration method considering site-specific characteristics was applied in three site(Gyodong bridge site, Saemanguem reclaimed land site, and Andong dam site). In addition, validation of the proposed method based on cross validation is described.

Chapter 7.Conclusions and Recommendations

Summary and conclusions for this study are described and recommendations for the further study are presented.

Chapter 2 Literature Review

2.1 Optimization of Geotechnical Datasets

2.1.1 Description of outliers in geotechnical datasets

The various previous studies were described about the spatial uncertainty of geotechnical properties. Especially, Kulhawy(1992) proposed three primary sources of uncertainty in geotechnical design parameters: the inherent soil variability, the measurement uncertainty, and the transformation uncertainty. First, the inherent soil variability is inartificially occurred by the process of natural geological features. Second, the measurement uncertainty is caused by equipment, operators, and random effects during test. Finally, transformation uncertainty is caused during transforming into design soil parameters with empirical and theoretical models. These uncertainties can have negative effects on geotechnical design. Thus, it is necessary to reduce and remove these uncertainties with appropriate statistical methods. Generally, these uncertainties which should be removed were called outliers in statistics (Barnett and Lewis, 1994; Grubbs, 1969). In other words, the outlier is an observation in a data set which appears to be inconsistent with the remainder of that set of data.

2.1.2 Detection method of outliers for geotechnical interpolation

There are a lot of outlier detection techniques in statistics as shown Fig. 2.1. In this study, the outlier detection method based on cross-validation by Kim(2014) was modified, and the modified method was applied.

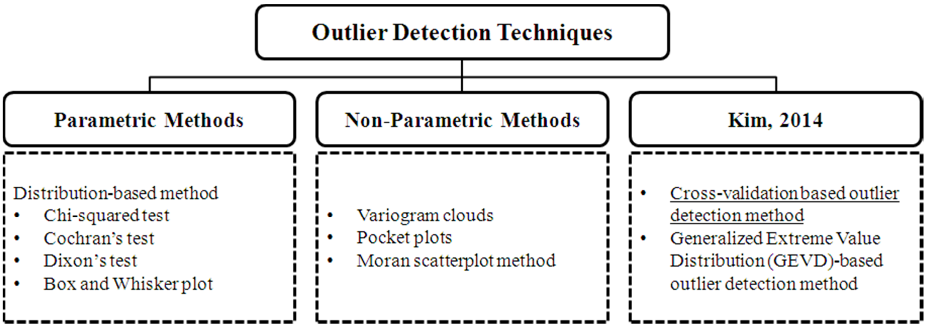

Figure 2.1 Taxonomy of previous outlier detection method (Kim,2014)

Cross-validation based outlier detection method (Kim, 2014)

Cross-validation is a type of blind test to determine whether the target point has the tendency of the surrounding base values using kriging. This method was developed to evaluate the susceptibility of variogram models or kriging models (Isaaks et al., 1989; Delfiner, 1976; David, 1976; Knudsen and Kim, 1978). It is adapted to evaluate the local reliability of the measured properties. The local reliability for each observation is evaluated based on the difference between measured and estimated values with the following procedures.

1) Compute an experimental variogram from the entire set of sample data and fit a plausible model to it.

2) Estimate the value at each sampling point by kriging sequentially after excluding the measured target value there.
3) Calculate the difference between the estimated value and the measured value.

The variogram for the testing data is presented with the exponential model in Figure X.X. It is calculated considering the effects of a spatial trend on the variogram. The correlation length of original measurements without trend effects is 110m.

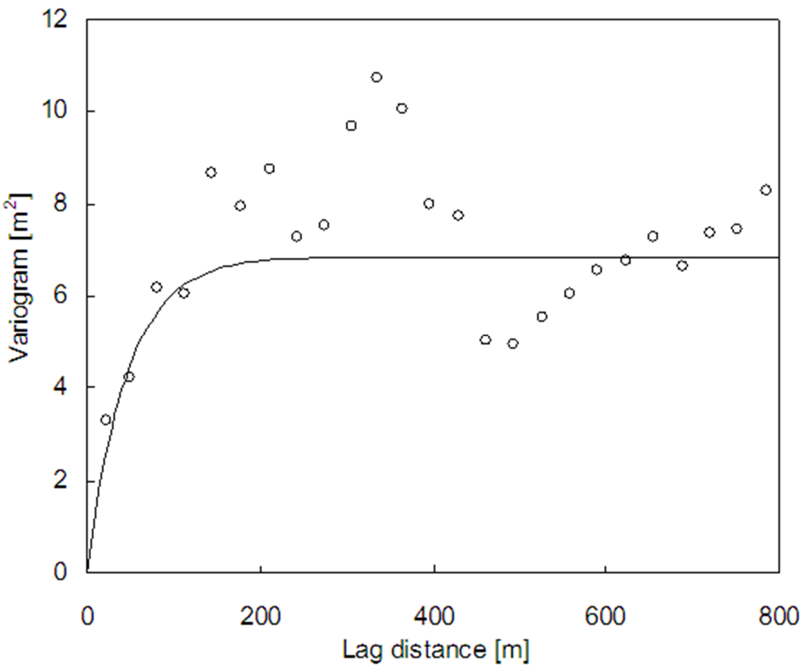

Figure 2.2 Variogram of the original data based on the exponential model (Kim,2014)

The cross-validation based outlier detection method is applied to the testing data, and the measured values and the estimated values by the cross-validation are compared in Figure X.X. The solid line in Figure X.X is the line where the estimated values are equal to the measured values, and the dotted lines are outlier criteria to select the least predictable 10% data points with the other measurements. The hollow points are the outliers as determined by this method.

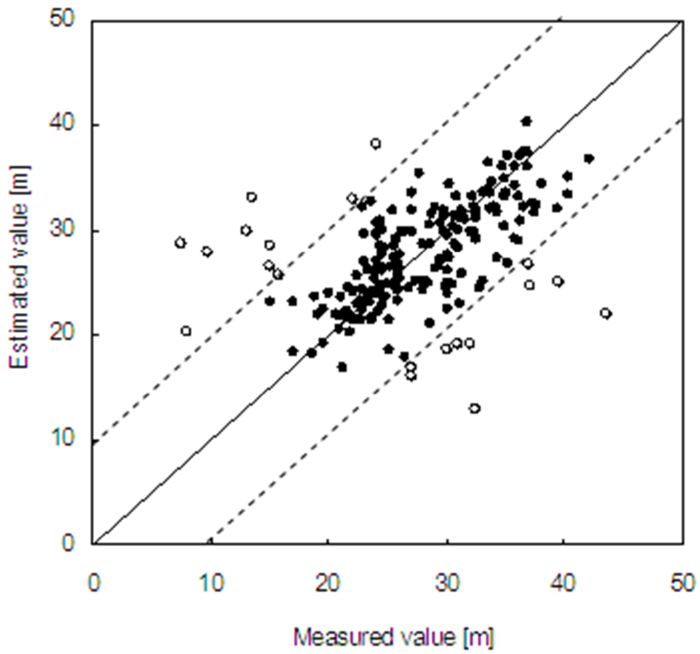

Figure 2.3 The measured soil depth to the bed rock vs. the estimated values by the cross-validation method (Kim,2014)

2.2 Geo-statistical Interpolation

2.2.1 Previous researches of 3D spatial geotechnical information

The geotechnical parameters in field should be investigated to design structure. In most cases, the subsurface information is investigated based on the boring data which represent 1D soil profiles of each point. However, in spite of that borehole test is simple and accurate, borehole test are carried out discontinuously in target area. Engineers have limitations in the appropriate comprehensions of continuous soil properties (Jaime and Mohan, 1990; Joh et al., 2006). Thus, Engineer need to determine the geotechnical information in unsight and unknown area. Such a lack of information in unsight and unknown area can be compensated by building 3D spatial geotechnical information structures (Kupfersberger and Deutsch, 1999; Weissmann et al., 1999; Koltermann and Gorelick, 1996).

Geo-statistics is a statistics method used to model the spatial information from discrete data based on spatial interpolation (Deutsch, 2002). Applying the geo-statistical techniques in numerous borehole datasets, previous researchers attempted to estimate the multi-dimensional distribution of soil properties (Ozturk, 2002; Ryu et al., 2003).

Geophysical surveys such as seismic refraction prospecting and electrical resistivity surveys are carried out to provide continuous soil properties for all locations within a given area. However, geophysical surveys have limitations in the fact that the tomographic results do not guarantee actual soil properties. Because geophysical survey data didn’t indicate direct soil properties, geophysical survey data should be transformed into geotechnical design parameter. There are several approaches to integrate inhomogeneous geophysical survey data or borehole data using geo-statistical methods. (Kim et al., 2012a; Gallerini and Donatis, 2009; Oh et al., 2004; Jaime and Mohan, 1990). Especially, Kim (2014) proposed the 3D geo-statistical integration by applying indicator kriging with outlier detection method as mentioned above previous section ("2.1.1 Description of outliers in geotechnical datasets) in order to combine the advantages of both the borehole data and the geophysical survey data.

2.2.2 Geo-statistical method

Kriging is one of geo-statics methods, which accounts for a spatial correlation of physical values. A basic idea of kriging is to estimate the value at a given point, which is unknown, by computing a weighted average of the known values in the neighbors of the point. According to the satisfaction to the stationary assumptions, kriging is classified with simple kriging, ordinary kriging(OK), and universal kriging(UK). For OK method, the stationary assumption or intrinsic assumption should be satisfied(Li et al., 2000), that is, there should be a constant expectation in the whole field or at least in a target area. On the other hand, the stationary assumption is not necessary for UK method which supposes that the mathematical expectation is a function of a spatial location. Evidently, the UK is suitable for non-stationary cases. The kriging interpolation can be expressed as

$$Z(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i)$$

(2.1)

Where $Z(x_0)$ is the predicted value at the location x_0, $Z(x_i)$ is the measured value at location x_i, N indicates the number of measured points surrounding the predicting location, λ_i is the weight assigned to measured points, and can be solved by following OK system:

$$\sum_{i=1}^{N} \lambda_i \gamma(x_i, x_j) + \mu = \gamma(x_j, x_0) \qquad j = 1,2, \dots, n$$

$$\sum_{i=1}^{N} \lambda_i = 1$$

(2.2)

The corresponding estimated error of the OK method is

$$\sigma_{OK}^2 = \sum_{i=1}^{N} \lambda_i \gamma(x_i, x_0) + \mu$$

(2.3)

Where $\gamma(h)$ is the variogram value with lag distance h, and N(h) is the number of lag distance. Practically, an experimental variogram curve should be made from sampling values, and then the theoretical variogram ,which is one of analytic functions, should be fit.

For the UK method, the expectation is not constant and a function of the spatial locations,

$$E[Z(x)] = m(x)$$

$$Z(x) = m(x) + R(x)$$

(2.4)

Where E[Z(x)] is the mathematical expectation function, and R(x) is the residual between Z(x) and the drift m(x) at location x. The m(x) is usually fitted by Nth order polynomial,

$$m(x) = \sum_{i=1}^{N} a_i x^i$$

(2.5)

Where a_i is the coefficient of drift polynomial. Since interpolation is always a local calculation, m(x) is the local drift. Generally, a linear or quadratic polynomial is enough to express the drift. The variogram of Z(x) is solved by R(x) and the weights are assigned by the UK system:

$$\sum_{i=1}^{N} \lambda_i \gamma(x_i, x_j) + \sum_{k=1}^{N} \mu_k {x_i}^k = \gamma(x_j, x_0), \quad j = 1,2, \dots, n$$

$$\sum_{i=1}^{N} \lambda_i {x_i}^k = x_0^k \quad k = 1,2, \dots, n$$

(2.6)

Where the second expression is non-bias condition. The corresponding estimated error of the UK method is expressed as

$$\sigma_{OK}^2 = \sum_{i=1}^{N} \lambda_i \gamma(x_i, x_0) - \gamma(x_0, x_0) + \sum_{l=0}^{N} \mu_l x_0^l$$

(2.7)

Chapter 3 Optimization of Borehole Test Datasets

3.1 Standardization of Geo-layer Boundaries

Borehole test is one of basic site investigation method. The borehole is not only simple to analysis, but also relatively accurate because of sampling the subsoil and observing the stratum directly. So many engineers regard the borehole data as the actual soil properties. However, the borehole test has a limitation to investigate perfect soil properties, and the borehole data also have uncertainties because of the inherent soil variability, the measurement uncertainties, and the transformation uncertainties (Kulhway et al., 1992).

A borehole consists of the “known” section and the “unknown” section as shown in Fig. 3.1. The “known” section indicates the section where the soil characteristics are acquired through the core samples of the borehole test, whereas the “unknown” section indicates the section where the soil characteristics are acquired through indirect means such as the drilling sound, the rate of penetration, and the slime. If the geo-layer boundary is positioned in the unknown section, the geo-layer boundary is determined by subjective judgments of the investigator without clear standards. It means the geo-layer boundaries in borehole log are determined differently by respective investigator.

When the boring logs in the target area were actually compared, the determination locations of the geo-layer boundary differed for each investigator. Even the same investigator sometimes determined irregular geo-layer boundaries. To exclude these subjective judgments of the borehole test investigator, the geo-layer boundaries of the borehole data were standardized by determining the midpoint of the unknown section as geo-layer boundaries.

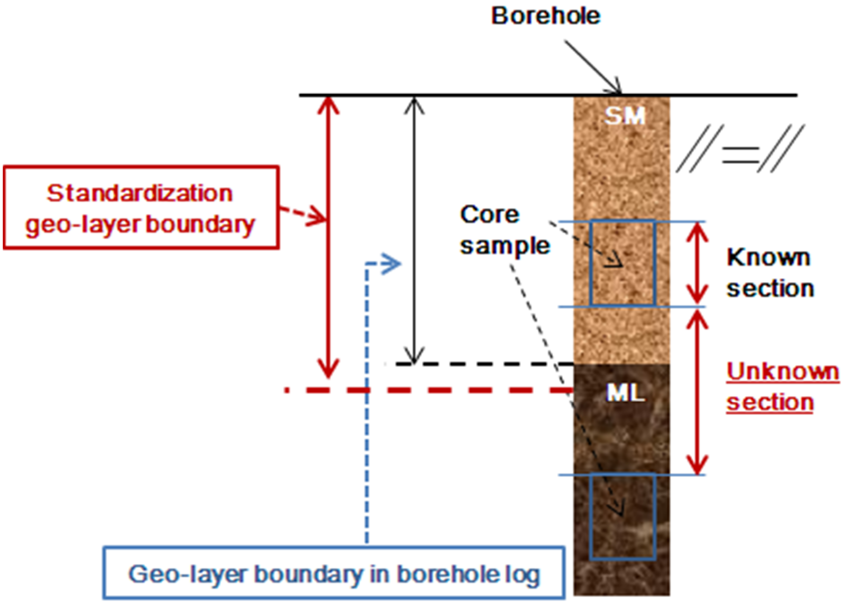

Figure 3.1 Standardization of the geo-layer boundary

3.2 Outlier Analysis

Outliers indicate the datasets which appear to be inconsistent with the remainder of the datasets. Borehole test have uncertainties such as the inherent soil variability, the measurement uncertainty, and the transformation uncertainty. Due to errors that result from uncertainties of borehole tests, borehole datasets have outliers which need to be removed. It is hard to determine the distinct outliers from the site investigation data. However, it is possible to determine the relatively outlying data using a outlier analysis (cross validation), which is a type of blind test to determine whether the target point has the tendency of the surrounding base values using kriging (Isaaks and Srivastva, 1989). According to Kim (2014), the outlier thresholds of all geo-layers were applied equally (10%). It means that the number of outlier is 10% of the number of entire data.

However, the outlier threshold in bore datasets by Kim(2014) (10%) has limitation, because 10% in borehole datasets is determined as outliers regardless of geo-layer and site-specific conditions. The outlier threshold would be different in various site conditions. The most suitable outlier thresholds in site-specific condition which is called the “optimum outlier threshold” must be determined.

In this study, the optimum outlier threshold is defined to consider the spatial correlations among borehole datasets as shown in Fig. 3.2. The determination method of the optimum outlier threshold is as follows. First, the RMSE (Root Mean Square Error) with nine assumed outlier thresholds (0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%) is calculated for all geo-layers. For example, if the outlier threshold is 5%, the RMSE is calculated excluding 5% of entire datasets. Second, the point where the rate of change for correlations is highest is determined. Third, two linear regression lines (red lines in Fig. 3.2) at the point are drawn. Finally, the intersection point of the two regression lines indicates the optimum outlier threshold. In order to modify the borehole datasets, the optimum outlier thresholds are used. The modified borehole datasets are then utilized for the 3D geo-statistical integration.

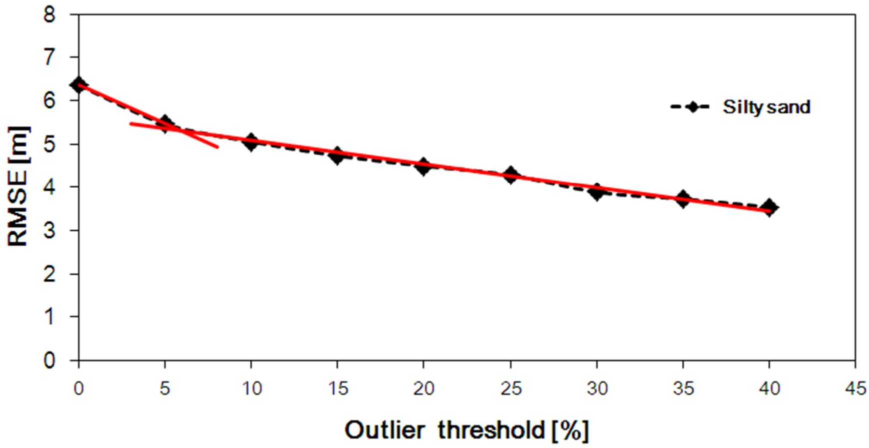

Figure 3.2 Method of determining optimum outlier threshold

3.3 Geo-statistical analysis using only optimized borehole datasets

Using geo-statistical method, 3D strata information in four application sites are estimated and compared. Site area, number of borehole, density of borehole, and RMSE using cross-validation were compared as shown as Table 3.2. Target site is four area in Korea: Gyodong bridge site, Saemanguem reclaimed land site, Andong dam site, Mokdong site. Gyodong bridge site is offshore site where the flow velocity is very rapid and the range of tide is large. Saemanguem reclaimed land site is large scale offshore area as against small density of investigation. Andong dam site is mountainous area where the variability of elevation is high. Mokdong site is a urban flatland in Korea.

1) Before analysis was conducted, the higher density of borehole is, the higher accuracy of 3D strata information would be expected. However, as shown Table 3.1, the density of borehole in Andong dam site, where the RMSE among sites is highest, is higher than that in Saemanguem reclaimed land site and Mokdong site: Gyodong bridge site is linear, so Gyodong bridge site is excluded in comparison of density of borehole. It is due to variability of topography in Andong dam site. Andong dam site is mountainous area and has high variability of topography. Actually, the variability of elevation is higher than the others because of highest standard deviation and range as shown Table 3.2. As a result, the accuracy of using only borehole data is influenced by variability of topography, not density of borehole.

Table 3.1 Comparison of investigation condition in each site

	G site	S site	A site	M site
Site area [km^2]	1.62 (=1.62×1)	44.4 (=6×7.4)	0.243 (=0.340×0.715)	0.889 (=1.460×609)
Number of borehole [EA]	17	22	24	21
Density of borehole [EA/km^2]	1.04×10^{-2}	4.95×10^{-7}	9.87×10^{-5}	2.36×10^{-5}
RMSE (using only borehole data)	6.62	4.90	10.68	4.19

Table 3.2 Comparison of variability of ground elevation in each site

	G site	S site	A site	M site
Max. [m]	0	-2	194	9.9
Min. [m]	-25	-18	101	6.4
Average [m]	-15.3	-5.7	143	7.6
Standard deviation [m]	7.5	3.7	32	0.9

Chapter 4 Determination of Site-specific Geo-layer Criteria

4.1 Construction of 3D Geophysical Data

Results of the geophysical survey obtained generally in testing sites were not digital datasets, but mainly 2D tomography graphics. Therefore, the 2D tomography of the geophysical survey first needs to be transformed into 2D digital datasets as shown in Fig. 4.1.

Fig. 4.1-(a) shows the 2D tomography of the geophysical survey. As in Fig. 4.1-(b), the size of the grid is set, and the grids are overlapped into 2D tomography as shown in Fig. 4.1-(c). Finally, the 2D digital datasets of geophysical tomography are determined by digitizing the contour lines which indicate the geophysical values (ex. 2.2 ohm-m, 10.0 ohm-m etc.) as shown in Fig. 4.1-(d).

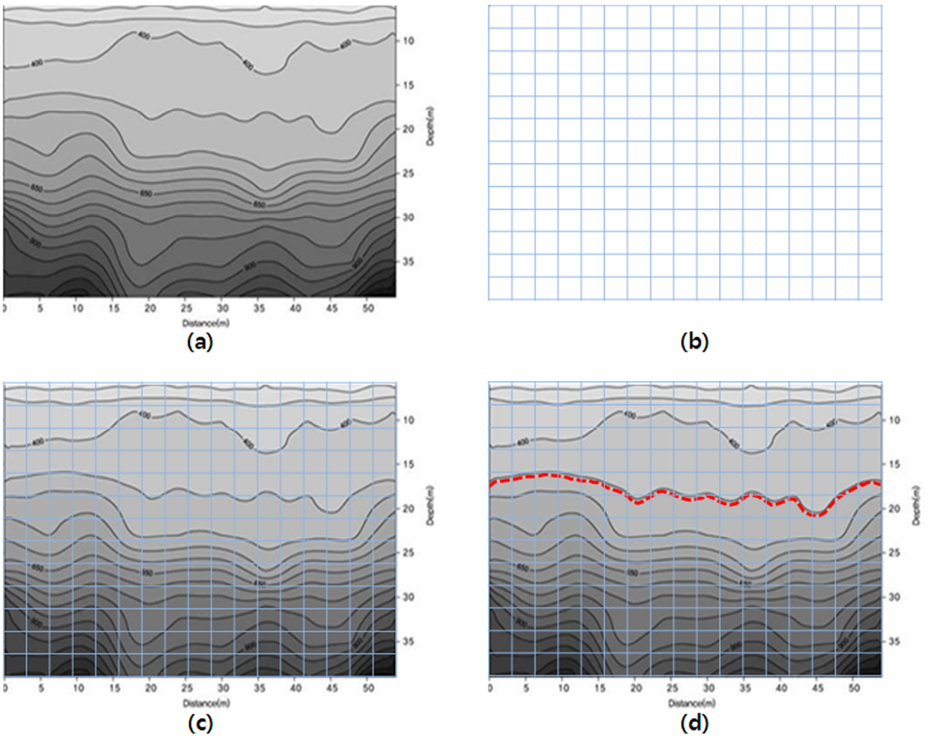

Figure 4.1 Conceptual process of digitizing 2D tomography

After digitizing the 2D tomography, 2D datasets are transformed into the 3D geophysical database which has spatial location information. To build up the 3D geophysical database, 3D ordinary kriging was performed in this study. After the 3D geophysical database is determined, the optimized borehole data and the geophysical data in same location are compared to determine site-specific geo-layer criteria.

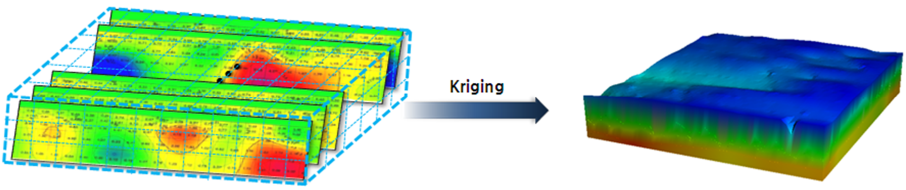

Figure 4.2 Conceptual process of building 3D geophysical database

4.2 Determination of Site-specific Geo-layer Criteria

To do 3D geo-statistical integration, the site-specific geo-layer criteria which are the relation between geo-layer and geophysical value must be determined. According to Kim(2014), to do 3D geo-statistical integration, the existing geo-layer criteria are utilized. However, the existing geo-layer criteria don't consider with site-specific condition. Therefore, the geo-layer criteria considering site-specific condition should be determined in this chapter.

The geophysical values of soils have spatial variability. Therefore, it is necessary to determine the classification criteria considering the site-specific geophysical variability. The strata of borehole datasets was compared with the 3D geophysical datasets at the same spatial locations, and the geophysical values at each geo-layer were extracted as shown Fig. 4.3. The site-specific geo-layer criteria are determined by 3 methods as follows.

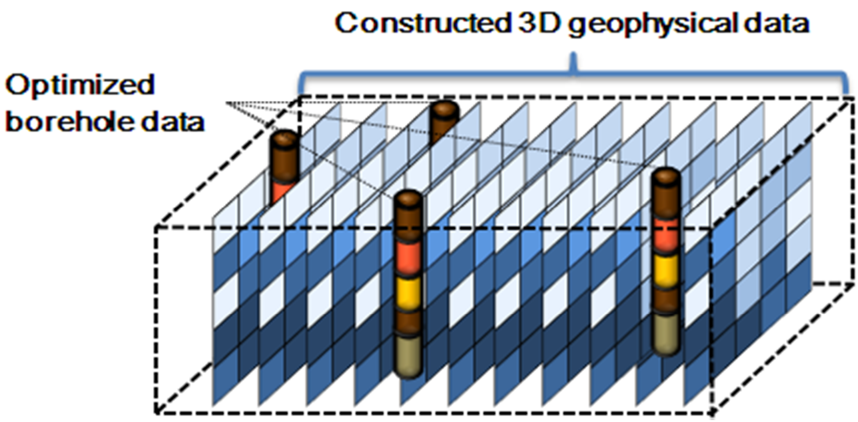

Figure 4.3 Conceptual image of comparing strata of borehole data with 3D geophysical data

4.2.1 Method of using normal distribution

Normal distribution is very commonly used in probability theories. The Normal Distribution function is as shown in Eq. 4.1. The parameter μ indicates the average in a normal distribution. The parameter σ is its standard deviation. A normal distribution is symmetric with respect to the average, and is non-zero over the entire real line.

$$f(x,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{4.1}$$

The normal distribution of each layer is as shown in Fig. 4.4. In order to determine the site-specific geo-layer criteria which are appropriate for the testing site, various confidence levels (α) were applied. The site-specific geo-layer criteria are the averages of the maximum geophysical value of the overlying layer and the minimum geophysical value of the underlying layer in various confidence levels. Then the most suitable criteria are determined by comparing criteria in various confidence levels.

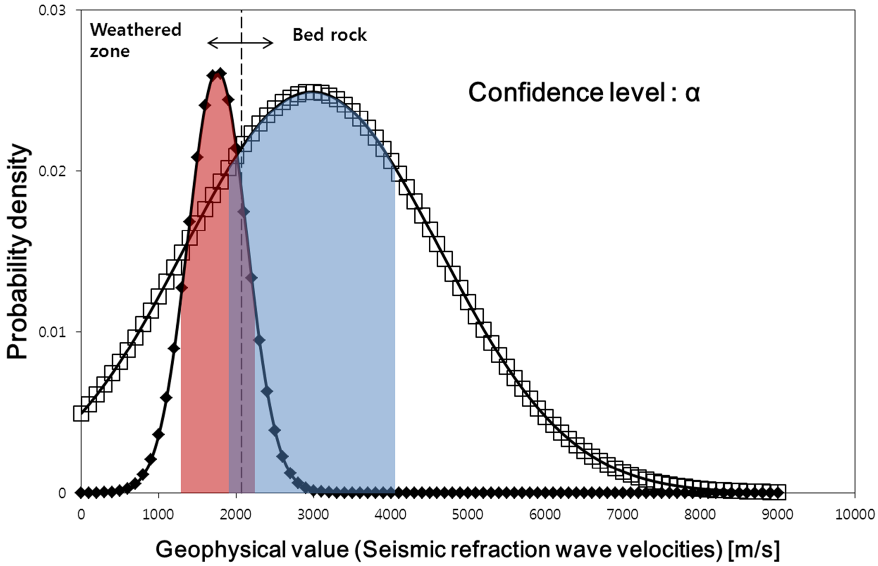

Figure 4.4 Determination of geo-layer criteria by using normal distributions of geo-layers

4.2.2 Method of using average

The second method to determine the site-specific geo-layer criteria is by using the average geophysical value for each geo-layer. The statistical characteristic of geophysical value for each geo-layer is as shown in Fig. 4.5. In Box-whisker plot, the bottom and top of the box indicate the 1st and 3rd quartiles, and the line inside the box indicates the average. The ends of whiskers indicate a minimum and maximum.

The site-specific geo-layer criteria in this method are the average values of the average geophysical value of the overlying layer and the average geophysical value of the underlying layer as shown Fig. 4.5. For example, the site-specific geo-layer criteria between weathered rock and bed rock is the average value (=1850) between the average geophysical value of weathered rock (=1400) and the average geophysical value of bed rock (=2300).

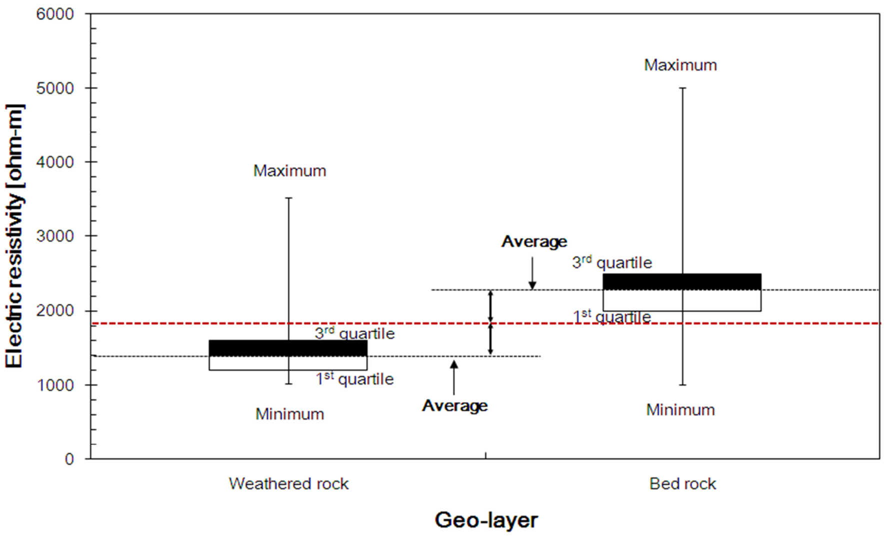

Figure 4.5 Determination of geo-layer criteria by using average of geophysical values

4.2.3 Method of using 1st quartile and 3rd quartile

The range between the 1st and 3rd quartiles indicates 50% of entire distribution and means approximately representative nature of entire geophysical values. The site-specific geo-layer criteria are the averages of the 3rd quartile geophysical values of the overlying layer and the 1st quartile geophysical values of the underlying layer. The results using the 1st and 3rd quartile are determined as shown in Figure 4.6. For example, the site-specific geo-layer criteria between the weathered rock and the bed rock is the average (=1800) between the 3rd quartile geophysical value of the weathered rock (=1600) and the 1st quartile geophysical value of the bed rock (=2000).

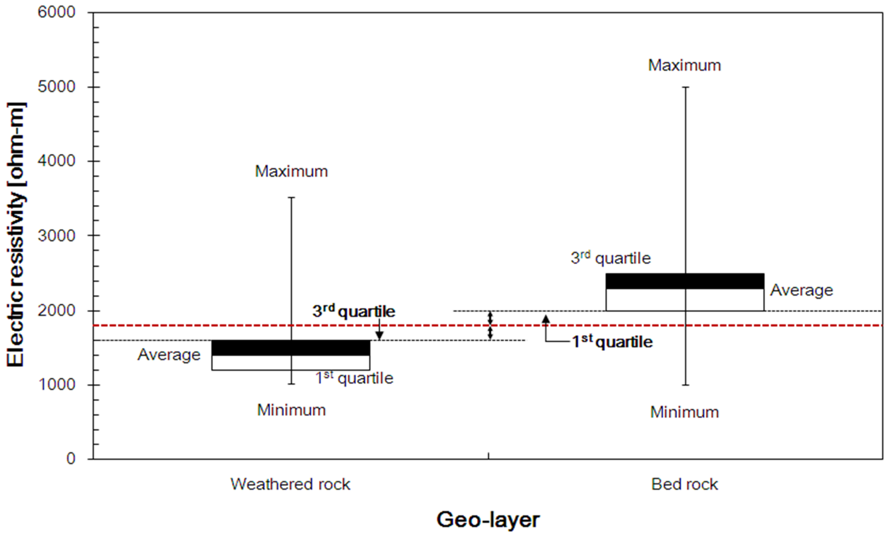

Figure 4.6 Determination of geo-layer criteria by using 1st quartile and 3rd quartile of geophysical values

4.2.4 Determination of optimum site-specific geo-layer criteria

The site-specific geo-layer criteria in three methods are determined. In order to select the most suitable site-specific geo-layer criteria, the estimated thickness of geo-layer obtained through the application of the site-specific geo-layer criteria was compared with the thickness of geo-layer in the borehole data through cross-validation. The Root Mean Squared Errors

(RMSEs) from the cross-validation results of the three methods were computed for all geo-layers. Then the criteria having the lowest RMSE are the optimum site-specific geo-layer criteria.

Chapter 5 3D Geo-statistical Integration

In this study, the indicator kriging, which is a non-linear kriging method, is used among the geo-statistical methods. Indicator kriging is characterized by geo-statistical non-linear procedures to model the variability of spatial attributes. Indicator kriging requires a non-linear transform, called indicator transform, which transforms each value of datasets into indicator values (Deutsch and Journel, 1998). Indicator kriging is the incorporation of borehole datasets (soft data), or local information that is a proxy to the variable of interest and need not relate directly, to supplement hard data (Goovaerts, 1997). Soft data can compensate for a lack of spatially exhaustive observations by providing information at predicted location where no hard data is available.

Prior to carry out indicator kriging, the determination of indicator threshold is essential to conserve the geotechnical characteristics based on borehole datasets. When spatial measurements of a variable are transformed to binary indicators (i.e., 1 if eaqual a given threshold and 0 if different from a given threshold) and the resulting indicator variogram is modeled, indicator kriging produces the probability of the measured variable to exceed the threshold value (Kim, 2014).

In this study, the seven assumed criteria of geophysical value for geo-layers are determined as indicator threshold: 3/5(60%), 3/4(75%), 7/8(88%), 100%, 9/8(112%), 6/5(120%) and 5/4(125%) of the site-specific geo-layer criteria determined in the previous chapter. Based on the assumed classification criteria, the preceded 3D geophysical data are stratified and integration with borehole datasets is carried out by using indicator kriging to identify which is the most site-specific fitted criteria.

In this study, indicator kriging is carried out for the depth to the geo-layer boundaries with the optimized borehole data and the 3D geophysical data based on the 7 assumed classification criteria. Given a set of k possible categories, indicator coding consists of defining the probability of occurrence [0,1] for each category:

$$\mathrm{E}\{\mathrm{I}(\mathrm{u};\mathrm{s}_k)\} = \mathrm{Prob}\{\mathrm{S}(\mathrm{u}) = \mathrm{s}_k\} = \mathrm{i}(\mathrm{u};\mathrm{s}_k) \tag{5.1}$$

where u is a given spatial location, s_k is a particular category for the categorical S(u), and $\mathrm{i}(\mathrm{u};\mathrm{s}_k)$ is the indicator at location u for category s_k.When analyze with borehole data and geophysical data, specifically along a core at a given location u, the coding for entire datasets is exclusively defied as

$$\mathrm{i}(\mathrm{u};\mathrm{s}_k) = \begin{Bmatrix} 1\ if\ S(u) = s_k \\ 0\ if\ S(u) \neq s_k \end{Bmatrix}, k = 1,2,3,\ldots,\mathrm{n} \tag{5.2}$$

In this study, the depth of geo-layer boundaries is coded as 1 at the locations of the boreholes. The depth of value which corresponds to each assumed criteria in geophysical data is coded as 1, and the others is coded as 0. The 3D spatial structure of the indicator could be studied by means of the indicator experimental variogram $\gamma_I(\mathrm{h};\mathrm{s}_k)$:

$$\gamma_I(\mathrm{h};\mathrm{s}_k) = \frac{1}{2N(h)}\sum_{\alpha=1}^{N(h)}[i(u_\alpha;s_k) - i(u_\alpha + h;s_k)]^2$$

(5.3)

where h is the separation vector, N(h) is the number of pairs of data values whose spatial separation is h, s_k is a given category, $i(u_\alpha;s_k)$ is the indicator at a given location u_α for the category s_k (Deutsch et al., 1998; Seifert et al., 1999). The 3D spatial structure of the indicator means the probability to correspond the geo-layer boundary.

Finally, RMSEs using indicator kriging with seven assumed criteria of geophysical value for geo-layers are plotted as shown Fig. 5.1. Regression lines for geo-layers are drawn, and the geophysical value in lowest RMSEs is the optimum indicator threshold. Using indicator kringin with optimum indicator thresholds, the reliable 3D strata information can be estimated.

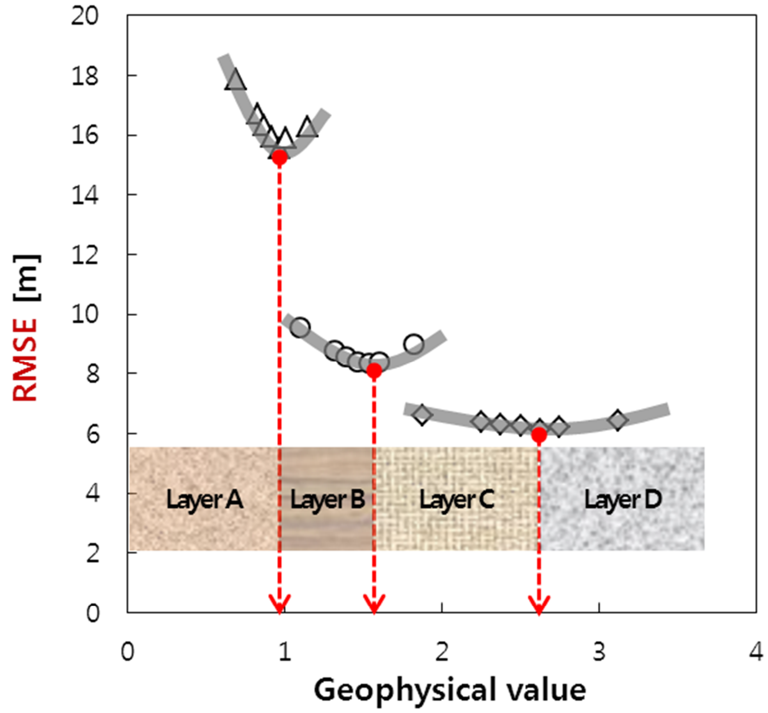

Figure 5.1 Determination of optimum indicator thresholds

Chapter 6 Systematic Field Application

6.1 Gyodong Bridge Site

6.1.1 Site description

First filed applied the proposed method is Gyodong bridge in Korea. At the site, there are many existing borehole data and overlapping geophysical survey data such as electric resistivity (17 boring data and about 1620m of electric resistivity survey results as shown in Fig. 6.1). The investigations of Gyodong bridge site is carried out in a straight line. The elevations of the site vary from 0m to -25m. In this site, the variability of strata is large because of very rapid flow velocity and large range of tide.

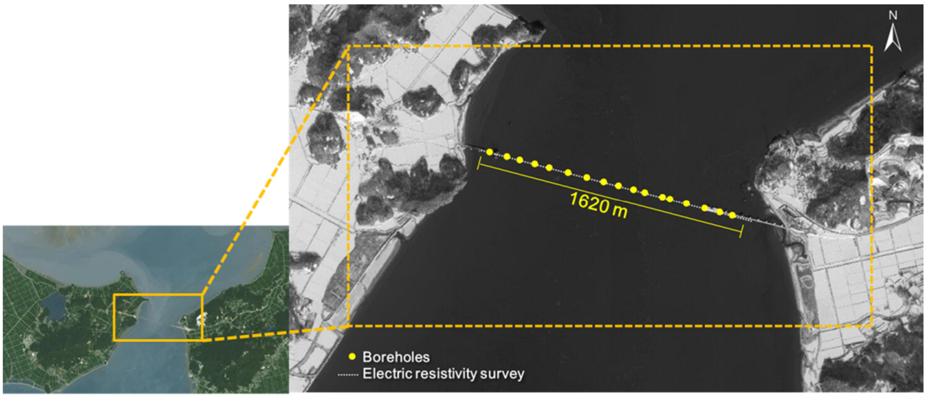

Figure 6.1 Satellite image map with locations of boreholes and elerectric resistivity at Gyodong bridge site

6.1.2 Application of the proposed method

Optimization of borehole datasets

The standardization of geo-layer boundaries for 17 borehole data at Gyodong bridge site is first conducted to exclude the subjective judgements of the investigator. Then, the standardized borehole datasets have to be optimized, which is called cross validation. Especially, the number of outliers at target site is determined by optimum outlier threshold [%] as shown in Fig.6.2. There are 4 geo-layers in this target site: SM, GM, Weathered zone, Bed rock. The optimum outlier threshold is determined for each geo-layer. According to Fig.6.2, there are no the RMSEs of the outlier threshold more than 10% in the bed rock, because all the remains in case of more than 10% outlier threshold is same and the cross validation with same values occur system error. So, in case of bed rock, the optimum outlier threshold is determined as 5%. Finally, the optimum outlier thresholds and the number of optimum outlier are respectively shown as Table 6.1.

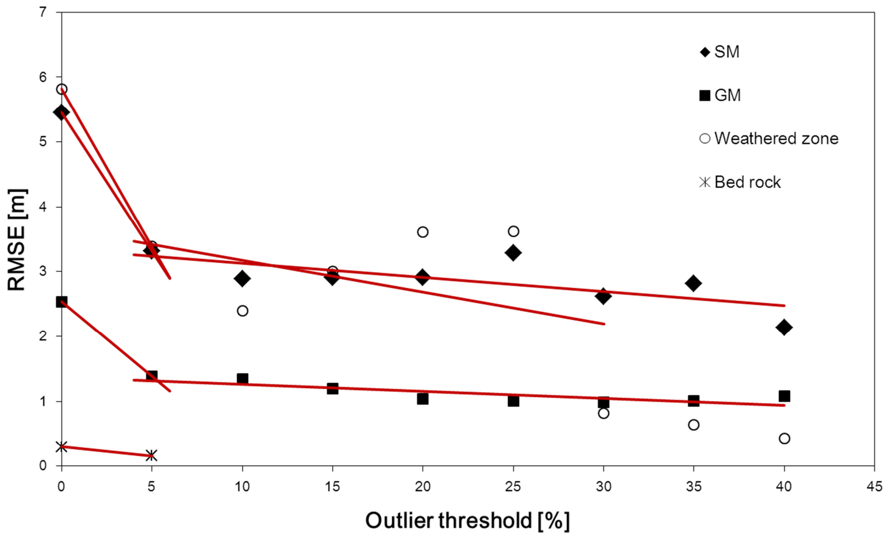

Figure 6.2 Optimum outlier analysis at Gyodong bridge site

Table 6.1 Determination of outlier threshold and number of optimum outlier at Gyodong bridge site

Geo-layer	Outlier threshold [%]	Number of optimum outlier [EA]
SM	5.2	1
GM	5.3	1
WS	5.3	1
Bed rock	5.0	1

Determination of site-specific geo-layer criteria

Before the site-specific geo-layer is determined, the 3D geophysical datasets must be transformed from the 2D geophysical tomography by using digitizing and kriging. The optimized borehole datasets are overlapped with 3D geophysical datasets. Then, the geophysical values at borehole locations are extracted and the site-specific geo-layer criteria for each geo-layer are determined by comparing the geophysical values at borehole locations.

Based on the normal distribution theory, the normal distributions of electric resistivity for each geo-layer are drawn as shown Fig. 6.3.

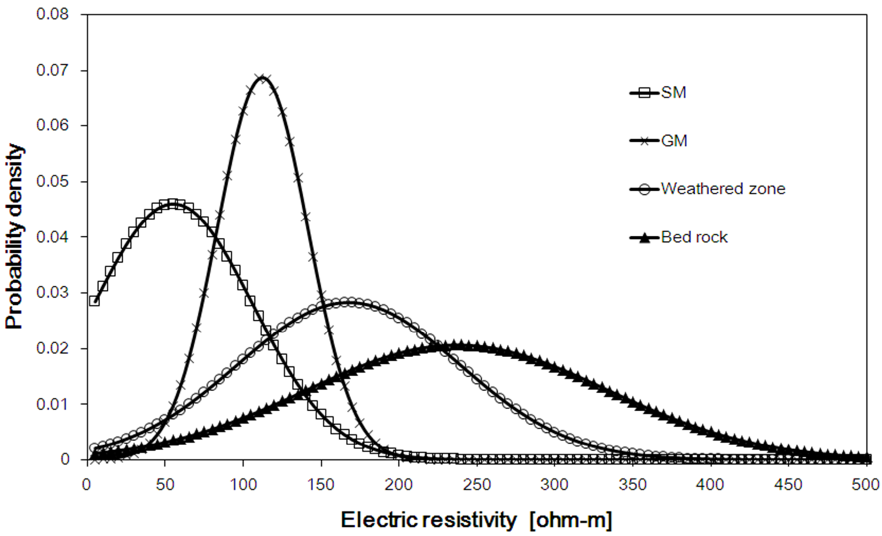

Figure 6.3 Normal distribution of electric resistivity for geo-layer at Gyodong bridge site

From each normal distribution, the range of electric resistivity in several confidence levels is determined, and then the averages of the maximum electric resistivity of the overlying laver and the minimum electric resistivity of the underlying layer are determined as the site-specific geo-layer criteria in Table 6.2. In case of the confidence level more than 68%, the site-specific criteria did not determined because the site-specific criterion for underlying geo-layer is lower than that for overlying geo-layer. In addition, as the result of applying each site-specific geo-layer criteria to estimate strata, the site-specific geo-layer criteria for geo-layer is most suitable because the RMSE in case of applying site specific geo-layer criteria in 38% confidence level was the lowest(=5.20).

Table 6.2 Determination of site-specific geo-layer criteria in various confidence level using normal distribution at Gyodong bridge site

Confidence level	Geo-layer	Min. [ohm-m]	Max. [ohm-m]	Site-specific geo-layer criteria [ohm-m]	RMSE [m]
68%	SM	4.0	106.2	94.8	5.29
	GM	83.3	141.4	118.9	
	Weathered Zone	96.5	238.8	189.6	
	Bed rock	140.3	334.2		
49%	SM	20.9	89.3	91.1	5.22
	GM	92.9	131.8	125.9	

	Weathered Zone	120.0	215.3	193.8	
	Bed rock	172.3	302.2		
38%	SM	29.6	80.7	89.2	5.20
	GM	97.8	126.9	129.5	
	Weathered Zone	132.1	203.2	196.0	
	Bed rock	188.8	285.7		
30%	SM	35.2	75.0	88.0	5.26
	GM	101.0	123.7	131.8	
	Weathered Zone	139.9	195.4	197.4	
	Bed rock	199.4	275.0		

Second method of determining site-specific geo-layer criteria is using the average of geophysical values. The statistical characteristics of geophysical values are shown as Fig. 6.4. In Box-whisker plot, the line inside the box indicates the average of values. The site-specific geo-layer criteria in this method are the average values of the average geophysical value of the overlying layer and the average geophysical value of the underlying layer. The average of electric resistivity and site-specific criteria using the average of electric resistivity in target area is shown as Table 6.3.

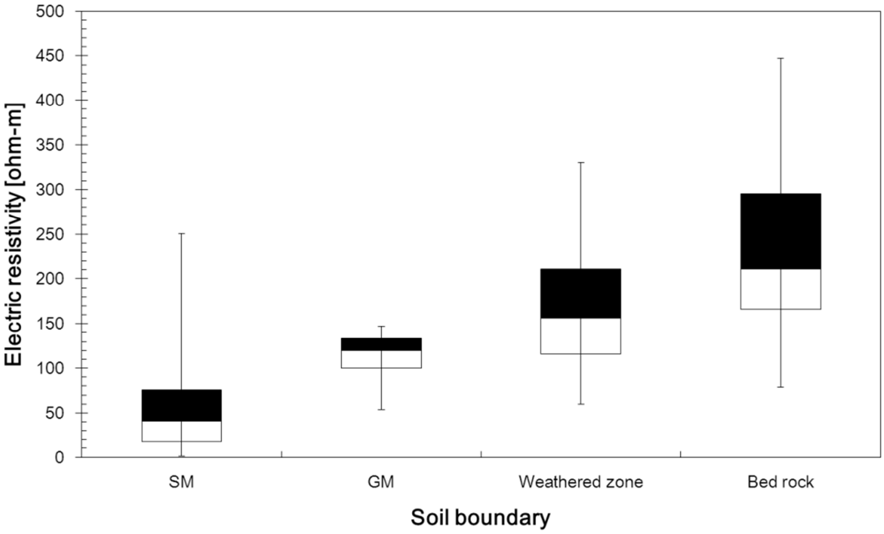

Figure 6.4 Box-whisker plot of electric resistivity for geo-layer at Gyodong bridge site

Table 6.3 Determination of site-specific geo-layer criteria using average of electric resistivity at Gyodong bridge site

<table>
<tr><th>Geo-layer</th><th>Average
[ohm-m]</th><th>Site-specific geo-layer
criteria [ohm-m]</th><th>RMSE [m]</th></tr>
<tr><td rowspan="2">SM</td><td rowspan="2">55.1</td><td></td><td rowspan="4">5.38</td></tr>
<tr><td rowspan="2">83.7</td></tr>
<tr><td rowspan="2">GM</td><td rowspan="2">112.3</td></tr>
<tr><td>140.0</td></tr>
</table>

<table>
<tr><td rowspan="2">Weathered Zone</td><td rowspan="2">167.7</td><td></td><td rowspan="4"></td></tr>
<tr><td rowspan="2">202.4</td></tr>
<tr><td rowspan="2">Bed rock</td><td rowspan="2">237.2</td></tr>
<tr><td></td></tr>
</table>

Third method to determine site-specific geo-layer criteria is using 1st quartile and 3rd quartile of geophysical values. In Fig. 6.4, the top and bottom of the box indicate 1st quartile and 3rd quartile of geophysical values. The site-specific geo-layer criteria are the averages of the 3rd quartile resistivity of the overlying layer and the 1st quartile electric resistivity of the underlying layer. The 1st quartile and 3rd quartile of electric resistivity and site-specific geo-layer criteria in target site were determined as shown Table 6.4.

Table 6.4 Determination of site-specific geo-layer criteria using 1st quartile and 3rd quartile of electric resistivity at Gyodong bridge site

<table>
<tr><th>Geo-layer</th><th>1st quartile [ohm-m]</th><th>3rd quartile [ohm-m]</th><th>Site-specific geo-layer criteria [ohm-m]</th><th>RMSE [m]</th></tr>
<tr><td rowspan="2">SM</td><td rowspan="2">18.1</td><td rowspan="2">75.4</td><td></td><td rowspan="8">5.25</td></tr>
<tr><td rowspan="2">87.8</td></tr>
<tr><td rowspan="2">GM</td><td rowspan="2">100.2</td><td rowspan="2">133.6</td></tr>
<tr><td rowspan="2">124.7</td></tr>
<tr><td rowspan="2">Weathered Zone</td><td rowspan="2">115.8</td><td rowspan="2">211.3</td></tr>
<tr><td rowspan="2">188.9</td></tr>
<tr><td rowspan="2">Bed rock</td><td rowspan="2">166.5</td><td rowspan="2">295.6</td></tr>
<tr><td></td></tr>
</table>

Among the site-specific geo-layer criteria by using 3 methods (as shown Table 6.5), the optimum site-specific geo-layer criteria which are the most suitable criteria in target site must be determined. As the result of comparing 3 methods, the RMSEs are calculated in Table 6.5. According to Table 6.5, the site-specific geo-layer criteria by using normal distribution were most suitable in this target site.

Table 6.5 Determination of optimum site-specific geo-layer criteria at Gyodong bridge site

	Site-specific geo-layer criteria [ohm-m]		
	Method 1	Method 2	Method 3
SM / GM	89.2	83.7	87.8
GM / Weathered zone	129.5	140	124.7
Weathered zone / Bed rock	196	202.4	188.9
RMSE	5.20	5.38	5.25

Method 1 : Using normal distribution

Method 2 : Using the average

Method 3 : Using the 1^{st} quartile and 3^{rd} quartile

3D geo-statistical integration

Final phase is 3D geo-statistical integration. First, in order to do indicator kriging, the 7 classification criteria must be determined as indicator threshold: 3/5(60%), 3/4(75%), 7/8(88%), 100%, 9/8(112%), 6/5(120%) and 5/4(125%) of the optimum site-specific geo-layer criteria (as shown Table 6.6). Based on the assumed classification criteria, the given 3D electric resistivity datasets are stratified, and the integration with boring datasets is performed using indicator kriging to identify which is the most site-specifically fitted criteria to classify the geo-layer as shown in Fig.6.5. The fitted curves were quadratic function and the electric resistivity at the lowest RMSE of fitted curve is most suitable to estimate strata. As a result, the 3D stratum in this testing site was determined with the most fitted criteria.

Table 6.6 Assumed classification criteria at Gyodong bridge site

	SM / GM	GM / Weathered zone	Weathered zone / Bed rock
60%	53.5	77.7	117.6
75%	66.9	97.1	147.0
87.5%	78.1	113.3	171.5
100%	89.2	129.5	196.0
112.5%	100.4	145.7	220.5
120%	107.0	155.4	235.2
125%	111.5	161.9	245.0

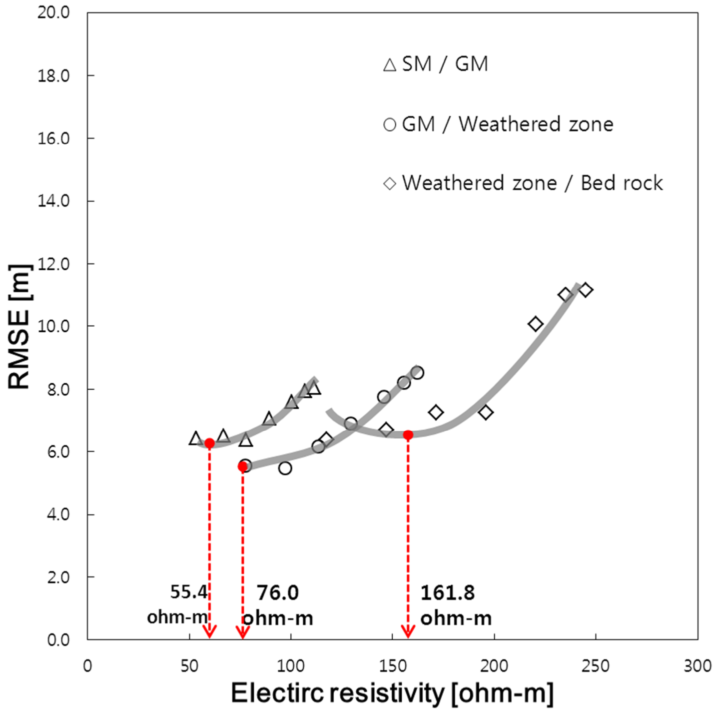

Figure 6.5 Determination of most fitted classification criteria at Gyodong bridge site

Validation of proposed method

To identify the geotechnical characteristics, borehole datasets are commonly used to estimate the 3D stratum. Therefore, to validate the proposed 3D geo-statistical integration, the results of 3D geo-statistical integration were compared with the results of using only borehole datasets through cross-validation. Based on cross-validation, a borehole data was excluded and the value at the location excluded was estimated by using 3D geo-statistical integration. Cross-validation with all the borehole data were carried out. The RMSE with error between actual value and estimated value was calculated. The results of analysis are as shown in Table 6.7. The RMSE in the case of using only borehole datasets was 6.63 m, the RMSE is higher than that in the case of using 3D geo-statistical integration. Thus, the proposed 3D geo-statistical integration is more reliable than using only borehole datasets. The determined 3D stratum with 3D geo-statistical integration was displayed using a 3D visualization program developed by Seoul National University as in Fig. 6.6. The length of y-axis multiplied 10 because this site is very narrow area.

Table 6.7 Validation of proposed method by comparing using only borehole datasets based on cross-validation at Gyodong bridge site

Method	RMSE [m]
Using only borehole datasets	6.62
Proposed method	5.77

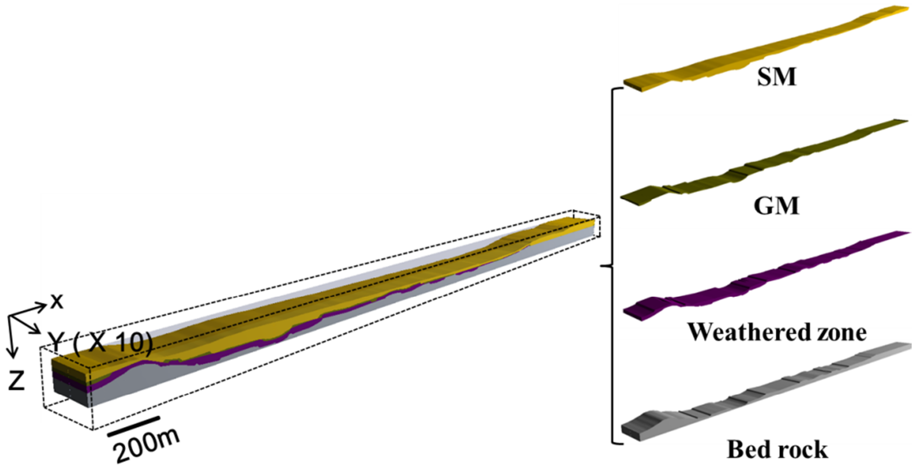

Figure 6.6 Visualization of 3D strata information at Gyodong bridge site

6.2 Saemanguem Reclaimed Land Site

6.2.1 Site description

The proposed method was applied on Saemanguem reclaimed land site in Korea. At the site, there are existing borehole datasets and overlapping geophysical testing datasets such as the electric resistivity (22 boring data and about 80km of electric resistivity survey results as shown in Fig. 6.7). The site investigation covers an area of 44.4 km^2 (6.0 km west to east $\times$7.4 km north to south) and an elevation varying from -2m to -18m.

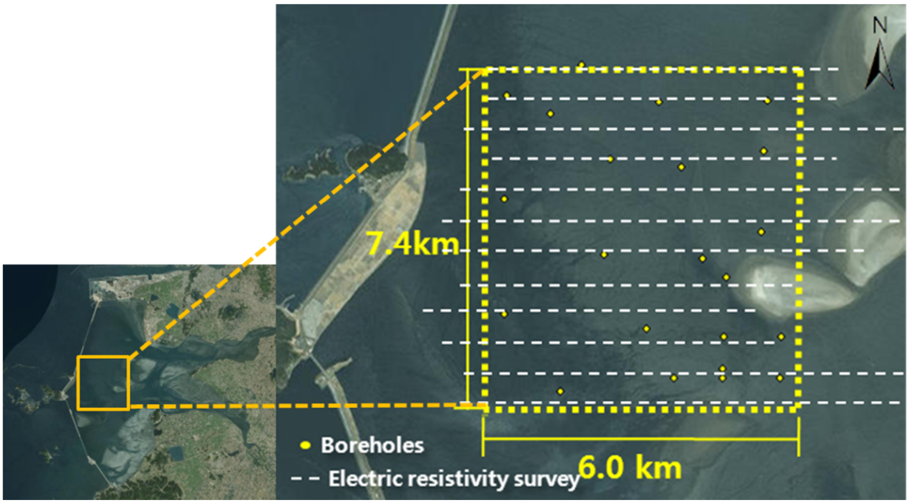

Figure 6.7 Satellite image map with locations of boreholes and elerectric resistivity at Saemanguem reclaimed land site

6.2.2 Application of the proposed method

Optimization of borehole datasets

The standardization of geo-layer boundaries was first carried out to exclude the subjective judgements of the investigator like the preceding. Then, the outlier analysis based on cross-validation was conducted. In this site, only 5 geo-layers which are soil deposit were utilized to analysis because of not investigating the other geo-layers. The first letter “U” and “L” of geo-layer name mean “Upper” and “Lower” respectively. As the result of the optimum outlier analysis, the optimum outlier threshold and the number of optimum outlier were determined as shown Fig. 6.8 and Table 6.8.

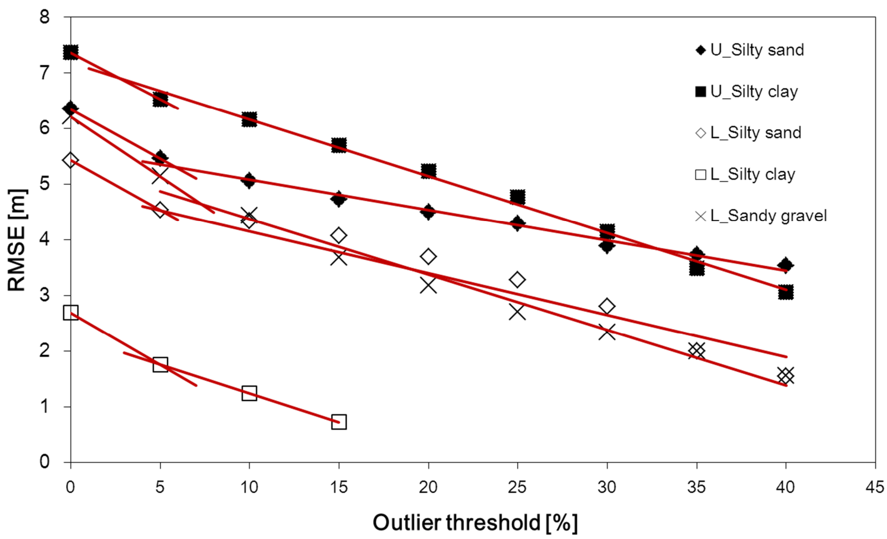

Figure 6.8 Optimum outlier analysis at Saemanguem reclaimed land site

Table 6.8 Determination of outlier threshold and number of optimum outlier at Saemanguem reclaimed land site

<table>
<tr><th colspan="2">Geo-layer</th><th>Outlier threshold [%]</th><th>Number of optimum outlier [EA]</th></tr>
<tr><td rowspan="2">Upper</td><td>Silty sand</td><td>5.9</td><td>2</td></tr>
<tr><td>Silty clay</td><td>2.9</td><td>1</td></tr>
<tr><td rowspan="3">Lower</td><td>Silty sand</td><td>4.0</td><td>1</td></tr>
<tr><td>Silty clay</td><td>5.0</td><td>2</td></tr>
<tr><td>Sandy gravel</td><td>7.3</td><td>2</td></tr>
</table>

Determination of site-specific geo-layer criteria

The 3D geophysical datasets at target site were constructed from the 2D geophysical tomography by using digitizing and kriging. The optimized borehole datasets and 3D geophysical datasets were overlapped. Then, the site-specific geo-layer criteria for each geo-layer are determined by using 3 methods.

First method is using normal distribution. Based on the normal distribution theory, the normal distributions of electric resistivity for each geo-layer are drawn as shown Fig. 6.9.

From each normal distribution, the range of electric resistivity in several confidence levels is determined, and then the averages of the maximum electric resistivity of the overlying laver and the minimum electric resistivity of the underlying layer are determined as the site-specific geo-layer criteria in Table 6.9.

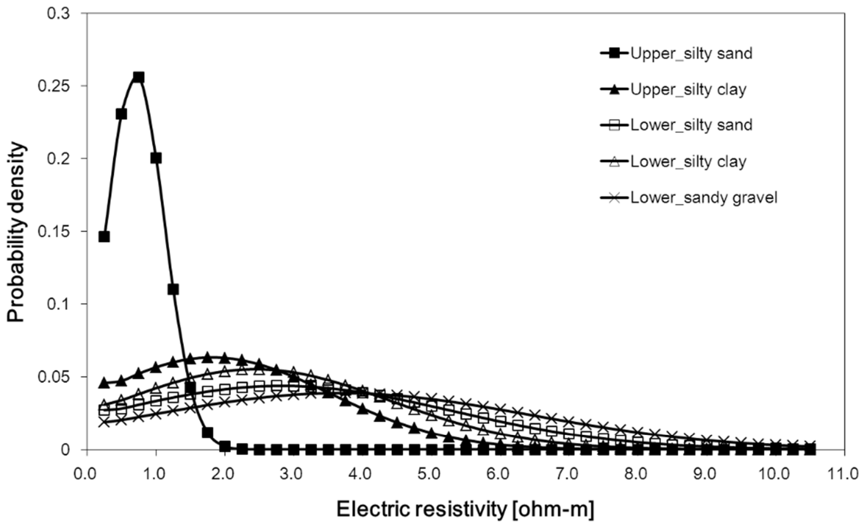

Figure 6.9 Normal distribution of electric resistivity for geo-layer at Saemanguem reclaimed land site

Table 6.9 Determination of site-specific geo-layer criteria in various confidence level using normal distribution at Saemanguem reclaimed land site

Confidence level	Geo-layer		Min [ohm-m]	Max. [ohm-m]	Site-specific geo-layer criteria [ohm-m]	RMSE [m]
49%	UPPER	Silty sand	0.42	0.98		-
					0.82	
		Silty clay	0.67	2.97		
					2.07	
		Silty sand	1.16	4.49		
					2.80	
	L	Silty	1.12	3.76		

	OWER	clay			2.78	
		Sandy gravel	1.80	5.55		
45%	UPPER	Silty sand	0.45	0.95	0.87	7.07
		Silty clay	0.79	2.85	2.09	
		Silty sand	1.34	4.31	2.79	
	LOWER	Silty clay	1.26	3.62	2.81	
		Sandy gravel	2.00	5.35		
38%	UPPER	Silty sand	0.49	0.91	0.93	6.81
		Silty clay	0.91	2.68	2.13	
		Silty sand	1.58	4.06	2.76	
	LOWER	Silty clay	1.46	3.43	2.85	
		Sandy gravel	2.28	5.07		
30%	U	Silty	0.58	0.82		6.87

	PPER	sand				
					1.07	
		Silty clay	1.33	2.31		
					2.21	
		Silty sand	2.12	3.53		
					2.71	
	LOWER	Silty clay	1.88	3.00		
					2.94	
		Sandy gravel	2.88	4.47		
20%	UPPER	Silty sand	0.59	0.81		6.85
					1.10	
		Silty clay	1.39	2.25		
					2.23	
		Silty sand	2.20	3.44		
					2.70	
	LOWER	Silty clay	1.95	2.93		
					2.95	
		Sandy gravel	2.97	4.37		

In this site, the ranges of each geo-layer were similar as shown Fig 6.9. So the site-specific geo-layer criteria were determined in the confidence level lower than 45%. The most suitable site-specific geo-layer criteria in case of using normal distribution were the criteria in 38% confidence level.

The second method is using the average of geo-physical values. The statistical characteristic value of electric resistivity for each geo-layer was as shown in Fig. 6.10 and the site-specific geo-layer criteria in this method was determined as shown Table 6.10

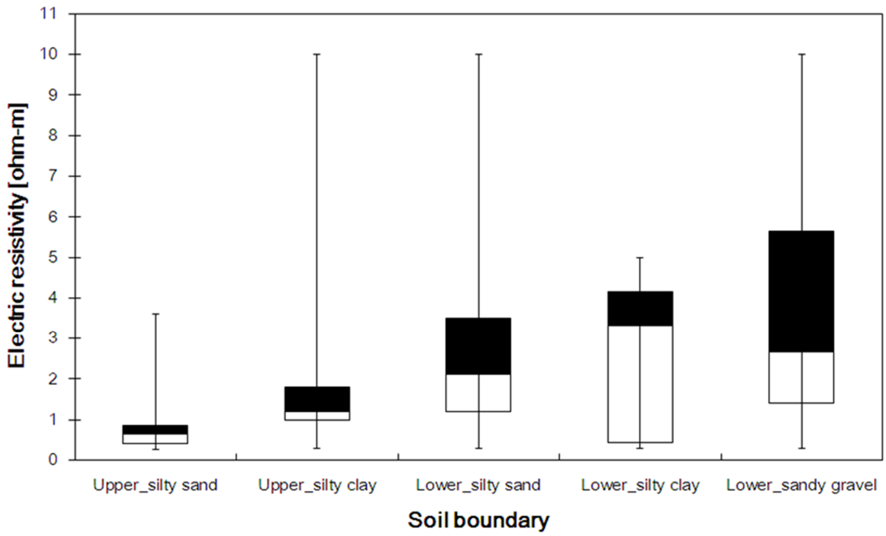

Figure 6.10 Box-whisker plot of electric resistivity for geo-layer at Saemanguem reclaimed land site

Table 6.10 Determination of site-specific geo-layer criteria using average of electric resistivity at Saemanguem reclaimed land site

Geo-layer		Average [ohm-m]	Site-specific geo-layer criteria [ohm-m]	RMSE [m]
Upper	Silty sand	0.70		7.28
			1.26	
	Silty clay	1.82		
			2.32	
Lower	Silty	2.82		

<table>
<tr><td rowspan="5"></td><td>sand</td><td></td><td rowspan="2">2.63</td><td rowspan="5"></td></tr>
<tr><td rowspan="2">Silty clay</td><td rowspan="2">2.44</td></tr>
<tr><td rowspan="2">3.06</td></tr>
<tr><td rowspan="2">Sandy gravel</td><td rowspan="2">3.67</td></tr>
<tr><td></td></tr>
</table>

The third method is using 1st quartile and 3rd quartile of geophysical values. The site-specific geo-layer criteria was determined in Table 6.11

Table 6.11 Determination of site-specific geo-layer criteria using 1st quartile and 3rd quartile of electric resistivity at Saemanguem reclaimed land site

<table>
<tr><th colspan="2">Geo-layer</th><th>1st quartile [ohm-m]</th><th>3rd quartile [ohm-m]</th><th>Site-specific geo-layer criteria [ohm-m]</th><th>RMSE [m]</th></tr>
<tr><td rowspan="4">Upper</td><td rowspan="2">Silty sand</td><td rowspan="2">0.42</td><td rowspan="2">0.87</td><td></td><td rowspan="10">6.75</td></tr>
<tr><td rowspan="2">0.92</td></tr>
<tr><td rowspan="2">Silty clay</td><td rowspan="2">0.98</td><td rowspan="2">1.81</td></tr>
<tr><td rowspan="2">1.50</td></tr>
<tr><td rowspan="6">Lower</td><td rowspan="2">Silty sand</td><td rowspan="2">1.20</td><td rowspan="2">3.51</td></tr>
<tr><td rowspan="2">1.97</td></tr>
<tr><td rowspan="2">Silty clay</td><td rowspan="2">0.44</td><td rowspan="2">4.14</td></tr>
<tr><td rowspan="2">2.77</td></tr>
<tr><td rowspan="2">Sandy gravel</td><td rowspan="2">1.40</td><td rowspan="2">5.65</td></tr>
<tr><td></td></tr>
</table>

Among the site-specific geo-layer criteria by using 3 methods (as shown Table 6.12), the optimum site-specific geo-layer criteria which are the most suitable criteria in target site must be determined. As the result of comparing 3 methods, the RMSEs are calculated in Table 6.12. According to Table 6.12, the site-specific geo-layer criteria by using the 1st quartile and 3rd quartile of geophysical values were most suitable in this target site.

Table 6.12 Determination of optimum site-specific geo-layer criteria at Saemanguem reclaimed land site

	Site-specific geo-layer criteria [ohm-m]		
	Method 1	Method 2	Method 3
Upper silty sand / Upper silty clay	0.93	1.26	0.92
Upper silty clay / Lower silty sand	2.13	2.32	1.50
Lower silty sand / Lower silty clay	2.76	2.63	1.97
Lower silty clay / Lower sandy gravel	2.85	3.06	2.77
RMSE	6.81	7.28	6.75

Method 1 : Using normal distribution

Method 2 : Using the average

Method 3 : Using the 1st quartile and 3rd quartile

3D geo-statistical integration

In order to do indicator kriging, the 7 classification criteria were determined as indicator threshold: 3/5(60%), 3/4(75%), 7/8(88%), 100%, 9/8(112%), 6/5(120%) and 5/4(125%) of the optimum site-specific geo-layer criteria (as shown Table 6.13). Based on the assumed classification criteria, the given 3D electric resistivity datasets are stratified, and the integration with boring datasets is performed using indicator kriging to identify which is the most site-specifically fitted criteria to classify the geo-layer as shown in Fig.6.11. The fitted curves were quadratic function and the electric resistivity at the lowest RMSE of fitted curve is most suitable to estimate strata. As a result, the 3D strata in this testing site were determined with the most fitted criteria.

Table 6.13 Assumed classification criteria at Saemanguem reclaimed land site

	Upper silty sand / Upper silty clay	Upper silty clay / Lower silty sand	Lower silty sand / Lower silty clay	Lower silty clay / Lower sandy gravel
60%	0.55	0.90	1.18	1.53
75%	0.69	1.13	1.48	1.91
87.5%	0.81	1.31	1.72	2.23
100%	0.92	1.50	1.97	2.55
112.5%	1.04	1.69	2.22	2.87
120%	1.10	1.80	2.36	3.06
125%	1.15	1.88	2.46	3.19

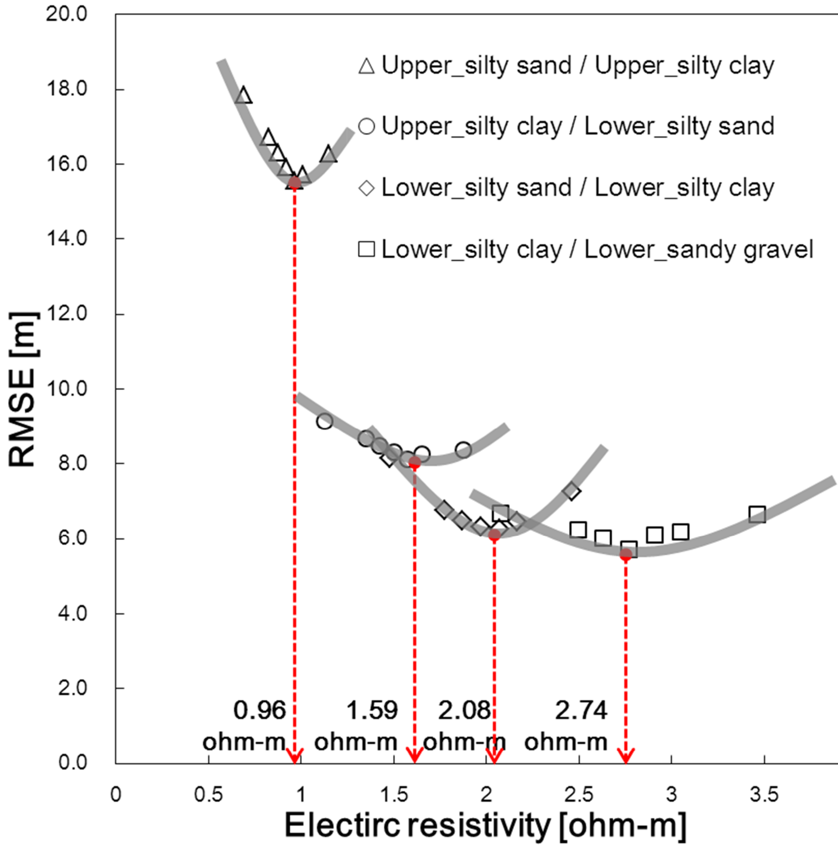

Figure 6.11 Determination of most fitted classification criteria at Saemanguem reclaimed land site

Validation of proposed method

The validation of proposed method was conducted alike the analysis in gyodong test site. The proposed method was compared with the using only borehole datasets as shown Table 6.14. The 3D geo-statistical integration considering site-specific characteristics is more suitable than using only borehole datasets which is mainly utilized to estimate 3D strata. The determined 3D stratum with 3D geo-statistical integration was displayed using a 3D visualization program developed by Seoul National University as in Fig. 6.12. The length of z-axis multiplied 20 because this site is very large area which has relatively shallow depth.

Table 6.14 Validation of proposed method by comparing using only borehole datasets based on cross-validation at Saemanguem reclaimed land site

Method	RMSE [m]
Using only borehole datasets	4.90
Proposed method	4.52

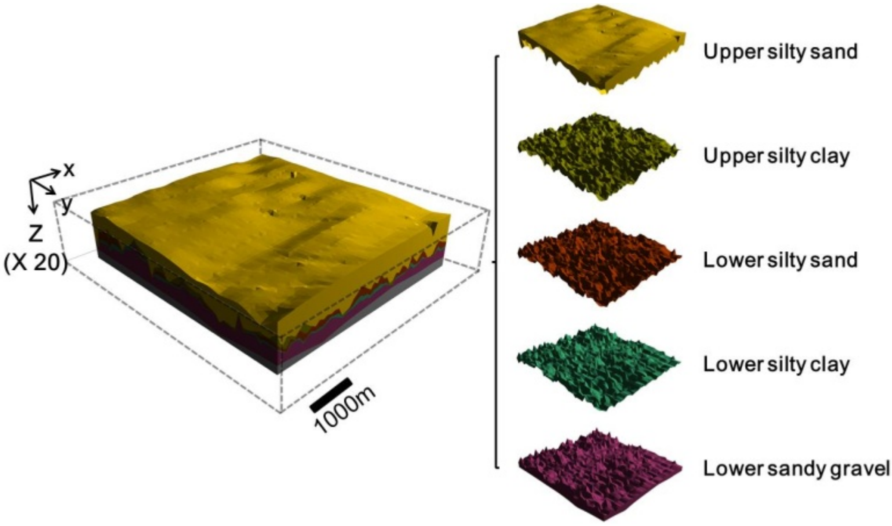

Figure 6.12 Visualization of 3D strata information at Saemanguem reclaimed land site

6.3 Andong Dam Site

6.3.1 Site description

Final test site is Andong dam site in Korea. Especially, Andong dam site is land site and relative small area. At the site, there are many existing borehole datasets and overlapping geophysical testing datasets such as the electric resistivity (24 boring data and about 4.5km of seismic refraction survey results as shown in Fig. 6.13). The site investigation covers an area of 243,100m^2 (715 m west to east ×340 m north to south) and an elevation varying from 194m to 101m. The variability of elevation is very large in this site.

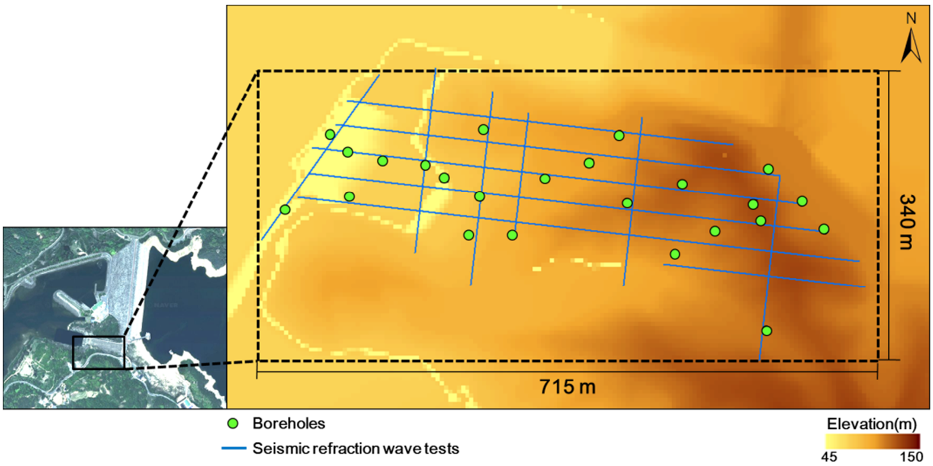

Figure 6.13 Digital terratin map with locations of boreholes and seismic refraction wave velocities at Saemanguem reclaimed land site

6.3.2 Application of the proposed method

Optimization of borehole datasets

The standardization of geo-layer boundaries was first carried out to exclude the subjective judgements of the investigator like the preceding. Then, the outlier analysis based on cross-validation was conducted with borehole datasets for 4 geo-layers as shown Fig. 6.14. The results of outlier analysis are shown in Table 6.15.

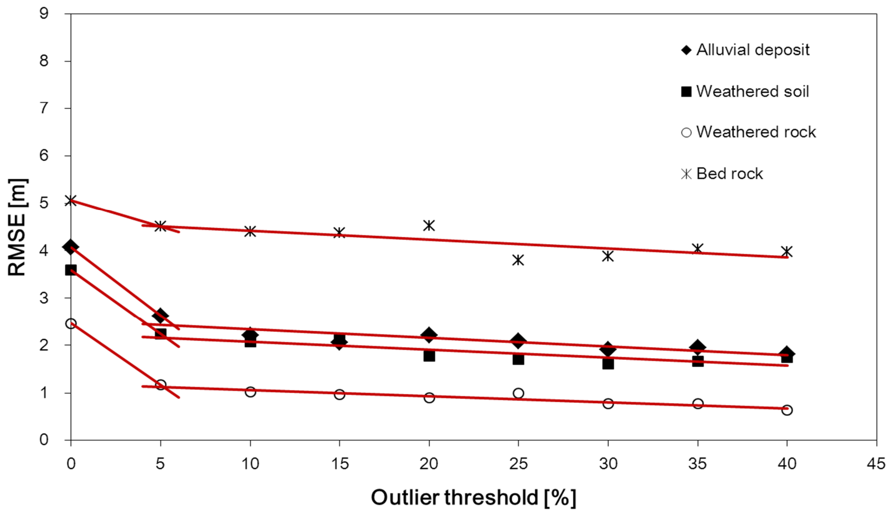

Figure 6.14 Optimum outlier analysis at Andong dam site

Table 6.15 Determination of outlier threshold and number of optimum outlier at Andong dam site

Geo-layer	Optimum rate of removed outlier [%]	Number of optimum outlier [EA]
Alluvial deposit	5.7	2
Weathered soil	5.3	2
Weathered rock	5.2	2
Bed rock	4.9	2

Determination of site-specific geo-layer criteria

The optimized borehole dataset and constructed 3D geophysical data were analyzed to determine site-specific geo-layer criteria. First, the site-specific geo-layer criteria using normal distribution were determined. The normal distributions of geophysical values are shown as Fig.6.15. The site-specific geo-layer criteria are determined in Table 6.16. In this site, the criteria in 40% of confidence level were more suitable than that of the other confidence levels.

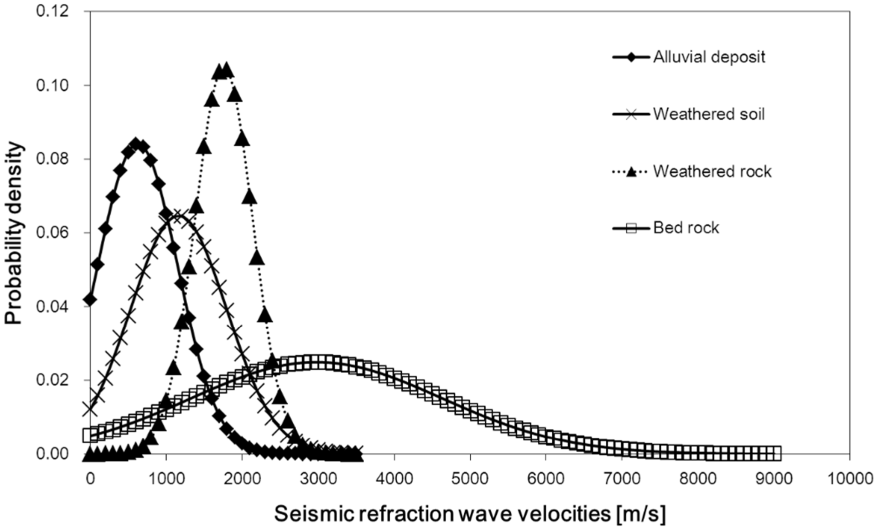

Figure 6.15 Normal distribution of seismic refraction wave velocities for geo-layer at Andong dam site

Table 6.16 Determined site-specific geo-layer criteria in various confidence level using normal distribution at Andong dam site

<table>
<tr><th>Confidence level</th><th>Geo-layer</th><th>Min. [m/s]</th><th>Max. [m/s]</th><th>Site-specific geo-layer criteria [m/s]</th><th>RMSE [m]</th></tr>
<tr><td rowspan="8">68%</td><td rowspan="2">Alluvial deposit</td><td rowspan="2">75</td><td rowspan="2">1171</td><td></td><td rowspan="8">2.76</td></tr>
<tr><td rowspan="2">836</td></tr>
<tr><td rowspan="2">Weathered soil</td><td rowspan="2">501</td><td rowspan="2">1823</td></tr>
<tr><td rowspan="2">1593</td></tr>
<tr><td rowspan="2">Weathered rock</td><td rowspan="2">1362</td><td rowspan="2">2153</td></tr>
<tr><td rowspan="2">1704</td></tr>
<tr><td rowspan="2">Bed rock</td><td rowspan="2">1255</td><td rowspan="2">4701</td></tr>
<tr><td></td></tr>
<tr><td>60%</td><td>Alluvial</td><td>181</td><td>1066</td><td></td><td>2.65</td></tr>
</table>

	deposit			847	
	Weathered soil	628	1696	1567	
	Weathered rock	1438	2077	1832	
	Bed rock	1587	4370		
50%	Alluvial deposit	268	979	856	2.53
	Weathered soil	733	1591	1546	
	Weathered rock	1501	2014	1937	
	Bed rock	1860	4096		
40%	Alluvial deposit	347	900	864	2.49
	Weathered soil	828	1496	1527	
	Weathered rock	1558	1957	2033	
	Bed rock	2108	3848		
35%	Alluvial deposit	384	863	868	2.49

<table>
<tr><td rowspan="6"></td><td rowspan="2">Weathered soil</td><td rowspan="2">873</td><td rowspan="2">1451</td><td></td><td rowspan="6"></td></tr>
<tr><td rowspan="2">1518</td></tr>
<tr><td rowspan="2">Weathered rock</td><td rowspan="2">1558</td><td rowspan="2">1957</td></tr>
<tr><td rowspan="2">2078</td></tr>
<tr><td rowspan="2">Bed rock</td><td rowspan="2">2108</td><td rowspan="2">3848</td></tr>
<tr><td></td></tr>
<tr><td rowspan="8">30%</td><td rowspan="2">Alluvial deposit</td><td rowspan="2">420</td><td rowspan="2">826</td><td></td><td rowspan="8">2.49</td></tr>
<tr><td rowspan="2">872</td></tr>
<tr><td rowspan="2">Weathered soil</td><td rowspan="2">917</td><td rowspan="2">1407</td></tr>
<tr><td rowspan="2">1509</td></tr>
<tr><td rowspan="2">Weathered rock</td><td rowspan="2">1611</td><td rowspan="2">1904</td></tr>
<tr><td rowspan="2">2122</td></tr>
<tr><td rowspan="2">Bed rock</td><td rowspan="2">2340</td><td rowspan="2">3616</td></tr>
<tr><td></td></tr>
</table>

Second, the site-specific geo-layer criteria using the average of geophysical values were determined. The statistical characteristics of Seismic refraction wave velocities for geo-layer in this site is shown as Fig. 6.16 and the site-specific geo-layer criteria are described in Table 6.17.

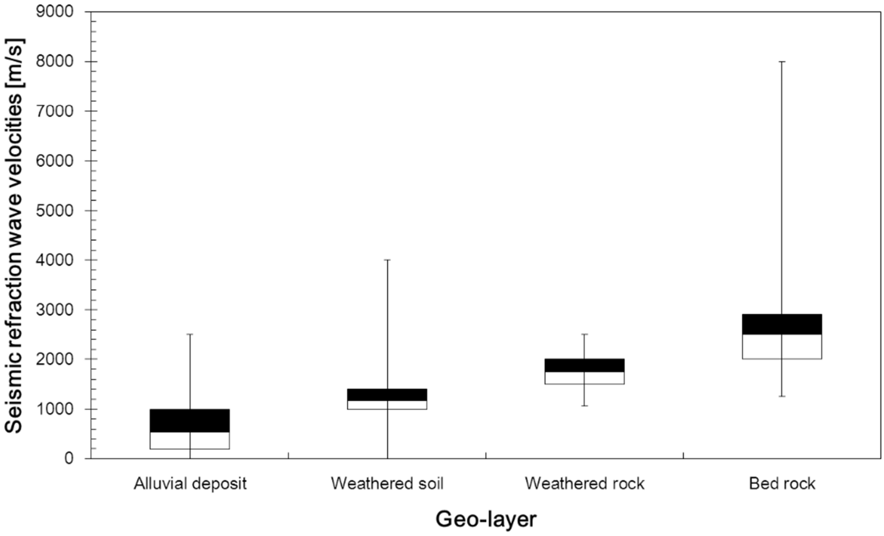

Figure 6.16 Box-whisker plot of seismic refraction wave velocities for geo-layer at Andong dam site

Table 6.17 Determination of site-specific geo-layer criteria using average of seismic refraction wave velocities at Andong dam site

<table>
<tr><th>Geo-layer</th><th>Average
[m/s]</th><th>Site-specific geo-layer criteria
[m/s]</th><th>RMSE
[m]</th></tr>
<tr><td rowspan="2">Alluvial deposit</td><td rowspan="2">623</td><td></td><td rowspan="8">2.80</td></tr>
<tr><td rowspan="2">893</td></tr>
<tr><td rowspan="2">Weathered soil</td><td rowspan="2">1162</td></tr>
<tr><td rowspan="2">1460</td></tr>
<tr><td rowspan="2">Weathered rock</td><td rowspan="2">1758</td></tr>
<tr><td rowspan="2">2368</td></tr>
<tr><td rowspan="2">Bed rock</td><td rowspan="2">2978</td></tr>
<tr><td></td></tr>
</table>

Third, the site-specific geo-layer criteria using 1st quartile and 3rd quartile of seismic refraction wave velocities were determined as shown Table 6.18.

Table 6.18 Determination of site-specific geo-layer criteria using 1st quartile and 3rd quartile of seismic refraction wave velocities at Andong dam site

<table>
<tr><th>Geo-layer</th><th>1st quartile [m/s]</th><th>3rd quartile [m/s]</th><th>Site-specific geo-layer criteria [m/s]</th><th>RMSE [m]</th></tr>
<tr><td rowspan="2">Alluvial deposit</td><td rowspan="2">182</td><td rowspan="2">1000</td><td></td><td rowspan="8">2.51</td></tr>
<tr><td rowspan="2">1000</td></tr>
<tr><td rowspan="2">Weathered soil</td><td rowspan="2">1000</td><td rowspan="2">1400</td></tr>
<tr><td rowspan="2">1450</td></tr>
<tr><td rowspan="2">Weathered rock</td><td rowspan="2">1500</td><td rowspan="2">2000</td></tr>
<tr><td rowspan="2">2000</td></tr>
<tr><td rowspan="2">Bed rock</td><td rowspan="2">2000</td><td rowspan="2">2907</td></tr>
<tr><td></td></tr>
</table>

As a result, the optimum site-specific geo-layer criteria are criteria using normal distribution as shown Table 6.19.

Table 6.19 Determination of optimum site-specific geo-layer criteria at Andong dam site

	Site-specific geo-layer criteria [m/s]		
	Method 1	Method 2	Method 3
Alluvial deposit / Weathered soil	864	893	1000
Weathered soil / Weathered rock	1527	1460	1450

Weathered rock / Bed rock	2033	2368	2000
RMSE	2.49	2.80	2.51

Method 1 : Using normal distribution

Method 2 : Using the average

Method 3 : Using the 1st quartile and 3rd quartile

3D geo-statistical integration

After the optimum site-specific geo-layer criteria were determined, the 7 classification criteria were determined as indicator threshold: 3/5(60%), 3/4(75%), 7/8(88%), 100%, 9/8(112%), 6/5(120%) and 5/4(125%) of the optimum site-specific geo-layer criteria (as shown Table 6.20). Based on the 7 assumed classification criteria, the given 3D seismic refraction wave velocities datasets are stratified, and the integration with borehole datasets is performed using indicator kriging to identify which is the most site-specifically fitted criteria to classify the geo-layer as shown in Fig.6.17. The fitted curves were quadratic function and the seismic refraction wave velocities at the lowest RMSE of fitted curve are suitable to estimate strata. As a result, the 3D strata in testing site were determined with the most fitted criteria.

Table 6.20 Assumed classification criteria at Andong dam site

	Alluvial deposit / Weathered soil	Weathered soil / Weathered rock	Weathered rock / Bed rock
60%	518	916	1220

75%	648	1145	1525
87.5%	756	1336	1779
100%	864	1527	2033
112.5%	972	1718	2287
120%	1037	1832	2440
125%	1080	1909	2541

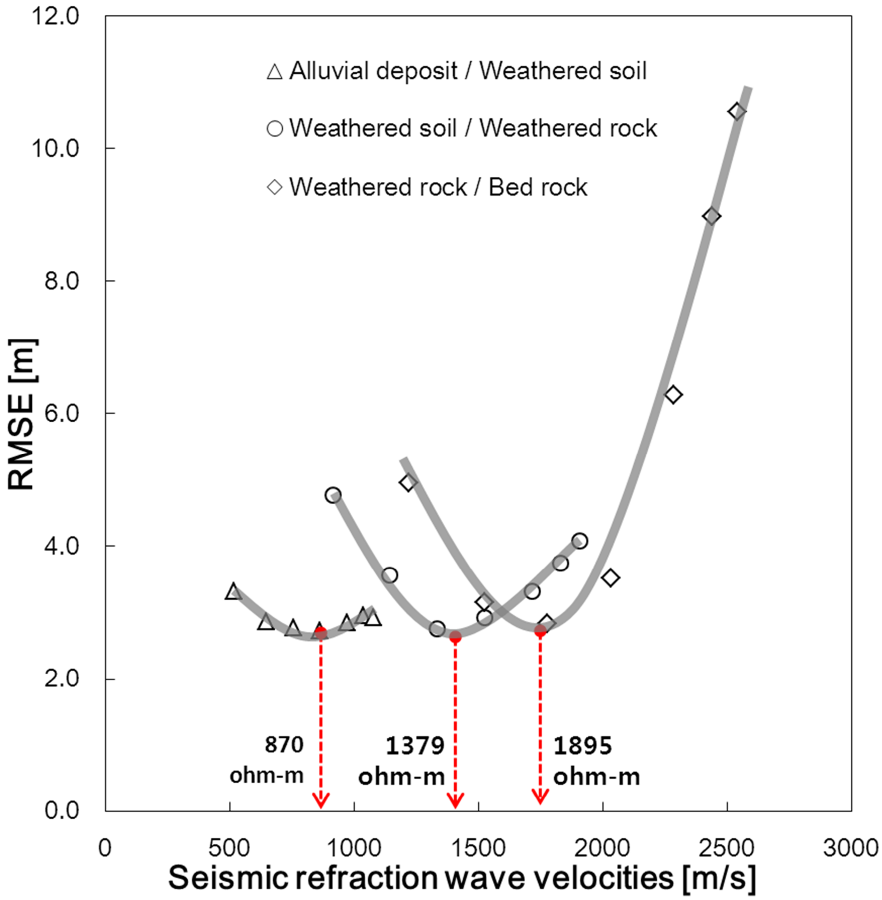

Figure 6.17 Determination of most fitted classification criteria at Saemanguem reclaimed land site

Validation of proposed method

In order to validate the proposed method, cross-validation were applied for both using only borehole datasets and using the proposed method. Finally, the proposed method is more reliable than using only borehole datasets as shown 6.21. The 3D strata in target site were determined and described using a 3D visualization program developed by Seoul National University in Fig. 6.18.

Table 6.21 Validation of proposed method by comparing using only borehole datasets based on cross-validation at Andong dam site

Method	RMSE [m]
Using only borehole datasets	10.68
Proposed method	3.06

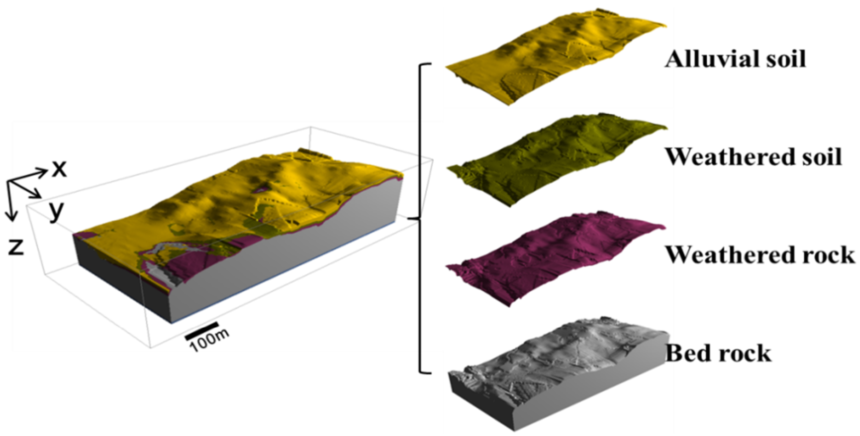

Figure 6.18 Visualization of 3D strata information at Andong dam site

6.4 Summary and Discussions

3D geo-statistical integration considering site-specific characteristics was applied in various testing sites: Gyodong bridge site, Saemanguem reclaimed land site, Andong dam site. Mokdong site was excluded because of having no geophysical data.

1) The most suitable method determining the optimum site-specific geo-layer criteria is using normal distribution or using 1st and 3rd quartile as shown Table 6.22. In case of using normal distribution, the method is more complicated than the others. However, the reliability of using normal distribution has similar with the reliability of using 1st quartile and 3rd quartile. Therefore, for the engineers, using 1st quartile and 3rd quartile of geophysical values are recommended in order to save time and efforts.

Table 6.22 Comparison of each method to determine site-specific geo-layer criteria in each site

	RMSE		
	G site	S site	A site
Using normal distribution	5.20	5.38	5.25
Using average	6.81	7.28	6.75
Using 1st quartile and 3rd quartile	2.49	2.80	2.51

2) The determined 3D strata using proposed method were more improved than that using only borehole datasets in testing sites as shown Table 6.23.

Table 6.23 Comparison of RMSE as result of cross-validation in each target site

Method	RMSE [m]		
	G site	S site	A site
Using only borehole datasets	6.62	4.90	10.68
Proposed method	5.77	4.52	3.06

3) Especially, the result in Andong dam site was shown that 3D geo-statistical integration is much more effective than using only borehole datasets as shown Table 6.23. Conditions of site investigation in each site are shown as Table 6.24. First, this result was due to which the seismic refraction velocity is more reliable to estimate strata than the electric resistivity. The electric resistivity survey is the investigation method for electric characteristic of geo-layer. Even though geo-layers are different, in case of having same electric characteristic, it is hard to classify geo-layers (KSEG, 2002). In addition, geophysical survey data in Saemanguem reclaimed land site and Andong dam site is respectively parallel and intersected. In case of parallel geophysical data, 3D strata information using

parallel geophysical data also have parallel orientation characteristics and have a bad influence in results of analysis.

Table 6.24 Conditions of site investigation in application sites

	G site	S site	A site
Site area [m^2]	1620	44400000	243100
Number of borehole [EA]	17	22	24
Density of borehole [EA/m^2]	1.04×10^{-2}	4.95×10^{-7}	9.87×10^{-5}
Density of geophysical data [m/m^2]	1	1.76×10^{-3}	1.42×10^{-2}
Type of geophysical data	Electric resistivity	Electric resistivity	Seismic refraction velocity
Configuration of investigation line	-	Parallel	Intersected

Chapter 7 Conclusions

The previous researches have limitations in considering site-specific conditions and mainly using only borehole datasets. A geo-spatial data integration method based on geo-statistics was proposed to estimate the 3D strata information. The proposed method is modified to consider the site-specific conditions in site. First, the optimization of borehole data is conducted to remove the various uncertainties of borehole test by standardizing the geo-layer boundaries and applying optimum outlier analysis based on cross-validation. The integrity of borehole datasets for analysis can be procured by optimization phase. Especially, the site-specific conditions of borehole data are considered by optimum outlier analysis. Second, the optimum site-specific geo-layer criteria by which the geophysical values are transformed with geo-layer information are determined. In order to determine the optimum site-specific geo-layer criteria, 3 methods were proposed. The 3 method are using normal distribution of geophysical values, using average of geophysical values, and using 1st quartile and 3rd quartile of geophysical values. In each site, the most suitable method was different. Therefore, the site-specific conditions could be considered by applying and comparing 3 methods. Finally, the proposed method was applied in Korean 3 testing sites (Gyodong bridge site, Saemanguem reclaimed land site, and Andong dam site), and the 3D strata information in testing sites were determined and visualized by using indicator kriging which is one of geo-statistical methods.

The proposed method was validated based on cross-validation. As a result, the proposed method has a lower RMSE than using only borehole datasets. Consequently, 3D strata information using proposed method in three sites is more improved than results using only borehole datasets. In addition, the proposed method was applied with various geophysical data such as electric resistivity or seismic refraction wave velocity. It was confirmed that both electric resistivity and seismic refraction wave velocity could be utilized to estimate 3D strata information in site. The further researches are recommended to supplement by applying more various geophysical data and various site.

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초 록

3차원 층상정보는 다양한 건설현장 설계 및 시공 과정에서 필수적이다. 일반적으로 대상 현장의 3차원 층상정보를 결정하기 위해서 주로 시추조사 자료가 활용되고 있다. 시추조사 자료는 다른 지반조사 방법에 비하여 상대적으로 정확한 층상 정보를 제공하지만, 전체 대상지역을 1차원의 점 형태로 조사하기 때문에 대상지역의 연속적인 정보를 얻기가 어렵다는 단점을 가지고 있다. 이와 대조적으로 지구물리탐사 토모그래피는 연속적인 2차원 단면의 형태로 보다 넓은 영역에 대해 조사가 이루어진다. 그러나 지구물리탐사 토모그래피의 경우 직접적인 지반공학적 층상정보를 나타내지 않으므로 경험적인 방법에 의하여 지반공학적 정보로 변환되는 과정이 필요하다. 그러므로 서로 다른 특징을 가진 이종(異種) 지반조사 자료를 결합하여 함께 분석을 수행한다면 보다 신뢰성 있는 층상 정보를 획득할 수 있다.

시추조사 자료는 일반적으로 참값으로 여겨지지만, 실제 시추조사 자료는 다양한 불확실성으로 인하여 전체 자료의 경향에서 벗어나는 이상치를 포함하고 있다. 따라서, 정확한 층상정보 추정을 위해서는 시추조사 자료의 이상치를 제거하여 최적화하는 과정이 필요하다. 추가적으로 시추조사자료와 지구물리탐사 자료는 지역에 따라 변동성을 가지므로, 통합분석을 수행할 때 이러한 지역적 변동성을 고려할 필요가 있다.

본 연구에서는 시추조사 자료와 지구물리탐사 자료를 지역적 변동성을 고려하여 분석하는 3차원 지구통계학적 통합분석을 제안하였다. 지역적 변동성을 고려한 교차검증 기반의 이상치

분석을 통해 시추조사 자료를 최적화하였으며, 지구물리탐사 자료를 3차원 층상 정보로 변환하기 위한 지역적 특성을 고려한 층상 기준을 결정하였다. 최종적으로 대상지역의 최적화된 시추조사 자료와 물리탐사 자료에 지구통계학적 방법인 지시자 크리깅을 적용하여 3차원 층상 정보를 추정하였다. 추가적으로, 제안한 방법의 적용성을 검증하기 위하여 국내의 3개의 적용 및 검증하였다.

주요어 : 시추조사, 지구물리탐사, 전기 비저항 탐사, 굴절법 탄성파 탐사, 이상치 분석, 지시자 크리깅, 3차원 지구통계학적 통합분석

학 번 : 2013-23148