Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering
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doi:10.3233/978-1-61499-656-9-2817

Estimation of long-term settlement and determination of additional sampling positions using GIS

Estimation de l'installation long-terme et détermination des positions supplémentaires d'échantillon en utilisant (le) GIS

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ABSTRACT
We estimate the ground information for the interesting region by using the results obtained from in-situ and laboratory tests with GIS (Geographic Information Systems). Incheon International Airport that was reclaimed is the objective area in this paper. The settlements of the ground surface have been measured at the beginning of the construction. Since the primary consolidation in this site has been completed, the settlement due to the secondary consolidation was expected and predicted by the SSCI (Secant Secondary Compression Index). To estimate the long-term settlement in the future, geostatistics, such as the 'Kriging interpolation method' and the 'IDWI (Inverse Distance Weighted Interpolation) method' in GIS was used. The results by the IDWI method are compared with those by Kriging interpolation method. Using the concept of 'thoroughness', additional sampling positions are proposed. As a result, it is known that 1) the GIS can be useful tool to estimate soil parameters at any point without the measurement in site or test in the lab; 2) the long-term settlement estimated by the Kriging interpolation method show better agreement with the measured ones than IDWI method; and 3) the GIS can be useful to estimate the long-term settlement in the future and additional sampling positions.

RÉSUMÉ
Nous éstimons l'information du sol sur la région intéressante par l'utilization de résultats obtenus des essais sur le site et dans le laboratoire avec le système d'information géographique. L'aéroport international d'Incheon, qui était reclamé, est le site objectif dans cet article. L'installation de la surface du sol était mesurée au début de construction. Puisque la consolidation primaire dans ce site était complète, l'installation dûe à la consolidation secondaire était espèrée et predu par le SSCI (Secant Secondary Compression Index). Pour éstimer l'installation long-terme dans le futur, les géostatistiques, tel que la 'méthode de l'interpolation de Krigeage' et la 'méthode d'IDWI (Inverse Distance Weighted Interpolation) dans le système d'information géographique, étaient utilisés. Les résultats par la méthode de IDWI sont comparés avec ceux par la méthode de l'interpolation de Krigeage. En utilisant le concept de 'thoroughness', les positions supplémentaires d'échantillon sont proposées. Par conséquent, on est connu que 1) le système d'information géographique peut être utile pour éstimer des paramètres de sol au point quelconque sans le mesure sur le site ou essai dan le laboratoire ; 2) l'installation long-terme éstimée par la méthod de l'interpolation de Krigeage est plus approche a celle mesurée que la méthode d'IDWI ; 3) le système d'information géographique peut être utile pour éstimer l'installation long-terme dans le futur et les positions suppléntaires d'échantillon.

1 INTRODUCTION

The soft ground has been continuously improved to overcome a limited area and to use coastal region extensively. Although the properties are estimated by in-situ and laboratory tests, the behavior of the soft ground still has lots of uncertainties. This is because the data obtained from the samples represents 0.001% or less of the total volume of soils. However, in most cases, these soil properties tested at certain positions are used to infer soil behavior at the neighboring positions by taking mean values.

In this study, the soil properties throughout the area were estimated by using the geostatistical method, such as the IDWI and the Kriging interpolation method in GIS. In addition, the SSCI proposed by Mesri and Stark (1997) was applied to estimate long-term settlements. Using the concept of "thoroughness" proposed by Tsai and Frost (1999), the additional sampling positions could be proposed.

2 BASIC CONCEPT

Figure 1 illustrates the process for the estimation of long-term settlement and determination of additional sampling positions. Since GIS is well not known for geotechnical engineer, some words are briefly defined in this paper.

2.1 *GIS (Geographic information systems)*

The GIS is defined as an information system that is used to input, store, retrieve, manipulate, analyze and output the geographical data. This supports decision making for planning and management of land use, natural resources, environment, transportation, urban facilities, and other administrative records (Sarkozy, 1999). The most important function of the GIS is to analyze both the spatial data and their attributes for decision support. The GIS data are stored in the form of the layer on the coordinate plane. A set of the spatial data consists of the cartographic data and the attribute data. Here, the cartographic data indicates the data in the position within the space coordinate system or time-space coordinate system. The attribute data means the data which does not include spatial concept. This data, for example, includes the information of the road, drainage, sorts, or the thickness of the soil and land utilization, etc. Therefore, there is no restriction in the quantity of the information for this data. Also, it is very convenient in engineering analysis because it was designed to treat data effectively.

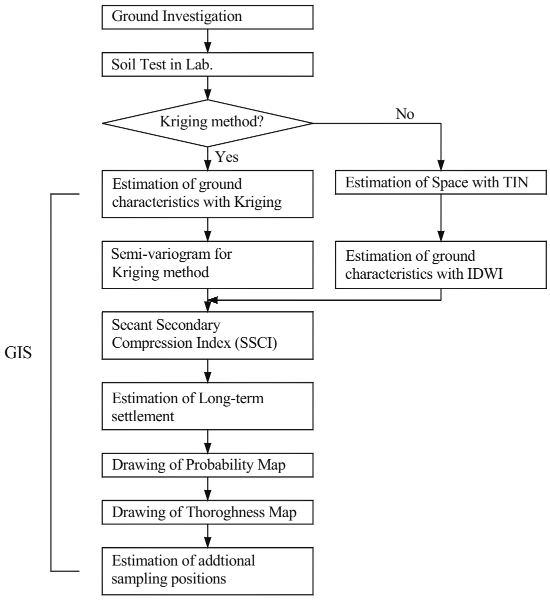


Figure 1. Flow chart for this study

2.2 *Geostatistical interpolation method*

2.2.1 *IDWI (Inverse distance weight interpolation) method*

The objective area was subdivided by the TIN (triangular irregular net) to use the GIS, and it was separated into triangulation following Voronoi diagram as shown in Fig. 2 (Sarkozy, 1999).

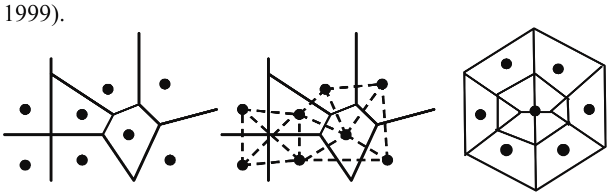


Figure 2. Voronoi diagram (Sarkozy, 1999)

The basic concept of Voronoi diagram is to make triangle by connecting each point to obtain the circumcenter of each triangle. Many circumcenter of each triangle become virtual points. And the virtual points can be connected to make new triangle. In this way, the triangulation is completed and unknown values are determined by using the IDWI method as following:

$$f(x, y) = \sum_{i=1}^{n} w_i \cdot f_i \tag{1}$$

$$w_i = h_i^{-p} \Big/ \sum_{i=1}^{n} h_i^{-p} \tag{2}$$

where n = the number of points that are used for interpolation; f_i = attribute data; p = power parameter (=2); h_i = distance between measured and interpolated point; w_i = weighting factor of each point.

2.2.2 *Kriging interpolation method*

Sarkozy (1999) proposed that geostatistics, which is distinguished from statistics, deals with the spatial distribution of data. Spatial correlation and continuity should be defined to predict unknown values. Among various techniques used in the analysis of spatial distribution, linear function for the Kriging interpolation method is adopted to determine unknown values as:

$$z^* = \lambda_1 z_1 + \lambda_2 z_2 + \cdots + \lambda_n z_n = \sum_{i=1}^{n} \lambda_i z_i \tag{3}$$

where z* is measured value, z is interpolated value, and λ is weighting factor.

2.2.3 *Application of semi-variogram model for Kriging*

The application of the Kriging interpolation method is very important to define the criterion for the spatial correlation of attribute data (Sarkozy, 1999). The spatial variation is quantified by the semi-variogram. The semi-variogram is estimated by the sample semi-variogram which is computed from the input point data set. The sample semi-variogram is calculated from the sample data with the following equation:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} \{z_i(x) - z_i(x+h)\}^2 \tag{4}$$

where n is the number of pairs of sample points separated by distance h.

Figure 3 shows that the distribution of interpolated points and co-variance between measured and interpolated points can be determined by drawing a semi-variogram of measured points. Although the actual variance is highly irregular along the distance, the trend of the predicted one shows good agreement with an actual one, especially, within the range of about 200 m.

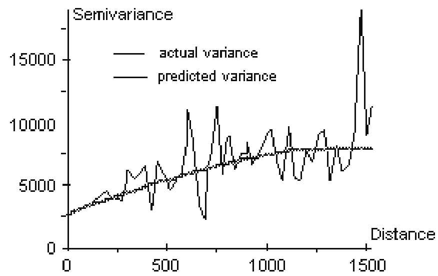


Figure 3. Semi-variogram

3 ANALYSIS AND DISCUSSION

3.1 *Long-term settlements*

3.1.1 *Estimating soil characteristics in entire area*

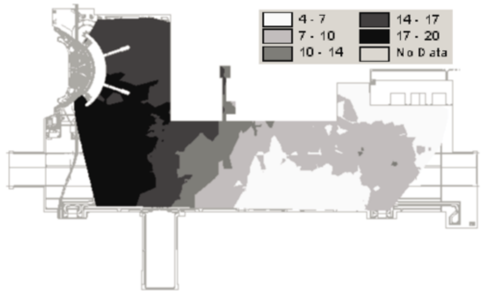
The settlements had been measured on the ground surface at the beginning of the construction at Incheon International Airport. The analysis was performed using the data measured, such as soft ground thickness, initial void ratio, coefficient of permeability, and ground surface level, etc. The IDWI method and the Kriging interpolation method are applied to the cartographic data. Figure 4 shows the soft ground thickness by using the IDWI method and the Kriging interpolation method. On the other hand, distributions of the other soil characteristics such as initial void ratio, coefficient of permeability, and primary compression index, etc were also estimated in the similar way.

3.1.2 *Determination of Semi-variogram model*

The actual variogram of ground property are compared with some semi-variogram models to investigate the correlation of in-situ data along the distance. Figure 5 shows the comparison of the actual variance of initial void ratio with various semi-variogram models. It is known that the spherical model among them is close to the actual variance. Especially, it shows a close correlation within the range of about 400 m. The correlation within the range of 800 m is analyzed as shown in Fig. 6.

Consequently, the use of spherical model with correlation distance of about 400 m is the most adequate to this site. In addition, the spherical model and some models in semi-variogram model has also ‘nugget effects’ that replaces point value with a new one at the measured point owing to the non-zero value at a distance 0 as shown in Fig. 6.

(a) IDWI method (unit: m)



(b) Kriging interpolation method (unit: m)
Figure 4. Distribution of the thickness of soft ground

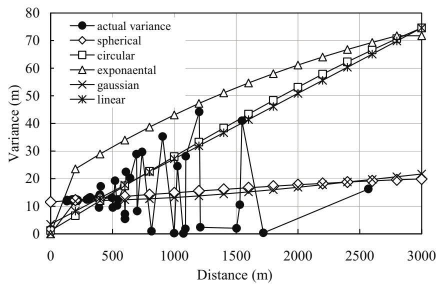


Figure 5. Comparison of various semi-variogram models

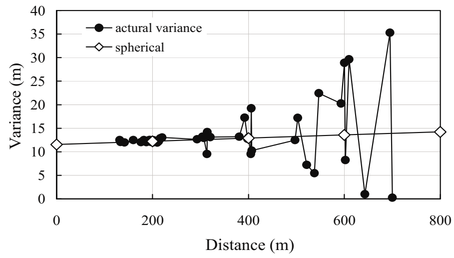


Figure 6. Spatial correlation within 800 m

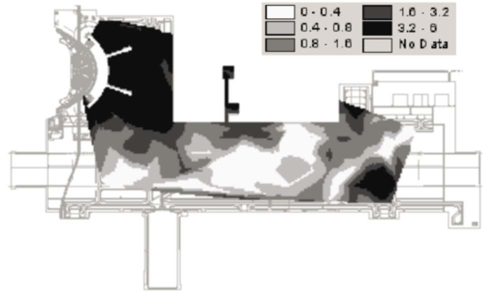
3.1.3 *Estimation of long-term settlement*

It is assumed that the primary consolidation has been completed since the average consolidation ratio was up to 95% (Kim et al., 2002). The long-term settlements were estimated by using Eqn. 5 and the GIS technique (Kim et al., 2002; Lee et al., 2004). Figure 7 shows and the long-term settlement after 30 years later.

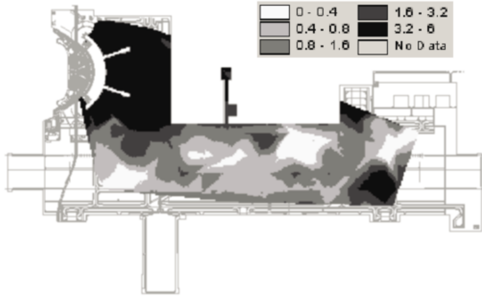
$$S = \frac{\left(C_{\alpha}^{"}/C_{\alpha}\right)\cdot\left(C_{\alpha}/C_{c}\right)\cdot C_{c}}{1+e_{p}} L_{p} \log\frac{t}{t_{l}} \tag{5}$$

where S is settlement during secondary consolidation; $C^{"}_{\alpha}$ is SSCI; C_c is primary compression index; e_p is void ratio after primary consolidation; L_p is thickness after primary consolidation; t_l is time at starting second consolidation; t is any time during second consolidation (Mesri and Stark, 1997).

On the other hand, the comparison of settlements between the IDWI and the Kriging interpolation method with the measured ones is shown in Fig. 8. As a result, the Kriging interpolation method gives better prediction than the IDWI method in this site.



(a) IDWI method (unit: cm)



(b) Kriging interpolation method (unit: cm)
Figure 7. Long-term settlements after 30 years later

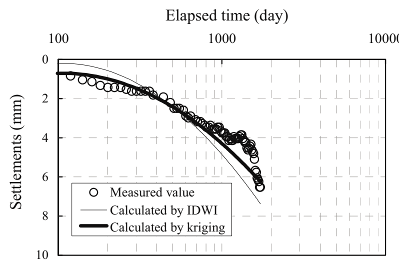


Figure 8. Comparison between the measured and the predicted results

3.2 *Determination of additional sampling positions*

3.2.1 *Probability Map*

In the problem of settlements in soft ground, there is the allowable value for the serviceability of upper structure. Probability map indicating the probability of satisfaction for threshold value is contoured (Fig. 9). First, the secondary consolidation settlements are calculated by using subsurface investigation data whose types are points. And then, the results are compared with threshold value and assigned as an indicator value of 1 or 0, depending on whether it is higher or lower than the threshold value as shown in Eqn. 6 (Parsons and Frost, 2002). The resulting indicators are then interpolated throughout the whole, and expected values are generated as probability values (Fig. 9). The estimated ground settlements in this site are expected to be smaller than the allowable criterion. In this study, it is assumed that the threshold value b is 5 mm to determine probability more efficiently.

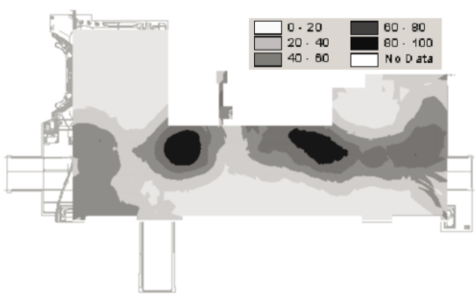


Figure 9. Probability contour (unit: %)

$$if \quad x_i < b \;\; x_i = 1 \tag{6}$$
$$if \quad x_i > b \;\; x_i = 0$$

where, b = threshold value.

3.2.2 *Thoroughness*

The thoroughness is calculated by using a transformation function to probability mentioned previously to yield an index that allows for graphical representation of the zone where the variable of interest crosses a specific threshold (Parsons and Frost, 2000). The thoroughness is intended to complement traditional data analysis procedure by allowing enhanced visual analysis of the data. The thoroughness function used in this study links the reliability of results of the site investigation to the results obtained by using Eqn. 7.

$$T = |100 - 2P| \tag{7}$$

where T is the thoroughness; P is the probability of a given outcome(%).

As illustrated in Fig. 10, the thoroughness linearly decreases from 100% to 0% where the probability is 50% and this linearly increases to 100% where the probability is 100%. In other words, the lowest thoroughness indicates intermediate probability (50%) that an event will occur.

Figures 11 and 12 show the contour of thoroughness at Incheon International Airport before and after additional samplings, respectively. In Fig. 12 the imaginary six sampling positions within dotted areas were inserted to verify the increment of thoroughness. And probability and thoroughness calculated again. Comparing the results in Fig. 11 and Fig. 12, apparently, the thoroughness increases around the additional sampling positions (dotted areas in Fig. 12).

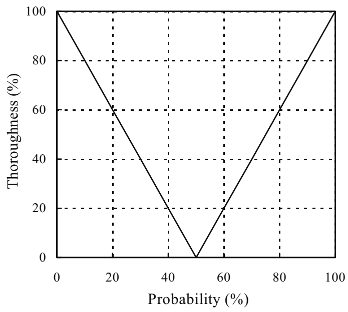


Figure10. Thoroughness function (Parsons and Frost, 2000)

4 SUMMARY AND CONCLUSIONS

In this study, the secondary settlement of the ground at Incheon International Airport was estimated by using the results obtained from in-situ and laboratory tests with GIS. The spherical model used in the Kriging interpolation method has nugget effects which replace the intact value of point type with a new one at the measured point. Finally, the interpolated values between the IDWI method and Kriging interpolation method need to be additionally analyzed.

1. The Kriging interpolation method and the IDWI method in the GIS were used to determine the ground properties in a large reclamation site.
2. The analysis using the semi-variogram model was performed and it was verified that the spherical model is the most acceptable one to estimate the several data in this study.
3. The long-term settlement of Incheon International Airport was estimated by using secant secondary compression index, and probability was illustrated by applying an arbitrary threshold value. Also, the thoroughness was determined by using thoroughness function.
4. The long-term settlement estimated by the Kriging interpolation method, show better agreement with the measured one than the IDWI method.
5. The method to determine additional sampling positions is proposed. Subsequently, it is confirmed that the thoroughness increases by adding sampling positions.

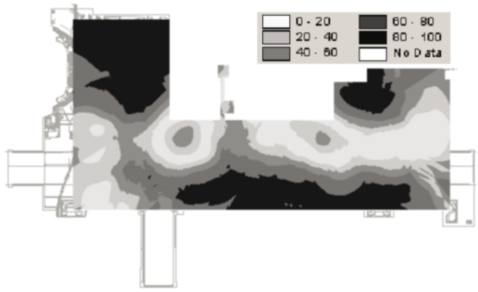


Figure 11. Thoroughness contour before additional sampling (unit: %)

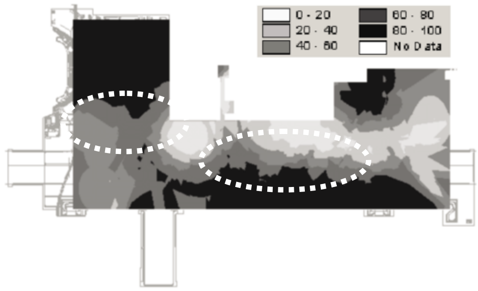


Figure 12. Thoroughness contour after additional sampling (unit: %)

ACKNOWLEDGMENTS

The authors express sincere gratitude to Assistant Manager, Ki-Kwang Seong at Incheon International Airport Corporation and Mr. Si-Dong Yoo in Hongik University for their help on this research.

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