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An Estimation of Long-term Settlements in the Large Reclamation Site and Determination of Additional Sampling Positions Using Geostatistics and GIS

GIS 및 지구통계학을 적용한 대규모 매립지반의 장기 침하량 예측 및 추가 지반조사 위치의 결정

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요 지

지반기술자는 지반의 구조 및 잠재적 거동을 예측하기 위해서 현장조사 데이터를 사용한다. 대부분의 경우 이러한 데이터들은 전체 지반 체적의 1/100,000도 되지 못한다. 이렇게 얻어진 시료에 대한 실내시험 및 현장시험을 통하여 지반의 특성치를 결정한다. 그러나 이렇게 추정된 결과치는 예측치이며 Legget(1979)의 지적과 같이 실제 흙의 상태와는 매우 다르게 평가될 가능성을 가지고 있으며, 이러한 경우는 샘플링과 예측 과정을 일반적인 규정에 따라 실시하는 경우에도 발생할 수 있다. 그동안 지반 물성치와 관련된 불확실성을 규명하고자 하는 노력이 이루어졌지만, 전체 지반 조사 계획의 정확도 및 각각의 지반 조사 위치나 잠재적 조사 위치의 상대적인 중요성을 정량적으로 평가할 수 있는 방법으로 일반적으로 받아들여지는 방법이 아직까지는 없는 실정이다. 본 논문에서는 지구 통계학적 방법인 크리깅 내삽법(kriging interpolation method) 및 역거리 내삽법(inverse distance weighted interpolation method)을 이용하여 지반 정수를 추정하고 그 정확도를 비교하였다. 또한 장기 침하량을 예측할 수 있는 새로운 방법을 제시하였다. 그리고 이 방법을 "신뢰도"(Tsai and Frost, 1999)와 지구 통계학적 방법을 접목시켜서 지반 조사 계획의 조사정밀도를 평가하는 공간적인 분석 방법을 제시하였다. 그리고 마지막으로 추가 지반조사 계획이 이루어지는 경우, 추가 지반조사위치를 결정할 수 있는 방법을 제시하였다. 아울러, 보다 정확한 해석을 위한 방법으로 시각적 도시, 해석 및 자료 관리의 기능이 뛰어난 GIS 프로그램(ARC-Info)을 이용하였다.

Abstract

For geotechnical applications, engineers use data obtained from a site investigation to interpret the structure and potential behavior of the subsurface. In most cases, these data consist of samples that represent 1/100,000 or less of the total volume of soil. These samples and associated field and lab testing provide the information used to estimate soil parameter values. The resulting values are estimated ones and there exists some likelihood that actual soil conditions are significantly different from the estimates. This may be the case even if the sampling and interpretation procedures are performed in accordance with standard practice. Although these efforts have been made to characterize the uncertainty associated with geotechnical parameters, there is no commonly accepted method to evaluate quantitatively the quality of an investigation plan as a whole or the relative significance of individual

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sampling points or potential sampling points. In this paper, the geostatistical methods, 'Inverse distance weighted interpolation method' and 'kriging interpolation method' for estimating soil parameter values, are compared with each other to examine the accuracy of these methods. And new method for estimating the long-term settlements is proposed. This method combines the concept of investigation plan "thoroughness" with geostatistical techniques to develop a spatially sensitive estimate of the site investigation plan quality, referred to as continuous thoroughness, because it applies to geotechnical parameters that exist at every point throughout the sampling area. Finally, the method for locating additional sampling positions is proposed. The approach was implemented using a geographic information system platform(ARC-Info) so that the visual, analytical, and data management benefits of GIS could be utilized for a more detailed analysis.

Keywords : Additional sampling positions, GIS, Inverse distance weighted interpolation method, Kriging, Secant secondary compression index, Thoroughness

1. Introduction

The development of soft ground is continuously increased for the overcome of a limited area and the use of a coastal region. However, the properties of ground in estimating the behavior of soft ground have a lot of uncertainty in comparison with the related theories. This is due to samples representing 1/100,000 or less of the total volume of soils. In most cases, the results obtained in neighboring sampling positions are used directly without correction or the mean value of results in neighboring sampling positions is used in order to estimate those of unknown place.

In this study, the soil properties at unknown positions were estimated by using the kriging interpolation method and the inverse distance weighted interpolation method that corresponds to geostatistical method. These mothods were implemented by using geographic information system(GIS). Also, the long-term settlements were estimated by applying these data to the theory of secant secondary compression Index. This method combines the concept of investigation plan "thoroughness" (Tsai and Frost, 1999) with geostatistical techniques to develop a spatially sensitive estimate of the site investigation plan quality, referred to as continuous thoroughness, because it applies to geotechnical parameters that exist at every point throughout the sampling area. Finally, the method to determine additional sampling positions is proposed.

2. Basic Concept

2.1 Geographic Information System (GIS)

GIS is defined as an information system that is used to input, store, retrieve, manipulate, analyze and output geographically referenced data, in order to support decision making for planning and management of land use, natural resources, environment, transportation, urban facilities, and other administrative records. The most important function of GIS is to enable the analysis of the spatial data and their attributes together for decision support. GIS data are stored in layer form on coordinate plane. GIS involves spatially arranged data while other information systems process number or character informations. A set of spatial data consist of cartographic data and attribute data. Here, cartographic data means the position within space coordinate system or time-space coordinate system and attribute data means the data which do not include spatial concept. Attribute data can include the informations of road, drainage, sorts or thickness of soil and land utilization etc. and there is no restriction in quantity of these information. Also, it is very convenient in engineering analysis because it is designed to treat data effectively.

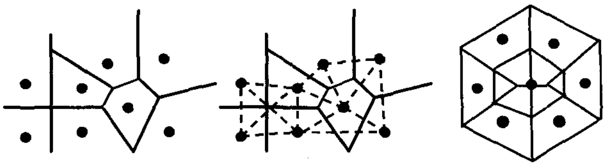


Fig. 1. Voronoi diagram

2.2 Geostatistical Interpolation Method

2.2.1 Inverse Distance Weight Interpolation Method

In this study, we subdivide whole analysis area by TIN(triangular irregular net) to take advantage of GIS. The whole analysis area is divided into triangulation by using Voronoi diagram as shown in Fig. 1.

The basic concept of Voronoi diagram is to make triangulation by connecting each points to obtain the circumcenter of each triangulation. The line connecting internal and external point of triangulation becomes set of vertical bisector in accordance with the principle of circumcenter. In this way, the triangulation is made up and unknown values are determined by using inverse distance weighted interpolation method as following Eqns. (1) and (2).

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

$$w_i = \frac{h_i^{-p}}{\sum_{j=1}^{n} h_j^{-p}} \tag{2}$$

where, n = number of points that are used in interpolation

f_i = attribute

p = power parameter (=2)

h_i = distance between known and unknown points

w_i = weighting factor of each point

2.2.2 Kriging Interpolation Method

Geostatistics which is distinguished from statistics is to consider spatial distribution of data. Firstly, spatial correlation and continuity must be defined to predict unknown values. Among various techniques used in the analysis of spatial distribution, linear function is adopted in kriging interpolation method to determine unknown values as following Eqn. (3)

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

where, z^* : estimated value

I : number of known value

λ_i : weighting factor

The ordinary kriging is designed to have a mean residual or null error, and assumed that the value of neighborhood is known to determine weighting factor at specific point. The residual can be calculated by using the following Eqn. (4).

$$b_{\bar{z}} = E(\bar{z}) - E(z) = (\sum \lambda_i - 1)E(z) \tag{4}$$

In Eqn. (4), the sum of λ_i must be 1 to satisfy the unbias. Also, the weighting factor is determined from surrounding values that are already known according to distance. In general, the distribution at arbitrary position (σ_k^2) can be determined by using the Eqn. (5).

$$\sigma_k^2 = E\{(z - z^*)^2\} \tag{5}$$

As shown in Eqns (3) and (5), the results can be changed according to λ_i, and λ_i is determined by the minimum kriging variance(σ_k^2). Combining Eqn. (3) with (5), Eqn. (6) can be obtained

$$\sigma_k^2 = \sigma^2 - 2\sum_{i=1}^{n} \lambda_i \sigma_{oi}^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \lambda_j \sigma_{ij}^2 \tag{6}$$

As shown in the above Equation (6), σ_k^2 is the function of λ and $(\sigma_k^2)'$ must be zero to get the minimum value of Eqn. (6) and differential Eqn. of Eqn. (6) becomes as following Eqn. (7).

$$\therefore \sum_{i=1}^{n} \lambda_i \sigma_{li}^2 = \sigma_{ol}^2 \tag{7}$$

And, Eqn. (7) can be transformed into matrix form as following

$$\begin{pmatrix} \sigma_{11}^2 & \sigma_{12}^2 & \cdots & \sigma_{1n}^2 \\ \sigma_{21}^2 & \sigma_{22}^2 & \cdots & \sigma_{21}^2 \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{n1}^2 & \sigma_{n2}^2 & \cdots & \sigma_{nn}^2 \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \end{pmatrix} = \begin{pmatrix} \sigma_{o1}^2 \\ \sigma_{o2}^2 \\ \vdots \\ \sigma_{on}^2 \end{pmatrix} \tag{8}$$

Eqn. (8) can be expressed by Eqn. (9). It is referred ordinary kriging method.

$$\begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \end{pmatrix} = \begin{pmatrix} \sigma_{11}^2 & \sigma_{12}^2 & \cdots & \sigma_{1n}^2 \\ \sigma_{21}^2 & \sigma_{22}^2 & \cdots & \sigma_{21}^2 \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{n1}^2 & \sigma_{n2}^2 & \cdots & \sigma_{nn}^2 \end{pmatrix}^{-1} \begin{pmatrix} \sigma_{o1}^2 \\ \sigma_{o2}^2 \\ \vdots \\ \sigma_{on}^2 \end{pmatrix} \quad (9)$$

2.2.3 Application of Semi-variogram Model

The application of kriging interpolation method is very important to define the criterion for the spatial correlation of attribute data. The variance(σ_{11}, σ_{12}, $\cdots$ σ_{nn}) at unknown points and the co-variance(σ_{o1}, σ_{o2}, $\cdots$ σ_{on}) between known and unknown points must be defined to determine the weighting factor(λ_1, λ_2, λ_3, $\cdots$ λ_n) and they can be defined by Eqn. (10).

$$2\gamma(h) = E\ [(z(x) - z(x+h))^2] \quad (10)$$

Generally, semi-variogram means the half value of variogram as following Eqn. (11).

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} [z(x) - z(x+h)]^2 \quad (11)$$

The distribution of unknown points and co-variance between known and unknown points can be determined by drawing a semi-variogram of known points(Fig. 2). As shown in Fig. 2, actual variance is distributed very irregularly but, shows a good agreement with a predicted variance curve.

The semi-variogram models used to determine the fitted curves from the trend of distribution between

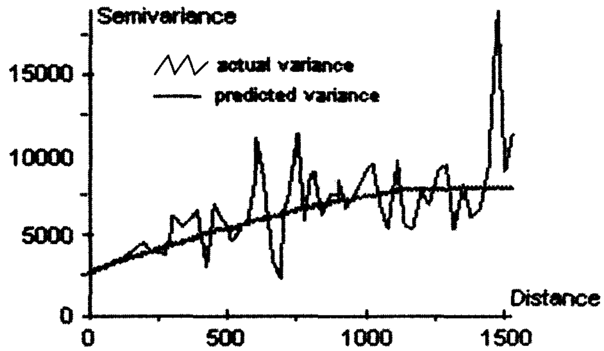
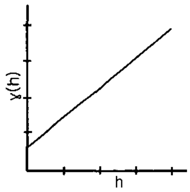
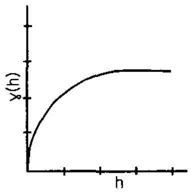
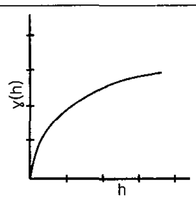
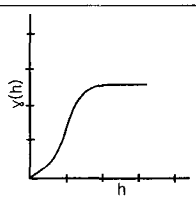


Fig. 2. Semi-variogram

Table 1. Semi-variogram Model

	Model Shape	Model Function
Linear		$\gamma(h) = C_o\ \text{Linear}_a(h) = C_0\frac{h}{a}$, for $0 \le h \le a$; C_0, for $h > a$
spherical		$\gamma(h) = C_o\ \text{Sph}_a(h) = C_0\left[1.5\left(\frac{h}{a}\right) - 0.5\left(\frac{h}{a}\right)^3\right]$, for $0 \le h \le a$; C_0, for $h > a$
exponential		$\gamma(h) = C_o\ \text{Exp}_a(h) = C_0\left[1 - \exp\left(-\frac{h}{a}\right)\right]$ for $h \ge 0$
Gaussian		$\gamma(h) = C_o\ \text{Gauss}_a(h) = C_0\left[1 - \exp\left(-\frac{h^2}{a^2}\right)\right]$ for $h \ge 0$

known points are shown in table 1.

2.3 Estimation of Long-term Settlements

2.3.1 Secondary Consolidation Behavior After the Removal of Preloading

In case of preloading, the reduction in effective stress occurs and the ground swells after the removal of preloading. The swelling is induced by the spreading of negative porewater pressure and increases significantly with time. The behaviors of soils, when removing pre-loading, can be divided into the primary swelling behavior and the secondary swelling behavior such as consolidation process that takes place by compression as shown in Fig. 3. Here, the ending time of primary swelling can be estimated by Terzaghi's swelling theory and is known to be 60% degree of average swelling from lab test. The behavior of ground after removal of preloading is shown in Fig. 3.

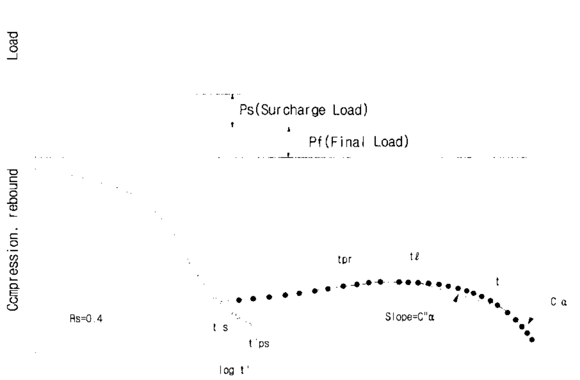


Fig. 3. Principle of t_l, C'_α, C''_α(Mesri et al, 1991)

where, t_l = the time required to complete secondary swelling

t_{pr} = the time required to complete primary swelling

As shown in Fig. 3, C'_α is the tangential secondary compression index which means the tangent of time-settlements curve at arbitrary time, and has a small value at the early stage but increases slowly with time. However, the mathematical integration process is needed to determine the settlements by using C'_α-C_c relationship at arbitrary time but this process is a tedious one because of complicated calculation process. It is more convenient to use the secant secondary compression index(C''_α) which is the slope of the line connecting the point of time when secondary swelling is over(t_l) with the point of time(t) we want to estimate secondary consolidation settlements by using following Eqn. (12).

$$S = \frac{C''_\alpha}{1+e_p} L_p \log \frac{t}{t_l} \tag{12}$$

where, S = secondary consolidation settlements

e_p = void ratio at the ending time of the primary consolidation

L_p = soft ground thickness at the time of the primary consolidation

However, it is more accurate to use Eqn. (13) that used the C''_α/C_α relationship, because C''_α is closely related to t_l as well as the effective overburden pressure ratio(R'_s). This is illustrated by expansion theory.

$$S = \frac{C''_\alpha/C_\alpha \times C_\alpha/C_c \times C_c}{1+e_p} H_p \log \frac{t}{t_l} \tag{13}$$

2.3.2 Expansion Theory

The time-swelling relationship is easily verified by Terzaghi's traditional consolidation theory. Terzaghi regarded the time dependent swelling process as the inverse process of consolidation and verified it by laboratory tests(Mesri et al., 1978). His theory can be represented as Eqn. (14) and it is the basic constitutive equation of swelling theory.

$$\left(\frac{\partial e}{\partial t}\right)_p = \frac{(1+e_0)^2}{\gamma_w} \frac{\partial}{\partial z}\left(\frac{k}{1+e} \frac{\partial \bar{u}}{\partial z}\right) \tag{14}$$

Eqn. (14) can be transformed into Eqn. (17) by using dimensionless coefficients in Eqn. (15) and Eqn. (16). T_s can be used as T_v which is used in Terzaghi's consoli-dation theory.

$$\mu = \frac{\bar{u}}{\Delta p} \tag{15}$$

$$\lambda = \frac{z}{H_0} \tag{16}$$

$$T_s = \frac{k_0(1+e_0)^2 \sigma_0'}{0.434\ \gamma_w C_c} \frac{t}{H_0^2} \tag{17}$$

The degree of consolidation and average degree of consolidation representing the progressing state of consolidation in Terzaghi's consolidation theory can be expressed in forms of the degree of swelling and average degree of swelling representing the progressing state of swelling by Eqn. (18) (19).

$$\beta = \frac{e - e_0}{e_p - e_0} \tag{18}$$

$$\overline{\beta} = \frac{1}{H}\int_0^H \beta \, dz \tag{19}$$

The observed distribution of average degree of swelling($\overline{\beta}$) is compared with the theoretical distribution as shown in Fig. 4. T_s- $\overline{\beta}$ relationship obtained by using Terzaghi's swelling theory is very similar to that observed as shown in Fig. 4.

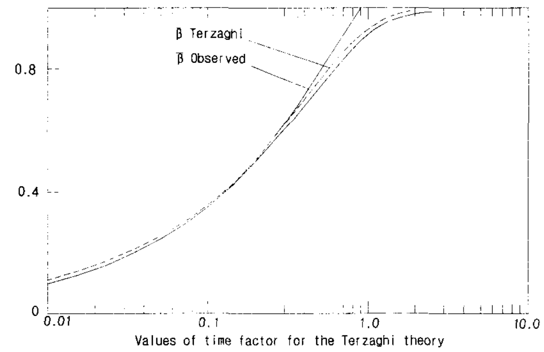


Fig. 4. T_s- $\overline{\beta}$ relationship (Mesri & Rokhsar, 1974)

As shown in Fig. 5, t_l/t_{pr} increases with R'_s.

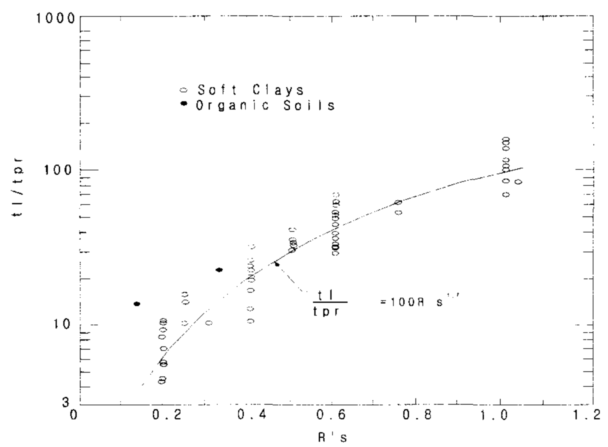


Fig. 5. The relationship of the R'_s, t_{pr} and t_l (Mesri et al. 1997)

where, $R_s' = \frac{\sigma'_{vf} + \Delta\sigma_{vs} - \sigma'_{vf}}{\sigma'_{vf}} = \frac{\sigma_{vs}}{\sigma'_{vf}} - 1$ (20)

σ'_{vf} : effective stress after removal of preloading

$\sigma_{vs} = \sigma'_{vf} + \Delta\sigma_{vs}$

$\Delta\sigma_{vs}$: preloading load

In Fig. 3, it is noticed that the ratio of tl and tpr increases with an increase in the effective overburden stress(R'_s). When preloading is removed immediately, coefficient of permeability(k_0) is easily determined through the relationship between permeability index(C_k) and Δe as following Eqn. (21).

$$C_k = \frac{\Delta e}{\log \Delta k} \tag{21}$$

Generally, C_k is in the range of 0.02 to 2 and Tavenas et al.(1983) suggested Eqn. (22) by performing laboratory test.

$$C_k = 0.5\, e_0 \tag{22}$$

2.3.3 Estimation of the Secondary Consolidation Settlements

The secondary consolidation settlements after removal of preloading can be determined by substituting C''_α/C_α, C_α/C_c, and tl into Eqn. (13). In case of C_α/C_c, C_c can be determined by using the results of consolidation test of soil samples which are taken in-situ and C_α can be determined by applying inverse analysis method to the measured data of long-term settlements, t_{pr} can be determined by using Eqn. (17) after the acquisition of T_{60} from Fig. 4. Then, the time(t_l) when secondary consolidation begins can be obtained from Fig. 5. Also, C''_α/C_α can be determined by substituting t_l and t into Fig. 6.

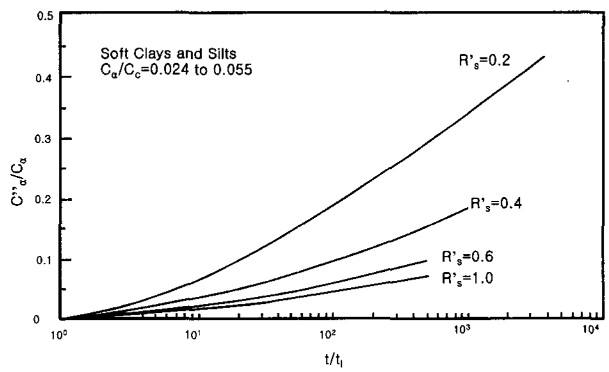


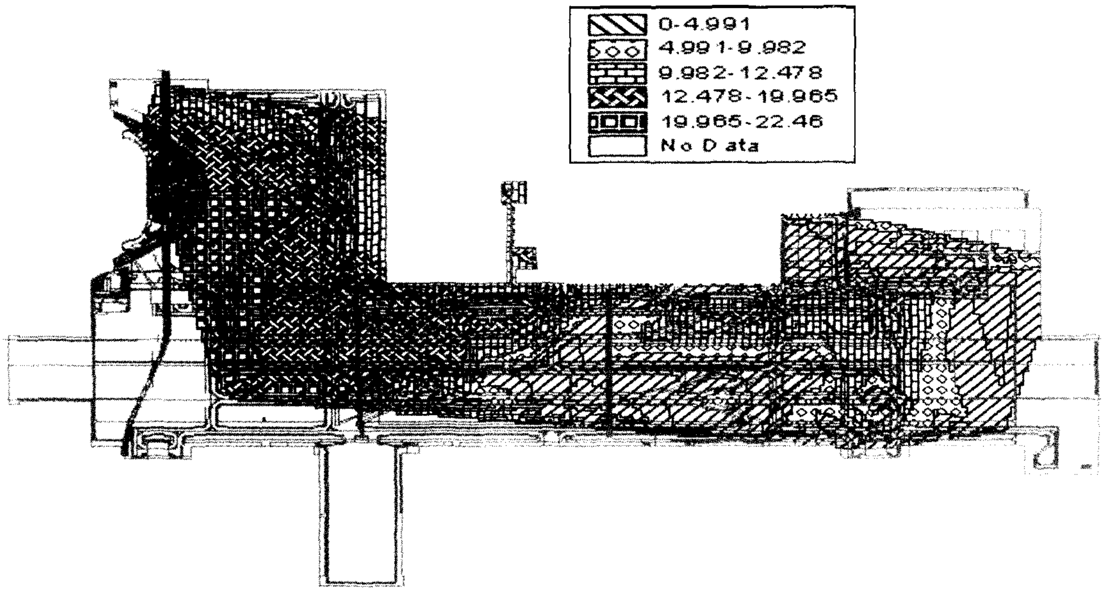
Fig. 6. C"α/Cα in Soft clays and silts (Mesri et al. 1997)

3. Analysis and Discussion

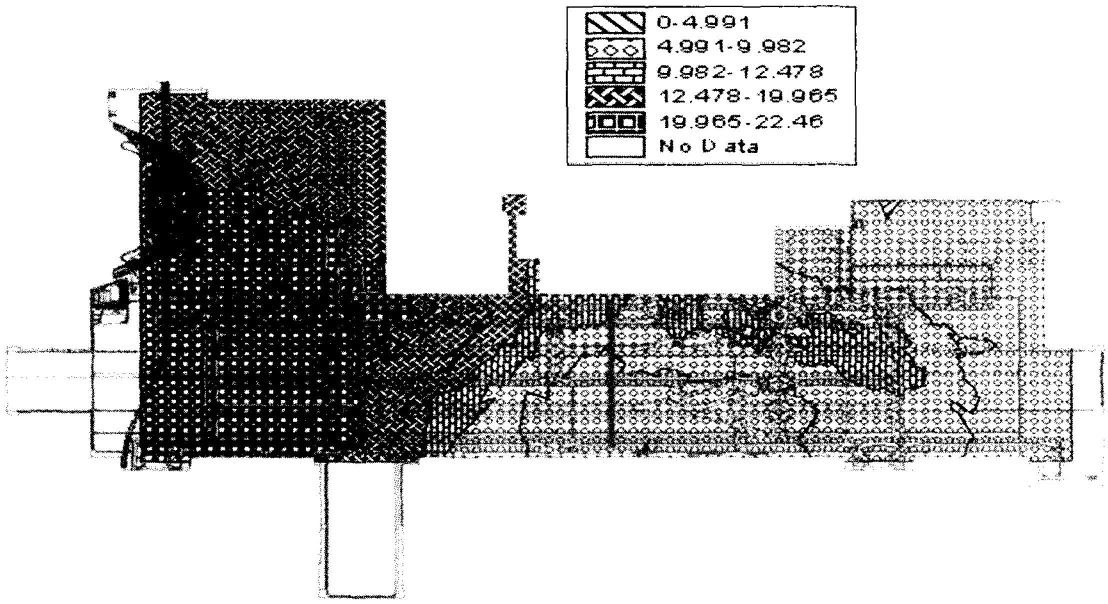
3.1 Long-term Settlements

3.1.1 Estimating Methods and Results

The data used in this study are obtained from the subsurface investigation data of the In-Cheon international air-port. The analysis is performed by inputting several data(ex. soft ground thickness, initial void ratio, coefficient of permeability and groundsurface level et al). And then, we apply the inverse distance weighted interpolation method and kriging interpolation method to cartographic data. Also, the long-term settlements were estimated by using the method presented in section 2.3 and the GIS technique which was proposed by Kim et al.(2002). The soft ground thickness and the long-term settlements after 30 years later are shown in Figs. 7 and 8. It is revealed that the primary consolidation is over because the average degree of consolidation was up to 95% when removing the preloading(Kim et al., 2002).

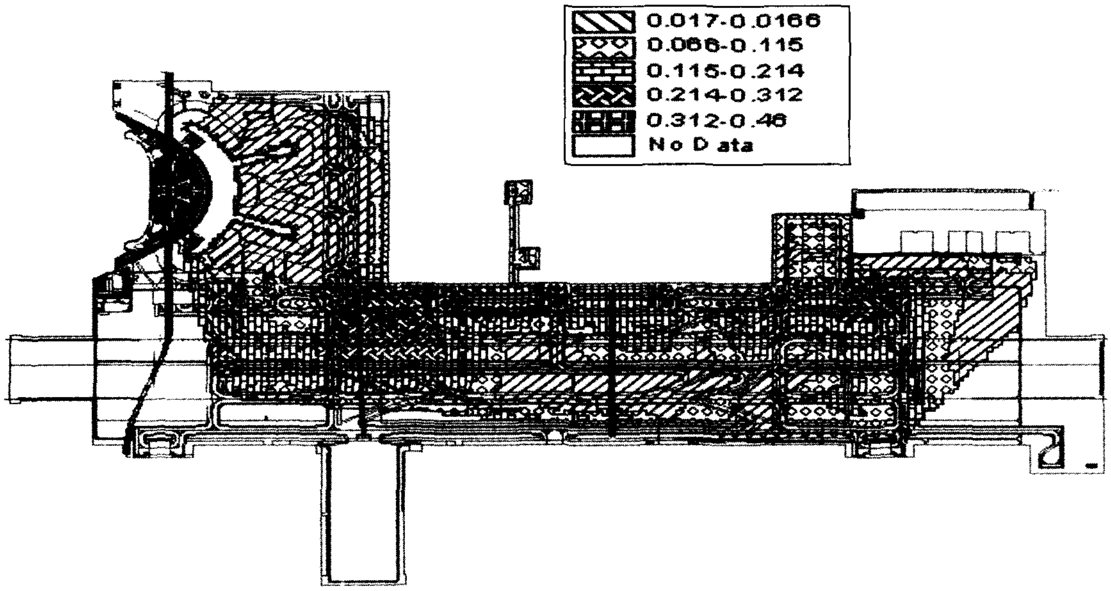


(a) Inverse distance weighted Interpolation method

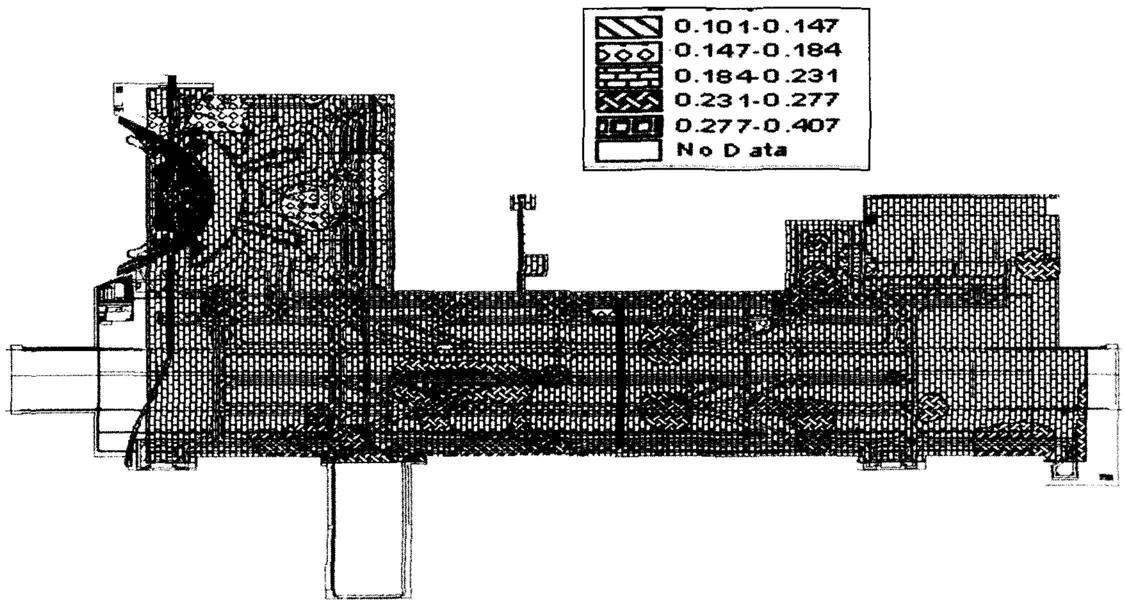


(b) Kriging Interpolation method

Fig. 7. Distribution of the thickness of soft ground



(a) Inverse distance weighted interpolation method



(b) Kriging interpolation method

Fig. 8. Long-term settlements after 30 years later

The distribution of results interpolated by kriging interpolation method is more smooth than that by inverse distance weighted interpolation method. In kriging method, the 'Nugget Variance' was considered. Here, the 'Nugget Variance' means that the variance does not converge on zero in spite of the fact that the distance converges on zero and it is possible to reflect such a feature in kriging method.

3.1.2 Application of Semi-variogram Model

In this study, the correlation between the semi-variogram of ground properties and semi-variogram models was analyzed to investigate the parametric behavior of *in-situ* data. The semi-variogram of initial void ratio was compared with various models listed in Table 1. The result is shown in Fig. 9.

Fig. 9 shows that the semi-variogram of initial void ratio is similar to spherical model. Especially, it shows a close similarity within range of 400. The correlation

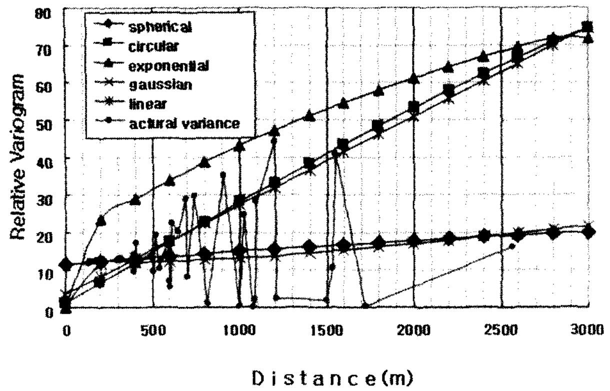


Fig. 9. Comparison of various semi-variogram models

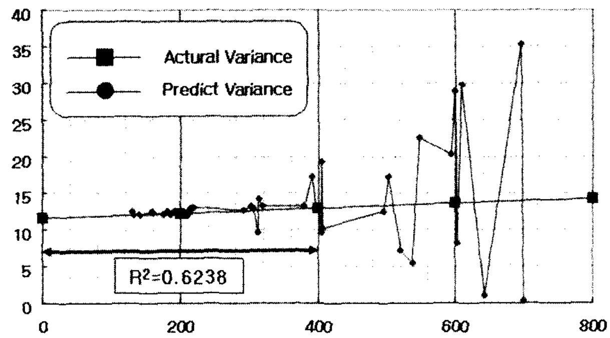


Fig. 10. Spatial correlation within 400m

within range of 400 is analyzed as shown in Fig. 10.

Consequently, correlation coefficient for the range of 400m is estimated to be about 0.6238, therefore, the use of spherical model is more adequate to this situation.

3.2 Determination of Additional Sampling Positions

3.2.1 Probability Map

In the problems of settlements in soft ground, there is the allowable value to discriminate the serviceability of upper structure. Probability map is one which is illustrated by the probability of satisfaction about the arbitrary boundary value. First, the secondary consolidation settlements are calculated by using the results of subsurface investigation data including point data. And then, the results are compared with boundary value and assigned as an indicator value of 1 or 0, depending on whether it is higher or lower than the boundary value (Eqn. (23)). The resulting indicator values are then kriged, and expected values generated are considered to be probability values directly(Fig. (11)). The settlements of In-cheon international airport was estimated to be smaller than the permissible criterion of 5cm. In this study, it is assumed that the boundary value b is 0.05 in order to determine probability map more efficiently for study.

$$\begin{aligned} &\text{if} \quad x_i < b \quad \text{set} \quad x_i = 1 \\ &\text{if} \quad x_i \geq b \quad \text{set} \quad x_i = 0 \end{aligned} \qquad (23)$$

where, b = boundary value

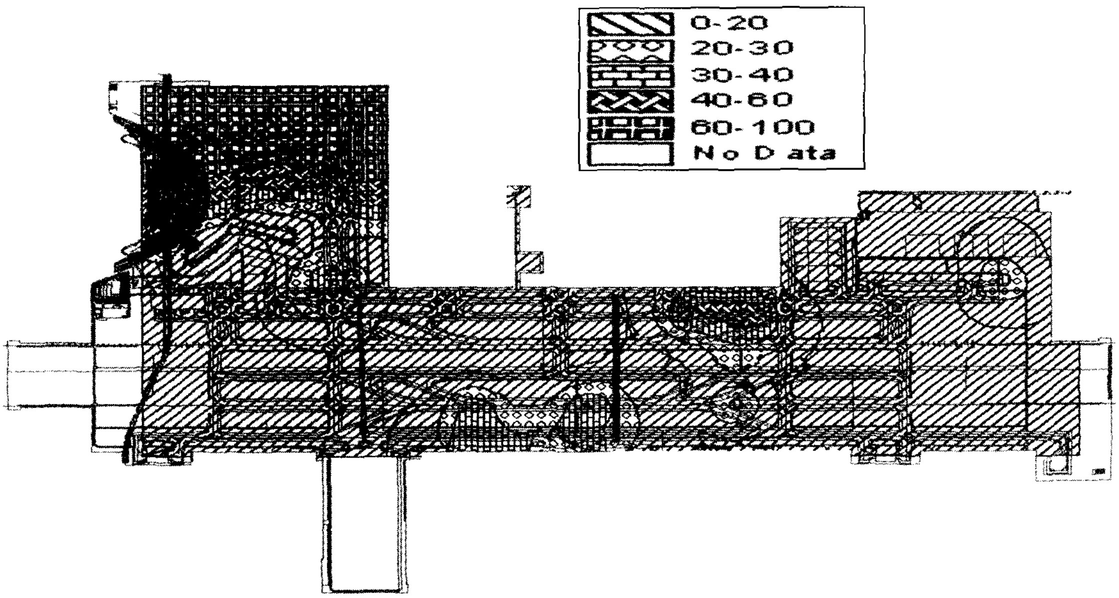


Fig. 11. Probability map (b=0.05)

3.2.2 Thoroughness

Values of thoroughness are calculated by applying a transform function to kriged probability values to yield an index that allows for graphical representation of the zone or zones where the variable of interest crosses a specific threshold. The thoroughness is intended to complement traditional data analysis procedure by allowing enhanced visual analysis of the data. The thoroughness function used in ARC-Info is related to the probability of the outcome (Eqn. (24)).

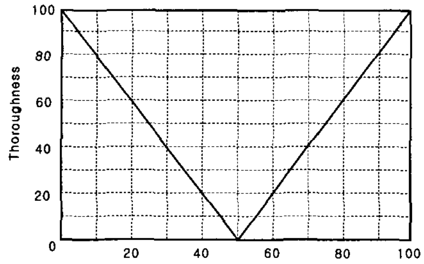


Fig. 12. Thoroughness function (Parson and Frost 2000)

As illustrated in Fig. 12, if the probability of the occurrence of an event is lower or high, the thoroughness

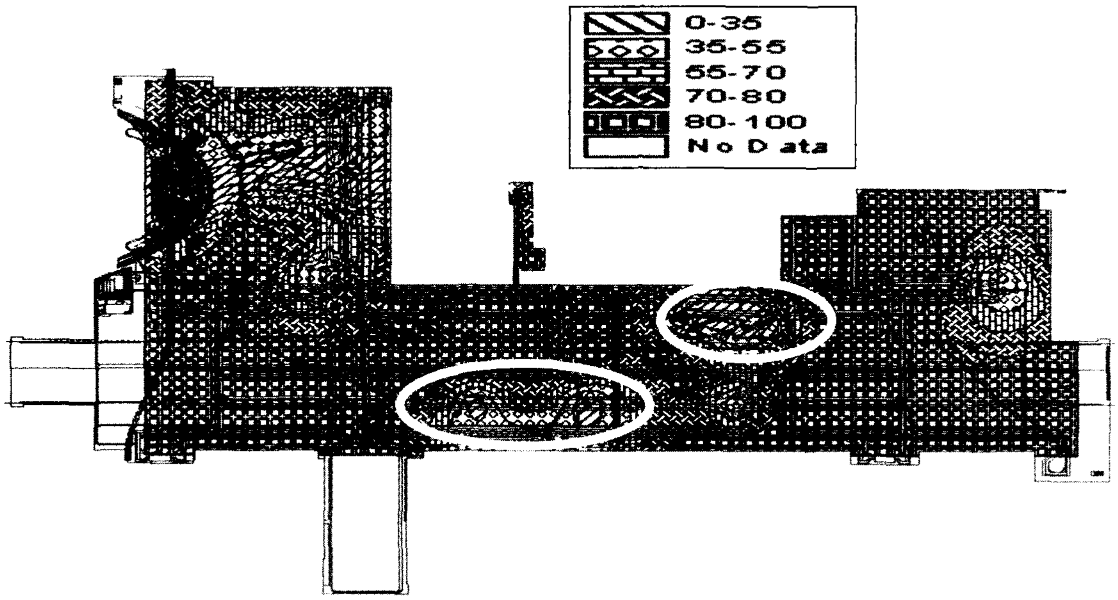


Fig. 13. Thoroughness map before additional sampling

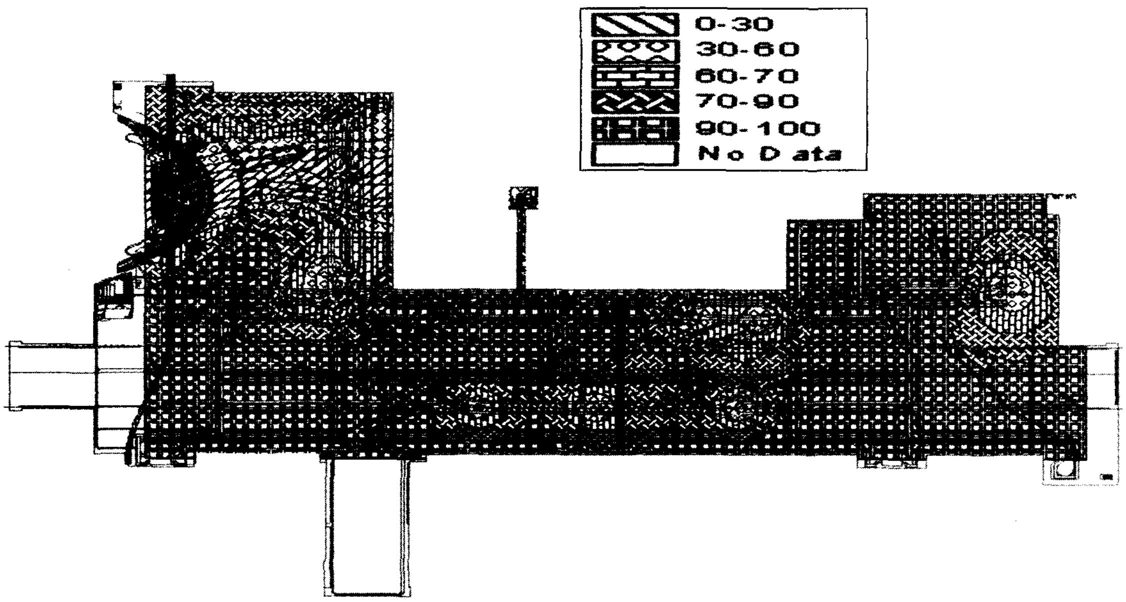


Fig. 14. Thoroughness map after additional sampling

will be high. Conversely, the low thoroughness values reflect intermediate probabilities that an event will occur.

$$T = | 100 - 2P | \quad (24)$$

where, T : thoroughness

P : probability of a given outcome(%)

Thoroughness map of In-cheon international airport is shown in Fig. 13. And the change of the thoroughness by additional sampling is shown in Fig.14. To verify the increase of thoroughness, the imaginary six sampling positions were assumed and probability and thoroughness were calculated again. Comparing Fig. 13 with Fig. 14, the increase of thoroughness is apparently represented.

4. Conclusion

(1) The kriging interpolation method and the inverse distance weighting interpolation method were applied to the GIS to determine the ground properties in large reclamation site.

(2) The results of kriging interpolation method are different from those of the inverse distance interpolation method in the aspect of its distribution, and kriging interpolation method is more smooth in its distribution.

(3) The analysis by using the semi-variogram models was performed and it was revealed that the spherical model is the most adequate for the estimation of the several data in this study.

(4) The long-term settlements of In-Cheon international airport were estimated by applying secant secondary compression index, and probability map was illustrated by applying an arbitrary boundary value. Also, the thoroughness map was determined by using thoroughness function.

(5) The method to determine additional sampling position is proposed and confirmed the increase of thoroughness according to additional sampling.

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