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Influence of estimation method of compression index on spatial distribution of consolidation settlement in Songdo New City

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ABSTRACT

This paper describes the influence of the method that estimates the compression index (C_c) on the spatial distribution of consolidation settlement (s_c) for Songdo New City. The spatial distribution of consolidation settlement can be evaluated by using the spatial distribution (Case 1), mean value (Case 2), and probability distribution (Case 3) of soil properties. For Case 1, ordinary cokriging was adopted to estimate the spatial distribution of C_c as it provides more reliable estimates than ordinary kriging. It is observed that the spatial distribution of s_c for Case 1 has significantly shorter scale variability than that for Case 2 because the short scale variability of the spatial distribution of C_c and void ratio (e_o) affect the spatial distribution of s_c for Case 1. It is also shown that the ratio of the area of $s_c > 100$ cm (design criterion) to the total area for Case 1 (7.7 %) is larger than that for Case 2 (0.5 %) because the ordinary cokriging estimate of C_c is larger than the mean value of C_c in some regions. The probabilistic analysis (Case 3) shows that the ratio of the area of $P(s_c > 100 \text{ cm}) >$ probabilistic criterion (α) to the total area increases as the coefficient of variation (COV) of $C_c/(1+e_0)$ increases and α decreases. For Songdo New City, the area ratio for the probabilistic design criterion (α) of 0.30–0.45 is found to be in the range of 2.9–19.4 %.

1. Introduction

To evaluate the spatial distribution of the consolidation settlement (s_c) in a large coastal reclamation area, geotechnical engineers need to correctly access the spatial characteristics of soil properties. However, it is difficult to evaluate the exact spatial characteristics of soil properties because the amount of geotechnical investigation data is insufficient in most cases. When there is a limited amount of geotechnical information, the spatial distribution of s_c can be evaluated by using one of three methods according to the spatial characteristics of soil properties: (1) a single deterministic value such as the mean value, which is used in the most geotechnical engineering design; (2) multiple deterministic values which differ at locations in the study area, where the spatial distribution of these values are estimated by an interpolation method such as kriging and inverse distance weighting methods (Soulie et al., 1990; Pan et al., 1993; Chiasson et al., 1995; Jaksa et al., 1997); and (3) a random variable, which is described by a probability distribution.

Geotechnical design methods commonly take two approaches: deterministic and probabilistic. In a deterministic approach, s_c is evaluated using the mean values or spatial distributions of soil properties. In a probabilistic approach, probability distributions of soil properties are used to evaluate the uncertainty of s_c because soil properties generally show inherent variability (Phoon and Kulhawy, 1999; Duncan, 2000; Baecher and Christian, 2003). The deterministic approach is generally used in most geotechnical problems while the probabilistic approach has been frequently used to evaluate the uncertainty of consolidation parameters (Corotis et al., 1975; Freeze, 1977; Athanasiou-Grivas and Harr, 1978; Chang, 1985; Hong and Shang, 1998; Zhou et al., 1999; Huang et al., 2010).

The objective of this study is to assess the influence of the spatial characteristics of the compression index (C_c) on the spatial distribution of s_c for Songdo New City. Three cases are used to evaluate the spatial distribution of s_c. Cases 1, 2 and 3 use the spatial distribution of C_c, the mean value of C_c, and the probability density function (PDF) of C_c, respectively. To obtain a reliable estimation of the spatial distribution of C_c for Case 1, ordinary cokriging and ordinary kriging are used. Cases 1 and 2 use the deterministic approach, whereas Case 3 uses the probabilistic approach because s_c is evaluated by considering the uncertainty of C_c. The spatial distributions of s_c evaluated by different approaches are compared in order to study the characteristics and dissimilarity of their distributions.

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2. Geostatistical approach

In a geostatistical approach, a spatial pattern is usually expressed by an experimental semivariogram $\gamma(\mathbf{h})$ which is computed as half of the average squared difference between paired data values separated by a vector $\mathbf{h}$:

$$\gamma(\mathbf{h}) = \frac{1}{2N(\mathbf{h})}\sum_{\alpha=1}^{N(\mathbf{h})}[z(\mathbf{u}_\alpha)-z(\mathbf{u}_\alpha+\mathbf{h})]^2 \tag{1}$$

in which $N(\mathbf{h})$ is the number of data pairs within a given class of distance and direction; $z(\mathbf{u}_\alpha)$ is the value at the start of the pair α at the location $\mathbf{u}_\alpha$; and $z(\mathbf{u}_\alpha+\mathbf{h})$ is the corresponding end value at a lag of $\mathbf{h}$ from the location $\mathbf{u}_\alpha$ (Journel and Huijbregts, 1978). In most situations, several soil properties are measured on each soil sample, and geostatistics is increasingly used to treat such multivariate soil information (Wackernagel, 1995; Goovaerts, 1998). A measure of the joint variability of two continuous attributes z and y is the experimental cross semivariogram which is needed in the cokriging system. The cross semivariogram is computed as follows:

$$\gamma_{ZY}(\mathbf{h}) = \frac{1}{2N(\mathbf{h})}\sum_{\alpha=1}^{N(\mathbf{h})}[z(\mathbf{u}_\alpha)-z(\mathbf{u}_\alpha+\mathbf{h})]\cdot[y(\mathbf{u}_\alpha)-y(\mathbf{u}_\alpha+\mathbf{h})] \tag{2}$$

Experimental values for a finite number of separation vectors are obtained using a semivariogram. A theoretical semivariogram model should be fitted to these experimental values to obtain the semivariogram values for any possible separation vectors used in the kriging system. The spherical, exponential, and Gaussian models are frequently used as basic models. The semivariogram stops increasing and fluctuates around a specific value at a specific separation distance. The specific value and separation distance are called the sill and range, respectively. The range denotes the distance beyond which data values appear independent (Isaaks and Srivastava, 1989; Goovaerts, 1997).

In many cases, the geostatistical approach is used to estimate the spatial distribution of geo-layers and soil properties at unsampled locations (Christakos, 1985; Soulie et al., 1990; Chiasson et al., 1995; Jaksa et al., 1997; Parsons and Frost, 2002; Baise et al., 2006; Mendes and Lorandi, 2008; Marache et al., 2009). Among kriging algorithms, ordinary kriging and ordinary cokriging are frequently used in geotechnical problems. Ordinary kriging estimates the value of a continuous attribute z at any unsampled location $\mathbf{u}$ using the neighboring z-data $\{z(\mathbf{u}_\alpha), \alpha=1,\ldots,n\}$ available over the study area. Ordinary kriging estimates this value as a linear combination of the neighboring z-data:

$$z^*_{OK}(\mathbf{u}) = \sum_{\alpha=1}^{n(\mathbf{u})}\lambda_\alpha^{OK}(\mathbf{u})z(\mathbf{u}_\alpha) \tag{3}$$

in which z^*_{OK} is the ordinary kriging estimator; λ_α^{OK} is the weight assigned to $z(\mathbf{u}_\alpha)$; and $n(\mathbf{u})$ is the number of data involved in the estimation. The $n(\mathbf{u})$ weights λ_α^{OK} are determined to minimize the error variance $\sigma_E^2(\mathbf{u})=\mathrm{Var}\{Z^*(\mathbf{u})\text{-}Z(\mathbf{u})\}$ under the constraint of unbiasedness of the estimator. This requires solving of the following ordinary kriging system which includes the $(n(\mathbf{u})+1)$ linear equations with $(n(\mathbf{u})+1)$ unknowns, the $n(\mathbf{u})$ weights λ_β^{OK} and the Lagrange parameter μ_{OK} that accounts for the constraint on weights (Journel and Huijbregts, 1978; Goovaerts, 1997):

$$\begin{cases}\displaystyle\sum_{\beta=1}^{n(\mathbf{u})}\lambda_\beta^{OK}(\mathbf{u})\gamma\left(\mathbf{u}_\alpha-\mathbf{u}_\beta\right)-\mu_{OK}(\mathbf{u})=\gamma(\mathbf{u}_\alpha-\mathbf{u}) \\ \qquad\qquad\qquad\qquad \alpha=1,\ldots,n(\mathbf{u}) \\ \displaystyle\sum_{\beta=1}^{n(\mathbf{u})}\lambda_\beta^{OK}(\mathbf{u})=1\end{cases} \tag{4}$$

When observations are poorly correlated in a study area, the prediction of the primary attribute of interest is generally improved by considering secondary correlated continuous attributes. In the case of a single secondary attribute Y, the ordinary cokriging estimate z^*_{OCK} is determined as a linear combination of both neighboring primary and secondary data as follows:

$$z^*_{OCK}(\mathbf{u}) = \sum_{\alpha=1}^{n(\mathbf{u})}\lambda_\alpha^{OCK}(\mathbf{u})z(\mathbf{u}_\alpha)+\sum_{\alpha'=1}^{n'(\mathbf{u})}\nu_{\alpha'}^{OCK}(\mathbf{u})y(\mathbf{u}_{\alpha'}) \tag{5}$$

in which λ_α^{OCK} and $\nu_{\alpha'}^{OCK}$ are the weights applied to the $n(\mathbf{u})$ z-samples and $n'(\mathbf{u})$ y-samples, respectively. The objective of ordinary cokriging is to minimize the error variance under the unbiasedness constraint, which yields a system of $n(\mathbf{u})+n'(\mathbf{u})+2$ linear equations (Journel and Huijbregts, 1978; Goovaerts, 1997, 1998):

$$\begin{cases}\displaystyle\sum_{\beta=1}^{n(\mathbf{u})}\lambda_\beta^{OCK}(\mathbf{u})\gamma_{ZZ}\left(\mathbf{u}_\alpha-\mathbf{u}_\beta\right)+\sum_{\beta'=1}^{n'(\mathbf{u})}\nu_{\beta'}^{OCK}(\mathbf{u})\gamma_{ZY}\left(\mathbf{u}_\alpha-\mathbf{u}_{\beta'}\right) \\ \qquad -\mu_Z^{OCK}(\mathbf{u})=\gamma_{ZZ}(\mathbf{u}_\alpha-\mathbf{u}) \quad \alpha=1,\ldots,n(\mathbf{u}) \\ \displaystyle\sum_{\beta=1}^{n(\mathbf{u})}\lambda_\beta^{OCK}(\mathbf{u})\gamma_{YZ}\left(\mathbf{u}_{\alpha'}-\mathbf{u}_\beta\right)+\sum_{\beta'=1}^{n'(\mathbf{u})}\nu_{\beta'}^{OCK}(\mathbf{u})\gamma_{YY}\left(\mathbf{u}_{\alpha'}-\mathbf{u}_{\beta'}\right) \\ \qquad -\mu_Y^{OCK}(\mathbf{u})=\gamma_{YZ}(\mathbf{u}_{\alpha'}-\mathbf{u}) \quad \alpha'=1,\ldots,n'(\mathbf{u}) \\ \displaystyle\sum_{\beta=1}^{n(\mathbf{u})}\lambda_\beta^{OCK}(\mathbf{u})=1 \\ \displaystyle\sum_{\beta'=1}^{n'(u)}\nu_{\beta'}^{OCK}(\mathbf{u})=0\end{cases} \tag{6}$$

in which μ_Z^{OCK} and μ_Y^{OCK} are Lagrange parameters to account for the constraints on primary and secondary data weights, respectively. Also input information comprises the values of direct (γ_{ZZ} and γ_{YY}) and cross semivariograms (γ_{ZY} or γ_{YZ}) for different lags.

The reliability of kriging estimates is evaluated by comparing the estimated values and known values at each location. This method is called the cross validation. The mean absolute error (MAE) and mean squared error (MSE) measure the accuracy of the kriging estimates:

$$MAE = \frac{1}{n}\sum_{\alpha=1}^{n(\mathbf{u})}[|z(\mathbf{u}_\alpha)-z^*(\mathbf{u}_\alpha)|] \tag{7}$$

$$MSE = \frac{1}{n}\sum_{\alpha=1}^{n(\mathbf{u})}[z(\mathbf{u}_\alpha)-z^*(\mathbf{u}_\alpha)]^2 \tag{8}$$

in which $z^*(\mathbf{u}_\alpha)$ is an estimate of value $z(\mathbf{u}_\alpha)$ at location $\mathbf{u}_\alpha$. The small MAE and MSE values represent the more accurate prediction, on a point-by-point basis.

3. Study site and available data

Songdo New City is located in the southwest of Incheon, South Korea, with an area of 53.4 km^2. The study site was built on an artificial island, which was reclaimed with silty sand dredged from the west coast of Incheon. The study site at Songdo New City is composed of seven sections according to the land-use plan. Among these sections, Sections 1 and 3 are selected as the study area (Figure 1).

The data obtained from the geotechnical investigation for Sections 1 and 3 are used to determine the statistics of soil properties and to estimate the spatial distributions of geo-layers in Songdo New City. Fig. 2 shows the locations where the data of the soil properties were obtained and the borehole locations where the stratifications were obtained. The subsoil of the study area consists of eight units as shown in Fig. 3: a reclaimed sandfill ($N_{SPT}<15$), upper soft silty clay ($N_{SPT}<6$), upper silty sand ($N_{SPT}>30$), lower medium and stiff silty clay ($N_{SPT}>10$),