Geostatistics-based Spatial Quality Control of Vacuum Preloading in Dredged Materials

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ABSTRACT: Degree of consolidation and remained end-of-primary (EOP) settlement are the two major parameters in quality control of vacuum preloading in soft clays. This study applied geostatistics in predicting spatial distribution of these two indices over a large vacuum preloading site to evaluate the quality of soil improvement. One hundred and forty-four (144) ground settlement markers have been installed over the site, and observations have been taken for more than four months. The Asaoka method was utilized to estimate the ultimate total settlement, and further to interpret the degree of consolidation and remained EOP settlement at each monitoring point. Spatial maps of the two indices at three different periods were then achieved using geostatistics with a full evaluation of soil spatial variability and spatial interpolation on the observations. These maps can provide reliable information to guide the schedule of vacuum preloading for the investigated site.

Keywords: vacuum preloading; primary consolidation; geostatistics; quality control

1. Introduction

The vacuum preloading instantly applies a nominal vacuum load over an engineering site to improve the capacity and reduce the post-construction settlement of large-area soft clays. Sand drains and prefabricated vertical drains are usually incorporated in the vacuum preloading technique to distribute the vacuum pressure and discharge pore water [1]. Compared with the fill surcharge method, the vacuum preloading method reduces the risk of stability and facilitates the consolidation rate at a lower cost [1]. Moreover, the vacuum preloading can be combined with the fill surcharge when a high surcharge load is desirable. Due to these advantages, the vacuum preloading method has been widely used in a number of countries [1, 2].

The vacuum preloading has its particular advantage in soil improvement of land reclamation projects, where marine soft clay slurry dredged from seabed is usually used as fill material. To control the quality of ground improvement, the degree of consolidation and remained end-of-primary (EOP) settlement are consecutively monitored during the preloading. For large-scale land reclamation, these two quality control indices are generally spatially variable due to the heterogeneity nature of the dredged materials. In other words, the consolidation rates at different spatial locations may vary significantly. It is therefore necessary to employ some spatial interpolation methods to obtain spatial maps of the two quality control indices to guide the engineering practice.

The geostatistics has gained increasing interest in geotechnical engineering to obtain the regional maps of soil parameters based on limited observations. The main advantage of the geostatistics is that the spatial variability characteristics of a soil parameter can be quantified and further considered in the spatial interpolation. Successful applications of the geostatistics in geotechnical issues include soil profiling [3, 4], pile foundation [5, 6] and liquefaction analysis [7].

This study investigates the settlements of a reclaimed site in the Pearl River estuary in Guangzhou, China. The site was treated with the vacuum preloading technique. A large number of ground settlement markers were instrumented over the site to obtain the settlements at different locations and treatment periods. Significant differential settlements were observed at the site, indicating the strong heterogeneity of the subsoils. The geostatistics is thus applied to delineate the spatial distribution of degree of consolidation and remained EOP settlement to guide the ground improvement schedule.

2. Site conditions and instrumentation

The testing site, located at the eastern Guangzhou in the Pearl River estuary, China, was reclaimed to serve as a large harbor for commercial use. The site is approximately 480 m by 800 m in size and the whole area of the site was filled with dredged material that mainly composed of alluvium silty sands and marine soft clays and slurries. The general soil profile within 30 m beneath the ground surface at the site involves:

- a coarse sand with a thickness of 0.5 – 4.1 m;
- a soft clay (slurry) with a thickness of 4.8 – 22.2 m;
- a mud unit with a thickness of 0.4 – 5.4 m; and
- a soft clay with a thickness of 0.5 – 5.1 m.

Table 1 summarizes the mean values of main physical properties of the soils. Most soils at the site are clayey deposits with high compressibility, low strength and low permeability.

Table 1. Mean values of main physical properties of subsoils

Soil units	w (%)	ρ (g/cm^3)	e	w_L (%)	I_P
Coarse sand	19.3	2.06	0.564	24.0	10.1
Soft clay	114.0	1.40	3.066	75.5	37.2
Mud	93.1	1.47	2.509	62.0	29.8
Soft clay	45.4	1.74	1.258	42.0	18.7

To reduce the settlement after construction, ground improvement techniques have to be applied. The vacuum preloading combined with prefabricated vertical drains method was adopted due to its capability of improving large-area soft soils at a relatively low cost. During the vacuum preloading, a nominal vacuum load of 85 kPa was maintained instantly over the site. The lateral displacements and excess pore water pressure were monitored to examine the stability during the preloading. The criteria for terminating the vacuum preloading include that the primary degree of consolidation is larger than 90% and the remained end-of-primary (EOP) settlement is less than 25 cm.

Since the site is too large, the vacuum loads were not applied simultaneously over the whole area. The testing site was divided into twelve (12) blocks (denoted as T1, T2, …, T12) as shown in Fig. 1. The first set of loads was applied on the T1 and T5 blocks on Aug 4, 2017. After one month, the second set of loads was applied on the T2, T8, T9 and T12 blocks at mid-September, 2017. One month later, the third set of loads was applied on the T3, T4 and T6 blocks at mid-October, 2017. The last set of loads was finally applied on the T7, T10 and T11 blocks one month after the third set of loads was applied. Each set of loads was applied for more than four months. Vertical drains with lengths larger than 25 m were installed with a lateral separating distance of 1 m over the site. These drains all penetrated through the clay units into the underlying sandy soils.

To monitor the quality of the ground improvement, twelve (12) ground settlement markers were instrumented in each block to report the total settlements at different spatial coordinates. The layout of the markers is also shown in Fig. 1. The total number of ground settlement markers is thus one hundred and forty-four (144). The separating distance between two adjacent ground settlement markers is in the range of 37 to 66 m. Such a large number of observations and a small separating distance ensure that the potential differential settlements inside a block and between different blocks can be simultaneously captured. At the initial state of preloading, the monitoring was conducted every day. After loading was applied for one month, the settlement tended to reach a relatively steady state and thus the monitoring was conducted every two days.

3. Results of settlement monitoring

The monitoring was consecutively conducted during the preloading for each ground settlement marker. A representative profile of the preloading and settlement observations is given in Fig. 2. This profile corresponds to the first block (T1), and six sets of settlement observations are presented in Fig. 2. Before applying the preloading, some settlements are observed due to the spreading of sand mat and vertical drains. After applying the preloading on Aug 4, 2017, the ground settlement started to increase rapidly. When the loading had been applied for approximately three months (on Nov 1, 2017), some settlement observations (T1-4 and T1-6) reached a relatively steady state, whereas other observations still showed notable increment.

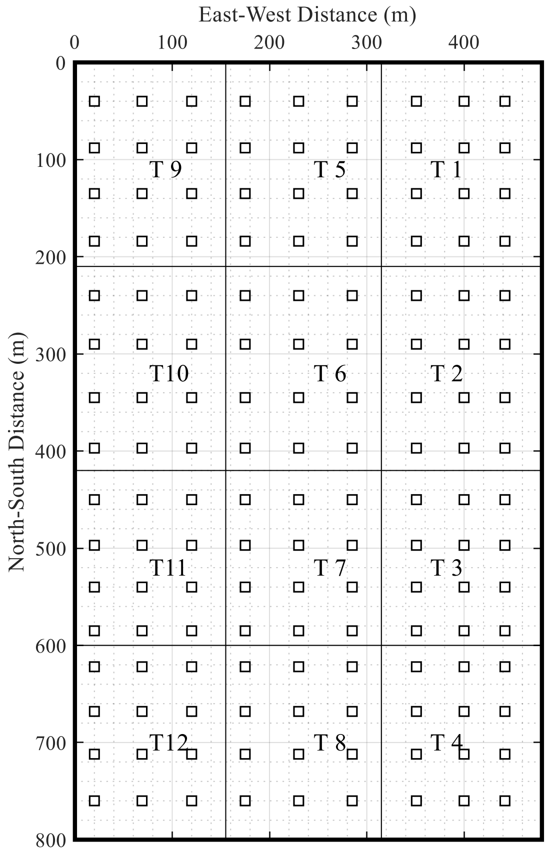

Figure 1. Layout of ground monitoring markers

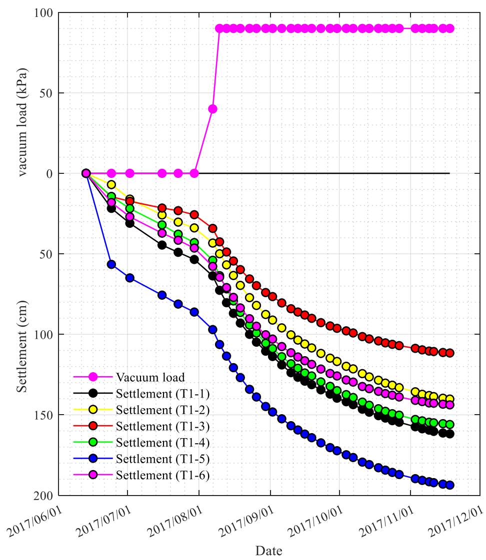

Figure 2. Settlement observations at T1 block

It is interesting to note that although the six ground settlement markers are located within the same block, their final settlement values are quite different. The highest settlement value of 193 cm is observed at the T1-5 marker. The lowest settlement value of 111 cm is observed at the T1-3 marker. This large differential settlement (82 cm) implies that the soil properties within the 160 m × 210 m block may be quite variable over space. This is not surprising, because the subsoils were formed by filling various dredged materials including clays, silts and sands. The heterogeneous nature of the dredged material makes the ground settlement complicated to predict, even though large amount of observations are available at the site. It is therefore useful to apply interpolation techniques to delineate the spatial distribution of degree of consolidation and remained EOP settlement, and finally to achieve a comprehensive understanding on the quality of vacuum preloading.

4. Evaluation of EOP settlement

The preliminary step of obtaining spatial map of a geotechnical index such as the degree of consolidation is to provide its observation or estimate at each spatial location. Therefore, the final EOP settlement, degree of consolidation and remained EOP settlement are calculated at each marker location in this section. This is achieved by the widely used Asaoka method [8]. In the Asaoka method, the settlement observations are plotted against the elapsed time, and then a series of settlement S_1, S_2, …, S_j, S_{j+1}, … are selected at equally spaced times t_1, t_2, …, t_j, t_{j+1}, … such that $t_{j+1} - t_j$ = constant. The S_{j+1} is then plotted against S_j to obtain a straight line. This straight line is extrapolated to intersect a 45° line through the origin (i.e., $S_j = S_{j+1}$). The intersection point corresponds to the final EOP settlement.

Define a and b as the slope and intercept of the s_{j+1}–S_j line obtained through curve fitted method. The total EOP settlement is calculated as follows:

$$S_\infty = \frac{b}{1-a} \tag{1}$$

where S_∞ is the total EOP settlement.

A representative example (T1-2 marker) of the Asaoka method is illustrated in Fig. 3. The fitted parameters are a = 0.92 and b = 11.39 cm. Therefore, S_∞ = 11.386/(1 – 0.924) = 149.82 cm. After obtaining the total EOP settlement, the degree of consolidation can be directly obtained by dividing the current primary settlement by S_∞. The remained EOP settlement is computed by S_∞ minus the current primary settlement.

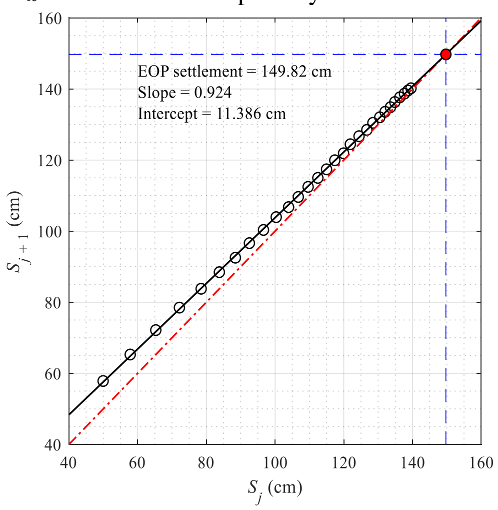

Figure 3. Observed settlements at T1-2 ground settlement marker

The magnitude of the finally calculated EOP settlement at each ground settlement marker is illustrated in Fig. 4. It is indicated that the total EOP settlement varies over a wide range of 50 cm to 200 cm. Even in the same block, the predicted total EOP settlements can be significantly different. For example, the largest differential settlement in the T8 block is more than 100 cm. This observation further indicates the inherent heterogeneity of the dredged materials at the testing site. It is thus demanding to develop the spatial mappings of settlement indices over the whole region to comprehensively evaluate the quality of the ground improvement technique. This objective is achieved in the next section.

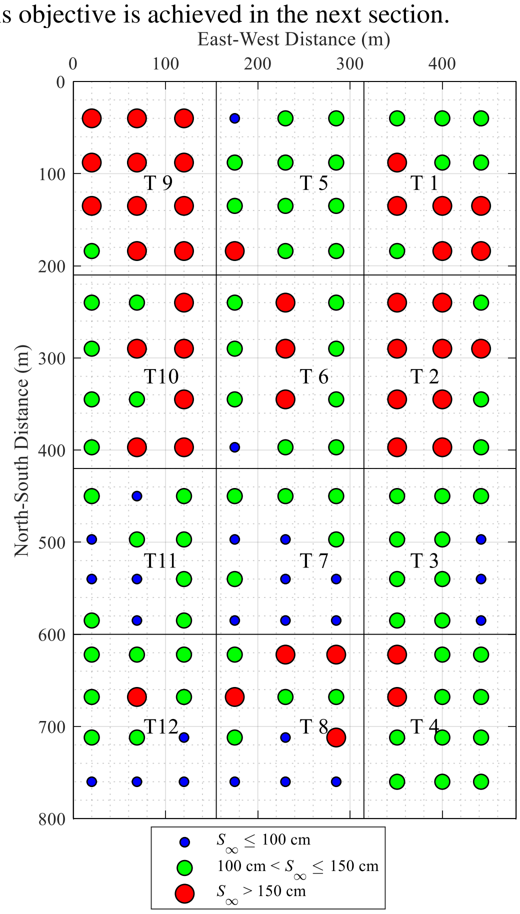

Figure 4. Calculated total EOP settlements at the testing site

5. Spatial mapping for quality control

The geostatistics provides a powerful tool to predict the spatial distribution of geotechnical parameters based on limited observations. This approach involves three main steps including a trend removal to ensure the stationarity of data, a spatial variability analysis to describe the self-similarity of soil parameters at different locations and a Kriging interpolation based on the results of the spatial variability analysis. In this study, the trends within the consolidation degree and remained EOP settlement are removed first. Then the spatial variability characteristic is captured by a semivariogram function with three model parameters including the nugget, range (a) and sill (c). The nugget describes the impact of small-scale (smaller than the sampling interval) spatial variability and measurement error on the observations. The range evaluates the maximum allowable separating distance from a sampled location to an unsampled location to achieve an effective prediction. A large value of range indicates more data in the vicinity of the unsampled location can be used for prediction. The sill is usually close to the variance and thus describes the magnitude of scatter of a geotechnical parameter with respect to its mean value. More details on semivariogram are available in the literature [4, 7].

The semivariogram functions are usually directional over space. It is therefore necessary to conduct semivariogram analysis in different directions. Fig. 5 illustrates a representative example of semivariogram functions in the two horizontal directions for the degree of consolidation, which corresponds to the final observation case. An isotropic exponential semivariogram function with a horizontal range of a = 210 m and a sill value of c = 26 is obtained based on the curve fitting. This range is considered rational, as it is consistent with the horizontal scale of fluctuation values ranging from 0.1 to 555 m, depending on the site scale, as reported in the literature [4]. This indicates that when the horizontal lag distance between two spatial locations is less than 210 m, the observed degree of consolidation at one location can be used to predict that at the other location.

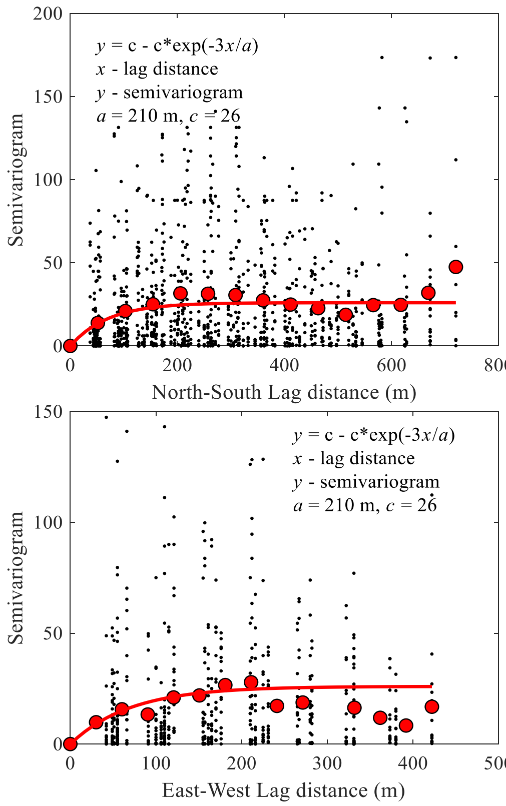

Figure 5. Representative estimated semivariogram functions for degree of consolidation at the testing site

The above calculation is repeated for the degrees of consolidation and remained EOP settlements at different time periods of the vacuum preloading. The calculated semivariogram functions are then incorporated in the ordinary Kriging method to obtain different spatial maps of the quality control indices. Detailed formulas of the ordinary Kriging method are available in the literature [4, 7], and thus they are not presented here.

Considering the different loading times, the following three elapsed times are selected to present the spatial maps of the two quality control indices at different stages: two months, four months and eight months after the first loading was applied. At the first stage, the first two sets of load were applied in the T1, T2, T5, T8, T9 and T12 blocks. At the second stage, the third set of load was applied in the T3, T4 and T6 blocks. At the third stage, the last set of load was applied and therefore all blocks were under vacuum loading. In these three cases, the performance of the vacuum preloading can be examined at its initial, steady and final stages, respectively. The estimated maps of the degree of consolidation and remained EOP settlement at the three stages are shown in Fig. 6. The applied loads are also illustrated by arrow symbols in Fig. 6. Note that the vertical axis indicates the elapsed time after the first set of vacuum preloading, instead of spatial coordinates.

The results in Fig. 6 indicate that at the initial stage (two months case), soils within the loading blocks have experienced a significant increase of degree of consolidation and a notable reduction of remained EOP settlement. Most degree of consolidation values in the T1 and T9 blocks had reached more than 80% and most remained EOP settlement values were less than 40 cm after two months of loading. The degree of consolidation values in the T2, T8, T9 and T12 blocks are slightly smaller, compared with the T1 and T5 blocks. This is because the elapsed time of the vacuum load in the former four blocks was only one month, half of those in the latter two blocks. Nevertheless, most degree of consolidation values in the T2, T8, T9 and T12 blocks still reached more than 40%. This observation implies that the consolidate rates in the first two months were comparable and they dominated the primary consolidation.

At the steady stage (the four months case), the consolidation continued to increase and the remained EOP settlement decreased within the T1, T2, T5, T8, T9 and T12 blocks. However, this increasing/decreasing rate became less significant compared with that at the initial stage. Nevertheless, a significant increase of the consolidation and reduction of remained EOP settlement was observed at the T3, T4 and T6 blocks, where the third set of loads was applied. At this stage, minor consolidation was also observed at the boundaries of unloaded blocks that were adjacent to the loading blocks, perhaps due to the presence of lateral drainage conditions formed by the embedded sandy or silty soil seams.

At the final stage (the eight months case), all blocks were under the vacuum preloading. It is shown in Fig. 6 that most degree of consolidation values exceeded 90% and the remained EOP settlement values were predicted to be less than 25 cm at this stage. These two key quality control indices are close to the criteria of unloading. Therefore, it implies that the vacuum preloading has successfully reduced the post-construction settlement of the dredged materials for the testing site.

Nevertheless, it is also indicated in Fig. 6 that the degree of consolidation values inside a block are still notable. For instance, the minimum value of degree of consolidation in the T1 block at the final stage is approximately 88%, whereas its largest value reaches 100%. Such a large differential consolidation indicates that the heterogeneity of the dredged materials is very significant, even at small scales (i.e., within the 160 m × 210 m block).

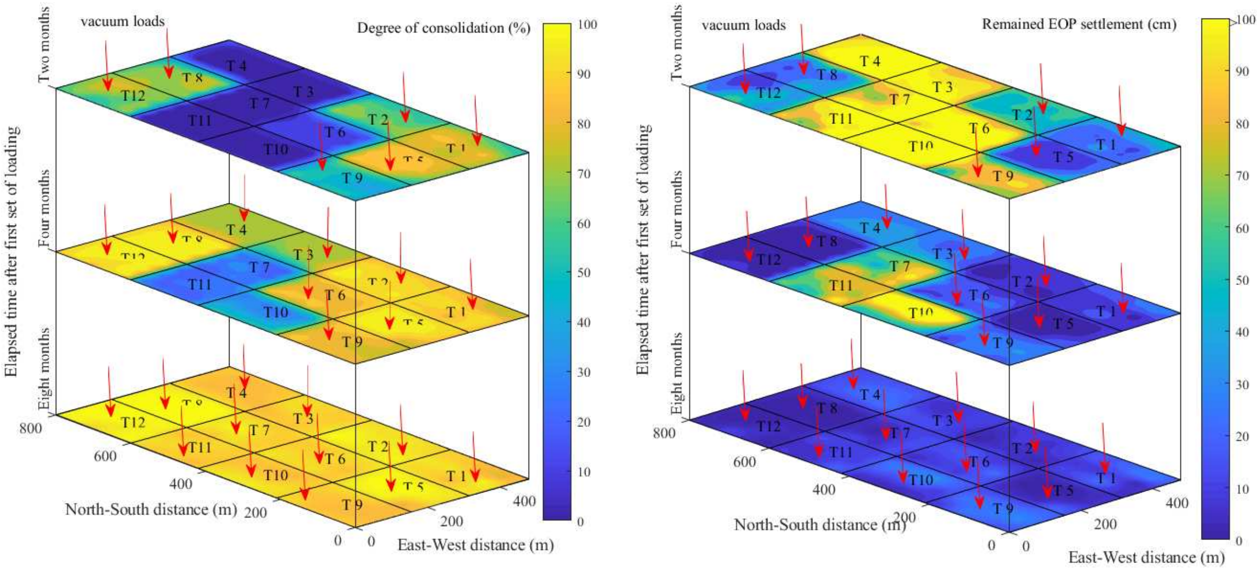

Figure 6. Spatial maps of degree of consolidation and remained EOP settlement at three different stages.

It is also shown in Fig. 6 that albeit the loading periods of the T4 and T9 blocks are much longer than those of T10 and T11 blocks, the remained EOP settlements of the former (5 – 25 cm) are larger than those of the latter (0 – 20 cm). This indicates that a long loading period does not have to produce a more effective reduction of the post-construction settlement. The quality of the vacuum preloading is strongly related to the soil properties of the subsoils. When the subsoils are strongly heterogeneous, such as the dredged materials in this study, it is helpful to take the spatial variability of soil properties into account in the ground improvement management. The results of this study show that the geostatistics is a useful tool to obtain the spatial distributions of the two quality control indices for complicated sites.

6. Conclusions

This study investigated the quality of the vacuum preloading technique in improving a soft clay site that was composed of dredged materials containing sandy and silty soil seams. One hundred and forty-four ground monitoring markers were instrumented over the site to monitor the surface settlement over the whole site. The ultimate total settlement values estimated using the Asaoka method implied that the differential settlements were very significant over space. Therefore, the geostatistics was used to report the spatial distribution of degree of consolidation and remained end-of-primary (EOP) settlement over the site, and thus to achieve a better understanding on the quality of the ground improvement technique. It was shown that the maps produced by geostatistics can clearly indicate the change of consolidation status at different preloading stages. Based on the obtained maps, majority of the primary consolidation was accomplished in two months after the application of the vacuum preloading. The final degree of consolidation values were more than 90% and the remained EOP settlement values were less than 25 cm after four months of vacuum preloading. However, notable spatial variations of the two quality control indices were observed by the geostatistics-based maps, implying that it is important to consider the spatial variability of consolidation behaviors of the dredged materials during vacuum preloading.

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