# Uncertainties in Geologic Profiles versus Variability in Pile Founding Depth

L. M. Zhang, M.ASCE[1]; and S. M. Dasaka[2]

**Abstract:** How the design and actual founding depths of foundations correspond to the variability of geological conditions has long been a concern. This paper evaluates the spatial variability characteristics of as-built and estimated founding depths of driven steel H piles with reference to the spatial variability characteristics of geologic profiles at a weathered soil site in Hong Kong. Spatial variability characteristics are evaluated in terms of variance and scale of fluctuation. The variability of three founding depth indicators, i.e., the depth of Grade-III bedrock, the depth of standard penetration test blow count "N" of 200 blows/0.3 m (SPT-200), and the depth of completely decomposed granite over the site was estimated. It is found that pile founding depths exhibit greater variations than those of the geologic profiles due to the presence of design model errors, judgment errors, and construction effects. The as-built founding depths are mostly between the SPT-200 profile and the Grade-III bedrock profile. The variances of as-built pile length are similar to those with depth of SPT-200 but less than those with depth of Grade-III bedrock. The scale of fluctuation of as-built pile length is on the order of 20 m when kriging is used and 10 m when kriging is not used, which are less than those with depths of SPT-200 and Grade-III bedrock.

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## Introduction

The founding depths of piles depend on several key factors such as loading conditions, ground conditions, pile specifics, and characteristics of the pile-ground interface formed during construction. The uncertainties in these key factors contribute to the variability of the final founding depths across a construction site. The final pile lengths may, therefore, deviate significantly from the lengths estimated during the design stage (e.g., Holt et al. 1982), and additional costs may be borne by the developer or the contractor. Given the pile type and required pile capacity for a specific pile foundation project, the developer, the designer, and the contractor have one common concern: how do the design and actual founding depths correspond to the variability of the geological conditions of the ground revealed before the start of construction?

The spatial characteristics of soil and rock properties for various applications have been evaluated using either geostatistics or random field modeling (Vanmarcke 1977; Kulatilake and Ghosh 1988; DeGroot and Baecher 1993; DeGroot 1996; Fenton 1999; Jaksa et al. 1999; Murakami et al. 2006; Liu and Chen 2006). The uncertainties involved in the design of a foundation have been studied systematically by Phoon and Kulhawy (1999), and their effect on the bearing capacity of a shallow foundation is shown by Sivakumar Babu et al. (2006). Yet, thorough case studies that compare the variability of design and actual pile lengths and the uncertainties in geological conditions have been rather limited. The objectives of the present study are as follows:

1. To map the static and as-built pile lengths of driven piles over a construction site in Hong Kong, as well as the depths of three indicative geologic profiles at the same site; and
2. To compare the spatial variation characteristics of the static and as-built pile lengths with those of the depths of the indicative geologic profiles.

This paper is organized as follows. First, the geological conditions at the study site and the methods for determining the pile lengths in the design and construction stages are described. Then, random field theory is used to characterize and compare the spatial variability of the geological profiles, the design pile lengths, and the as-built pile lengths. Finally, sources of uncertainty in the static and dynamic analysis models and in construction that affect the correspondence between the design and as-built founding depths and the geologic profiles are discussed. No attempt is made to assess the relative contributions to the uncertainty in the as-built pile lengths inherent in the many steps of the design and construction processes.

## Geological Conditions

Fig. 1 shows the plan of the pile construction site. Seven building blocks are scheduled at the study site. Among them, driven steel H-piles are adopted as the foundations for Blocks 2, 3, 5, and 7, and large-diameter bored piles are adopted for the remaining three

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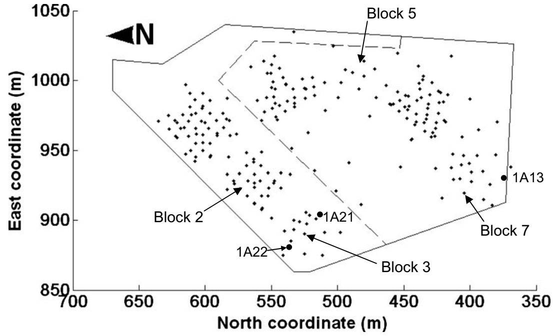


**Fig. 1.** Plan of the driven pile construction site and borehole locations over the site

blocks. This paper focuses on studying the variability of the driven pile foundations.

More than 83 boreholes were sunk for the four driven-pile supported building blocks to characterize the physical features of the soil, i.e., soil layering, type of soil, degree of weathering, and depth of groundwater table. The locations of these boreholes are shown in Fig. 1. The site is underlain consecutively by a fill layer, marine deposits, an alluvium layer, and decomposed granitic rocks, as illustrated by three sample borehole logs in Fig. 2. The locations of the three sample boreholes are marked in Fig. 1. For the purpose of engineering design, the rocks are classified into six categories based on the degree of weathering and other distinguishing physical features (GEO 2000): (1) fresh (Grade I); (2) slightly decomposed (Grade II); (3) moderately decomposed (Grade III); (4) highly decomposed (Grade IV); (5) completely decomposed (Grade V); and (6) residual (Grade VI). The standard penetration test (SPT) is routinely carried out as part of a preliminary soil investigation. Depths of Grade III, Grade V, and SPT-N of 200 blows/0.3 m are generally considered as important indicators for the preliminary assessment of depths of driven piles. In general, the depth of completely decomposed granite (CDG) profile is followed by the SPT-200 profile, then by the Grade-III rockhead profile. A detailed study of these indicators and their spatial characteristics was reported by Dasaka and Zhang (2006).

## Estimated and As-Built Pile Lengths

Fig. 3(a) shows the locations of the steel H piles for each of the four building blocks and Fig. 3(b) shows a close-up view of the piles for Block 2. Grade 55C $305 \times 305 \times 233$-kg/m H sections were used. The depth and width of each pile section were 338 and 325.5 mm, respectively, and the cross-sectional area was 0.0285 $m^2$. The yield strength of the piles was 415 $MN/m^2$. The structural compressive capacity of a pile was therefore 11.83 MN ($=0.0285\ m^2 \times 415\ MN/m^2$). Following the Code of Practice (Buildings Department 2004), the design structural capacity of the pile section was taken to be 60% of the structural compressive capacity, i.e., 7096 kN. The required pile length, or the founding depth, was determined such that the geotechnical capacity of the pile would be greater than 7,096 kN. A safety factor of 2.0 was applied to the pile capacity, bearing in mind that sufficient proof load tests would be conducted to verify the piles (Buildings Department 2004).

The design and construction process of the steel H piles at the site proceeded in the following manner:

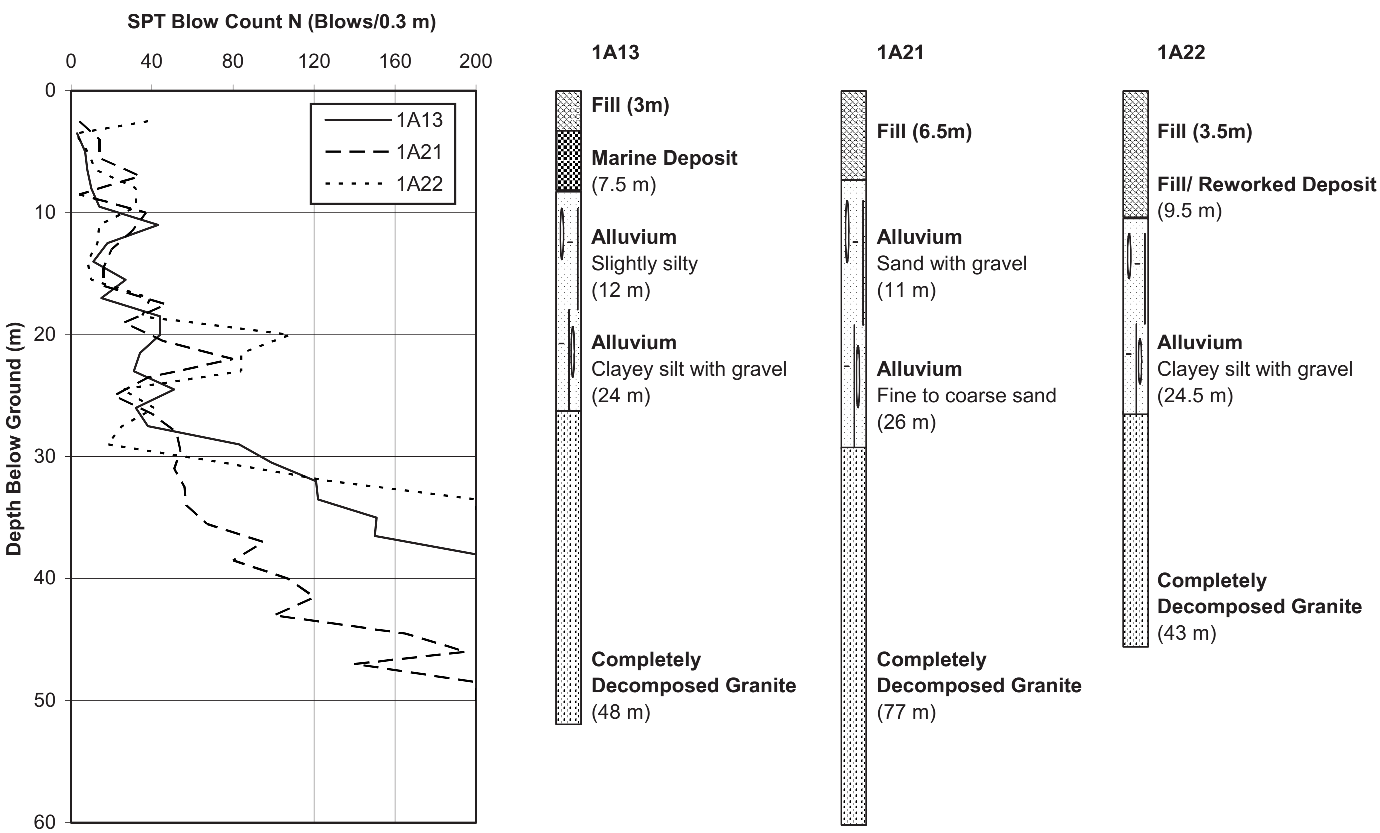


**Fig. 2.** Three sample borehole logs and SPT-N values

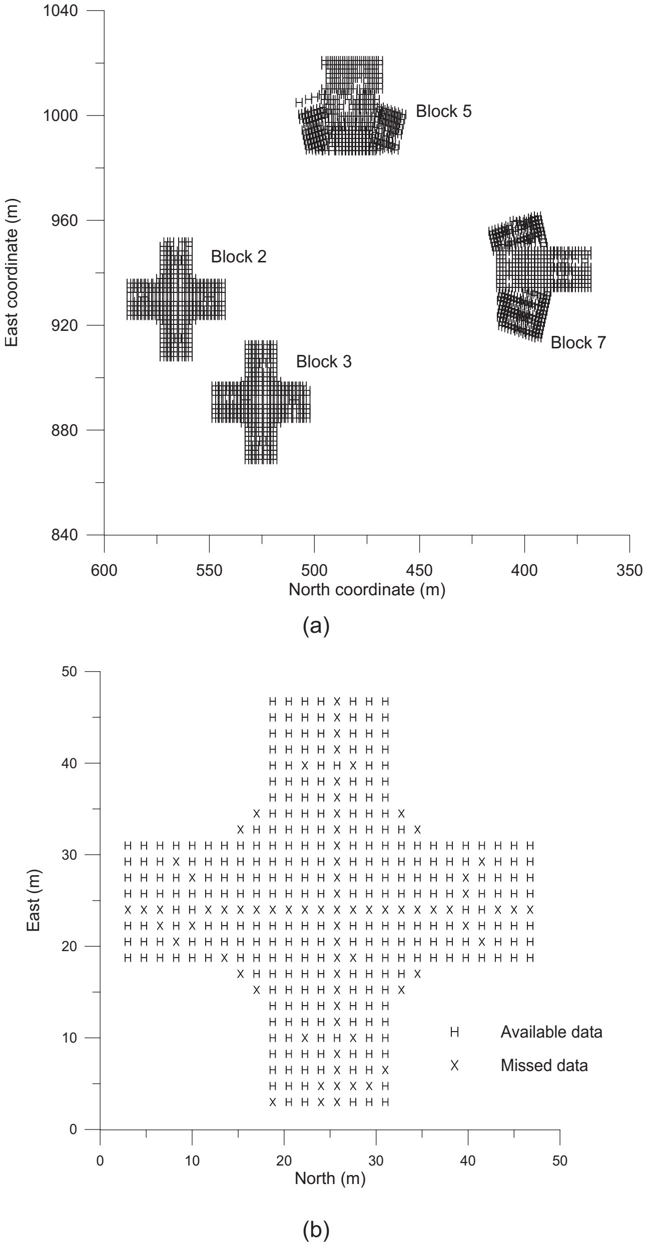


**Fig. 3.** Driven pile locations: (a) Blocks 2, 3, 5, and 7; (b) close-up view of Block 2

1. Evaluate subsurface data and perform static pile capacity analysis.
2. Select preliminary driving criteria based on a dynamic formula, in particular, Hiley's formula (Hiley 1925) for piles final set by either drop hammers or hydraulic hammers and HKCA's formula (Hong Kong Construction Association 1995) for piles final set by hydraulic hammers.
3. Drive early test piles within the footprint and instrumented preliminary test piles outside the footprint, and use pile driving analyzers, assisted by analysis with CAse Pile Wave Analysis Program (CAPWAP), to evaluate the pile capacity, driving stresses, and the hammer performance.
4. Load test the early test piles to the required capacity (7,096 kN) and the instrumented preliminary test piles to failure of the piles or the pile sections. Following the code of practice (Buildings Department 2004), a pile is deemed to have failed when (1) the load is larger than the structural compressive capacity of the pile; (2) the Davisson (1972) failure criterion has been met; or (3) the residual pile-head settlement after removing the full test load is larger than the greater of ($D/120+4$ mm) and 25% of the pile settlement at the full test load, where $D$=least dimension of the pile section.
5. Perform a final evaluation of the driving criterion for the production piles based on results of the static loading tests.
6. Perform a final static pile capacity analysis based on results of the static loading tests on the instrumented preliminary piles.
7. Drive production piles according to the final driving criteria.
8. Select 1% of the production piles for proof load tests.

The above procedure resembles the one summarized by Bell et al. (2002). Details of pile driving control and pile loading performance have been described by Zhang (2005), Zhang et al. (2006a), and Zhang and Wang (2007). Two pile lengths, i.e., a pile length satisfying adopted driving criteria and another length from static analysis (hereafter referred to as "static pile length"), are obtained following the above procedure. The former pile length is often larger than the static pile length and is therefore taken as the final pile length. The distributions of the as-built pile length and the static pile length over the site are presented separately in the following two sections.

## Pile Length from Static Analysis

Steel H piles are considered as small displacement piles because the radial zone of soil disturbance by pile driving may be limited if soil plugs do not form. Based on the results of preliminary site investigation, the pile lengths can be estimated using a static analysis method. The ultimate resistance of a pile, $Q_p$, is estimated by

$$Q_p = N_q \sigma'_{vo} A_b + \sum_{i=1}^{i=n} A_{si} \sigma'_{avei} K_{si} \tan \delta_{si} \tag{1}$$

where $N_q$, $\sigma'_{vo}$, and $A_b$=bearing capacity factor due to overburden pressure, the effective overburden pressure at the pile toe, and the area of pile base, respectively; $n$=number of soil layers along the pile shaft; and $K_{si}$, $\sigma'_{avei}$, $\delta_{si}$, and $A_{si}$=coefficient of horizontal earth pressure, the average effective overburden pressure, the interface friction angle between soil and pile material, and the surface area of pile shaft in the $i$th soil layer, respectively. At this site, the groundwater table was observed at a depth of approximately 2 m below the ground surface. The effective friction angle, $\phi'$, is estimated from the average SPT "N" over the depth under consideration using the chart proposed by Schmertmann (1967). Fill and marine deposits may impose a drag load on the pile. Hence, to be on the safer side, the contribution of these layers toward the frictional component of the pile capacity is neglected in static calculations. The bearing capacity factor, $N_q$, which is used to estimate the toe resistance of the pile, depends on the friction angle, $\phi'$, which, in turn, depends on the stress level around the pile toe (Schmertmann 1975). Using the measured SPT "N" value in the vicinity of the pile toe, the effective friction angle is estimated to be approximately 40°, and the corresponding $N_q$ factor is approximately 200. However, to be on the safer side, it is common to use a $N_q$ value of 75 in static calculations, which corresponds to an effective friction angle of 35°. The interface friction angle, $\delta_s$, in the case of driven piles is assumed to be 0.7 times of $\phi'$. The coefficient of horizontal earth pressure, $K_s$, depends on the method of pile construction (GEO 1996). For small-displacement driven piles it is observed to vary from $K_0$ to $1.4K_0$,

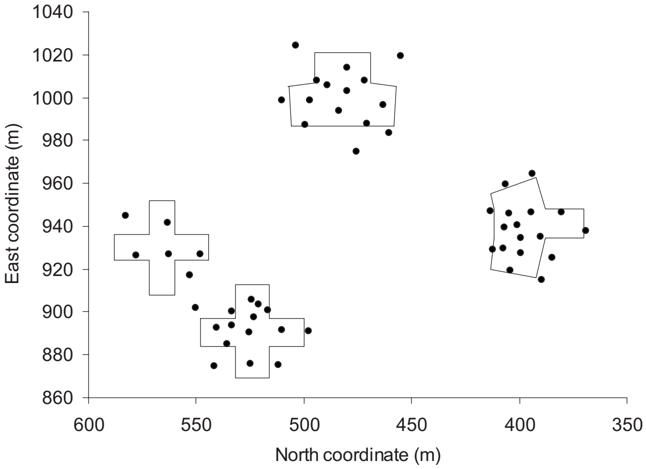


**Fig. 4.** Locations of boreholes with complete information for static pile length calculation

where $K_0$=coefficient of horizontal earth pressure at rest, which is a function of stress history, but not a fundamental soil property. A value of $1.25K_0$ is assumed in this study for the static analysis. Many factors affect the in situ state of stress in soils, such as overconsolidation, aging, and chemical bonding (Kulhawy and Mayne 1990). Overconsolidation is probably the most influential for the majority of soils. For normally consolidated soils, Jaky's formula, $K_0=1-\sin\phi'$, provides a reasonable estimate of $K_0$. Though there may be some cohesion in undisturbed weathered soils, its contribution to the ultimate shaft resistance is generally negligible, as the effect of construction on the cohesion at the pile-soil interface is difficult to evaluate (GEO 1996). The randomness of the variables is not considered in the static analysis.

The concept of a "limiting vertical stress" or a "critical depth" was not incorporated in the analyses of the unit toe resistance and unit shaft resistance of the piles because of doubt about the validity of the concept. Kulhawy (1994) and Fellenius and Altaee (1995) commented that the critical depth concept originates from the omission of residual forces and test sequence history.

By adopting the procedure delineated above, the static pile lengths are estimated at 53 borehole locations in the site shown in Fig. 4, where complete soil profile information is available. The designer calculated individual pile lengths based on the information of the boreholes nearest to the piles. Table 1 shows the results of static pile length for Blocks 2, 3, 5, and 7. The table also shows the statistics of all piles when the four blocks are combined as a single unit. These estimated pile lengths vary from 49.7 to 53.7 m, with a mean value of 50.8 m and a standard deviation of 0.77 m. The coefficient of variation is in a small range of 0.6–2.9%.

## As-Built Pile Length

The number of piles with complete as-built information, the minimum and maximum as-built pile lengths, as well as the mean and standard deviation of as-built pile length for each of the four building blocks and for all four blocks combined are summarized in Table 2. Among all the four blocks, the longest mean pile lengths are in Block 7 and the shortest in Block 2, with mean values of 50.3 and 58.3 m, respectively. The standard deviation of the pile length, which represents the variation of individual pile lengths from the mean pile length, tends to increase with the mean pile length, which is true for many random variables as the coefficient of variation may be driving the problem. In Table 2, the pile lengths for Blocks 3, 5, and 7, and the combined set exhibit coefficients of variation on the order of 6 to 12%, while the value for Block 2 is about 4%. The smaller standard deviation in Block 2 reveals that the soil properties near the pile tip locations within Block 2 as well as the workmanship in constructing the piles in Block 2 are more uniform than those within Block 7.

Fig. 5 shows the variation of depths of weathering profiles and as-built pile lengths in the north direction for the individual blocks. The data of the Grade-III profile are not sufficient for Block 7 because the Grade-III profile is far below the founding levels beneath the block. The as-built pile length profile is deeper than the SPT-200 profile but is, in general, above the Grade-III granite profile. For Blocks 3 and 7, the difference between the depths of as-built pile founding levels and Grade-III granite is over 30 m at some locations. It shows that the soils above the

**Table 1.** Embedded Lengths of Piles from Static Analysis Based on Borehole Information and SPT-N Values

| | Block 2 | Block 3 | Block 5 | Block 7 | All four blocks |
|---|---|---|---|---|---|
| Number of boreholes | 6 | 15 | 15 | 17 | 53 |
| Minimum pile length (m) | 49.7 | 50.0 | 50.0 | 50.2 | 49.7 |
| Maximum pile length (m) | 53.7 | 51.6 | 51.0 | 51.2 | 53.7 |
| Mean pile length (m) | 51.1 | 50.7 | 50.6 | 50.7 | 50.8 |
| Standard deviation (m) | 1.50 | 0.39 | 0.28 | 0.30 | 0.77 |
| Coefficient of variation (%) | 2.9 | 0.8 | 0.6 | 0.6 | 1.5 |

Note: The shaft resistance in fill and marine deposits is ignored.

**Table 2.** As-Built Pile Lengths (Based on Dynamic Formulas and Site Control)

| | Block 2 | Block 3 | Block 5 | Block 7 | All four blocks |
|---|---|---|---|---|---|
| Number of piles[a] | 289 | 287 | 351 | 408 | 1,335 |
| Minimum pile length (m) | 43.8 | 40.6 | 43.3 | 45.0 | 40.6 |
| Maximum pile length (m) | 55.0 | 64.8 | 63.3 | 79.8 | 79.8 |
| Mean pile length (m) | 50.3 | 51.4 | 57.5 | 58.3 | 54.9 |
| Standard deviation (m) | 2.1 | 5.1 | 3.2 | 6.7 | 6.0 |
| Coefficient of variation (%) | 4.2 | 9.9 | 5.6 | 11.5 | 10.9 |

[a]Number of piles with complete information.

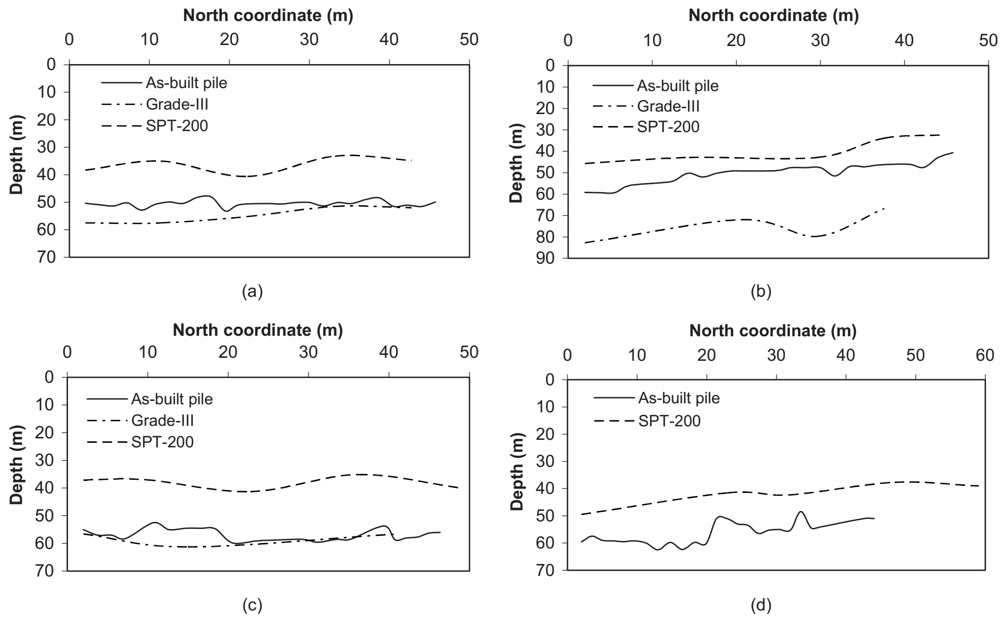


**Fig. 5.** Variation of depths of weathering profiles and as-built pile lengths in (a) Block 2; (b) Block 3; (c) Block 5; and (d) Block 7

Grade-III rock (i.e., Grade-IV and V soils, fill and alluvium) are strong enough to provide necessary bearing capacity. However, in Blocks 2 and 5, this difference is not more than 10 m, and at some points, piles are found in the Grade-III rock. These findings may not be uncommon, as geology at the site, which is one of the factors influencing the as-built pile lengths, may differ significantly even at two closely spaced locations. Fig. 6 shows the three-dimensional view of the as-built pile length profile for all the blocks, sandwiched between the SPT-200 profile on top and the Grade-III profile at bottom.

Figs. 7 and 8 show the histograms of pile lengths obtained from the static as well as dynamic analysis for the individual blocks, respectively. For the combined case, the mean and standard deviation of pile lengths estimated by the static analysis are less than those for the as-built pile lengths. The larger standard deviation of as-built pile lengths shows that the actual pile lengths are highly variable. These observations will be explained later in the paper.

The means and variances of static and as-built pile lengths obtained from the procedures delineated above are compared with those of depths of the Grade-III, SPT-200, and CDG profiles and presented in Tables 3 and 4, respectively. From Table 3, it is observed that the means of static and as-built pile lengths are greater than the mean depth of the SPT-200 profile but smaller than the mean depth of the Grade-III profile. Table 4 shows that the variance of the depth of the Grade-III profile is greater compared to the variances of pile lengths and depths of other geologic profiles.

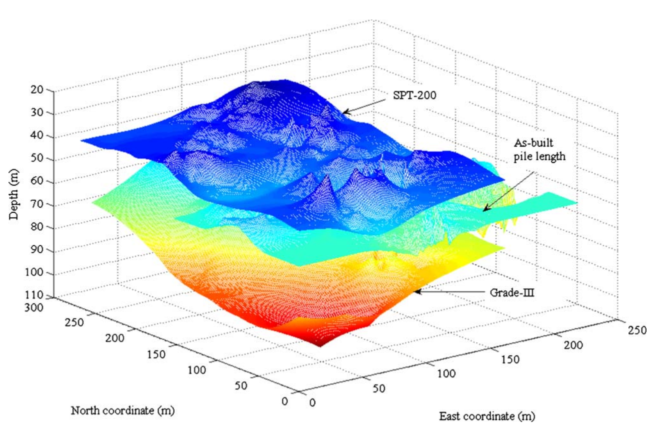


**Fig. 6.** Profiles of depths of SPT-200 and Grade-III for the whole site, and as-built pile lengths for Blocks 2, 3, 5, and 7

## Spatial Variations of Geologic Profile and Pile Founding Depth

Pile founding depth, depths of the SPT-200 profile, and the Grade-III profile are random variables in the space. For any particular variable, points which are very close together tend to have similar values, i.e., the values are highly correlated. Points which are far apart may have quite different values, or the values are poorly correlated. The correlation between two points tends to decrease with their separation distance. The scale of fluctuation is the distance beyond which the field is effectively uncorrelated (Fenton 1997). A small scale of fluctuation implies that only data points in a close distance are correlated and that far-apart data points are not correlated. Vanmarcke (1977), Fenton (1997), Jaksa et al. (1999), and others described basic concepts and methods of data reduction related to the spatial variation of geotechnical properties.

To evaluate spatial variability of a set of data using statistical models based on geostatistics or random field modeling, it is essential that the data are stationary; namely, the statistical properties of the data are unaffected by any shift of the spatial origin or statistically the first two moments (mean and variance) are required to be constant. If the data set is nonstationary, it must be transformed to a stationary set by removing a low-order polynomial trend of no higher than quadratic (e.g., Brooker 1991).

### *Geostatistics*

A semivariogram, a frequently used function in geostatistics, characterizes the dependency existing between variables at differ-

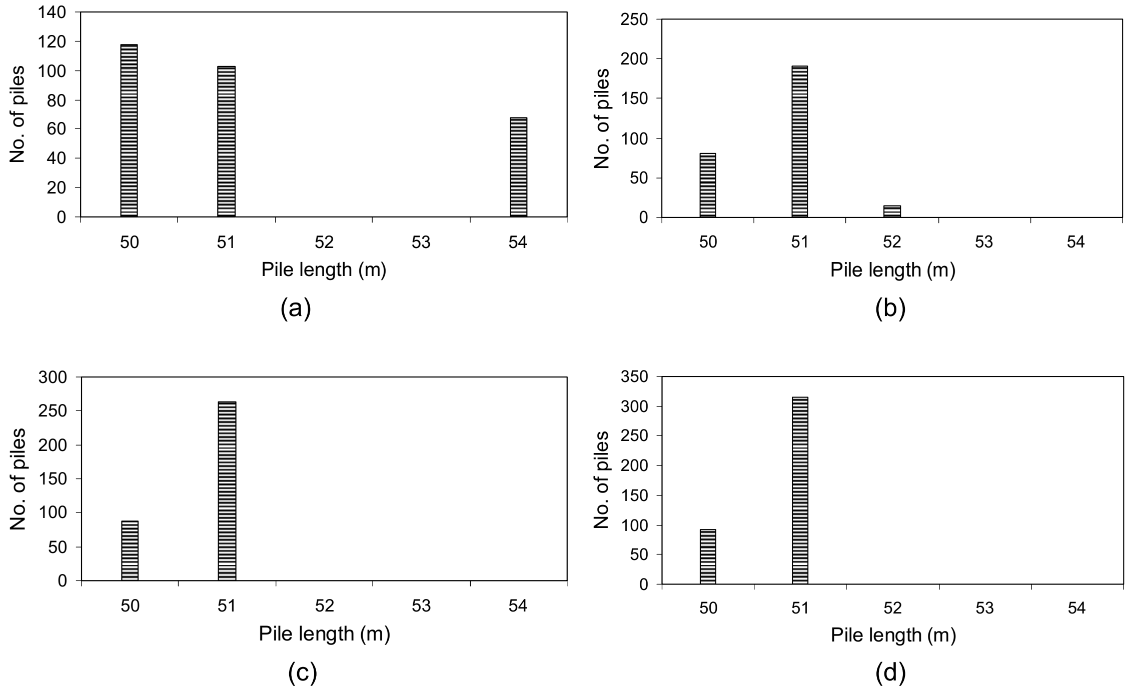


**Fig. 7.** Histograms of static pile length: (a) Block 2; (b) Block 3; (c) Block 5; and (d) Block 7

ent points in space. The semivariance (or the value of the semivariogram) for a separation distance of $h$ is the average squared difference in variable values between pairs of input sample points separated by $h$. If the semivariogram does not level off for large values of separation distance, it indicates that the data set is nonstationary (Kulatilake and Ghosh 1988). However, when the borehole or pile locations are spaced in an irregular pattern over a site, the evaluation of the semivariogram is not an easy task. This case calls for the grouping of distances and directions into classes (Olea 1999) and evaluating semivariance considering all the data grouped in each direction or class.

The experimental variogram obtained using the above procedure has to be fitted to the standard analytical variogram models, and the parameters of the best fit should be used in further analy-

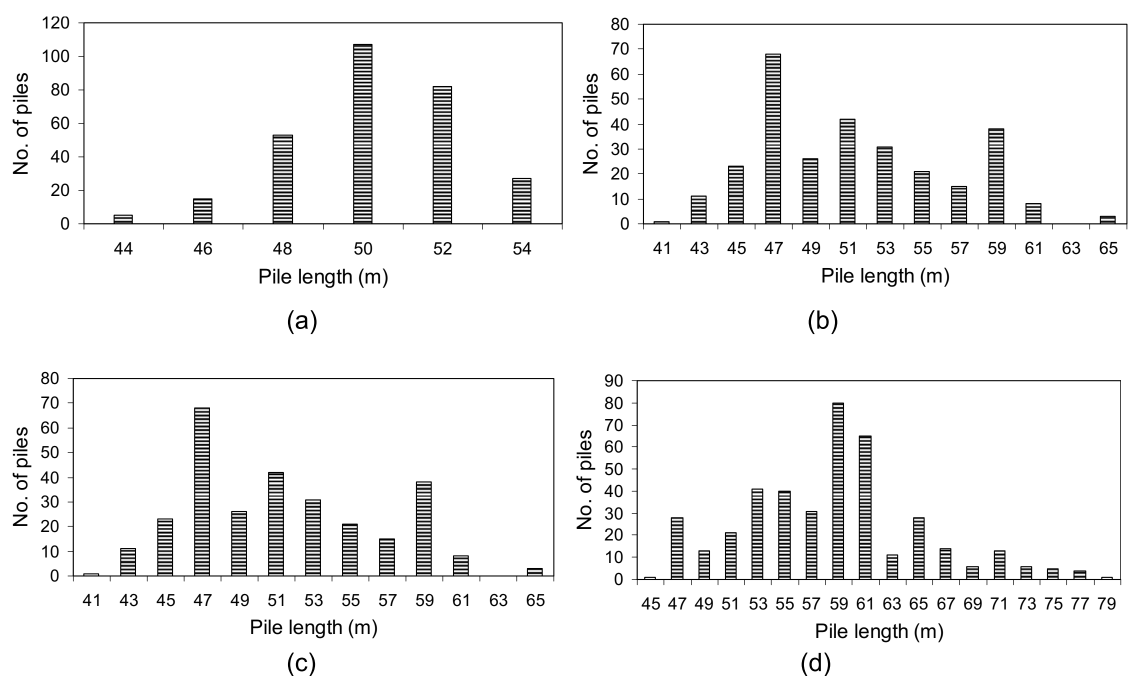


**Fig. 8.** Histograms of as-built pile length: (a) Block 2; (b) Block 3; (c) Block 5; and (d) Block 7

**Table 3.** Mean Depths of Profiles of Top of CDG, SPT-200, Grade-III, As-Built Pile Length, and Static Pile Length

| | Block 2 | Block 3 | Block 5 | Block 7 | All four blocks |
|---|---|---|---|---|---|
| Depth of top of CDG (m) | 19.4 | 19.9 | 13.0 | 21.7 | 18.5 |
| Depth of SPT-200 (m) | 36.8 | 36.4 | 39.0 | 40.6 | 38.2 |
| Depth of Grade-III (m) | 52.9 | 74.2 | 59.0 | 93.1 | 69.8 |
| As-built pile length (m) | 50.3 | 51.4 | 57.5 | 58.3 | 54.4 |
| Static pile length (m) | 51.1 | 50.7 | 50.6 | 50.7 | 50.8 |

sis. Clark (1979) provided a number of semivariogram models and described the process of fitting a model to an empirical semivariogram by a trial-and-error approach.

In geotechnical engineering practice, data from the routine exploration program may not be sufficient to quantify the variability of in situ soil properties. In order to predict the unknown/missed value of static/as-built pile length at an unsampled location, a geostatistical estimation technique, kriging, is commonly used. Recently, Murakami et al. (2006) used the kriging technique to map land subsidence in the northern Kanto plain of Japan. More details of kriging methodology are given by Murakami et al. (2006).

## *Random Field Modeling*

A classical way of describing random functions is through the autocorrelation function that is the coefficient of correlation between values of a random function at a separation distance of $h$. A common method used for estimating the sample autocorrelation functions of soil properties is the method of moments. The spatial correlation of a soil property can be modeled as the sum of a trend component and a residual term (Vanmarcke 1977)

$$x = z + e \tag{2}$$

where $x$=measurement at a given location; $z$=trend component; and $e$=residual off the trend. The residuals off the trend tend to exhibit spatial correlation. The degree of spatial correlation among the residuals can be expressed through an autocovariance function

$$c(k) = E[\{P(Z_i) - t(Z_i)\}\{P(Z_j) - t(Z_j)\}] \tag{3}$$

where $k$=vector of separation distance between point $i$ and point $j$, implying that the separation distance between point $i$ and point $j$ is $h=k\delta$, where $\delta$=distance between two neighboring points when the data are regularly patterned; $E[\cdot]$=expectation operator; $P(Z_i)$=datum taken at location $i$; and $t(Z_i)$=value of the trend at location $i$. The normalized form of the autocovariance function is known as the autocorrelation function

$$\rho(k) = \frac{c(k)}{c(0)} \tag{4}$$

where $c(0)$=autocovariance function at zero separation distance, which is the variance of data. Note that covariance $c(k)$ equals $c(0)$ minus the semivariance. It is not possible to evaluate $c(k)$ or $\rho(k)$ with certainty but only to estimate them from samples obtained from a population. As a result, the sample autocovariance at a separation distance of $k\delta$, $c(k)^*$, and the sample autocorrelation at a separation distance of $k\delta$, $r(k)$, are generally evaluated. The sample autocorrelation function is the graph of $r(k)$ for $k=0,1,2,\ldots,m$, where $m$=maximum number of $\delta$ allowed to obtain reliable estimates. Generally, $m$ is taken as a quarter of the total number of data points in a time series analysis of geotechnical data (Box et al. 1994). Beyond this number, the number of pairs contributing to the autocorrelation function diminishes and produces unreliable results. The sample autocorrelation function at a separation distance of $k\delta$, $r(k)$, is generally evaluated using the following equation:

$$r(k) = \frac{\dfrac{1}{(N-k-1)}\sum_{i=1}^{N-k}(X_i - \bar{X})(X_{i+k} - \bar{X})}{\dfrac{1}{(N-1)}\sum_{i=1}^{N}(X_i - \bar{X})^2} \tag{5}$$

where $N$=number of data available; $X_i$ and $X_{i+k}$=values of the variable at points $i$ and $i+k$, respectively; and $\bar{X}$=mean value of the variable.

If no measurement error or noise is present, $r$ becomes 1.0 at a separation distance of zero. The autocorrelation characteristics of depths of geologic profiles or pile lengths can be characterized by either autocorrelation distance, or scale of fluctuation. Analytical models are fitted to the sample autocorrelation functions using the ordinary least-squares error approach. Some of the frequently used models and the relation between autocorrelation distance and scale of fluctuation for these models are presented by Jaksa et al. (1999).

## *Spatial Autocorrelation Characteristics of Geologic Profiles*

In this section, variability of various geologic profiles used in geotechnical design for this site is presented for better understanding of the geology and to make a comparison between the statistics of geologic variability and those of pile-length variability. Table 5 shows the estimated parameters of autocorrelation structure for three profiles commonly used in geotechnical design,

**Table 4.** Variances of Depths of Profiles of Top of CDG, SPT-200, Grade-III, As-Built Pile Length, and Static Pile Length

| | Block 2 | Block 3 | Block 5 | Block 7 | All four blocks |
|---|---|---|---|---|---|
| Depth of top of CDG ($m^2$) | 3.0 | 0.8 | 1.7 | 3.0 | 10.4 |
| Depth of SPT-200 ($m^2$) | 4.6 | 27.1 | 10.5 | 41.0 | 21.1 |
| Depth of Grade-III ($m^2$) | 18.5 | 57.0 | 12.6 | 57.3 | 154.1 |
| As-built pile length ($m^2$) | 4.5 | 26.2 | 9.9 | 44.8 | 35.6 |
| Static pile length ($m^2$) | 1.93 | 0.17 | 0.09 | 0.08 | 0.30 |

**Table 5.** Parameters of Spatial Correlation Structure for Geological Profiles Using Data from the Whole Site

| | Grade-III | SPT-200 | Top of CDG |
|---|---|---|---|
| Fitting function | Squared exponential | Simple exponential | Simple exponential |
| Scale of fluctuation (with kriging) (m) | 141.1 | 44.6 | 59.2 |
| Scale of fluctuation (without kriging) (m) | 84.7 | 18.5 | 8.6 |

i.e., top of CDG, SPT-200, and Grade-III (Dasaka and Zhang 2006). The following points are noted from the results:

1. The scale of fluctuation is observed to decrease with increasing weathering grade. The Grade-III profile exhibits longer scales of fluctuation than the SPT-200 and CDG profiles. The scale of fluctuation of the Grade-III profile is more than 140 m, which concludes that the depth of the Grade-III profile fluctuates mildly about its mean within the site. The variability of the Grade-III profile is less than that of other profiles at shallower depths.
2. The scales of fluctuation obtained using combined data, i.e., measured data from site investigation and predicted data from kriging, are much longer than those obtained using the measured data alone.
3. The scale of fluctuation increases with an increase in size of sampling domain. The results obtained from the analyses reveal that the data from the whole site exhibit longer scale of fluctuation than those obtained using the data from any of the single blocks.

### Spatial Correlation of Static Pile Length

Two procedures are adopted in the estimation of spatial correlation characteristics of static and as-built pile lengths. To enhance the number of data points, in the first procedure, kriging is used to predict the pile lengths in each building block at an interval of 1 m using the existing data, and the pile length data so obtained are used to estimate their spatial correlation characteristics in each block, as well as the spatial correlation characteristics of all the four blocks together.

Fig. 9 shows the semivariograms for static pile lengths using the data from the individual blocks, obtained using the procedure delineated above. The figure shows clear peaks in the semivariance at separation distances varying from 10 to 20 m for the static pile lengths in Blocks 2, 3, 5, and 7. This means the static lengths of piles separated by distances over 10–20 m are essentially not correlated. The autocorrelation functions for the data are shown in Fig. 10. Subsequently, the scales of fluctuation of static pile lengths in the individual blocks are obtained through fitting the autocorrelation functions and are shown in Table 6. Fig. 11 shows the estimated semivariogram for the combined data from all four blocks. Unlike the data from the individual blocks, the semivariogram for the whole static-pile-length data exhibits several clear peaks; hence, a representative scale of fluctuation cannot be esti-

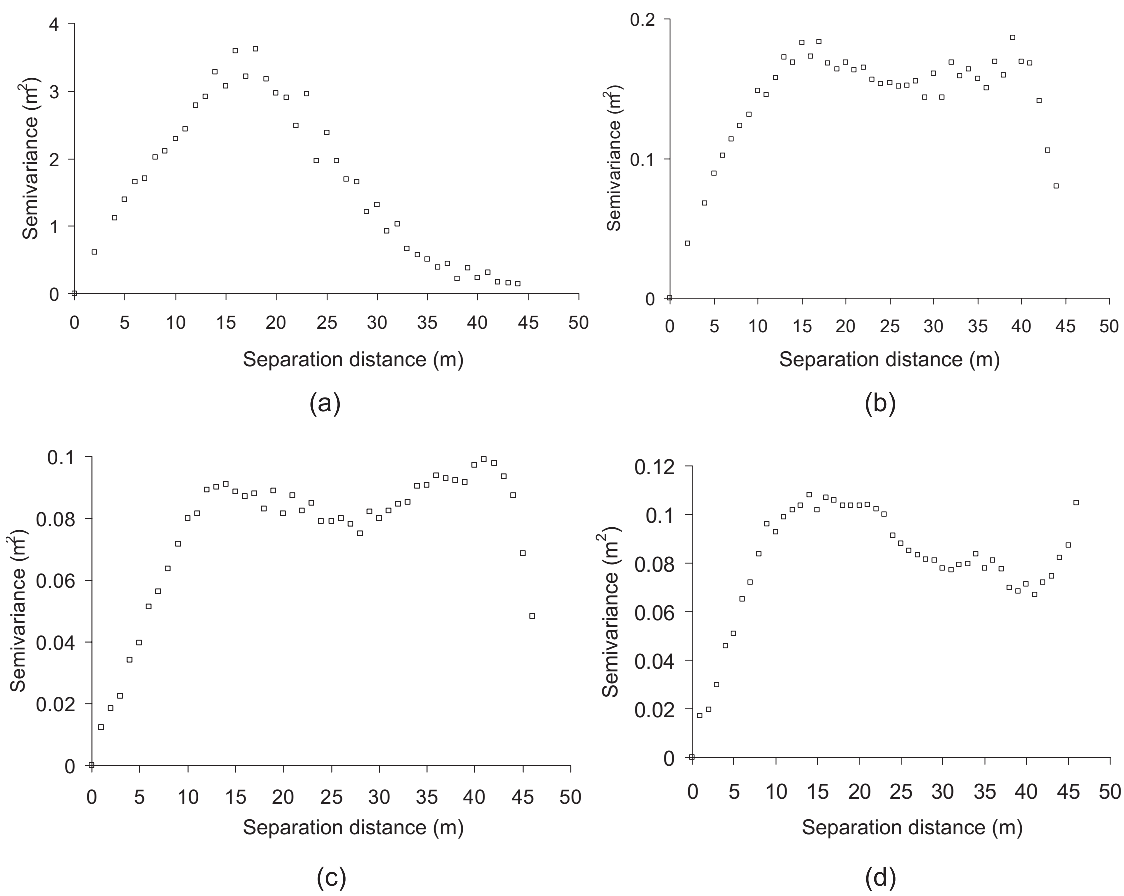


**Fig. 9.** Semivariograms for static pile length using the data of (a) Block 2; (b) Block 3; (c) Block 5; and (d) Block 7

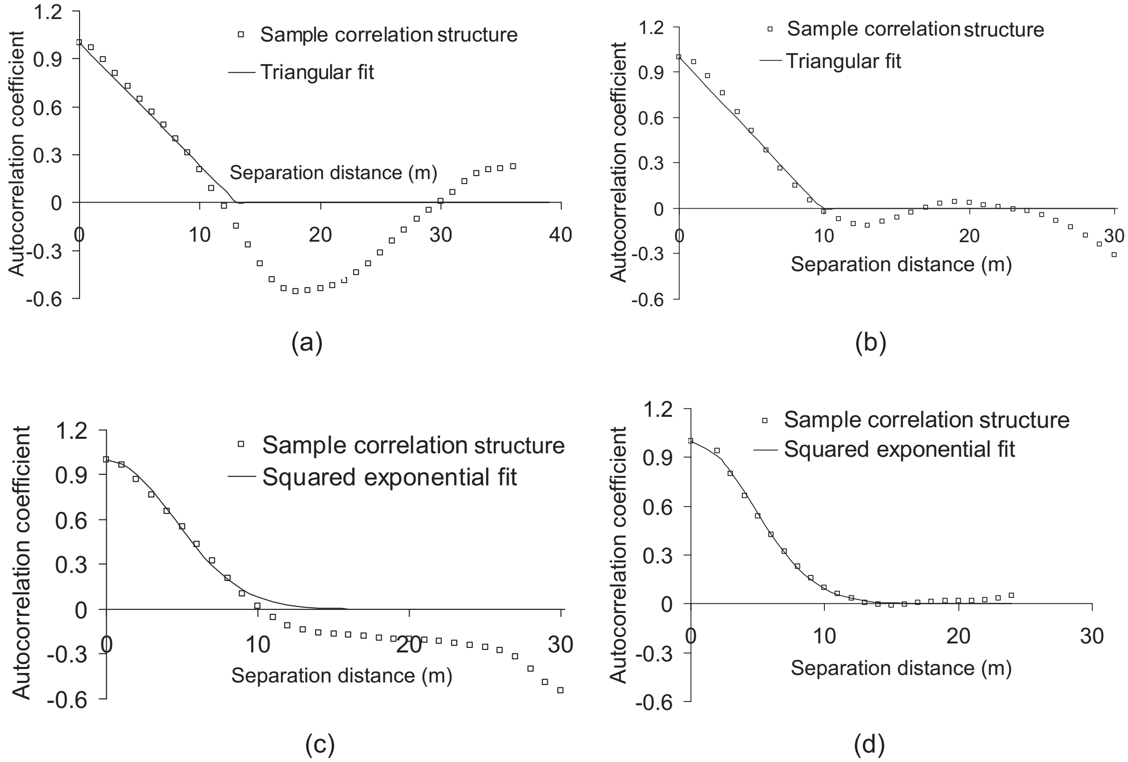


**Fig. 10.** Autocorrelation functions for static pile length using the data of (a) Block 2; (b) Block 3; (c) Block 5; and (d) Block 7

mated in this case. Instead, an alternative procedure has been adopted. In this procedure, the estimated static pile length data are directly used without kriging. The estimated scales of fluctuation of pile lengths are presented in the final row of Table 6. To compare with the results obtained in the former procedure, the scales of fluctuation are also estimated for the static-pile-length data in the individual blocks. From the results presented in Table 6, it is noted that except for Block 7, the scales of fluctuation of static pile length from the former procedure are larger than those from the latter procedure. The scale of fluctuation of static pile length is on the order of 10 m whether kriging is used or not.

### Spatial Correlation of As-Built Pile Length

Fig. 12 shows the semivariograms of as-built pile lengths for the data from the individual blocks. The semivariograms in Fig. 12 level off at separation distances between 10 and 40 m, showing that the as-built pile length data are stationary. Similarly, the autocorrelation functions for these data sets are shown in Fig. 13. Fig. 14 shows the semivariogram and autocorrelation function for as-built pile lengths when the data from all the four blocks are considered. The scales of fluctuation are also obtained through fitting the autocorrelation functions. The estimated scales of fluctuation of as-built pile length when kriging is used are shown in Table 6. The scales of fluctuation are more variable from block to block for as-built pile lengths than for static pile lengths when kriging is used. The scales of fluctuation of as-built pile length are, in general, longer than those of static pile length when kriging is used. Unlike in the case of static pile lengths (Fig. 11), the semivariogram of as-built pile lengths considering the data from all four blocks exhibits a clear peak at a separation distance of around 40 m, and the scale of fluctuation is estimated as 34.9 m. This value of scale of fluctuation is larger than those obtained using the data from the individual blocks. Hence, a size effect on

**Table 6.** Scales of Fluctuation of Static and As-Built Pile Lengths

| | Static pile length (m) | | As-built pile length (m) | |
|---|---|---|---|---|
| | With kriging | Without kriging | With kriging | Without kriging |
| Block 2 | 13.1 | 9.5 | 16.0 | 9.2 |
| Block 3 | 10.6 | 5.1 | 17.0 | 7.7 |
| Block 5 | 11.2 | 4.3 | 10.2 | 6.7 |
| Block 7 | 11.6 | 13.6 | 20.6 | 9.6 |
| All four blocks | N/A | 10.7 | 34.9 | 9.8 |

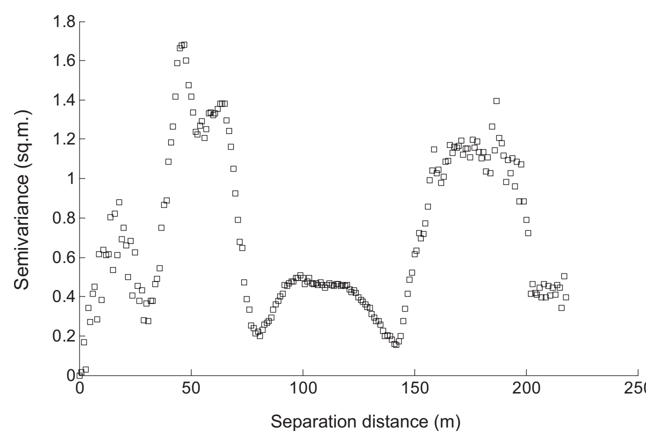


**Fig. 11.** Semivariogram for static pile length using the data of Blocks 2, 3, 5, and 7 together

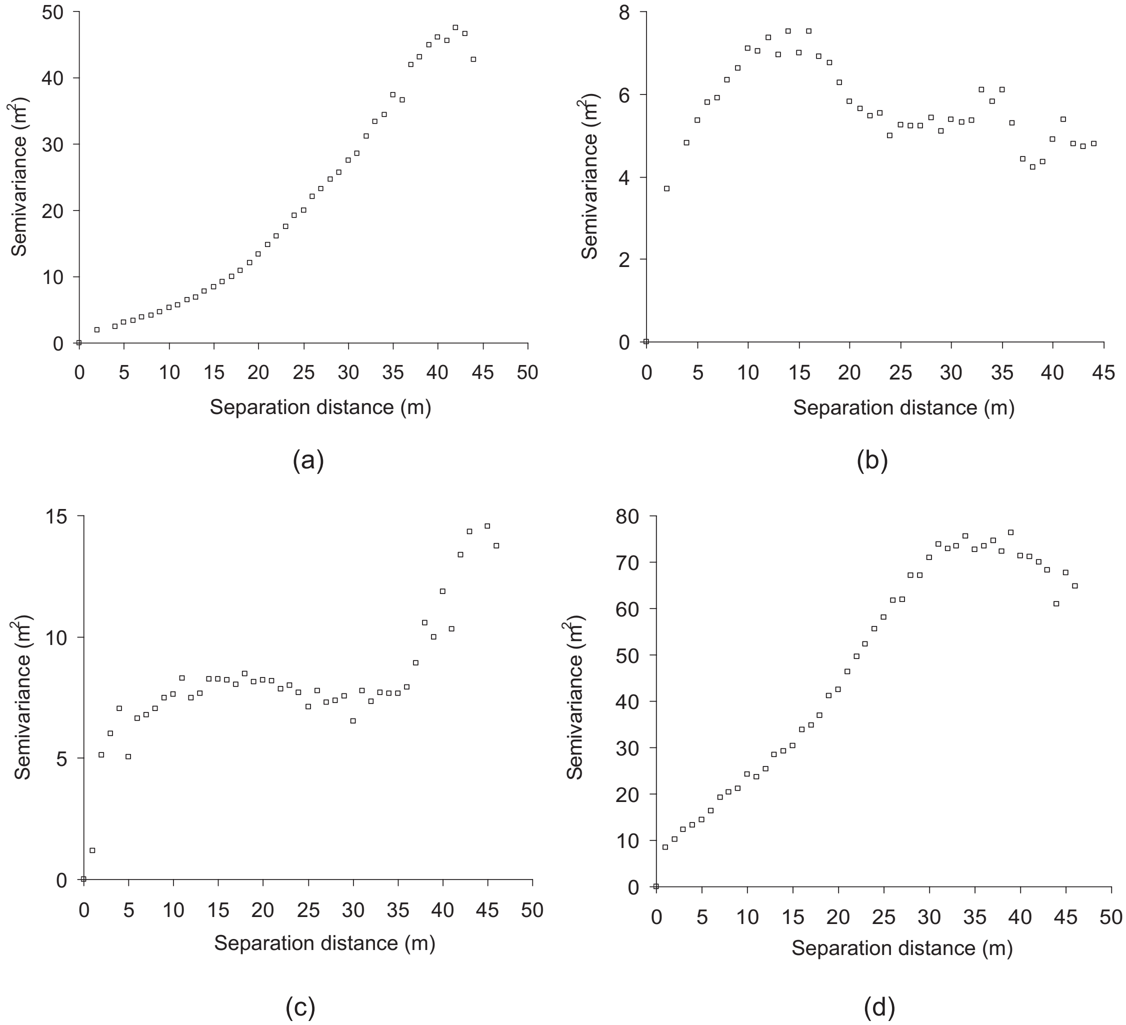


**Fig. 12.** Semivariograms for as-built pile length using the data of (a) Block 2; (b) Block 3; (c) Block 5; and (d) Block 7

the estimation of scale of fluctuation cannot be ruled out. Further study in this direction will be useful to support the dependency of correlation scales on the sample size.

Spatial correlation characteristics of as-built pile lengths are also estimated using the measured pile lengths alone without using kriging (a second procedure), as adopted for the static pile length. The results obtained are also presented in Table 6. The scale of fluctuation of as-built pile length is on the order of 20 m when kriging is used and 10 m when kriging is not used. The first procedure (using kriging) produced longer scales of fluctuation for both the individual blocks and all four blocks combined when compared to the second procedure (without kriging). The data used in the first procedure are regularly spaced and the spacing of individual data points is 1 m. However, in the second procedure only the available data are considered, neglecting the missing data; hence, the data used in the analysis are not regularly spaced. The possible reasons for the longer scales of fluctuation obtained in the former procedure may be due to the effect of spacing of individual data points. The kriged data are spaced at 1 m. However, the minimum spacing of as-built piles is 1.575 m in Blocks 2 and 3, 1.45 m in Block 5, and 1.5 m in Block 7.

Phoon and Kulhawy (1999) and many others reported values of horizontal scale of fluctuation of some geotechnical properties in the range of 3–80 m or larger. Gambino and Gilbert (1999) indicated the possibility of a horizontal correlation distance as large as 1,980 m for offshore clays. However, these values should not be compared directly with the scales of fluctuation of the pile lengths in this paper because geotechnical profiles are only one of the factors that govern the pile lengths.

## Uncertainties in Geologic Profiles versus Variability in Pile Founding Depth

The spatial variability of the geologic profiles and the pile founding depths can be represented by their respective sample variances and scales of fluctuation. The results in Table 3 and Figs. 5 and 6 show that the average as-built founding depths are mostly between the SPT-200 profile and the Grade-III granite profile. Particularly, the results in Table 4 show that the variances of depth of SPT-200 are similar to those of as-built pile length. The good relation between the SPT-200 profile and as-built pile lengths is due to the similarity of the SPT test and the pile driving operation, both involving dropping weights and measuring set. In fact, a SPT blow count of 200 blows/300 mm corresponds to a final set of 15 mm/10 blows, which is similar to the final set determined using Hiley's formula for most of the piles at the study site. Fig. 15 shows the allowable sets and actual final sets of 1,408 piles at the study site. The average pile length is 54.9 m. The actual final sets are in the range of 1 to 44 mm/10 blows, with

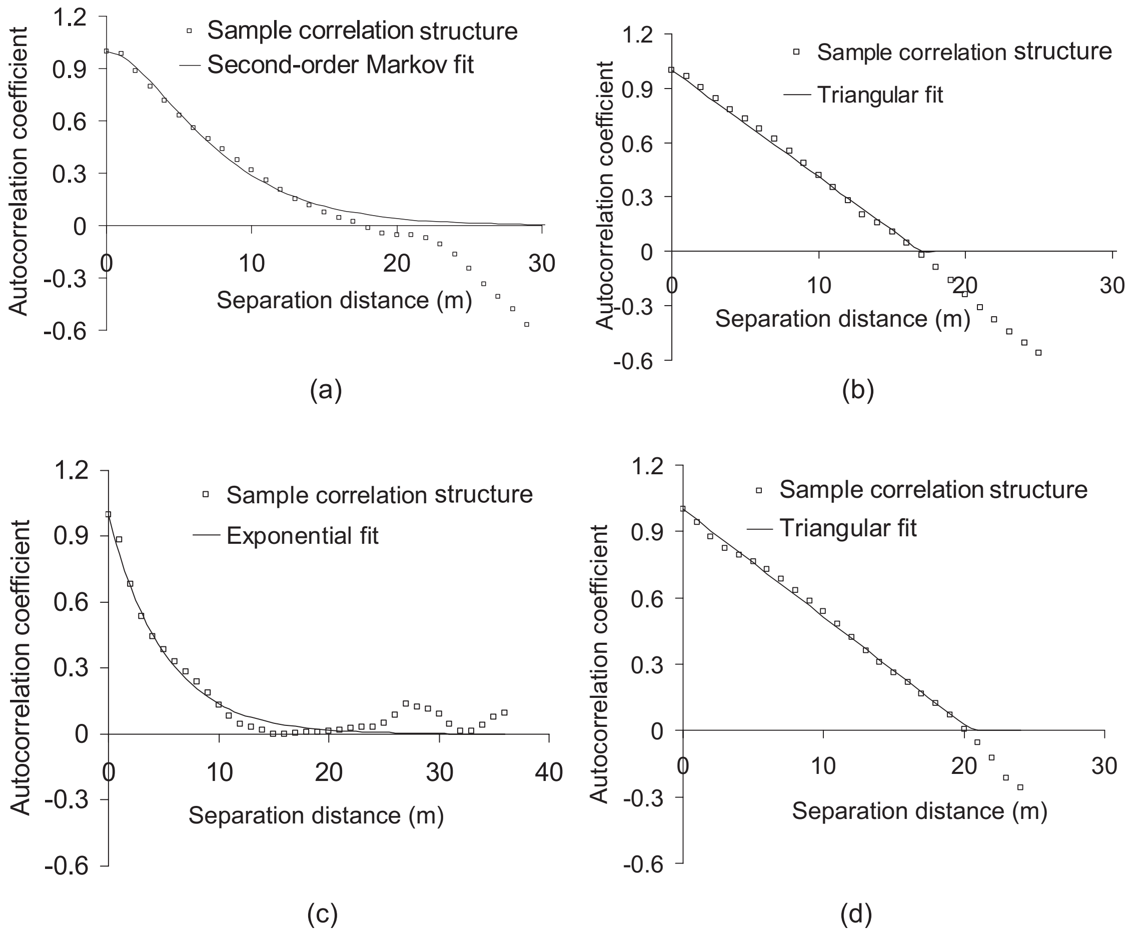


**Fig. 13.** Autocorrelation functions for as-built pile length using the data of (a) Block 2; (b) Block 3; (c) Block 5; and (d) Block 7

a mean value of 13.8 mm/10 blows, which is close to 15 mm/10 blows.

The scales of fluctuation for the as-built founding depths (Table 6), calculated either with kriging or without kriging, are, however, significantly smaller than those for the SPT-200 profile and the Grade-III granite profile shown in Table 5. In other words, the fluctuations in the as-built founding depth are much larger than the fluctuations in the geologic features of the ground. A question then arises: what causes the added fluctuations in as-built pile lengths over those in geologic profiles? For the driven steel H piles at this construction site, the design model errors, judgment error, and construction effects have contributed to the added uncertainties. The three aspects of uncertainty are discussed in the following.

The final length of each working pile was determined on site using primarily Hiley's formula or its variations based on hammer energy, measured set, and measured elastic rebound values. Ideally, a pile should be driven to the depth at which the calculated pile capacity using Hiley's formula based on the set and elastic rebound values is equal to the required capacity. The formula is known to be on the safe side for the long piles at this site. Based on a comparison between predicted capacity values and measured

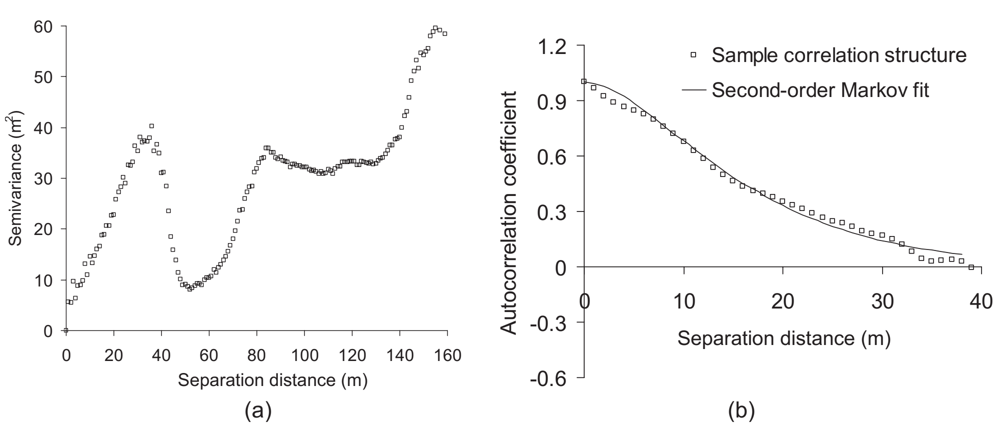


**Fig. 14.** (a) Semivariogram and (b) autocorrelation function for as-built pile length using the data of Blocks 2, 3, 5, and 7 together

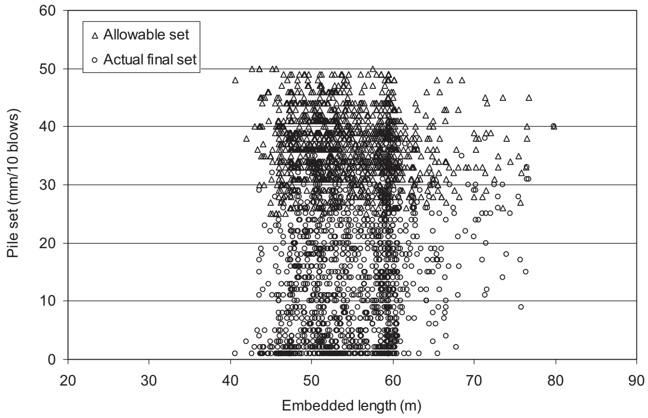


**Fig. 15.** Allowable sets and actual final sets of 1,408 piles at the study site

capacity values from static load tests on 31 cases of steel H piles of 31–87 m long in similar weathered soil grounds, the mean of the ratio of measured capacity to predicted capacity (i.e., the model bias factor) is 1.57 and the coefficient of variation of the ratio is 0.28 (Zhang et al. 2006b). Due to the large model error, the final founding depths or as-built pile lengths based on the formula are on average longer than necessary. Human judgment error on the final set introduced additional conservatism during the final driving process. At the study site, a large number of piles were driven in a sequence and the final set tests on these piles were carried out later in a batch. A particular pile was usually subject to a sequence of blows without its final set exactly known. The contractor would drive the pile to a small set so that it would normally pass the final set test performed sometime later. As a result, the actual final set values were smaller than the allowable set values. Fig. 15 compares the allowable sets and the actual final sets of 1408 piles at the study site. The mean actual final set is 13.8 mm/10 blows, which is substantially smaller than the mean allowable set of 36.7 mm/10 blows. Such error from human judgment, compounded with the model error, led to even greater pile lengths.

Assumptions in the static analysis could distort the correspondence between depths of geologic profiles and pile founding depths. The friction angle values interpreted using the Schmertmann methods based on effective overburden stress and SPT blow count are mostly larger than 35°. Yet in the calculation of the toe resistance, the friction angle is capped at 35°. Hence the uncertainty in the shear strength of the soil at great depths is largely ignored and the resulting variance of static pile length is much smaller than the variances of the depths of SPT-200 and Grade-III profiles (Table 4). The spatial variation of static pile length therefore does not reflect well the geologic profile at the founding depth. The capping of the soil friction angle to 35° in estimating the toe resistance and the use of a coefficient of lateral earth pressure of $1.25K_0$ in estimating the shaft resistance also results in an underestimation of the pile capacity. A calibration against the static load test results reported by Shek (2005) reveals that the static analysis method is associated with a model bias factor of 1.51 and a coefficient of variation of 0.26. It should be noted, however, that errors in the static analysis contributed little to the variability of the as-built pile lengths for the project concerned. This is because, as shown in Fig. 5, the static pile lengths are, in most cases, shorter than the pile lengths determined using the dynamic formula during construction; hence the results of the static analysis did not control the design and construction.

Construction effects, i.e., setup effects, predrilling, and ground vibrations, involved in the study site also altered the correspondence between depths of geologic profiles and pile founding depths. Although the final set tests were most often performed at the end of driving, many tests were performed after irregular intervals. The capacity of the pile at the time of the restrike test would often be greater than that at the end of driving. Dynamic tests with a 55.9-m-long steel H pile (Shek et al. 2006) show that, under identical impact energy, the set value changed from 32 mm/10 blows at the end of driving to 22, 8, and 1 mm, respectively, 3, 14, and 35 days after the end of driving. The founding depth was therefore affected by the setup effect. It is well known that the pile capacity depends on the shearing behavior at the pile-soil interface. Construction processes that significantly alter the properties at and near the interface can greatly weaken the correspondence between geologic profiles and pile founding depths. At the study site, predrilling was applied where boulders were encountered during pile driving. This involved extracting the pile, drilling through the boulders, backfilling the hole with sand, and driving the pile again through the backfill. The shaft resistance in the backfill was believed to be smaller than in the in situ soils and therefore a slightly longer pile length would be required. Additionally, extraction of a long pile was sometimes assisted with a vibrator. The strong vibration disturbed the surrounding piles under installation and caused larger sets of these piles upon restrikes shortly after the pile extraction. It therefore resulted in longer pile lengths.

The uncertainties of as-built depth brought about during construction are significant but are harder to quantify than the geologic uncertainties. Presently, methodologies are available to separate model uncertainty and parameter uncertainty from the total prediction uncertainty (e.g., Zhang et al. 2009). Further research is needed to separate the uncertainty components in the as-built pile lengths inherent in the many steps of the design and construction processes.

## Summary and Conclusions

The spatial correlation characteristics of static and as-built pile lengths are studied in this paper using the data obtained from a weathered soil ground and these characteristics are compared with those of three geologic profiles at the same site. The following conclusions are derived:

1. The founding depths of piles are largely confined by the geological profiles. The average as-built depths are mostly between the SPT-200 profile and the Grade-III granite profile. The variances of as-built pile length are similar to those with depth of SPT-200 but less than those with depth of Grade-III granite. The standard deviation of as-built pile length tends to increase with the mean pile length and the coefficient of variation is on the order of 4–12%. The good relation between the SPT-200 profile and as-built pile lengths is due to the similarity of the SPT test and the pile driving operation, both involving dropping weights and measuring set.
2. The scale of fluctuation of as-built pile length is on the order of 20 m when kriging is used and 10 m when kriging is not used. The scale of fluctuation of static pile length is on the order of 10 m whether kriging is used or not. These scales of fluctuation are less than those with depth of SPT-200 (on the order of 20–45 m) and far less than those with depth of

Grade-III granite (on the order of 80–140 m).

3. The correspondence between the pile founding depths and the depths of geologic profiles is distorted by design model errors, human judgment error, and construction effects. The model errors of the dynamic formula and the static analysis, the judgment error during the final stage of pile driving, and the setup and ground vibration effects involved at the study site are discussed. These sources of errors add uncertainty to the as-built pile lengths and generally lead to unnecessarily long piles. For the construction site investigated, the mean actual final set of 13.8 mm/10 blows is substantially smaller than the mean allowable set of 36.7 mm/10 blows, and the as-built lengths are on average 7% longer than the static pile lengths. However, various uncertainty components in the as-built pile lengths have not been separated in this study.
4. The scales of fluctuation of both static and as-built pile lengths are greater when kriging is used. The data from the whole site exhibit a longer scale of fluctuation than those obtained using the data from the individual blocks. Hence, a scale effect on the scale of fluctuation cannot be ruled out. However, when kriging is not employed, such a size effect is not found in the estimated scales of fluctuation of pile lengths.

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