

# Characterization and Estimation of Geotechnical Variability in Ankara Clay: A Case History

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**Abstract** An important component in reliability-based design is the geotechnical property variability. Generic estimates are used often, but calibration to a local geologic setting is preferable. In this case history, a methodology is shown that employs local geotechnical data to estimate the total variability, using Ankara Clay for illustration. A literature review is used to estimate the inherent variability, which is modeled as a random field with coefficient of variation (COV) and scale of fluctuation. The resulting inherent variability COVs are much smaller than the generic ranges. Local correlations between various laboratory and field tests and soil strength and compressibility parameters then are developed to quantify the transformation uncertainties. The various sources of uncertainty are combined through a second-moment method to estimate the total geotechnical variability as a function of the test type and correlation used. The results show: (1) the COVs for direct laboratory measurements are significantly smaller than those obtained through correlations, and (2) depending on the geotechnical data available, the local COVs can be

very different from the generic guidelines. These could lead to unconservative designs. These issues are illustrated by a simple design example.

**Keywords** Ankara Clay · Reliability-based design · Geotechnical variability

## 1 Introduction

Geotechnical engineers are well aware of the existence of many sources of uncertainties within the design process. Traditional geotechnical design uses a factor of safety (FS) to reduce the possibility of adverse system performance, and typical values between 2 and 3 are used in conventional foundation engineering applications. However, the selection of a FS is essentially subjective, requiring only a global appreciation of design aspects such as method of analysis, method of property evaluation, and the inaccuracies in the design equations against the backdrop of previous experience (Kulhawy and Phoon 1996). As a result, based on how the design models and parameters are selected, the same FS might imply very different levels of risk, which is undesirable.

For geotechnical engineering applications, it is difficult, if not impossible, to maintain a consistent level of adverse performance risk without a theoretical framework that recognizes, quantifies, and manipulates uncertainties explicitly. This framework can be

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constructed through reliability-based design (RBD) that is formulated in the language of probability theory. However, in geotechnical practice, there has been rather slow progress in employing RBD, compared to other engineering disciplines (e.g. Phoon and Kulhawy 1999b). A primary reason for this slow progress is the difficulty in estimating the variability of the design properties of geo-materials, which is essential for any RBD procedure (e.g. Phoon et al. 1995).

Geotechnical variability is complex and results from various sources. The three primary sources are: (1) inherent soil variability, (2) measurement error, and (3) transformation uncertainty (e.g. Kulhawy 1992). To evaluate these sources consistently, Phoon and Kulhawy (1999a, b) established a general framework and recommended a specific methodology to evaluate these sources and to integrate them into the total variability that would be used in RBD. Information from many sources and specific correlation models were used in this process, resulting in generic guidelines for total variability.

Generic guidelines such as these are useful as first-order approximations on the probable ranges of soil property COVs, and they have been employed in many recent RBD applications (e.g. Chalermyanont and Benson 2005; Huang and Wang 2007; Haldar and Babu 2008; Cassidy et al. 2008; Babu et al. 2006). However, more optimal results can be achieved in RBD applications by using local data, because the sources of variability, especially the inherent soil variability, are related to a particular soil type and a specific regional geology. In addition, there is widespread use of empirical correlations that relate field measurements with design soil properties, all of which have significant uncertainties. Accordingly, selection of the correlation equation will influence the transformation uncertainty. Again, local correlations should be preferred.

This paper provides a case history example of how local geotechnical data can be used effectively to estimate the total variability for input into RBD. The Phoon and Kulhawy (1999a, b) framework is used to characterize and estimate the geotechnical property variability for Ankara Clay (an obvious choice for the first author), which has a rather heterogeneous character (Kasapoglu 2000) and significantly varying engineering properties (Aras et al. 1991). First, the inherent variability is estimated based on extensive

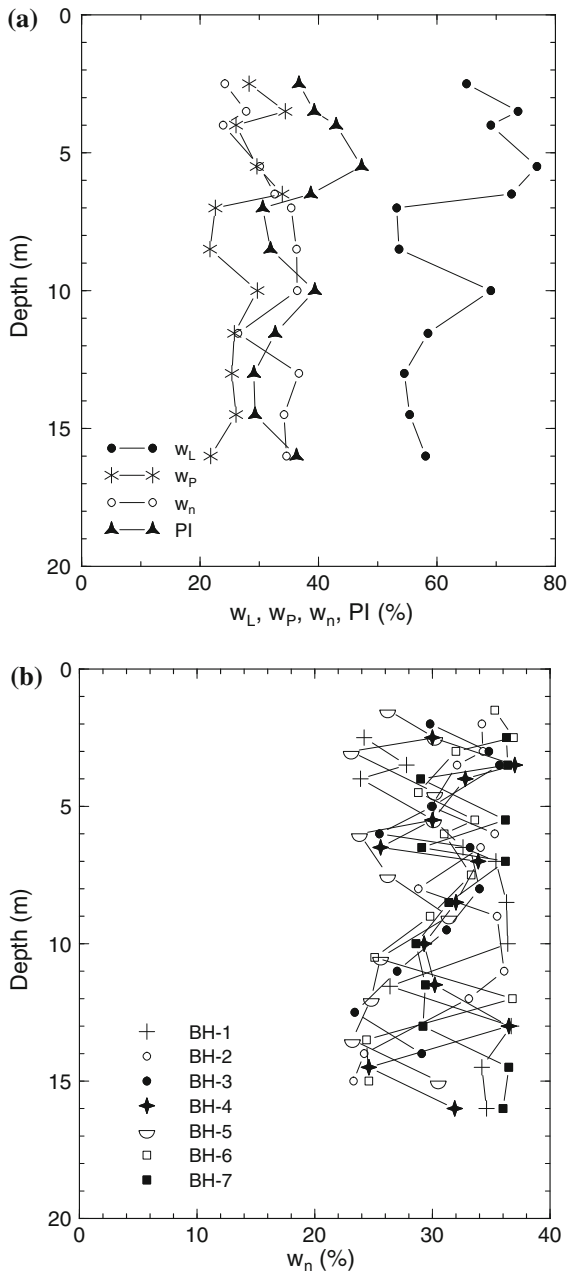
review of the literature on Ankara Clay, and then it is modeled as a random field that is defined by the coefficient of variation (COV) and scale of fluctuation. Second, the transformation uncertainty is quantified through local correlations specifically developed for Ankara Clay. Third, a first-order second-moment probabilistic approach is used to combine these uncertainties consistently, including the generic values of measurement error, for determining the total variability for selected design soil properties of Ankara Clay. Finally, the results are compared with generic COVs suggested in the literature to illustrate the overall merit of local calibrations. The implications of using local data in RBD are demonstrated by a simple design example.

## 2 Brief Review of Geotechnical Properties of Ankara Clay

The Ankara Basin trends approximately ENE-WSW, is 18–20 km long, and is a 6–8 km wide depression bounded by a series of highlands. The soils filling this basin are fluvial red clastics of Late Pliocene age and Quaternary alluvial deposits (Erguler and Ulusay 2003). The sedimentary sequence in the basin consists mainly of debris-flow conglomerate, wedge to through cross-bedded conglomerate-sandstone, and finer reddish-brown clastics resulting from alluvial fan, braid plain, and flood plain deposits, respectively (Kocyigit and Turkmenoglu 1991). The finer reddish-brown clastics are referred to in Turkish geotechnical studies as “Ankara Clay” (Ordemir et al. 1965).

About two-thirds of the Ankara settlement area, with about three million inhabitants, is sitting on Ankara Clay (Tonoz et al. 2003). This clay is composed of clayey, sandy, and gravelly levels of variable thicknesses; locally, at shallow depths, there are very thin lime levels, lime nodules, and concretions within clayey levels from lenses with no lateral continuity (Erguler and Ulusay 2003). Erol (1973) reported that the thickness of this clayey sequence changes locally, but it exceeds 200 m. Ordemir et al. (1965) described Ankara Clay as an inorganic, preconsolidated clay, with natural water content ( $w_n$ ) and plastic limit ( $w_p$ ) ranging between 20 and 35%, and liquid limit ( $w_L$ ) ranging between 55 and 75%. The shrinkage limit varies between 15 and 20%. Surgel (1976) indicated a plasticity index (PI) range

of 20 to 40%, which suggests high plasticity. The unit weight ranges between 17.5 and 19.5 kN/m<sup>3</sup>, and the specific gravity is between 2.60 and 2.70 (Ordemir et al. 1965). Figure 1a illustrates the typical vertical spatial variability for some geotechnical index properties of Ankara Clay, using data from a single



**Fig. 1** Typical spatial variability with depth for some geotechnical properties of Ankara Clay: **a** data from a single borehole; **b** data from seven boreholes in close proximity at a single site

borehole, while Fig. 1b illustrates this variability in the natural water content for seven boreholes in close proximity at a single site. Both figures exhibit significant spatial variability.

The steady increase in population, as a result of migration from rural areas to the city of Ankara, has necessitated the construction of many engineering works on or within this overconsolidated clay with high swelling potential. Because of the significant variation in the geotechnical properties of Ankara Clay, there has been wide variation in the performance of foundation excavations and cut slopes (Teoman et al. 2004). The majority of published studies on the geotechnical properties of Ankara Clay have focused on the swelling characteristics (e.g. Birand 1963; Ordemir et al. 1965; Doruk 1968; Omay 1970; Uner 1977; Furtun 1989; Cokca 1991; Erguler and Ulusay 2003; Tonoz et al. 2003), or its potential use as a landfill liner (Sezer et al. 2003; Met and Akgun 2005). In contrast, this paper contributes to a thorough and quantitative assessment of the uncertainties in key index and performance properties of Ankara Clay.

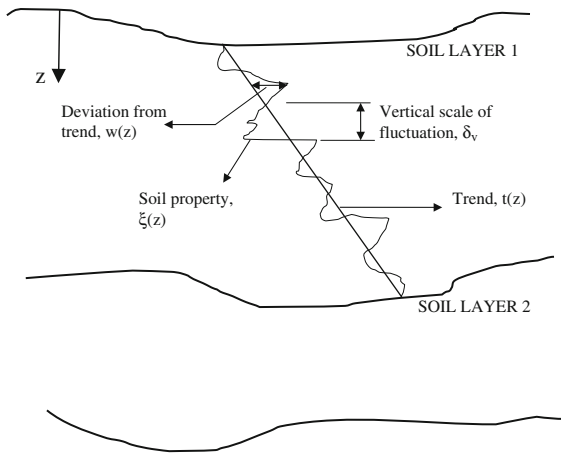
### 3 Inherent Variability of Ankara Clay

#### 3.1 Random Field Model for Inherent Soil Variability

Inherent variability results primarily from the natural geologic processes that produced and continually modify the soil mass in situ (Kulhawy 1992). This spatial variation, illustrated in Fig. 2, can be decomposed conveniently into a smoothly varying trend function  $t(z)$  and a fluctuating component  $w(z)$  as follows (Phoon et al. 1995):

$$\xi(z) = t(z) + w(z) \tag{1}$$

in which  $\xi$  = in situ soil property and  $z$  = depth. The inherent soil variability can be represented by the fluctuating component, if  $w(z)$  is modeled as a homogeneous random field, as suggested by Vanmarcke (1983). To be homogeneous, the mean and variance of  $w(z)$  should be constant with depth, and the correlation between  $w(z)$  at two different depths should be a function only of their separation distance, rather than their absolute positions (Vanmarcke 1983). A constant mean of  $w$  equal to zero can be obtained if the data are detrended. The correlation as



**Fig. 2** Inherent soil variability (Modified from Phoon et al. 1995)

a function of separation distance is generally satisfied for data from a homogeneous soil layer (Phoon et al. 1995). The standard deviation of inherent soil variability ( $s_w$ ) is calculated as:

$$s_w = \sqrt{\frac{1}{n-1} \sum_{i=1}^n [w(z_i)]^2} \quad (2)$$

in which  $n$  = number of data points and  $w(z_i)$  = fluctuation at depth  $z_i$ . If the standard deviation is normalized with respect to the trend, a dimensionless property is obtained (Vanmarcke 1983):

$$\text{COV}_w = s_w/t \quad (3)$$

in which  $\text{COV}_w$  = coefficient of variation of inherent variability.

The vertical scale of fluctuation ( $\delta_v$ ) or correlation distance, which is the distance within which the soil property shows strong correlation, also is required to model inherent variability. Vanmarcke (1977) introduced the following approximation to estimate  $\delta_v$ :

$$\delta_v \approx 0.8d^1 \quad (4)$$

in which  $d^1$  = average distance between the points where the fluctuating soil property and its trend function have equal values along the soil profile.

### 3.2 COV of Inherent Soil Variability for Ankara Clay

An extensive literature review was conducted to estimate the COV values of inherent soil variability

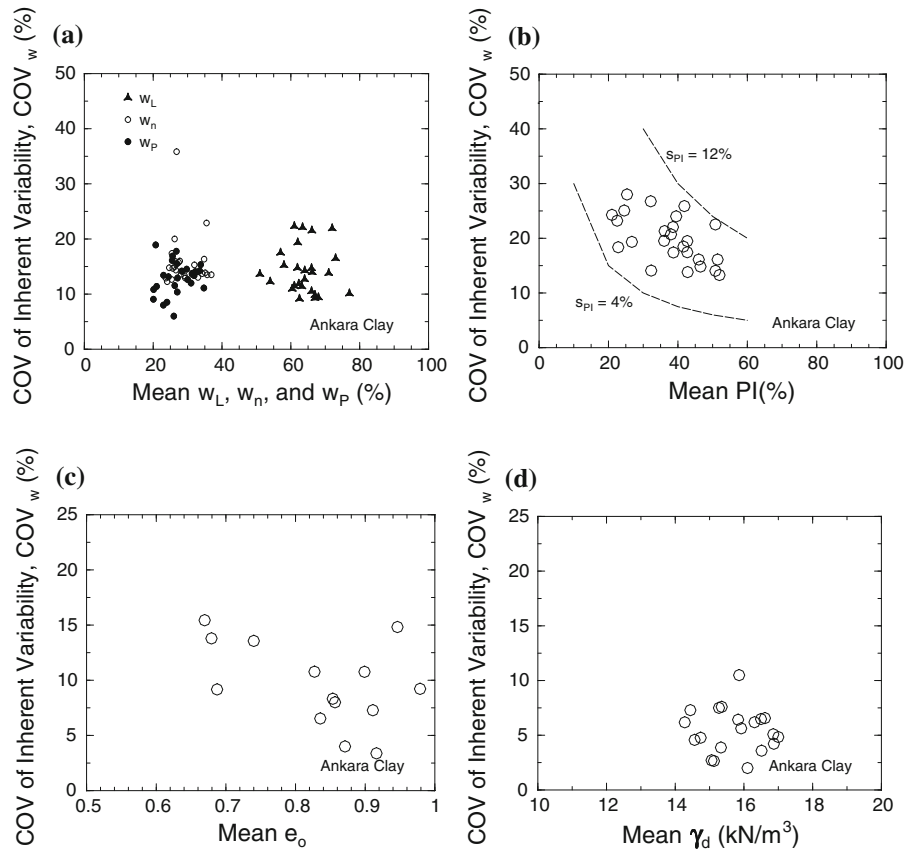
for Ankara Clay. However, in this process, it is not possible to remove completely the interference from other sources of uncertainty (Phoon and Kulhawy 1999a); therefore, larger COVs than those of the actual inherent soil variability can be obtained. The extraneous sources of uncertainty were minimized by considering data from a single geologic unit and applying linear detrending to all data sets that exhibit an obvious trend. Since it is reasonable to assume that measurement errors and the effect of time on the soil properties are minimal for soil data obtained in research programs, where good equipment and procedural controls are likely to be maintained (Orchant et al. 1988), all data used herein were extracted from research studies. It is not possible to remove the extraneous uncertainties completely, especially those associated with time (Reyna and Chameau 1991), from the inherent soil variability. Therefore, it is clear that all of the  $\text{COV}_w$  values herein should be considered as upper bounds for inherent variability.

#### 3.2.1 Liquid Limit, Plastic Limit, and Natural Water Content ( $w_L$ , $w_P$ , and $w_n$ )

Figure 3a shows the COV of inherent variability ( $\text{COV}_w$ ) for  $w_L$ ,  $w_P$ , and  $w_n$  of Ankara Clay plotted against the mean of these values, as obtained from the literature review. No trend of  $\text{COV}_w$  with the mean is present. For  $w_L$  and  $w_P$ ,  $\text{COV}_w$  ranges between 9 and 22%, and 6 and 19%, respectively. If the single outlier is removed, the corresponding range for  $w_n$  is between 12 and 22%. These values are within the typical ranges suggested by Phoon and Kulhawy (1999a) for  $\text{COV}_w$  of these soil properties.

#### 3.2.2 Plasticity Index (PI)

Values of  $\text{COV}_w$  for PI are plotted versus the mean PI in Fig. 3b. Although the data are limited, there is a trend of decreasing  $\text{COV}_w$  with increasing mean PI, which is consistent with the findings of Phoon and Kulhawy (1999a). This trend is bounded approximately by a constant standard deviation range between 4 and 12%, which also was suggested by Phoon and Kulhawy (1999a) using a larger database of various soil types. Note that, if the trend in the data is neglected, the range of  $\text{COV}_w$  for PI can be given as between about 13 and 28%.



**Fig. 3** COV of inherent variability versus mean of  $w_L, w_n, w_p, PI, e_o,$  and  $\gamma_d$  for Ankara Clay

### 3.2.3 In Situ Void Ratio ( $e_o$ ) and Dry Unit Weight ( $\gamma_d$ )

The  $COV_w$  values for  $e_o$  and  $\gamma_d$  are plotted versus the mean  $e_o$  and  $\gamma_d$  in Fig. 3c and d, respectively. For both, the data do not suggest any obvious trend. For  $e_o$ , the range of  $COV_w$  is between about 3 and 16%. The range of  $COV_w$  is between 2 and 8% for  $\gamma_d$ , if the single outlier is neglected.

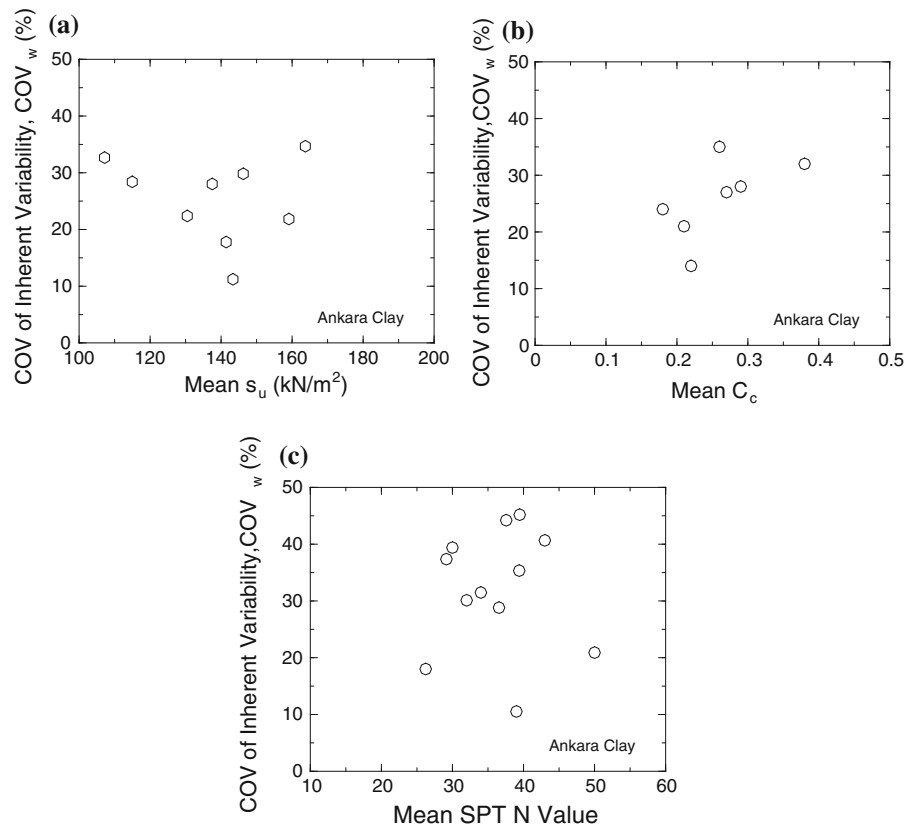
### 3.2.4 Undrained Shear Strength ( $s_u$ ), Compression Index ( $C_c$ ), and Standard Penetration Test $N$ Value

The published data that can be used to evaluate the  $COV_w$  for  $s_u, C_c,$  and SPT  $N$  value are very limited. As shown in Fig. 4, the  $COV_w$  ranges from 11 to 35%, 14 to 35%, and 10 and 46% without any trend for  $s_u, C_c,$  and SPT  $N$ , respectively.

### 3.2.5 Comparison of Generic and Local Inherent Variability

Table 1 summarizes the inherent variability data for the geotechnical properties described above. Comparable data from the literature for various fine-grained soils are given in Table 2. A comparison of the mean of  $COV_w$  ranges in these tables shows that, except for  $C_c$ , the inherent variability  $COV_w$  values for Ankara Clay are consistently smaller than the “generic” guidelines. In addition, except for  $C_c$  and SPT  $N$  value, the ranges of  $COV_w$  given in Table 1 are significantly narrower than the generic ranges. This result shows the possible advantage of developing and using statistics for a specific soil type in RBD. Note that the  $COV_w$  range for  $C_c$  given in Table 2 includes only two local soil types, Bangkok and Gulf of Mexico Clays, both of which are relatively homogeneous. This fact is the probable reason for the comparable  $COV_w$  values of  $C_c$  given in Tables 1 and 2.

**Fig. 4** COV of inherent variability versus mean of  $s_u$ ,  $C_c$ , and SPT  $N$  for Ankara Clay



**Table 1** Inherent variability of some geotechnical properties of Ankara Clay

Property	No. of data groups	No. of tests per group	Property value		Property COV <sub>w</sub> (%)	
			Range	Mean	Range	Mean
$w_L$ (%)	25	4–24	50–79	64	9–22	14
$w_P$ (%)	25	4–25	20–35	26	6–19	12
$w_n$ (%)	26	4–18	23–37	29	12–22	14
PI (%)	25	4–24	21–52	38	13–28	19
$e_o$	14	4–25	0.65–0.98	0.84	3–16	9
$\gamma_d$ (kN/m <sup>3</sup> )	20	3–12	14–17	15.8	2–8	5
$s_u$ (kN/m <sup>2</sup> )	9	4–8	106–186	148	11–35	23
$C_c$	7	3–8	0.18–0.38	0.26	14–35	26
SPT $N$	12	6–31	23–60	38	10–46	29

#### 4 Vertical Scale of Fluctuation for Geotechnical Properties of Ankara Clay

Where possible, the vertical scale of fluctuation of the geotechnical properties was estimated using Eq. 4, after fitting the data with a linear trend function. Values of the vertical scale of fluctuation

for the liquid limit, natural water content, undrained shear strength, and SPT  $N$  value of Ankara Clay are given in Table 3. Also shown are values for clay soils in general, as given by Phoon et al. (1995). Although the data are limited, the results obtained herein are comparable to those reported by others.

**Table 2** Inherent variability of geotechnical properties for fine grained soils (compiled from Phoon et al. 1995; Lacasse and Nadim 1996; Baecher and Ladd 1997; Zhu et al. 2001)

Property	No. of data groups	No. of tests per group	Property COV <sub>w</sub> (%)	
			Range	Mean
w <sub>L</sub> (%)	38	15–299	7–39	18
w <sub>P</sub> (%)	23	32–299	6–34	16
w <sub>n</sub> (%)	40	17–439	7–46	18
PI (%)	33	15–299	9–57	29
e <sub>o</sub> (all soil types)	–	–	7–30	–
γ <sub>d</sub> (kN/m <sup>3</sup> )	8	4–315	2–13	7
s <sub>u</sub> (kN/m <sup>2</sup> )	42	24–124	6–80	32
C <sub>c</sub> , C <sub>r</sub>	–	–	20–28	–
SPT <i>N</i>	2	2–61	37–57	44

**Table 3** Vertical scale of fluctuation values for Ankara Clay

Property	No. of data groups	Scale of fluctuation (m)		
		Range	Mean	Mean for clays <sup>a</sup>
w <sub>L</sub>	2	4.0–6.2	5.1	5.7
w <sub>n</sub>	2	2.5–5.5	4.0	5.2
s <sub>u</sub>	4	1.0–3.0	2.0	2.5
SPT <i>N</i>	2	3.0–3.8	3.4	2.4

<sup>a</sup> Mean scale of fluctuation values reported by Phoon et al. (1995) for clays in general

### 5 Measurement Error

Measurement error enters the determination of soil properties through equipment, procedural-operator, and random testing effects (Phoon and Kulhawy 1999a). Lumb (1971) and Orchant et al. (1988) proposed the following simple model to describe the total variability of a measured soil property (ξ<sub>m</sub>):

$$\xi_m(z) = \zeta(z) + e(z) \tag{5}$$

in which *e* = measurement error. Using  $\zeta$  given by Equation 1, the following is obtained:

$$\xi_m(z) = t(z) + w(z) + e(z) \tag{6}$$

Note that, by definition, the measurement error (*e*) is not caused by the inherent soil variability (*w*), and therefore they are assumed to be uncorrelated (e.g., Lumb 1971; Baecher 1985; Filippas et al. 1988; Kulhawy et al. 1992; Phoon et al. 1995).

In principle, measurement errors can be estimated by quantifying the variations in repeated measurements of the same property on identical soil samples. For laboratory tests, very few studies of this kind can be found in the literature (e.g. Hammitt 1966; Johnston 1969; Sherwood 1970; Singh and Lee 1970; Minty et al. 1979); these results have been compiled by Phoon et al. (1995). For field tests, Kulhawy and Trautmann (1996) conducted a detailed analysis of the measurement error. Table 4 summarizes the COV of the measurement error (COV<sub>e</sub>) for properties of interest herein. Studies of measurement error are beyond the scope of this paper, so “generic” values are used herein.

### 6 General Framework for Estimating Geotechnical Property Variability of Ankara Clay

For directly measured laboratory or field test properties, the inherent variability and measurement error are the only sources of uncertainty that need to be addressed in the design process. Some examples of these properties are the undrained shear strength (s<sub>u</sub>) measured in triaxial tests, effective stress friction angle (φ') measured in direct shear or triaxial tests, and in situ horizontal stress coefficient (K<sub>o</sub>) measured by the self-boring pressuremeter test. However, many geotechnical properties are estimated from laboratory indices or measurements or from other types of field measurements. This process introduces the third source of uncertainty, transformation error, which occurs where



**Table 4** Measurement error of some laboratory and in situ tests (simplified from Phoon et al. 1995 and Kulhawy and Trautmann 1996)

Property	No. of data groups	No. of tests per group	Property value		Property COV (%)	
			Range	Mean	Range	Mean
$w_L$ (%)	26	41–89	17–113	36	3–11	7
$w_P$ (%)	26	41–89	12–35	21	7–18	10
$w_n$ (%)	3	82–88	16–21	18	6–12	8
PI (%)	10	41–89	4–44	23	5–51	24
$\gamma$ (kN/m <sup>3</sup> )	3	82–88	16.3–17.4	17.0	1–2	1
$s_u$ (kN/m <sup>2</sup> )	28	–	4–407	–	5–15	–
SPT $N$ value	–	–	–	–	15–45	–

these field or laboratory measurements are transformed into design soil properties using empirical or other correlation models (Kulhawy 1992).

These three sources of uncertainty can be combined consistently using the simple second-moment probabilistic approach suggested by Phoon et al. (1995), which is summarized as follows:

- Assume that the design geotechnical property ( $\xi_d$ ) is predicted using the following transformation function ( $T$ ):

$$\xi_d = T(t + w + e, \varepsilon) \quad (7)$$

in which  $\varepsilon$  = transformation uncertainty.

- Linearizing Eq 7 about the means of ( $w$ ,  $e$ ,  $\varepsilon$ ), which are all equal to zero, and using a first-order Taylor-series expansion (Benjamin and Cornell 1970), the mean ( $m_{\xi_d}$ ) and variance ( $s_{\xi_d}^2$ ) of  $\xi_d$  can be estimated as follows, by applying appropriate second-moment probabilistic techniques:

$$m_{\xi_d} \approx T(t, 0) \quad (8)$$

$$s_{\xi_d}^2 \approx \left(\frac{\partial T}{\partial w}\right)^2 s_w^2 + \left(\frac{\partial T}{\partial e}\right)^2 s_e^2 + \left(\frac{\partial T}{\partial \varepsilon}\right)^2 s_\varepsilon^2 \quad (9)$$

in which  $s_w^2$  = variance of inherent soil variability,  $s_e^2$  = variance of the measurement error, and  $s_\varepsilon^2$  = variance of the transformation error.

- The spatial average of the design property ( $\xi_a$ ) is used often instead of the design property at a point ( $\xi_d$ ). The mean of  $\xi_a$  is the same as that given in Eq. 8, but the variance is given by (Vanmarcke 1983):

$$s_{\xi_a}^2 \approx \left(\frac{\partial T}{\partial w}\right)^2 \Gamma^2(L) s_w^2 + \left(\frac{\partial T}{\partial e}\right)^2 s_e^2 + \left(\frac{\partial T}{\partial \varepsilon}\right)^2 s_\varepsilon^2 \quad (10)$$

in which  $\Gamma^2(\cdot)$  = variance reduction function, which is a function of the averaging interval ( $L$ ) as follows (Vanmarcke 1983):

$$\Gamma^2(L) = 1 \quad (\text{for } L = \delta_v) \quad (11)$$

$$\Gamma^2(L) = \delta_v/L \quad (\text{for } L > \delta_v) \quad (12)$$

Note that the vertical scale of fluctuation ( $\delta_v$ ) was defined in Eq. 4.

## 7 Evaluation of Geotechnical Property Variability in Ankara Clay

In this section, the above probabilistic framework is used to evaluate the total geotechnical variability for some design properties of Ankara Clay. Input values include the previously estimated inherent variability and scale of fluctuation, along with the generic measurement errors given in Table 4. Where required, up-to-date correlation equations between relevant geotechnical properties are developed specifically for Ankara Clay, which then are used to estimate the transformation uncertainty. The methodology is illustrated in detail below for the undrained shear strength, for both the direct laboratory measurement and the correlation with the SPT  $N$  value.

### 7.1 Undrained Shear Strength

#### 7.1.1 Direct Laboratory Measurement

For direct laboratory measurement of undrained shear strength, no transformation model is required, and



therefore Eq. 7 can be expressed as follows:

$$\zeta_d = s_u = t + w + e \tag{13}$$

The mean and variance of  $s_u$  are given as follows, using Eqs. 8 and 9:

$$m_{\zeta_d} = t \tag{14}$$

$$s_{\zeta_d}^2 = s_w^2 + s_e^2 \tag{15}$$

The COV of  $\zeta_d$ , which is defined as  $s_{\zeta_d}/m_{\zeta_d}$ , is given accordingly as:

$$COV_{\zeta_d}^2 = COV_w^2 + COV_e^2 \tag{16}$$

in which  $COV_w$  and  $COV_e = COV$  of inherent variability and measurement error, respectively. Finally, the COV of the spatial average can be obtained similarly from Eq. 10:

$$COV_{\zeta_a}^2 = \Gamma^2(L)COV_w^2 + COV_e^2 \tag{17}$$

The  $COV_w$  for the  $s_u$  of Ankara Clay was estimated to be between 11 and 35%, as shown in Table 1. Table 4 estimates the  $COV_e$  for undrained strength tests to be between 5 and 15%. By substituting these values into Eq. 16, the total point COV ( $COV_{\zeta_d}$ ) for  $s_u$  is calculated to be between 12 and 38%. The typical vertical scale of fluctuation for  $s_u$  was estimated as about 2.0 m for tests on Ankara Clay, as shown in Table 3. For a typical averaging length of 5 m, the amount of variance reduction is 0.4 from Eq. 12. Using these values in Eq. 17 results in a  $COV_{\zeta_a}$  between 8 and 27%.

Note that Phoon et al. (1995) estimated a generic range between 7 and 38% for the spatial average COV of  $s_u$  measured by unconfined compression and unconsolidated-undrained tests. For direct laboratory measurement of undrained shear strength, the use of local data does not result in a change for the lower bound COV; however, the upper bound COV is reduced by more than 10%.

### 7.1.2 Correlation With SPT N Value

Kulhawy and Mayne (1990) noted that a reasonable correlation between the undrained shear strength and the SPT  $N$  value can be achieved, provided the correlation is restricted to one type of geology. Sarigol (1988) compiled SPT  $N$  data along with the corresponding  $s_u$  values for Ankara Clay. These data

were used to develop the local correlation shown in Fig. 5a between  $s_u$ , normalized by the atmospheric pressure ( $p_a$ ), and the SPT  $N$  value. The probabilistic equation for this correlation is:

$$\log(s_u/p_a) = \log(0.17) + 0.58 \log(N) + \varepsilon \tag{18}$$

In exponential form, Eq. 18 becomes:

$$s_u/p_a = 0.17N^{0.58}10^\varepsilon \tag{19}$$

In terms of Eq. 7, Eq. 19 can be rewritten as:

$$\zeta_d = s_u = 0.17p_a(t + w + e)^{0.58}10^\varepsilon \tag{20}$$

in which the main parameter with uncertainty (SPT  $N$ ) is expressed as  $t + w + e$ . The mean and variance of the design parameter are estimated as:

$$m_{\zeta_d} = 0.17t^{0.58} \tag{21}$$

$$s_{\zeta_d}^2 = m_{\zeta_d}^2 \left[ 0.58^2 (COV_w^2 + COV_e^2) + (\ln 10)^2 s_\varepsilon^2 \right] \tag{22}$$

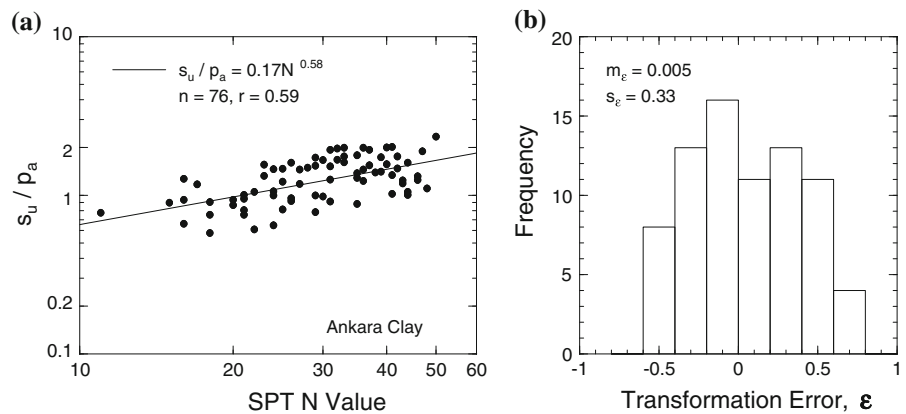
in which  $\ln$  = natural logarithm. The corresponding COV of the spatial average is given as:

$$COV_{\zeta_a}^2 = 0.58^2 [\Gamma^2(L)COV_w^2 + COV_e^2] + (\ln 10)^2 s_\varepsilon^2 \tag{23}$$

The distribution of transformation uncertainty, from the data given in Fig. 5a, is shown in Fig. 5b. The mean of transformation uncertainty ( $m_\varepsilon$ ) is 0.005, which is close to zero, as expected. The standard deviation of the transformation uncertainty ( $s_\varepsilon$ ) is 0.33, which is consistent with the significant dispersion around the correlation equation shown in Fig. 5a. The  $COV_w$  for  $N$  is estimated to be between 10 and 46%, as given in Table 1. The  $COV_e$  is between 15 and 45% in Table 4. Using these data, the total COV ( $COV_{\zeta_d}$ ) of  $s_u$  determined from SPT  $N$  is between 77 and 85%. For Ankara Clay, the vertical scale of fluctuation for  $N$  is about 3.4 m, as shown in Table 3. For an averaging length of 5 m, the amount of variance reduction is 0.68. Using these values in Eq. 23 results in a  $COV_{\zeta_a}$  between 77 and 83%.

Based on data from 25 clay sites in Japan, Phoon et al. (1995) suggested the spatial average COV for  $s_u$  that is estimated from SPT  $N$  to be between 38 and 54%, which is significantly lower than the values obtained herein. Therefore, for  $s_u$  correlated with SPT  $N$ , the use of guidelines developed using data from

**Fig. 5** Correlation between  $s_u/p_a$  and SPT  $N$  value for Ankara Clay and distribution of transformation error



other geologic settings does not allow the whole range of uncertainties to be taken into consideration in the case of Ankara Clay. This may also lead to unconservative results in RBD.

The difference between the  $COV_{\xi_a}$  values determined for the laboratory measured  $s_u$  and  $s_u$  estimated from an SPT  $N$  value is striking. Clearly the correlation between  $s_u$  and  $N$  in Fig. 5 dominates the resulting differences in estimating  $s_u$  variability, expressed as  $COV_{\xi_a}$ . Intuitively, most geotechnical engineers would have more confidence in the laboratory measured undrained shear strength than that obtained using a local correlation with SPT  $N$ , and they would employ a smaller FS for the former case. However, the simple probabilistic framework illustrated above offers an effective tool for the realization of a numerical comparison of expected uncertainties for different levels of information about the subsurface conditions.

## 7.2 Other Geotechnical Properties

For the other geotechnical properties, the evaluation methodology is similar. The input values, correlation equations, and the results are summarized in Table 5. Two examples of the correlations and the corresponding distributions of transformation error are given in Fig. 6.

## 7.3 Implications for Design

Table 5 summarizes the total geotechnical variability range for  $s_u$ ,  $C_c$ , and  $C_s$  in Ankara Clay. The results show that the COVs are relatively small for direct laboratory measurements. However, when these properties are estimated through correlations, the COVs

become quite large, which can have significant design implications, as illustrated below.

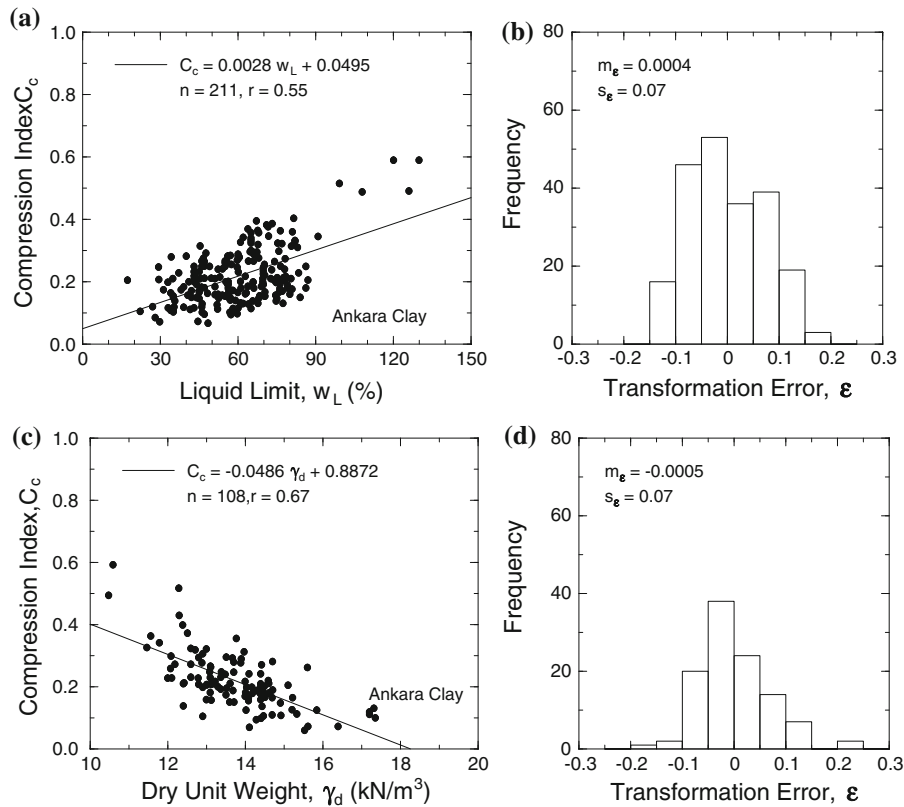
Consider the ultimate limit state design of a rigid drilled shaft in Ankara Clay, under lateral-moment loading. Using a general reliability calibration procedure, for a target reliability index ( $\beta_T$ ) = 3.2, Phoon et al. (1995) developed resistance factors that can be used for this case. The simplified RBD format is given below:

$$F_{50} = \Psi_h H_{hn} \quad (24)$$

in which  $F_{50}$  = 50-year return period load;  $\Psi_h$  = resistance factor; and  $H_{hn}$  = nominal lateral capacity of the drilled shaft. For  $\beta_T = 3.2$ , the resistance factors shown in Table 6 should be applied to Eq. 24.

Three design scenarios can be considered. In the first case, there are direct laboratory measurements of  $s_u$  for Ankara Clay, so that the total COV of  $s_u$  is between 8 and 27% in Table 5, which results in using a  $\Psi_h = 0.42$  in Eq. 24. In the second case, there is no knowledge of local calibrations of Ankara Clay, so “generic” values of COV from the literature must be used. Phoon and Kulhawy (1999b) specified a total COV range between about 10 and 70% for  $s_u$ , so an “average” approach would result in  $\Psi_h = 0.32$ . In the third case, consider only having SPT  $N$  measurements, without any information on specific or generic values for COV. Then the  $s_u$  must be estimated using Eq. 18, which results in a total COV range between 77 and 83% for  $s_u$ , as shown in Table 5. A maximum of  $\Psi_h = 0.23$  should be used for this case.

For a 50-year return period load of 500 kN, the required nominal lateral capacity of the drilled shaft for the first case is equal to 1,190 kN. For the second case, in which the “generic” values of COV were



**Fig. 6** Correlations between  $C_c$  and  $w_L$  and  $C_c$  and  $\gamma_d$  for Ankara Clay and distributions of transformation error

**Table 5** Geotechnical property variability for Ankara Clay

Property	Correlation	COV <sub>w</sub> (%)	COV <sub>e</sub> (%)	$\delta_v$ (m)	$s_\epsilon$	Property COV range (%)
$s_u$	Direct lab measurement	11–35	5–15	2.0	–	8–27
	$0.17 N^{0.58} p_a$	10–46	15–45	3.4	0.33	77–83
$w_L$	Direct lab measurement	9–22	3–11	5.1	–	9–25
$w_P$	Direct lab measurement	6–19	7–18	–	–	9–26
$w_n$	Direct lab measurement	12–22	6–12	4.0	–	12–23
PI	Direct lab measurement	13–28	5–51	–	–	14–58
$\gamma_d$	Direct lab measurement	2–8	1–2	–	–	2–8
$C_c$	Direct lab measurement	14–35	5–15	2.0	–	12–27
	$0.0028w_L + 0.0495$	9–22	3–11	5.1	0.07	33–37
	$0.2437e_o - 0.0056$	3–16	6–12	–	0.07	32–37
	$0.0065w_n + 0.0197$	12–22	6–12	4.0	0.08	37–41
	$-0.0486\gamma_d + 0.8872$	2–8	1–2	–	0.07	32–40
$C_s$	Direct lab measurement	14–35	5–15	2.0	–	12–27
	$0.0011w_L - 0.0209$	9–22	3–11	5.1	0.02	42–53

used, the required capacity increases to 1,563 kN for the same  $\beta_T$ . In the third case, a design with the same reliability index requires a drilled shaft capacity of at

least 2,174 kN. The required capacity increases more than 1.3 times where local COV information is not available. However, using only limited local

**Table 6** Undrained lateral–moment resistance factors for drilled shafts for  $\beta_T = 3.2$  (Phoon et al. 1995)

COV of $s_u$ (%)	$\Psi_h$
10–30	0.42
30–50	0.32
50–70	0.23

information in the form of a correlation with high dispersion around the mean regression results in even a higher required capacity than that obtained by generic variability guidelines.

## 8 Summary and Conclusions

An accurate estimate of property total variability is essential for geotechnical design. This variability includes inherent soil variability, measurement error, and transformation uncertainty. Values calibrated to a local geologic setting and local practices are preferable to broader generic estimates. This case history focused on characterizing and estimating the geotechnical property variability for Ankara Clay using second-moment probabilistic techniques that combine different sources of uncertainty consistently.

An extensive literature review was conducted to estimate the inherent variability ( $COV_w$ ) for  $w_L$ ,  $w_n$ ,  $w_p$ ,  $PI$ ,  $e_o$ ,  $\gamma_d$ ,  $C_c$ ,  $s_u$ , and SPT  $N$  value. The mean  $COV_w$  values for Ankara Clay range from about 5 to about 30%, which are much smaller than the generic ranges given in the literature and show the importance of using local soil type data. The smallest and largest  $COV_w$  correspond to  $\gamma_d$  and SPT  $N$ , respectively. The vertical scale of fluctuation was consistent with values reported in the literature.

The probabilistic framework presented by Phoon et al. (1995) and Phoon and Kulhawy (1999a, b) was used to evaluate the total geotechnical variability for some design properties of Ankara Clay. Details and examples are given to illustrate the process.

The COVs of undrained shear strength determined by different methods exhibited significant difference. For direct laboratory measurement, the COV varies between 8 and 27%, but the COV for local correlation with SPT  $N$  value ranged between 77 and 83%, which is larger than some COVs suggested in the literature.

For the compression and swelling indices, no

suggested values exist in the literature for the total variability COV. For  $C_c$  and  $C_s$ , the COVs estimated herein range from 12 to 41% and 12 to 53%, respectively, depending on the method of evaluation. The smallest COV is for direct laboratory measurement.

The COVs for local soil conditions and methodologies can be significantly different from those for generic correlations. In some cases, use of generic guidelines suggested in the literature can be unconservative. Local COVs should be estimated where possible. A simple design example illustrates how important this issue can be.

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