

Sensitivity of the state parameter inferred from the CPTu

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The state parameter (ψ) is a widely used index for assessing soil behaviour under shear, particularly in the context of contractive or dilative soil tendencies. Several empirical methods have been developed to estimate ψ from CPTu data, including the Been, Plewes and Robertson methods. This paper investigates the sensitivity of each method to variability in key input parameters through a One-At-a-Time (OAT) Monte Carlo analysis using 5 000 samples per parameter. The influence of variability in cone resistance, sleeve friction, pore pressure and stress-related parameters such as the lateral earth pressure coefficient (K_0) and the critical state friction ratio (M_{tc}) was evaluated using both global and local sensitivity analyses. Global sensitivity reflects the variation in ψ resulting from the statistical distribution of each parameter within the context of all other variables, while local sensitivity examines the relationship between ψ and each individual parameter when normalised to its mean, highlighting the strength and direction of their direct influence. Results show that the Been method is most sensitive to tip resistance, with notable local sensitivity to sleeve friction. The Plewes method is highly dependent on stress parameters, while the Robertson method is dominated by variability in tip resistance, but benefits from reduced complexity and lower input sensitivity overall.

1 INTRODUCTION

The critical state defined the condition at which soil continuously deforms at a constant shear stress (q), void ratio (e) and mean effective stress (p'), without undergoing volumetric strain, referred to as contraction or dilation (Jefferies & Been 2016). The relationship between the void ratio and effective mean stress at the critical state forms the critical state line (CSL) in $e - \ln p'$ space, expressed by Equation (1). The CSL provides a fundamental reference for evaluating soil behaviour under different stress conditions.

$$e_c = \Gamma_1 - \lambda_e \ln(p') \quad (1)$$

where e_c = void ratio at critical state; Γ_1 = void ratio at $p' = 1$ kPa and λ_e = the slope of the CSL in $e - \ln(p')$ space.

The state parameter (ψ), introduced by Been & Jefferies (1985), refines the traditional relative density approach for characterising soil's mechanical behaviour during shearing, i.e. whether it will contract or dilate. It is defined by Equation (2) as the difference in void ratio between the initial state (e_i) and the critical state (e_c) at the same mean effective stress.

$$\psi = e_i - e_c \quad (2)$$

Unlike relative density, the state parameter accounts for both density and stress level, making it a more comprehensive indicator of soil behaviour. A positive ψ indicates that the soil is looser than the critical state and likely to exhibit contractive behaviour, while a negative ψ suggests a denser state and a tendency to dilate. This concept is particularly valuable in liquefaction potential evaluations, slope stability, and general soil response under loading (Jefferies & Been 2016).

The reliable measurement of in-situ soil behaviour has been a significant challenge since the 1960s, largely due to the traditional reliance on laboratory testing of undisturbed samples, which were often affected by sampling disturbances. Cone penetration testing (CPT), introduced as an in-situ alternative (Begemann 1965), significantly improving soil characterisation practices. The CPT measures tip resistance (q_c) as the pressure applied to the cone tip during penetration and sleeve friction (f_s) which indicates the side friction along the penetrometer shaft. These measurements provided a basis for empirical correlations to soil properties, including relative density and the state parameter. The subsequent development of the piezocone (CPTu) allowed for the measurement of pore water pressure (u) during penetration

(Rust 1991), further enhancing the empirical correlations.

Since then, advancements in geotechnics have continuously revised the interpretation of in-situ soil parameters. However, questions regarding the reliability of these methods exist (Torres-Cruz, 2021). This study aims to evaluate the robustness of ψ inference methods through a detailed sensitivity analysis.

2 INFERRING STATE FROM THE CPTU

To establish a consistent relationship between CPTu measurements and the state parameter, normalisation of the raw measurements is essential. The normalised CPTu parameters are summarised in Table 1. The corrected tip resistance (q_t) can be normalised using either the vertical stresses, yielding Q , or the mean normal stress, yielding Q_p . Been & Jefferies (1992) mentioned that normalisation based on the mean normal stress provides greater flexibility, as it avoids the need to account separately for variations in the lateral earth pressure coefficient (K_0).

Table 1. The normalisation of CPTu measured parameters.

Dimensionless parameter	Normalisation equation
Normalised tip resistance (Q)	$Q = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \quad (3)$
Normalised tip resistance (Q_p)	$Q_p = \frac{q_t - p_0}{p'_0} \quad (4)$
Normalised tip resistance (Q_{tn})	$Q_{tn} = \frac{q_t - \sigma_{vo}}{P_a} \left(\frac{P_a}{\sigma'_{vo}} \right)^n \quad (5)$
Normalised friction ratio (F_r)	$F_r = \frac{f_s}{q_t - \sigma_{vo}} \cdot 100 \quad (6)$
Excess pore pressure ratio (B_q)	$B_q = \frac{u_2 - u_0}{q_t - \sigma_{vo}} \quad (7)$

where σ_{vo} = initial vertical total stress; σ'_{vo} = initial vertical effective stress; p_0 = the initial mean normal total stress; p'_0 = the initial mean normal effective stress; P_a = atmospheric pressure; u_0 = ambient pore pressure; u_2 = dynamic pore pressure and n = stress exponent, a function of soil behaviour.

2.1 Been method

The first relationship between normalised tip resistance and the state parameter, Equation (8), was developed by Been et al. (1987), based on calibration chamber tests on dense sand. This approach laid the foundation for most empirical methods used to infer the in-situ state parameter. It assumes a linear relationship between $\ln(Q_p)$ and ψ , defined by parameters k and m as function of λ_{10} defined by Equation (9) and (10) respectively. These are valid under fully drained conditions.

$$Q_p = k e^{-m\psi} \quad (8)$$

$$k = 8 + \frac{0.55}{\lambda_{10} - 0.01} > 0 \quad (9)$$

$$m = 8.1 - \ln(\lambda_{10}) \quad (10)$$

where k = the intercept of the Q_p expression at $\psi = 0$; m = the gradient and λ_{10} = the slope of the CSL in $e - \log p'$ space.

The compressibility of the soil, captured by λ_{10} , is central to this relationship. However, the method requires a value of λ_{10} for each soil layer during penetration, which is often impractical in the field.

To address this, Been & Jefferies (1992) introduced a refinement by incorporating the soil behaviour type index (I_c) defined by Equation (11). This updated formulation in Equation (12) provides a more practical basis for estimating ψ from CPTu data and has been confirmed by Reid (2014).

$$I_{c,B\&J} = \sqrt{(3 - \log(Q(1 - B_q) + 1))^2 + (1.5 + 1.3 \log(F_r))^2} \quad (11)$$

$$\frac{1}{\lambda_{10}} = 34 - 10I_c \quad (12)$$

In this paper, the Been method refers to the empirical framework defined by Equations (8) to (12).

2.2 Plewes method

Although the Been method provides a way of inferring the state parameter in clean sands, many natural soils and tailings contain higher silt contents than the material used in the original calibration chambers. This increased silt content results in partially drained or undrained penetration conditions, rather than the fully drained conditions simulated by Been et al. (1987).

To account for this, they proposed a modified form of the normalised tip resistance, expressed as $\bar{Q}_p = Q_p(1 - B_q)$. They found that the coefficients k and m remained linearly dependent on λ_{10} and that this relationship was applicable across different drainage conditions.

Plewes et al. (1992) further developed this method using additional calibration chamber testing on dense sand, introducing updated expressions for the coefficients k and m , incorporating the critical state stress ratio, M_{tc} , as shown in Equation (13) to (15).

$$\bar{Q}_p = k e^{-m\psi} \quad (13)$$

$$k = \left(3 + \frac{0.85}{\lambda_{10}} \right) M_{tc} > 0 \quad (14)$$

$$m = 11.9 - 13.3\lambda_{10} \quad (15)$$

To simplify the estimation of λ_{10} , a practical correlation was proposed by Plewes et al. (1992), linking it directly to the measured sleeve friction ratio F_r , as shown in Equation (16). This new correlation was confirmed by Reid (2014).

$$\lambda_{10} = \frac{F_r}{10} \quad (16)$$

In this paper, the Plewes method refers to the framework defined by Equations (13) to (16). It is often used as a screening-level approach, offering quick and cost-effective interpretation of the in-situ state.

2.3 Robertson method

Based on an extensive case history database, several researchers observed that the normalised tip resistance (Q_{tn}) required refinement when applied to soils with increased fines content (Robertson & Wride 1998). This led to the development of a revised soil behaviour type index, $I_{c,R\&W}$ defined by Equation (17), which is incorporated into the stress normalisation exponent, n , in Equation (18). Together, these support the definition of the clean sand equivalent cone resistance, $Q_{tn,cs}$, shown in Equation (19), to better capture the behaviour of traditional and clay-like soils (Robertson 2010). The correction factor, K_c , incorporates the grain characteristics correction based on $I_{c,R\&W}$. The relationship between K_c and $I_{c,R\&W}$ was updated to account for transitional and clay-like soils, presented in Figure 1 (Robertson 2022).

$$I_{c,R\&W} = \sqrt{(3.47 - \log(Q))^2 + (\log(F_r) + 1.22)^2} \quad (17)$$

$$n = 0.381 I_{c,R\&W} + 0.05 \left(\frac{\sigma'_{vo}}{P_a} \right) - 0.15 \leq 1.0 \quad (18)$$

$$Q_{tn,cs} = K_c Q_{tn} \quad (19)$$

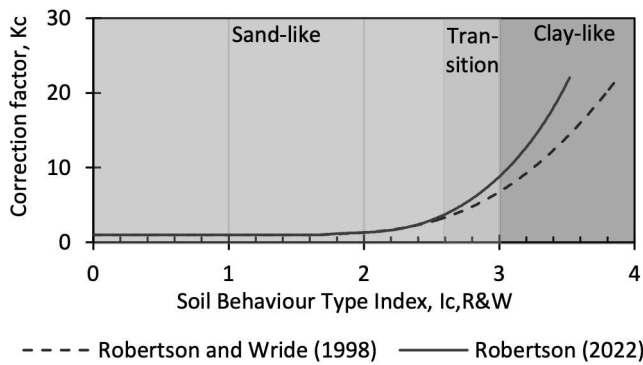


Figure 1. Updated calculation of the correction factor, K_c .

The relationship between the sand equivalent normalised tip resistance, $Q_{tn,cs}$ and ψ , in Equation (20), is therefore relevant to CPT penetration conditions other than the original drained conditions.

$$\psi = 0.56 - 0.33 \log(Q_{tn,cs}) \quad (20)$$

This results in what is further referred to as the Robertson method.

3 SENSITIVITY ANALYSIS OF THE INFERRED STATE PARAMETER

3.1 Parameter variability

To analyse the sensitivity of the inferred state parameter to input variables used in the methods described in Section 2, the typical variability of each input must first be reviewed. According to Kulawy (1992), uncertainty in geotechnical characterisation in in-situ testing arises from three primary sources:

- Uncertainty in the soil itself (inherent variability).
- Uncertainty in the measurement technique used, in this case the CPTu.
- Uncertainty in the model used to transform the measurement into an estimated soil property.

Although it is difficult to fully quantify these uncertainties, statistical data from literature and laboratory studies provide reasonable estimates of variability. The coefficient of variation (CoV) is often used to express variability in both soil properties and CPTu measurements. It represents a relative measure of dispersion and is defined by Equation (21).

$$CoV (\%) = \frac{\sigma}{\mu} \cdot 100 \quad (21)$$

where σ = standard deviation and μ = mean value.

In this study, mean values and CoVs were compiled from published literature and supplemented with laboratory measurements from miniature CPTu tests on gold tailings in a geotechnical centrifuge at a chosen depth of 250 mm. The selected parameters and their associated statistics are presented in Table 2, along with relevant sources.

Table 2. Statistical review of variation in key soil parameters.

Soil parameter	Mean	CoV (%)
Measured CPT tip resistance, q_c (kPa)	1560 ^c	27 ^{a, c}
Corrected CPT tip resistance, q_t (kPa)	1585 ^c	27 ^{a, c}
Measured CPT sleeve friction, f_s (kPa)	1.128 ^c	34.5 ^c
Dynamic pore pressure, u_2 (kPa)	83.6 ^c	20 ^c
Effective friction angle, ϕ' (°)	33 ^{a, c}	9 ^{a, c}
Lateral earth pressure coefficient, K_0	0.5 ^b	56 ^b
Adjusted q_c , q_{c1n} (kPa)	7.93 ^c	18 ^c
Normalised friction ratio, F_r (%)	0.08 ^c	35 ^c
Critical state friction ratio, M_{tc}	1.41 ^{d, c}	4.86 ^d
Slope of the CSL in $e - \ln p'$ space, λ_e	0.035 ^d	31.2 ^d

^a (Phoon & Kulhawey 1999a).

^b (Phoon & Kulhawey 1999b).

^c (Uzielli et al. 2005).

^d (Reid et al. 2021).

^e Laboratory measured property.

In addition to the mean and variability, the statistical distribution of each parameter must also be considered. Due to the inherent complexity and uncertainty of geotechnical data, assuming a uniform distribution is generally unrealistic (Phoon & Kulhawey 1999a). Instead, the following distributions are commonly applied:

- Normal distribution, characterised by symmetric variability around the mean, is typically assumed for parameters such as q_c , q_t , q_{cln} and F_r .
- Log-normal distribution, often used for strictly positive parameters related to strength or critical state, is assumed for K_0 , ϕ' , λ_e and M_{lc} .

With these statistical descriptors defined, a Monte Carlo simulation was set up using 5 000 samples per parameter. While the underlying distributions of the generated samples are not shown due to space constraints, the assumptions made reflect typical practice in geotechnical probabilistic analysis. Cross correlation between the mentioned parameters were accounted for during the analysis.

3.2 Sensitivity analysis

To evaluate the influence of input variability on the inferred state parameter, a sensitivity analysis was conducted by varying each key input parameter listed in Table 2, while keeping all other parameters constant. This approach isolates the effect of individual parameters on the state parameter within each method. The sensitivity index (S_i) is used to quantify the relationship between variability in each input parameter and the corresponding change in the output ψ . It is calculated using Equation (22), adapted from Saltelli et al. (2007).

$$S_i = \frac{\frac{\psi_i - \mu_\psi}{\mu_\psi}}{\frac{x_i - \mu_x}{\mu_x}} \quad (22)$$

where x_i = the specific parameter with variation; ψ_i = the state parameter associated with x_i ; μ_x and μ_ψ = mean value of the parameter.

This analysis follows a One-At-a-Time (OAT) approach, where one parameter is varied while the others are held constant at their mean values. This allows for the visualisation and quantification of the sensitivity of ψ to individual sources of input variability.

3.2.1 Been method

For the Been method, four variables with known variability, the three piezocone measurements (q_c , f_s and u_2) as well as the lateral earth pressure coefficient (K_0), were considered. By keeping the vertical total stress (σ_{vo}) and ambient pore pressure (u_0) constant, variation in the remaining inputs led to a range of values for Q_p , as well as the derived parameters k and m , ultimately resulting in variation in the state parameter. The distribution of the state parameter resulting from the variation in each individual parameter was assessed using the OAT method. This overall variation in state parameter demonstrates the global sensitivity (Homma & Saltelli 1996) of each parameter and is presented in Figure 2. The variation in state parameter due to u_2 was found to be negligible and therefore it has been excluded from this figure.

The mean state parameter for the Been method was -0.049. All parameters showed distributions centred around this value, with $\psi(f_s)$ showing the least variation. However, the spread of values differed significantly. The highest variability in the state parameter occurred due to variation in q_c , with a standard deviation of $\sigma = 0.039$, followed by K_0 ($\sigma = 0.025$) and f_s ($\sigma = 0.014$).

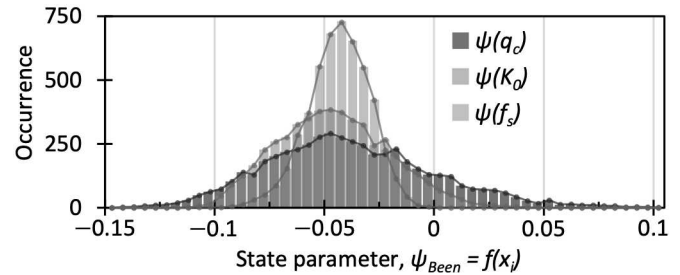


Figure 2. Global Been state parameter variation due to individual parameters.

The local sensitivity of the state parameter to each variable (sensitivity index, S_i) is presented as the slope of the curve in Figure 3. A steeper slope indicates a greater sensitivity index to that parameter.

It is evident that ψ_{Been} is highly sensitive to the tip resistance, both globally, as seen in the wide spread in Figure 2 and locally, as indicated by the steep slope in Figure 3.

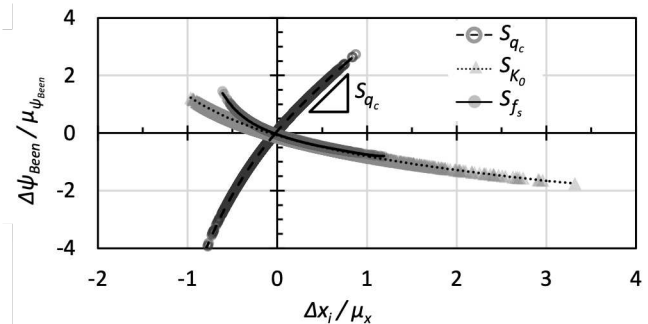


Figure 3. Local sensitivity of Been method state to inputs.

Although f_s appears less influential in the global analysis, the local sensitivity is significant. A change in f_s equal to half of its mean can lead to a change in state equal to the mean thereof. This highlights the importance of reliable sleeve friction measurements in the Been method, particularly for soils where f_s plays a dominant role, such as silty or sensitive clays, where small inaccuracies can significantly affect the inferred state parameter.

K_0 is also shown to have a substantial influence, both globally and locally. This is particularly noteworthy given the large uncertainty associated with estimating K_0 . A variation in K_0 of 1μ can result in a change of state parameter equal to its own mean.

3.2.2 Plewes method

The analysis of Plewes method included five variables with known distributions, namely the three piezocone measurements (q_t , f_s and u_2) as well as K_0 and the critical state stress ratio (M_{tc}).

As with the Been method, the global sensitivity of ψ to each variable was evaluated using the OAT method. The vertical total stress and ambient pore pressure were held constant, at the same values as in Section 3.2.1. The spread in the resulting state parameter due to each variable's distribution is presented in Figure 4. As with the previous method, the influence of u_2 was negligible and has been excluded from the figure.

The mean state parameter for the Plewes method was -0.248, significantly different to that inferred using the Been method. Among the variables, q_t showed the least variability in ψ_{Plewes} , while K_0 and f_s introduced similarly large spreads to the state parameter. The standard deviation in ψ_{Plewes} due to K_0 was $\sigma = 0.04$, compared to the $\sigma = 0.034$ for f_s , $\sigma = 0.027$ for M_{tc} and $\sigma = 0.004$ for q_t . This not only highlights the high correlation between ψ_{Plewes} and q_t , but the lack thereof for M_{tc} , K_0 and f_s .

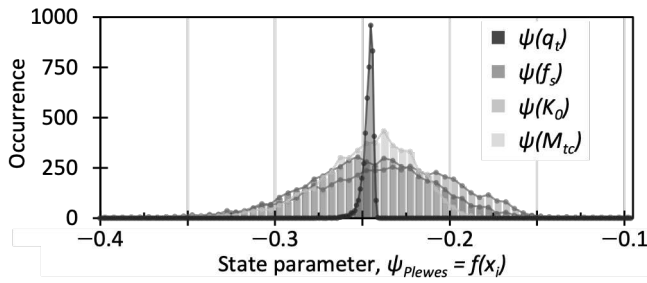


Figure 4. Global Plewes state parameter variation due to individual parameters.

The local sensitivity is presented in Figure 5, where again the slope indicates the sensitivity index (S_i) with the change in ψ_{Plewes} with respect to its mean, due to a change in a single variable with respect to the mean of that variable.

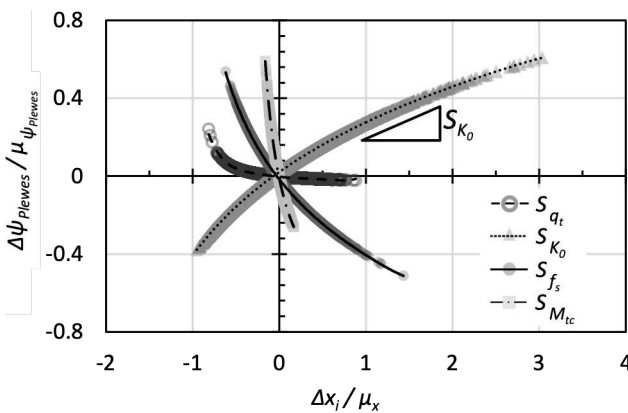


Figure 5. Local sensitivity of Plewes method state to inputs.

A near vertical slope, shown in Figure 5 for M_{tc} , indicates a high local sensitivity of ψ_{Plewes} to this parameter. A 10% variation in the mean value of M_{tc} results in a change in the state parameter of approximately 50% of its mean. A variation in K_0 of twice its mean value, results in a variation in ψ_{Plewes} of only half the mean thereof. The figure also highlights the non-linearity of the inferred state relationship to the various input parameters.

As with the Been method, the reliance on accurate measurements of f_s is critical for reliable estimation of the state parameter. Although the global influence of f_s is moderate, its local sensitivity is still significant, particularly in soils where sleeve friction plays a dominant role, such as silty or sensitive clays.

This analysis confirms that the Plewes method is particularly sensitive to the stress-related parameters K_0 and M_{tc} , both globally and locally. This underscores the importance of obtaining reliable estimates for these parameters.

3.2.3 Robertson method

The Robertson method considers four input parameters for estimating the state parameter: the corrected cone resistance (q_t), sleeve friction (f_s), dynamic pore pressure (u_2) and atmospheric pressure (P_a). As in the previous methods, the vertical stress and ambient pore pressure were held constant, and the variability of each input was analysed individually using the OAT approach. The variability due to the atmospheric pressure and dynamic pore pressure was found to be negligible.

The global sensitivity of $\psi_{Robertson}$ to each of the input variables is presented in Figure 6. The spread in $\psi_{Robertson}$ is overwhelmingly dominated by variability in q_t , with very little influence observed from f_s .

The mean state parameter for the Robertson method was -0.420. While the influence of f_s on the overall variability is minimal, the distribution of $\psi_{Robertson}$ due to q_t exhibits a much wider spread compared to the other inputs. This suggests that, despite the method's relative simplicity, its output remains highly sensitive to the variability in measured cone resistance. q_t resulted in a state parameter distribution with $\sigma = 0.097$, where f_s resulted in $\sigma < 0.002$.

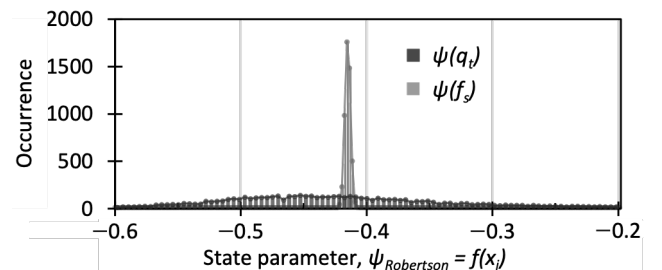


Figure 6. Global Robertson state parameter variation due to individual parameters.

The local sensitivity of the method is shown in Figure 7. Here, q_t again demonstrates the strongest influence on $\psi_{\text{Robertson}}$ with a noticeable slope compared to the very low local sensitivity exhibited by f_s , confirming its minor role in this method.

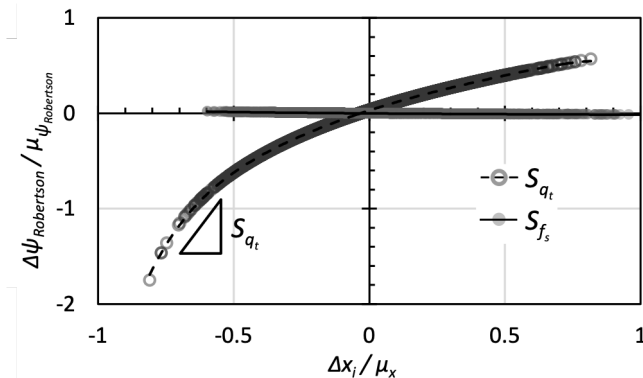


Figure 7. Local sensitivity of Robertson method state to inputs.

Compared to the Been and Plewes methods, the almost perfect horizontal relationship for f_s distributions and its impact on $\psi_{\text{Robertson}}$ shows a significant lack of sensitivity to sleeve friction variation, as well as for P_a and u_2 . This is contrasted by the non-linear relationship resulting from the q_t variation where an error of half the mean of q_t results in an error in $\psi_{\text{Robertson}}$ of more than half of its mean.

However, the strong dependence on q_t remains a concern. While the method benefits from simplicity and low reliance on other parameters, the accuracy of $\psi_{\text{Robertson}}$ is theoretically ultimately constrained by the accuracy and precision of the cone resistance measurement.

4 CONCLUSIONS

This study evaluated the sensitivity of three empirical methods (Been, Plewes, and Robertson) for estimating the state parameter from CPTu data. Using a One-At-a-Time (OAT) sensitivity analysis supported by Monte Carlo simulations, the influence of key input parameters on the inferred state parameter was quantified, both globally and locally.

The results show that each method exhibits distinct sensitivity profiles. The Been method is highly sensitive to the measured tip resistance (q_c) and moderately sensitive to both sleeve friction (f_s) and lateral earth pressure coefficient (K_o). The Plewes method displays significant sensitivity to stress-related parameters, particularly K_o and the critical state stress ratio (M_c), while also showing local sensitivity to f_s in silty or sensitive clays. The Robertson method demonstrates the least complexity, relying mainly on corrected tip resistance (q_t), with minimal sensitivity to other inputs. However, its heavy dependence on q_t

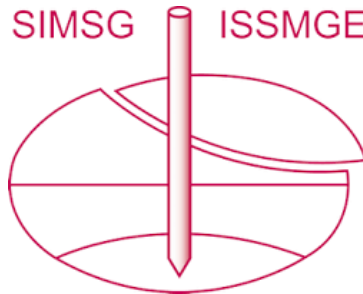
makes it vulnerable to any inaccuracy in this measurement.

It is recommended that other simulation models such as the FORM and PEM methods should be used in a similar statistical analysis and compared with the information presented in this paper.

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