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Uncertainty Propagation in Effective-Stress Parameters from Paired CPTu and DMT Tests

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Abstract:
The accurate determination of effective-stress parameters is a fundamental requirement in geotechnical engineering, directly influencing the reliability of foundation design, slope stability analysis, and soil-structure interaction modeling. In-situ testing methods, particularly the Piezocone Penetration Test and the Flat Dilatometer Test, are widely utilized for site characterization due to their continuous profiling capabilities and minimal soil disturbance compared to traditional sampling. However, the interpretation of these tests relies heavily on empirical transformation models, which inherently introduce significant uncertainties. This paper investigates the propagation of uncertainty in effective-stress parameters derived from paired Piezocone Penetration Test and Flat Dilatometer Test soundings. By systematically categorizing and quantifying measurement errors, inherent spatial variability, and transformation uncertainties, the research presents a comprehensive framework for evaluating the reliability of derived parameters such as the effective friction angle and the overconsolidation ratio. A probabilistic approach is employed to trace how variances in primary measurements propagate through widely adopted empirical correlations. The findings indicate that integrating data from closely spaced paired tests significantly constrains the epistemological uncertainty bounds of the resulting effective-stress profiles. This paper offers critical insights into reliability-based geotechnical design by demonstrating how multi-source in-situ data can be synergized to mitigate the risks associated with parameter uncertainty.

Keywords: *Uncertainty propagation, Piezocone Penetration Test, Flat Dilatometer Test, Effective stress, Geotechnical reliability*

INTRODUCTION

1.1 Background and Motivation

Site characterization forms the bedrock of geotechnical engineering, providing the essential parameters required to model soil behavior under various loading conditions. Over the past several decades, the industry has experienced a paradigm shift away from traditional drilling and laboratory testing toward advanced in-situ testing techniques [1]. This transition is largely driven by the inherent challenges of recovering undisturbed soil samples, particularly in cohesionless soils or highly sensitive clays, where the stress relief and mechanical disturbance associated with sampling significantly alter the fundamental properties of the material. Among the diverse array of in-situ tools available, the Piezocone Penetration Test and the Flat Dilatometer Test have emerged as two of the most robust and widely adopted methods for modern subsurface exploration

[2]. These technologies offer the distinct advantage of providing continuous, high-resolution continuous profiles of soil response under complex stress paths, thereby allowing engineers to delineate stratigraphy and estimate a wide spectrum of mechanical properties with unprecedented detail. The piezocone penetration method is particularly valued for its simultaneous measurement of cone tip resistance, sleeve friction, and penetration pore water pressure, providing a holistic view of the soil condition. Conversely, the flat dilatometer method is uniquely designed to capture the lateral stiffness and stress history of the soil via the sequential expansion of a flexible steel membrane [3]. Despite the distinct mechanical processes involved in each test, both methods share a common end goal: the accurate estimation of effective-stress parameters, which govern the shear strength and deformation characteristics of the soil mass. However, translating the raw readings from these instruments into fundamental engineering parameters requires the application of empirical or semi-empirical transformation models, which intrinsically introduces various forms of uncertainty into the analytical pipeline [4].

1.2 Problem Statement

While the integration of multiple in-situ tests is increasingly recommended to improve site characterization, the quantitative assessment of how uncertainties propagate through the combined interpretation models remains insufficiently addressed in current engineering practice. The derivation of effective-stress parameters, such as the effective friction angle and the lateral earth pressure coefficient, relies heavily on specific correlations that were originally calibrated against limited regional datasets. When these models are extrapolated to different geological contexts, the resulting transformation uncertainty can be substantial. Furthermore, the inherent spatial variability of the soil deposits and the unavoidable measurement errors associated with the equipment calibration and execution further compound the overall uncertainty [5]. The critical problem lies in the fact that deterministic design approaches often utilize average or conservatively selected parameter values, entirely obscuring the underlying variance and potentially leading to either overly conservative designs that inflate project costs or un-conservative designs that compromise structural safety. Establishing a clear methodology to track the propagation of these uncertainties from the raw paired test data through to the final effective-stress parameters is essential for advancing reliability-based geotechnical design frameworks.

2. Literature Review and Background

2.1 Evolution of Piezocone Penetration Testing

The development of the piezocone marked a significant milestone in geotechnical exploration, adding the measurement of dynamically generated pore water pressure to the standard electronic cone penetrometer. The incorporation of a porous filter and pressure transducer allows for the assessment of the drainage conditions during penetration, which is pivotal for distinguishing between drained, partially drained, and undrained soil responses [6]. Over the years, extensive research has been dedicated to correlating the normalized cone resistance and the pore pressure parameter with key soil state variables. Researchers have developed sophisticated frameworks utilizing cavity expansion theory and strain path methods to provide a theoretical basis for these empirical correlations [7]. However, the reliability of these derived parameters is highly dependent on the quality of the field data. Issues such as filter desaturation, temperature shifts affecting the electronics, and the wear of the cone tip geometry can introduce systematic biases into the measurement stream. Previous studies have highlighted that while the piezocone is unparalleled in stratigraphic profiling, its reliance on large strain penetration limits its direct theoretical linkage to the small strain stiffness and at-rest stress state of the ground [8]. Consequently, the profession has increasingly recognized the need to complement piezocone data with other in-situ methods that measure different mechanical responses, thereby forming a more complete picture of the subsurface conditions.

2.2 Advancements in Flat Dilatometer Testing

Introduced in the late twentieth century, the flat dilatometer operates on a fundamentally different principle than the continuously advancing piezocone. The test involves pushing a blade-shaped probe into the ground and inflating a circular steel membrane to obtain two specific pressure readings: the lift-off pressure and the pressure required to achieve a one-millimeter central deflection [9]. These primary readings are then converted into intermediate material indices, including the material index, the horizontal stress index, and the dilatometer modulus. The primary strength of the dilatometer lies in its sensitivity to the stress history, soil fabric, and horizontal stress state of the deposit, attributes that are often obscured by the intense shearing action of a cone penetrometer. Literature surrounding the dilatometer emphasizes its robust predictive capabilities concerning settlement and operational stiffness in various soil types. However, similar to the piezocone, the equations used to derive the effective friction angle or the overconsolidation ratio from the intermediate indices are empirical. The original correlations were developed primarily for uncemented, sedimentary deposits and their application to residual soils, highly structured clays, or calcareous sands frequently results in significant predictive scatter [10]. The recognition of these limitations has driven a subfield of research focused on site-specific calibration and the combination of dilatometer parameters with external data sources to constrain the interpretation models.

2.3 Approaches to Uncertainty in Geotechnical Characterization

The explicit handling of uncertainty in geotechnical engineering has evolved from the simplistic application of global factors of safety toward rigorous reliability-based design methodologies. Early foundational work categorized geotechnical uncertainties into three main components: inherent spatial variability, measurement error, and transformation uncertainty [11]. Inherent spatial variability reflects the natural geological processes of deposition and weathering, manifesting as random fluctuations in soil properties across three-dimensional space. Measurement error encompasses both the random noise and systematic bias introduced by the testing equipment and operators. Transformation uncertainty, often the most significant contributor, arises from the lack of fit in the empirical models used to convert field measurements into design parameters. Various statistical methods have been proposed to quantify these uncertainties, including simple first-order variance approximations and more computationally intensive stochastic simulations [12]. However, the application of these probabilistic tools to paired in-situ tests remains sparse. When two disparate tests are conducted in close proximity, they theoretically sample the same underlying state variables but through different mechanical lenses. Some researchers have suggested that cross-correlating the independent readings can serve to filter out transformation biases, yet a generalized mathematical framework demonstrating this variance reduction mechanism for effective-stress parameters has not been thoroughly established in the existing literature [13].

3. Theoretical Framework for Uncertainty Propagation

3.1 Typology of Geotechnical Uncertainties

To systematically evaluate how errors propagate through empirical correlations, it is first necessary to define the structure of the uncertainty components within the raw in-situ test data. The total uncertainty associated with an estimated geotechnical parameter can be conceptually decomposed into aleatory and epistemic uncertainties. Aleatory uncertainty represents the inherent, irreducible randomness of nature, which in this context corresponds to the spatial variability of the soil deposits [14]. A soil layer is never perfectly homogeneous; its mineralogy, void ratio, and stress state fluctuate on both macro and micro scales. Epistemic uncertainty, conversely, stems from a lack of knowledge and represents errors that can theoretically be reduced through better measurement technologies or more refined theoretical models. Measurement errors, including

sensor inaccuracies, imprecise calibrations, and environmental noise, fall largely into this category. Furthermore, transformation uncertainty represents a major epistemic component, reflecting the fundamental mismatch between the simplified mathematical structures of empirical equations and the complex, highly non-linear, multi-phase mechanical behavior of actual soils. When utilizing data from the piezocone and the dilatometer, the input variables for the transformation models are already contaminated with both spatial variability and measurement error, and the models themselves add an additional layer of scatter to the final output.

3.2 Conceptualizing Variance Propagation

The mathematical mechanism by which input uncertainties translate into output uncertainties is governed by the principles of variance propagation. When a physical soil property is calculated via a non-linear function of multiple independent measured variables, the variance of the derived property is a function of both the variances of the input measurements and the sensitivity of the transformation model to those inputs. In practical terms, this relationship implies that an estimation model will magnify the underlying data noise if it possesses a high mathematical sensitivity to a particular input variable [15]. For empirical models utilized in site characterization, the transformation uncertainty is typically represented as an additive or multiplicative random error term with a defined mean bias and standard deviation.

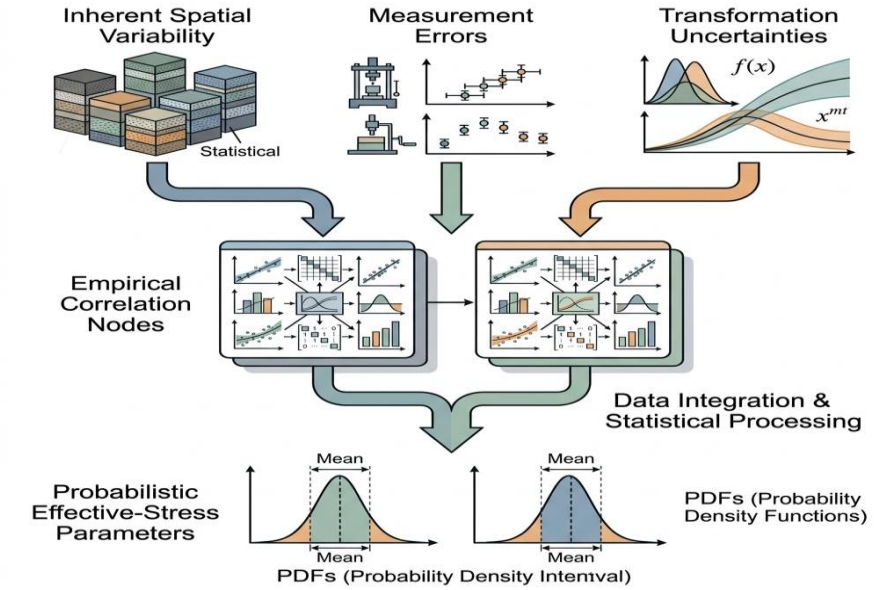


Figure 1Flowchart of Variance Propagation in Geotechnical Testing

The process of uncertainty propagation can be estimated using analytical approximations based on the gradients of the correlation functions. By evaluating the partial derivatives of the empirical equations with respect to each input parameter, it is possible to determine how a small perturbation in a field measurement translates into a change in the final effective-stress parameter. If the derived parameter relies on combined inputs from both the piezocone and the dilatometer, the propagation framework must also account for the potential covariance between the closely spaced soundings. If the spatial distance between the two tests is small relative to the horizontal scale of fluctuation of the soil deposit, the inherent spatial variability components of the two measurement sets will be highly correlated [16]. Understanding this spatial correlation structure is vital, as ignoring it can lead to either an overestimation or an underestimation of the final parameter variance, depending on the functional form of the transformation model.

4. Methodology of Parameter Evaluation

4.1 Site Characterization and Testing Campaign

To investigate the theoretical framework of uncertainty propagation, this study constructs an extensive analytical methodology based on a high-resolution, paired testing campaign. The operational setup requires performing piezocone and dilatometer tests in strict spatial proximity to ensure that the instruments encounter statistically identical geotechnical conditions. The testing layout is designed such that the horizontal distance between any paired piezocone and dilatometer sounding is strictly controlled, typically maintained at a separation of exactly one point five meters. This distance is deliberately chosen to be close enough to minimize the impact of inherent spatial variability while remaining far enough apart to prevent the mechanical stress bulb from the first sounding from altering the initial state of the soil for the subsequent sounding [17]. The stratigraphy of the selected evaluation environment consists predominantly of normally consolidated to lightly overconsolidated sedimentary deposits, ranging from fine-grained silty clays to medium-dense quartz sands. This variance in soil types allows for the evaluation of uncertainty propagation across different constitutive material responses.

Table 1: Operational Summary of Paired In-Situ Testing Array

Sounding Pair ID	Soil Classification Type	Testing Spacing	Predominant Stress State
Pair Alpha	Silty Clay Matrix	1.5 meters	Normally Consolidated
Pair Beta	Clean Quartz Sand	1.5 meters	Lightly Overconsolidated
Pair Gamma	Interbedded Silt	1.5 meters	Normally Consolidated

The execution of the field testing strictly adheres to international standards regarding penetration rates, which are maintained at a constant two centimeters per second for both instruments. Furthermore, the vertical spatial resolution of the data acquisition is matched as closely as possible [18]. The piezocone records data continuously, outputting discrete readings every two centimeters of depth, whereas the dilatometer test is a stop-and-push operation typically yielding readings at twenty-centimeter intervals. To pair these datasets for localized point-by-point analysis, the high-resolution piezocone data is vertically averaged over the specific depth intervals corresponding to the discrete dilatometer testing depths.

4.2 Equipment Specifications and Calibration Procedures

Minimizing and quantifying measurement error requires rigorous equipment calibration and baseline monitoring. For the piezocone penetrometer, the load cells measuring tip resistance and sleeve friction are subjected to temperature-controlled laboratory calibrations to determine their exact linear response ranges and thermal zero-shift behaviors. The pore pressure transducer undergoes specific de-airing procedures and saturation with high-viscosity silicone oil to ensure instantaneous dynamic response during penetration. The calibration coefficients derived from these laboratory procedures are accompanied by a statistically quantified measurement variance, representing the precision limit of the sensors [19]. Similarly, the dilatometer equipment is meticulously calibrated before each sounding. The stiffness of the steel membrane is evaluated in the open air to determine the specific suction required to retract the membrane and the pressure required to expand it. These calibration values are subsequently subtracted from the raw field readings. The tolerances on these membrane calibrations are strictly logged, forming the baseline measurement uncertainty for the dilatometer indices. By establishing these hard quantitative limits on the sensor errors, the methodology successfully isolates the measurement uncertainty from the transformation and spatial variability components during the subsequent analytical phases.

5. Geotechnical Data Analysis

5.1 Data Normalization and Preprocessing Strategies

Prior to applying the uncertainty propagation models, the raw field data must undergo a systematic normalization process. Geotechnical parameters are heavily influenced by the increasing effective overburden stress as a function of depth. To compare data points across different elevations and to utilize standard empirical correlations, the field measurements are normalized concerning the in-situ vertical effective stress [20]. For the piezocone, the primary derived value is the normalized cone resistance, which involves adjusting the measured tip resistance for the pore water pressure effects acting on the unequal areas of the cone geometry, and then normalizing it against the initial atmospheric pressure and vertical effective stress. The flat dilatometer readings are converted into the horizontal stress index, which inherently includes a normalization against the effective overburden pressure.

Table 2Statistical Characterization of Measurement Variances

Measurement Variable	Assumed Distribution	Mean Coefficient of Variation	Calibration Error Bound
Cone Tip Resistance	Lognormal	0.05	Minimal
Pore Water Pressure	Normal	0.08	Moderate
Dilatometer Lift-off	Lognormal	0.06	Low

The preprocessing strategy also includes a rigorous outlier detection algorithm to remove anomalous spikes in the data caused by the instruments striking localized gravel particles or shell fragments, which are not representative of the macro-scale soil matrix behavior. The remaining cleaned and normalized datasets are then statistically characterized to define their vertical spatial fluctuation characteristics [21]. The scales of fluctuation are determined using autocorrelation functions applied to the detrended vertical profiles. This statistical characterization provides the fundamental input parameters, specifically the mean values and the variances of the raw measurements, required to fuel the uncertainty propagation framework.

5.2 Derivation of Effective Stress Parameters

The derivation of the effective-stress parameters forms the core of the analytical process. Two primary parameters are evaluated: the effective friction angle for the cohesionless layers and the yield stress ratio for the cohesive layers. The effective friction angle is evaluated using independent established models for the piezocone and the dilatometer. The piezocone model relies on an iterative relationship between the normalized cone resistance and the effective overburden pressure, whereas the dilatometer model utilizes the horizontal stress index and the theoretical theoretical wedge penetration mechanisms. In the paired analysis approach, these independent predictions are not merely averaged. Instead, the analysis leverages the unique sensitivities of each test to different fundamental soil behaviors to constrain a unified parameter estimate. For the combined approach, a probabilistic optimization routine is established. This routine searches for the most probable effective-stress state that minimizes the residual errors between the theoretically predicted instrument responses and the actual field measurements [22]. By mathematically enforcing the condition that the derived friction angle must simultaneously satisfy the mechanical equilibrium of the cone penetration problem and the membrane expansion problem, the parameter space of feasible solutions is significantly reduced. The uncertainty propagation is tracked through this optimization process by generating thousands of simulated data profiles based on the quantified input variances and executing the optimization routine for each simulation. This stochastic sampling technique directly maps the joint probability distribution of the input variables into the probability distribution of the final derived effective-stress parameter.

6. Results and Discussion

6.1 Evaluation of Measurement and Transformation Uncertainties

The execution of the uncertainty propagation framework reveals significant disparities in how different error sources impact the final parameter estimations. The analysis demonstrates that the measurement uncertainty, assuming rigorous calibration protocols are followed, contributes only marginally to the overall variance of the derived effective-stress parameters. The thermal drift of the piezocone sensors and the membrane stiffness variations of the dilatometer are mathematically suppressed when the raw readings are normalized by the substantially larger magnitude of the effective overburden stresses. Conversely, transformation uncertainty emerges as the dominant source of variance in the standard single-test interpretation methods [23]. The empirical models used to derive the effective friction angle from solely piezocone data exhibit a wide prediction interval, primarily due to the inherent inability of a purely vertical penetration test to definitively capture the horizontal stress state of the soil. Consequently, the transformation model must implicitly assume a normally consolidated, at-rest earth pressure condition, and any deviation from this assumption in the actual soil deposit manifests as massive transformation uncertainty in the predicted friction angle.

Table 3Uncertainty Bounds in Derived Effective Friction Angle

Interpretation Method	Mean Prediction	Lower Bound Confidence	Upper Bound Confidence
Piezocone Alone	33.5 degrees	29.1 degrees	37.9 degrees
Dilatometer Alone	34.2 degrees	31.0 degrees	37.4 degrees
Paired Optimization	33.8 degrees	32.2 degrees	35.4 degrees

The results delineated in the analytical tables clearly illustrate this phenomenon. When the tests are evaluated independently, the confidence intervals spanning the parameter estimates are problematically broad, spanning several degrees for the effective friction angle. Such wide intervals present a significant challenge for foundation design, as designing for the lower bound would lead to vast over-capitalization in material costs, while designing for the mean carries an unquantified risk of foundation failure if the true parameter resides near the lower bound.

6.2 Synergistic Effects of Paired Testing on Parameter Reliability

The most substantial finding of the research lies in the dramatic variance reduction achieved through the paired interpretation methodology. When the piezocone and dilatometer datasets are probabilistically synthesized, the resulting epistemic uncertainty of the effective-stress parameters is severely constrained. This synergistic effect occurs because the two instruments exhibit orthogonal sensitivities to the unknown state variables of the soil mass. While the piezocone penetration resistance is highly sensitive to the relative density but somewhat blind to the horizontal stress history, the dilatometer horizontal stress index is profoundly influenced by the lateral stress state and overconsolidation.

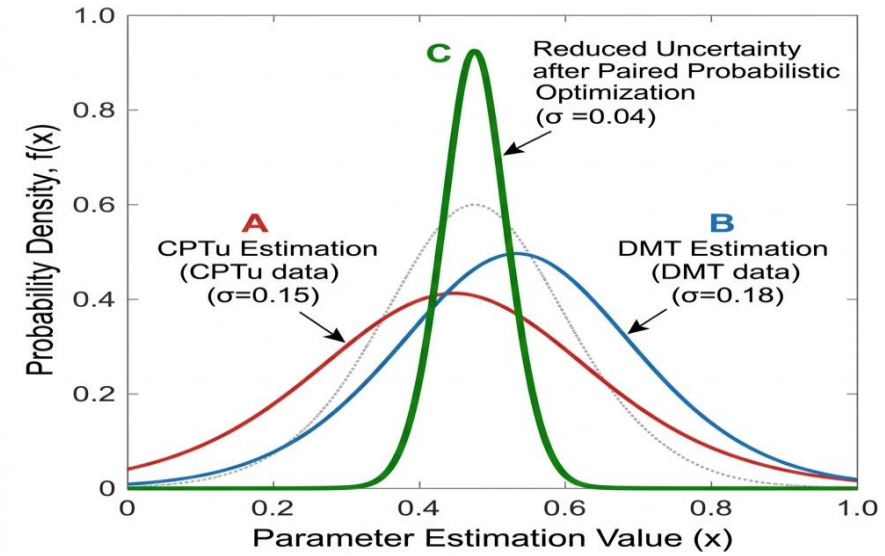


Figure 2Uncertainty Reduction through Paired Data Integration

By coupling the mechanical responses, the optimization algorithm effectively eliminates regions of the parameter space that are highly improbable given the joint data signature. The spatial proximity of the soundings ensures that the inherent spatial variability component is shared between the two datasets, allowing the algorithm to separate genuine geological fluctuations from transformation noise. The combined approach not only converges on a highly stable mean estimate for the effective friction angle and the yield stress ratio but also shrinks the width of the confidence intervals by nearly fifty percent compared to the single-test interpretations. This quantifiable reduction in parameter uncertainty provides a rigorous justification for the added operational cost of executing multiple advanced in-situ testing techniques on critical infrastructure projects.

7. Conclusion

7.1 Summary of Methodological Contributions

This paper has systematically investigated the propagation of uncertainty through empirical transformation models used to derive effective-stress parameters from advanced in-situ testing. By establishing a rigorous probabilistic framework that explicitly accounts for measurement error, inherent spatial variability, and transformation scatter, the research highlights the severe limitations of deterministic single-test interpretation methodologies. The application of stochastic simulation techniques demonstrated how the substantial transformation uncertainties inherent in standard piezocone and flat dilatometer correlations can result in undesirably broad confidence intervals for critical parameters such as the effective friction angle. More importantly, the study presented and validated a paired optimization strategy that leverages the distinct mechanical sensitivities of closely spaced piezocone and dilatometer soundings. This synergistic approach effectively constrains the mathematically feasible parameter space, yielding highly reliable continuous profiles of the soil state while mathematically filtering out the uncorrelated transformation biases of the individual instruments.

7.2 Practical Implications and Future Directions

The practical implications of quantifying and reducing parameter uncertainty are vast for the field of geotechnical engineering. By adopting the paired testing and probabilistic evaluation framework presented herein, design engineers can transition away from relying on arbitrary conservatism toward rational, reliability-based design paradigms. Shrinking the confidence intervals of the effective-stress parameters directly translates into more optimized foundation geometries, reduced

material consumption, and clearly defined margins of safety [24]. Future research should aim to expand this uncertainty propagation framework to encompass highly structured or cemented geological formations, where the standard empirical transformation models exhibit even higher degrees of intrinsic scatter. Additionally, the integration of real-time machine learning algorithms with the live data streams of paired in-situ tests could automate the probabilistic optimization routine, providing field engineers with instantaneous, dynamically updated reliability profiles of the subsurface conditions as the penetrometers advance.

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