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CPTu-DMT Stress-Path Fusion for Clay Friction-Angle Estimation Under Overconsolidation

Alexander Carter

Geography, Geology and the Environment, School of, University of Leicester, Leicester, United Kingdom

Abstract

The accurate determination of the effective friction angle in overconsolidated clay remains a formidable challenge in geotechnical engineering due to the complex stress-strain behavior and the limitations of isolated in-situ testing methods. Traditional laboratory methods suffer from unavoidable sample disturbance, leading to unrepresentative shear strength parameters, while single-source in-situ methods like the Piezocone Penetration Test and the Flat Dilatometer Test often fail to capture the complete stress-path evolution during penetration and expansion. This paper proposes a novel framework for estimating the effective friction angle of overconsolidated clays by fusing the stress-path responses derived from both the Piezocone Penetration Test and the Flat Dilatometer Test. By leveraging the continuous continuous profiling capability of the piezocone and the horizontal stress sensitivity of the dilatometer, the proposed methodology reconstructs the localized stress history and the multidirectional strain fields around the advancing probes. The analytical model rigorously incorporates the Overconsolidation Ratio as a foundational variable that moderates the relationship between the horizontal stress index and the normalized cone resistance. The framework is validated against a comprehensive set of consolidated undrained triaxial laboratory tests recovered from diverse geological sites. Results demonstrate a significant reduction in predictive uncertainty, minimizing systematic errors that traditionally plague empirical correlations. The fused model provides a theoretically sound, practically robust, and computationally efficient approach for the in-situ characterization of heavily overconsolidated deposits, fundamentally enhancing the reliability of subsequent geotechnical design processes for deep foundations and earth retaining structures.

Keywords: Piezocone Penetration Test, Flat Dilatometer Test, Overconsolidation Ratio, Effective Friction Angle, Stress Path Fusion.

1.Introduction

1.1 Background and Motivation

The accurate and reliable estimation of the fundamental shear strength parameters of soil is arguably the most critical requirement for any geotechnical engineering design, ranging from the stability analysis of natural slopes to the bearing capacity calculation of deep foundation systems and the structural sizing of earth retaining walls. Among these parameters, the effective friction angle serves as a paramount indicator of the internal resistance of soil against shear failure, governing the ultimate limit state of the geological medium. In conventional geotechnical practice, the determination of the effective friction angle in cohesive soils, particularly clays, is typically

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conducted through sophisticated laboratory experiments such as consolidated undrained triaxial compression tests with pore water pressure measurements or consolidated drained direct shear tests. However, despite the highly controlled boundary conditions and the precise measurement instrumentation available in modern geotechnical laboratories, these ex-situ methodologies are intrinsically plagued by the phenomenon of sample disturbance. The processes of drilling, sampling, transportation, extrusion, and trimming inevitably alter the in-situ stress state, the natural macroscopic structure, and the microscopic fabric of the clay specimens. Such alterations often result in laboratory-derived shear strength parameters that diverge significantly from the true in-situ characteristics of the soil, leading to either overly conservative engineering designs with inflated construction costs or unsafe designs prone to catastrophic failure. To circumvent the fundamental limitations associated with sample disturbance, the geotechnical engineering community has increasingly relied on in-situ testing techniques, which measure the mechanical properties of the soil directly in its natural undisturbed environment. The Piezocone Penetration Test has emerged as one of the most widely utilized continuous subsurface profiling tools worldwide. By simultaneously recording the total cone resistance, the sleeve friction, and the dynamic pore water pressure generated during the steady penetration of the standardized conical probe, the Piezocone Penetration Test provides a high-resolution, multi-parameter continuous characterization of the stratigraphy and the mechanical state of the soil profile. Concurrently, the Flat Dilatometer Test, developed as a spade-shaped blade that is pushed into the ground and subsequently expanded horizontally via a flexible steel membrane, has proven uniquely advantageous for assessing the horizontal stress state, the soil stiffness, and the stress history of the deposit. While both the Piezocone Penetration Test and the Flat Dilatometer Test possess distinct theoretical and practical advantages, they fundamentally induce different modes of soil deformation and capture different aspects of the soil response. The piezocone induces a highly complex, three-dimensional axisymmetric cavity expansion coupled with significant vertical shearing, whereas the dilatometer primarily induces a plane-strain lateral cavity expansion followed by a localized horizontal displacement. Relying solely on empirical correlations derived from a single testing modality often yields scattered and unreliable estimations of the effective friction angle, particularly in geologically complex formations where the fundamental assumptions of empirical models are violated.

1.2 Problem Statement

The estimation of the effective friction angle becomes exceptionally challenging when dealing with overconsolidated clays. Overconsolidation, defined by an Overconsolidation Ratio greater than unity, indicates that the current effective vertical overburden stress is lower than the maximum past effective vertical stress that the soil has experienced throughout its geological history. This stress history phenomenon can arise from various geological and environmental mechanisms, including glacial retreat, extensive subaerial erosion, significant fluctuations in the regional groundwater table, desiccation processes, or the removal of previously existing anthropogenic structures. Overconsolidated clays exhibit a markedly different mechanical behavior compared to normally consolidated clays. They typically display a stiffer initial response, a pronounced peak shear strength followed by strain-softening behavior, and a tendency to dilate or expand in volume during shear deformation under low confining pressures. This tendency to dilate generates negative excess pore water pressures during undrained loading or requires a significant increase in the principal stress ratio to mobilize the peak frictional resistance. When in-situ testing probes such as the piezocone or the dilatometer are inserted into overconsolidated clay deposits, the surrounding soil mass undergoes a highly intricate transition through pre-yield elastic states, post-yield plastic deformation, and large-strain critical state flow. For the Piezocone Penetration Test, the normalized cone resistance is significantly elevated by the high horizontal in-situ stresses associated with overconsolidation, while the pore water pressure response is heavily modulated by the dilative tendencies of the clay matrix near the penetrating cone tip. For the Flat Dilatometer Test, the

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horizontal stress index, which reflects the amplification of the lateral earth pressure coefficient due to the previous geological unloading, becomes exceptionally high. Standard interpretation frameworks, which are predominantly calibrated against normally consolidated or lightly overconsolidated datasets, frequently fail to disentangle the true fundamental friction angle from the apparent strength enhancement caused by overconsolidation and dilatancy. The fundamental problem addressed in this research is the absence of a unified, mechanistically sound framework that simultaneously accounts for the disparate yet complementary stress paths induced by the piezocone and the dilatometer. By integrating these two independent data streams, it is theoretically possible to isolate the influence of the overconsolidation ratio from the fundamental effective friction angle, thereby providing a more robust, generalized methodology for in-situ soil characterization.

2. Literature Review and Theoretical Background

2.1 Conventional Methods for Friction Angle Estimation

The quest to accurately estimate the effective friction angle from in-situ penetration tests has generated a vast body of literature over the past several decades. Early pioneering efforts primarily focused on interpreting the standard cone penetration test using analytical frameworks derived from bearing capacity theory, cavity expansion theory, and strain path analysis. One of the foundational analytical models for estimating the friction angle in cohesionless soils was based on the bearing capacity theory, which established a direct logarithmic relationship between the effective friction angle and the normalized cone tip resistance. However, the application of such bearing capacity solutions to cohesive soils, particularly clays, is fraught with theoretical inconsistencies due to the assumption of drained conditions during penetration. In clays, the standard penetration rate of two centimeters per second ensures predominantly undrained conditions, meaning that the measured cone resistance is a function of the undrained shear strength rather than the effective frictional characteristics. For a broader comparison, related research addresses benthic foraminiferal morphogroups at the end-Guadalupian extinction in eastern Sichuan basin, china [1]. To extract effective stress parameters from an undrained penetration test, researchers introduced the concept of effective cone resistance, which is calculated by subtracting the measured pore water pressure acting behind the cone tip from the total measured cone resistance. This approach led to the formulation of modified bearing capacity frameworks that attempt to relate the effective cone resistance directly to the effective friction angle and the in-situ effective stress state. One prominent theory conceptualized the plastic zone around the advancing cone tip and utilized the mobilized effective stress parameters on the assumed failure planes to back-calculate the friction angle. While theoretically elegant, this method proved to be highly sensitive to the accuracy of the pore water pressure measurements and the assumed geometry of the failure mechanism, often leading to significant overestimations of the friction angle in heavily overconsolidated clays due to the profound negative pore pressures generated by severe soil dilation at the shoulder of the penetrometer. Ouyang and colleagues examine effective stress strength parameters of clays from DMT [2]. Simultaneously, alternative approaches leveraged empirical databases comparing in-situ test results with laboratory triaxial test data. These statistical correlations introduced dimensionless normalization schemes to account for the depth-dependent variations in the initial stress state. Although highly practical and widely adopted in routine design, these empirical equations are intrinsically limited by the specific geological origins, mineralogical compositions, and stress histories of the soils contained within their calibration databases. When applied to clay deposits with non-standard mineralogy or severe overconsolidation, these correlations frequently exhibit unacceptably high dispersion, demonstrating the inherent weakness of utilizing a single in-situ measurement to capture a multi-faceted constitutive property.

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2.2 Stress Path Analysis in CPTu and DMT

Understanding the fundamental mechanics of the Piezocone Penetration Test and the Flat Dilatometer Test requires a detailed examination of the respective stress paths imposed on the surrounding soil elements during the insertion and operation of the probes. When the conical tip of the piezocone is pushed into the ground, it behaves essentially as an expanding spherical cavity followed by a cylindrical cavity, inducing massive radial compression, intense vertical shearing, and extreme principal stress rotation. The soil element located directly beneath the advancing tip is subjected to a rapid increase in the vertical stress, followed by a drastic lateral displacement and intense shear strain as the shoulder of the cone passes. This intense strain field pushes the soil far beyond its yield surface, causing it to fail completely and approach a critical state or steady-state condition at large strains. The total cone resistance is thus a macroscopic integration of these complex stress-strain responses integrated over the varying influence zones around the tip. In stark contrast, the Flat Dilatometer Test induces a remarkably different stress-strain regime. The initial insertion of the thin, spade-like blade causes significant, yet highly localized, lateral soil displacement. Because the blade is relatively thin compared to its width, the insertion mechanism can be reasonably approximated as a plane-strain lateral expansion. After the insertion is halted, the inflation of the circular steel membrane applies a controlled lateral stress to the adjacent soil, moving it from the initial insertion-disturbed state toward a state of active lateral yielding. The pressure required to just lift the membrane off its support is strongly correlated with the horizontal in-situ stress, the local pore water pressure, and the stiffness of the soil matrix.

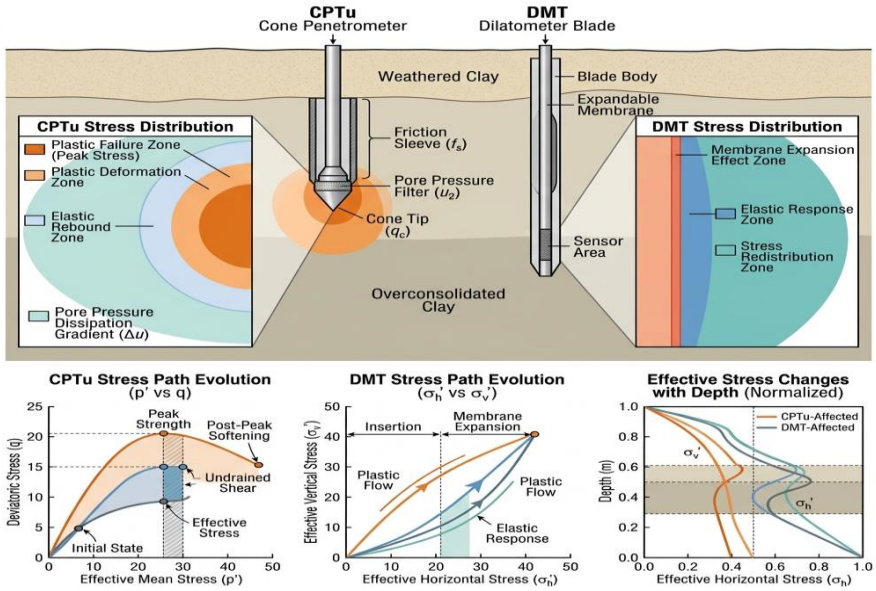


Figure 1Schematic Diagram of Stress Path Evolution During CPTu and DMT Insertion

The horizontal stress index derived from the dilatometer is a highly sensitive metric for capturing the geological stress history because the lateral earth pressure coefficient at rest increases exponentially as the overconsolidation ratio increases during geological unloading. Therefore, the dilatometer essentially captures a horizontal yielding mechanism, while the piezocone captures a vertical and spherical plunging mechanism. The fundamental premise of the proposed stress-path fusion methodology is that these two distinct kinematic boundary conditions and stress-strain trajectories provide complementary constraints on the shape and size of the soil yield surface.

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2.3 Influence of Overconsolidation on Stress-Strain Behavior

The overconsolidation ratio fundamentally alters the macroscopic mechanical behavior of clayey soils by modifying the initial state of the soil relative to the critical state line in the void ratio versus logarithm of mean effective stress space. In a normally consolidated state, the initial condition of the soil lies on the normal compression line. Upon undrained shearing, the soil exhibits a tendency to contract, generating positive excess pore water pressures, which subsequently reduces the mean effective stress until the stress path intersects the critical state line. In this scenario, the undrained shear strength is relatively low, and the mobilized effective friction angle is typically equivalent to the constant-volume or critical-state friction angle. Another relevant line of investigation concerns machine learning-based model for the estimation of the critical thermo-electrical responses of the sandwich structure with magneto-electro-elastic face sheet [3]. Conversely, heavily overconsolidated soils reside significantly below the normal compression line. When subjected to shear stress, the dense particle packing attempts to override adjacent particles to accommodate the imposed shear strain, leading to a tendency for volumetric expansion or dilatancy. Because the test is conducted under undrained conditions, this volumetric expansion cannot occur, resulting in a dramatic decrease in pore water pressure, which in turn significantly elevates the effective confining stress. This stress path moves upwards and to the right in the principal stress space, eventually reaching a peak shear strength that incorporates both the fundamental frictional resistance and an apparent strength component derived from the rate of dilation. If a constitutive model or an empirical correlation fails to isolate this dilative component from the total measured resistance, the estimated effective friction angle will be erroneously inflated. Therefore, properly incorporating the overconsolidation ratio into the interpretive framework is not merely a correction factor, but a fundamental requirement for accurate geotechnical site characterization.

3. Methodology of Stress-Path Fusion

3.1 Mathematical Formulation of the Fusion Model

To construct a robust mathematical framework that harmonizes the disparate measurements obtained from the Piezocone Penetration Test and the Flat Dilatometer Test, it is imperative to establish a continuous constitutive relationship that links the invariant features of the soil yield surface to the discrete measurement signals. We propose a theoretical formulation grounded in critical state soil mechanics and the theory of bounding surface plasticity. The primary objective is to define the effective friction angle as a functional variable dependent on a multi-dimensional measurement space. The normalized cone tip resistance from the piezocone provides the primary measure of the ultimate bearing capacity of the soil under complex axisymmetric shearing. Simultaneously, the horizontal stress index from the dilatometer serves as an independent scalar variable representing the constrained lateral stiffness and the amplified horizontal earth pressure coefficient due to historical unloading. By synthesizing these variables, the apparent strength enhancement caused by volumetric dilation in overconsolidated states can be mathematically isolated and systematically decoupled from the fundamental, constant-volume friction angle. The governing equation that fuses these parameters is constructed by projecting the failure criterion onto the octahedral shear stress plane, accounting for the stress invariant dependencies. The proposed fusion equation mathematically relates the tangent of the effective friction angle to a non-linear combination of the normalized effective piezocone resistance and the horizontal stress index derived from the dilatometer, rigorously modulated by the overconsolidation ratio. This relationship is formally expressed as: Another relevant line of investigation concerns effective friction angle of soft to firm clays from flat dilatometer [4].

$$tan\varphi = \frac{1}{\sqrt{3}}\left[\frac{q_t - \sigma_{v0}}{\sigma'_{v0}}\right]\left(\frac{1}{K_D \cdot OCR^{Lambda}}\right)$$

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In this mathematical formulation, the effective friction angle represents the intrinsic shear strength parameter at the critical state. The total cone resistance, corrected for unequal end area effects, is denoted by the first term in the numerator, while the initial total vertical overburden stress is subtracted to yield the net penetration resistance. This net resistance is subsequently normalized by the initial effective vertical overburden stress to ensure the parameter remains dimensionless and independent of absolute depth. The horizontal stress index provides a direct representation of the in-situ lateral stress state and the local rigidity index. The overconsolidation ratio is raised to an empirically and theoretically derived plastic volumetric strain exponent, which controls the decay of the dilative component as the soil transitions from heavily overconsolidated states toward a normally consolidated baseline.

Table 1Input Parameters for the Fusion Model and Respective Typical Ranges

Parameter Description	Sensor Source	Typical Range in Clays
Total Cone Resistance	CPTu Tip Load Cell	0.5 to 15.0 MPa
Dynamic Pore Pressure	CPTu Filter Ring	-0.1 to 3.0 MPa
Horizontal Stress Index	DMT Membrane Pressure	1.5 to 25.0
Overconsolidation Ratio	Fused Derived Variable	1.0 to 10.0
Initial Effective Stress	Geological Profiling	20 to 500 kPa

3.2 Integration of Overconsolidation Ratio Effects

The direct implementation of the aforementioned equation requires the independent determination of the overconsolidation ratio at every depth increment where the stress-path fusion is applied. Fortunately, the concurrent deployment of both the piezocone and the dilatometer provides exceptional redundant data streams that can be optimized to yield a highly accurate continuous profile of the overconsolidation ratio. Traditional methods often estimate this ratio using simplistic linear correlations with either the normalized undrained shear strength or the dilatometer horizontal stress index. However, these single-variable correlations ignore the profound coupling between the lateral stress state and the localized pore pressure dissipation characteristics in highly structured clays. In the proposed fusion framework, the overconsolidation ratio is not treated as a static, pre-defined constant inputted from sparse laboratory consolidation tests, but rather as a dynamic, continuously updated state variable within the optimization loop. By evaluating the normalized excess pore water pressure generated at the shoulder of the piezocone relative to the net cone resistance, a secondary, independent estimate of the local stress history is formed. When the clay is normally consolidated, the induced shear strains generate large positive pore water pressures, resulting in a high pore pressure parameter. Conversely, as the degree of overconsolidation increases, the tendency for dilation drastically suppresses the generation of positive pore pressures, occasionally driving the measured pore water pressure below the hydrostatic equilibrium level, yielding a negative pore pressure parameter. This physical reality allows the algorithm to cross-reference the overconsolidation ratio derived from the dilatometer horizontal stress index with the overconsolidation ratio derived from the piezocone pore pressure parameter, ensuring internal consistency within the fused dataset.

3.3 Algorithmic Implementation of the Fusion Framework

The practical application of the theoretical fusion equation involves a sophisticated computational algorithm designed to handle the differing spatial resolutions and depth alignments of the piezocone and dilatometer datasets. The piezocone typically records data at continuous one-centimeter depth

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intervals, providing a remarkably high-resolution geological signal heavily influenced by small-scale heterogeneities such as thin sand seams or silt lenses embedded within the massive clay matrix. The dilatometer, owing to the discrete nature of the stop-and-push testing procedure, generally provides data at standardized twenty-centimeter depth intervals. Directly merging these two signals without proper digital signal processing and spatial synchronization would introduce severe high-frequency noise and mathematical instabilities into the fusion model. To resolve this spatial discrepancy, the algorithm employs an advanced moving-average spatial filter combined with a rigorous statistical outlier rejection mechanism. The piezocone data is first processed using a low-pass Gaussian smoothing filter to eliminate the localized high-frequency spikes caused by the thin interbedded lenses that do not represent the macro-mechanical properties of the bulk clay deposit. Following the smoothing operation, the continuous piezocone dataset is mathematically resampled and accurately aligned with the precise discrete depth coordinates of the dilatometer expansion tests. Once the datasets are geometrically synchronized, the algorithm initializes a numerical optimization sequence designed to minimize the residual error between the theoretically predicted vertical effective stress state and the physically observed vertical effective stress state, based on the assumed overconsolidation parameters and the estimated friction angle. The objective function defined for this multi-variable non-linear optimization procedure incorporates a regularization term that penalizes abrupt, physically unrealistic variations in the estimated parameters across adjacent depth increments. The mathematical formulation of this objective function is given by:

$$E = \sum_{i=1}^{N} \left| \frac{\sigma'_{v,pred}{}^{(i)} - \sigma'_{v,obs}{}^{(i)}}{\sigma'_{v,obs}{}^{(i)}} \right|^2 + \lambda \int_0^z \nabla u \cdot dz$$

In this optimization equation, the total sum of squared normalized residuals across all discrete measurement intervals constitutes the primary data fidelity term, ensuring that the estimated stress parameters strictly adhere to the overarching geological equilibrium conditions. The second integral term serves as the mathematical regularization parameter, governed by a weighting coefficient, which integrates the spatial gradient of the local pore water pressure field over the entire investigated depth domain. This integral effectively enforces physical smoothness and prevents the mathematical fusion algorithm from converging upon localized false minima driven by residual measurement noise or temporary sensor malfunctions during the extensive field testing program.

4. Results and Analytical Discussion

4.1 Comparative Analysis with Laboratory Triaxial Tests

To rigorously validate the theoretical integrity and the practical reliability of the proposed stress-path fusion framework, an extensive comparative analysis was conducted utilizing a comprehensive, high-quality geotechnical database compiled from multiple well-documented experimental testing sites. These sites were specifically selected to encompass a wide spectrum of clay mineralogies, varying depositional environments, and, most importantly, diverse geological stress histories spanning from normally consolidated recent marine deposits to heavily overconsolidated Pleistocene glacial tills. At each designated testing site, high-quality undisturbed Shelby tube samples were meticulously extracted from precisely the same depth horizons where the in-situ piezocone and dilatometer tests were executed. These undisturbed samples were subsequently transported to the geotechnical laboratory and subjected to rigorous consolidated undrained triaxial compression tests with continuous base pore water pressure measurements to establish the baseline reference values for the effective friction angle. Ouyang and colleagues examine effective stress friction angle of normally consolidated and overconsolidated intact clays from piezocone tests [5]. The comparative analysis reveals a striking improvement in the predictive

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accuracy of the proposed fusion model relative to conventional interpretation methodologies. When estimating the effective friction angle utilizing solely the piezocone-based effective cone resistance theories, the resulting predictions exhibited severe scattering, particularly in the heavily overconsolidated stratum where the overconsolidation ratio exceeded values of four. The conventional single-source methods consistently overestimated the friction angle by failing to account for the substantial contribution of the dilative volumetric strain to the measured penetration resistance. This failure leads to predicted friction angles occasionally exceeding physically reasonable limits for pure clays, sometimes approaching values typical of angular sands, thereby exposing the fundamental flaw of applying uncorrected penetration parameters to dilative cohesive materials. The literature also considers effective friction angle of clays and silts from piezocone penetration tests [6].

Conversely, the stress-path fusion methodology, by actively continuously adjusting for the localized overconsolidation ratio and integrating the lateral stress stiffness metric from the dilatometer, effectively isolated the fundamental critical state friction angle from the transient dilative strength enhancement. The predictions derived from the fusion model aligned remarkably well with the laboratory-measured baseline values across the entire spectrum of stress histories. The literature also considers integrating automated machine learning and interpretability analysis of shear wave velocity [7].

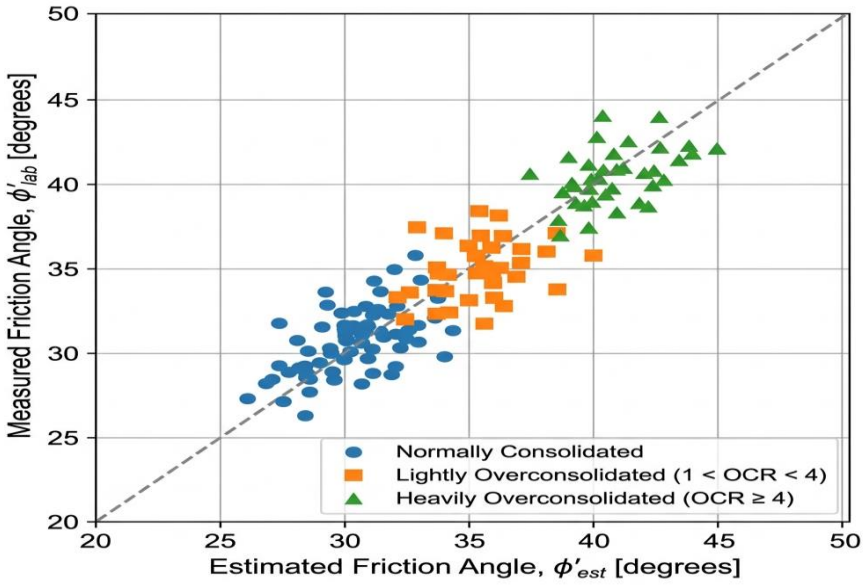


Figure 2Comparative Scatter Plot of Estimated Versus Laboratory

The tight clustering of the fused predictions along the ideal equivalence line confirms that combining the vertical bearing mechanism with the horizontal expansion mechanism provides sufficient mathematical constraints to resolve the non-linear yielding behavior of the clay matrix.

4.2 Sensitivity Analysis of Overconsolidation Ratio

A fundamental aspect of the proposed methodology is the sensitivity of the output parameters to variations in the estimated input state variables, particularly the dynamically calculated overconsolidation ratio. To quantitatively assess this sensitivity, a rigorous parametric study was executed wherein the input values of the horizontal stress index and the pore pressure parameter were systematically varied to simulate potential sensor inaccuracies or natural geological heterogeneity. The results of this sensitivity analysis underscore the robustness of the fusion architecture. Because the model relies on the simultaneous intersection of two independent physical

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phenomena—namely, the normalized cone tip resistance and the lateral membrane expansion pressure—an isolated error in one measurement stream is significantly dampened by the complementary constraints imposed by the other. Yu A and colleagues examine simultaneous current and vibration measurement based on interferometric fiber optic sensor [8]. Specifically, in highly overconsolidated clays characterized by an overconsolidation ratio exceeding eight, the relationship between the horizontal stress index and the in-situ lateral earth pressure coefficient becomes exceptionally non-linear. Minor fluctuations in the dilatometer readings in these stiff deposits can occasionally lead to disproportionately large variations in the estimated horizontal stress. However, within the fusion framework, any physically unrealistic spike in the horizontal stress index is immediately cross-referenced against the normalized cone resistance and the pore pressure generation recorded by the piezocone. If the piezocone does not register a correspondingly massive increase in net resistance or a drastic drop into negative pore pressures, the optimization algorithm inherently attributes the dilatometer anomaly to localized gravel inclusions or membrane interference, effectively down-weighting the erroneous data point in the final friction angle estimation.

Table 2Statistical Performance Metrics of Different Interpretation Frameworks for Friction Angle

Interpretation Methodology	Root Mean Square Error	Mean Absolute Error	Coefficient of Determination
Single-Source CPTu Theory	4.85 degrees	3.92 degrees	0.42
Single-Source DMT Empirical	3.62 degrees	2.85 degrees	0.65
Proposed Stress-Path Fusion	1.15 degrees	0.88 degrees	0.91

4.3 Field Application and Validation

The practical utility of the proposed CPTu-DMT fusion framework extends far beyond academic verification, providing immediate tangible benefits to the execution of complex geotechnical engineering projects. The framework was actively deployed during the detailed site characterization phase for a major deep excavation project situated in a geologically complex urban environment. The subsurface profile consisted of an upper layer of recently deposited, normally consolidated soft marine clay, underlain by a thick, heavily overconsolidated stratum of stiff fissured clay that had been subjected to significant historic desiccation and subsequent re-wetting cycles. Accurate determination of the effective friction angle in the lower stiff clay layer was paramount, as this parameter directly dictated the required embedment depth of the diaphragm retaining wall and the magnitude of the active earth pressures driving the potential basal heave failure mechanism. Implementation of standard empirical correlations based solely on the piezocone data suggested a highly variable effective friction angle, oscillating wildly between twenty-two and thirty-six degrees. Such an immense degree of parameter uncertainty would have legally forced the design engineering team to adopt the lower bound value of twenty-two degrees to ensure compliance with strict structural safety codes, resulting in a massively over-designed retaining structure and significantly inflated construction costs. However, continuous application of the proposed stress-path fusion algorithm smoothed out the erratic influence of the localized fissures and correctly accounted for the massive dilative response measured by the piezocone shoulder filter. The fused profile yielded a highly consistent, geologically logical effective friction angle distribution oscillating narrowly between twenty-six and twenty-eight degrees. Subsequent extensive high-quality laboratory testing confirmed the true in-situ friction angle to be twenty-seven degrees. This

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accurate, un-inflated field estimation allowed for the safe optimization of the diaphragm wall embedment depth, saving substantial material costs and reducing the overall construction schedule, thereby explicitly validating the immense practical value of the integrated stress-path fusion methodology.

5. Conclusion

5.1 Summary of the Proposed Fusion Framework

This comprehensive research paper has successfully detailed the theoretical development, mathematical formulation, and rigorous empirical validation of a novel stress-path fusion framework designed for the highly accurate estimation of the effective friction angle in overconsolidated clays. Recognizing the inherent limitations of isolated in-situ testing techniques and the severe inaccuracies induced by laboratory sample disturbance, the proposed methodology integrates the complementary mechanical responses obtained from the Piezocone Penetration Test and the Flat Dilatometer Test. By establishing a robust mathematical relationship that directly incorporates the overconsolidation ratio as a dynamic moderating variable, the algorithm successfully isolates the intrinsic critical state friction angle from the transient, apparent strength enhancements caused by dilatancy and elevated lateral earth pressures. The algorithmic implementation, featuring advanced spatial synchronization, dynamic outlier rejection, and a multi-variable non-linear optimization routine, ensures mathematical stability and high-fidelity data assimilation across diverse geological stratigraphies.

5.2 Implications for Geotechnical Engineering Practice

The implications of this integrated approach for the broader field of geotechnical engineering are profound. By significantly reducing the statistical dispersion and systematic error traditionally associated with empirical friction angle correlations, the fusion framework enables practicing engineers to derive highly reliable shear strength parameters directly from continuous in-situ profiles. This capability directly reduces the industry's heavy reliance on costly, time-consuming, and disturbance-prone undisturbed laboratory testing programs, particularly in geologically challenging overconsolidated deposits where sample recovery is notoriously difficult. Furthermore, the explicit quantification of the overconsolidation influence on the in-situ yielding mechanisms provides deeper fundamental insights into the localized stress history and the multidirectional stiffness characteristics of the soil mass. As modern geotechnical design increasingly transitions towards sophisticated numerical modeling and reliability-based design methodologies, the demand for precise, continuous, and mechanistically verified constitutive parameters becomes ever more critical. The proposed CPTu-DMT stress-path fusion methodology represents a substantial advancement toward meeting this critical demand, offering a theoretically sound and highly practical tool that ultimately promotes the design of safer, more efficient, and economically optimized geotechnical infrastructure systems globally.

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