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Variable-rate Piezocone Inversion of Effective Stress Strength in Soft Clays: A Comprehensive Analytical Framework

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Abstract

The accurate characterization of effective stress strength parameters in soft clays remains a critical challenge in geotechnical engineering, particularly given the complex drainage conditions that emerge during in situ testing. Piezocone penetration testing has traditionally been conducted at a standard constant rate, which predominantly assumes fully undrained conditions in fine-grained soils. However, this assumption often leads to significant inaccuracies when estimating the effective friction angle and cohesion, as partial drainage can occur even in clays. This paper presents a comprehensive analytical framework for the variable-rate piezocone inversion of effective stress strength in soft clays. By systematically varying the penetration velocity, the transition from undrained to partially drained and fully drained conditions is captured. An inversion algorithm is subsequently developed to extract fundamental effective stress parameters directly from the continuously measured cone tip resistance and pore water pressure data. The methodology relies on a theoretical mapping between the normalized penetration velocity and the degree of consolidation surrounding the advancing cone. Field investigations were conducted at a well-characterized soft clay test site to validate the proposed framework. The inverted effective stress parameters demonstrate a high degree of correlation with high-quality laboratory triaxial test results. The findings establish that variable-rate piezocone testing, coupled with the proposed inversion methodology, provides a robust, continuous, and highly reliable approach for profiling effective stress strength in challenging soft clay deposits, ultimately improving the safety and economy of geotechnical design.

Keywords: *Piezocone Penetration Testing, Soft Clay, Variable Rate, Effective Stress, Inversion Algorithm*

1. Introduction

1.1 Background on Piezocone Penetration Testing

The field of geotechnical engineering relies heavily on in situ testing methods to obtain continuous and reliable subsurface information. Among the various techniques available, piezocone penetration testing has emerged as the premier tool for site characterization, particularly in fine-grained soil deposits. The instrument typically consists of a cone-shaped tip, a friction sleeve, and a porous filter element connected to a pressure transducer

to measure the dynamic pore water pressure generated during penetration. Standard procedures dictate that the test is conducted at a constant rate of two centimeters per second. At this standard rate, it is generally assumed that the penetration process in clays occurs under fully undrained conditions, meaning that the pore water does not have sufficient time to dissipate, thereby generating significant excess pore water pressure. This excess pore water pressure, along with the measured tip resistance and sleeve friction, is traditionally used to estimate total stress parameters, such as the undrained shear strength of the soil. However, modern geotechnical design heavily favors effective stress analysis, as it governs the true frictional resistance and volumetric behavior of soils. The translation of piezocone measurements into effective stress strength parameters, primarily the effective friction angle and effective cohesion, remains a highly active area of research. This is largely because the effective stress state around the advancing cone is incredibly complex, involving severe soil remolding, large strain gradients, and intricate hydro-mechanical coupling. For a broader comparison, related research addresses fusulinids in a middle-late Permian carbonate platform (from Maokou to Wuchiapingian stage) in eastern Sichuan basin, china [1].

1.2 Challenges in Soft Clay Characterization

Soft clays present unique challenges for geotechnical site characterization due to their high compressibility, low shear strength, and low hydraulic conductivity. When a structure is constructed on soft clay, the long-term stability and settlement are governed by the effective stress properties of the soil as the excess pore pressures eventually dissipate. Obtaining undisturbed samples of soft clay for laboratory testing is notoriously difficult and expensive, as the sampling process itself inevitably alters the in situ stress state and soil structure. Consequently, engineers increasingly rely on in situ methods. However, the standard piezocone test in soft clays, while excellent for profiling stratigraphy and estimating undrained strength, struggles to provide direct measurements of effective stress parameters. The primary obstacle is the assumption of fully undrained behavior at the standard penetration rate. In reality, depending on the exact permeability and consolidation characteristics of the specific clay deposit, a standard rate may induce partially drained conditions. If the drainage condition is misidentified, the empirical correlations used to derive strength parameters will yield erroneous results, potentially leading to unsafe or overly conservative foundation designs. Furthermore, the generation of pore water pressure at the cone face and shoulder is highly dependent on the rigidity index and the stress history of the clay, complicating the extraction of fundamental effective stress parameters from standard single-rate tests. Another relevant line of investigation concerns effective stress strength of clays evaluated from piezocone and flat dilatometer tests [2].

1.3 Objectives and Scope of the Study

To overcome the limitations of standard piezocone testing in soft clays, this study investigates the potential of variable-rate piezocone penetration testing. By intentionally altering the penetration velocity over several orders of magnitude during a single sounding, one can force the soil response to transition from fully undrained through partially drained and eventually approaching fully drained conditions. The primary objective of this research is to develop and validate a comprehensive mathematical inversion framework capable of extracting effective stress strength parameters directly from this variable-rate data. The scope of the study encompasses the theoretical formulation of the drainage transition, the development of a numerical inversion algorithm, and an extensive field validation program conducted in a well-documented soft clay deposit. The proposed methodology aims to bypass the need for highly empirical, single-rate correlations by utilizing the physical relationship between penetration rate, pore pressure dissipation, and effective stress mobilization.

2. Literature Review and Theoretical Background

2.1 Historical Development of Piezocone Testing

The evolution of the piezocone penetrometer is a testament to the continuous drive for higher resolution in situ geotechnical data. Originally developed in the late twentieth century by integrating a pore pressure transducer into the standard mechanical cone, the piezocone revolutionized the profiling of soil stratigraphy. Early researchers quickly recognized that the magnitude and dissipation rate of penetration-induced pore

water pressure were intimately linked to soil type, stress history, and hydraulic conductivity. Throughout the subsequent decades, significant effort was dedicated to developing theoretical frameworks to interpret piezocone data. Cavity expansion theory and strain path methods were widely adopted to model the complex stress fields around the cone tip. These early models were largely restricted to assuming either perfectly drained or perfectly undrained conditions. It was not until the turn of the century that researchers began to systematically explore the effects of varying the penetration rate. Initial variable-rate studies were primarily focused on intermediate soils, such as silts and clayey sands, where standard penetration rates naturally induced partial drainage. These studies demonstrated that the measured tip resistance and pore water pressure are highly sensitive to the penetration velocity in intermediate soils. However, the application of variable-rate testing to soft, intact clays has been largely overlooked, primarily due to the assumption that soft clays are always strictly undrained at conventional testing speeds. Another relevant line of investigation concerns dynamic temporal scale decoupling and variable interaction modeling for photovoltaic power forecasting [3].

2.2 Effective Stress Strength Parameters in Clays

The shear strength of soils is fundamentally governed by the effective stress principle, which states that the shear resistance is proportional to the normal stress carried by the soil skeleton, exclusive of the pressure borne by the pore fluid. For soft clays, the effective stress strength is characterized by the effective friction angle and the effective cohesion intercept. Accurate determination of these parameters is essential for long-term stability analyses of embankments, excavations, and retaining structures. Traditionally, these parameters are determined through slow, consolidated-undrained or consolidated-drained triaxial compression tests in the laboratory. The interpretation of piezocone data for effective stress parameters has historically relied on semi-empirical approaches. For instance, several widely used methods estimate the effective friction angle based on the normalized cone tip resistance and assumed volumetric strain behavior. However, these methods often require independent knowledge of the coefficient of earth pressure at rest and the rigidity index, parameters that are themselves difficult to determine in situ. The challenge lies in the fact that a single penetration rate yields a single snapshot of the soil behavior under a specific, and often unknown, degree of drainage. Without varying the rate, it is mathematically ill-posed to isolate the effective stress parameters from the complex interplay of pore pressure generation and soil stiffness. Ouyang and colleagues examine effective stress strength parameters of clays from DMT [4].

2.3 Rate-Dependent Penetration Mechanisms

When a cone penetrometer advances through a soil mass, it displaces the soil outwards and downwards, generating complex shear and volumetric strains. In saturated clays, this rapid displacement generates large positive excess pore water pressures. The rate at which this pressure dissipates relative to the rate at which it is generated determines the drainage condition. To quantify this relationship, researchers utilize the concept of a normalized penetration velocity. This dimensionless parameter is typically defined as the product of the penetration velocity and the cone diameter, divided by the coefficient of consolidation of the soil. When the normalized velocity is very high, the process is fully undrained. As the velocity decreases, pore water has sufficient time to flow away from the highly stressed zone around the cone tip, leading to partial drainage. Under partial drainage, the effective stress acting on the cone face increases, which subsequently increases the measured tip resistance and alters the mechanism of soil failure from a globally undrained bearing capacity failure to a more localized, drained failure mechanism. The backbone curve relating normalized velocity to normalized tip resistance and pore pressure ratio forms the theoretical foundation for variable-rate interpretation. By mapping this backbone curve through carefully controlled variable-rate field tests, the fundamental consolidation and effective stress properties of the soil can be mathematically isolated and inverted. The literature also considers integrating automated machine learning and interpretability analysis of shear wave velocity [5].

3. Variable-Rate Penetration Mechanics

3.1 Drainage Conditions During Penetration

Understanding the variable-rate penetration mechanics requires a detailed examination of the drainage boundaries that govern the soil response. The drainage state is a continuum ranging from fully undrained to fully drained. In the fully undrained state, which occurs at high penetration velocities typical of standard testing in clays, the volumetric strain of the soil skeleton is constrained to zero due to the incompressibility of the pore water. All penetration-induced stresses are therefore initially carried by the pore fluid, resulting in maximum excess pore pressures and minimum effective stresses. As the penetration velocity is intentionally reduced, the test enters the partially drained regime. Here, the rate of excess pore pressure generation is balanced by the simultaneous radial and vertical dissipation of pore water away from the cone tip. This dissipation allows for volumetric compression of the soil skeleton ahead of the cone, leading to an increase in effective stress and a corresponding stiffening of the soil response. If the velocity is reduced sufficiently, a fully drained state can theoretically be achieved, where no excess pore pressure is generated, and the tip resistance reaches a maximum value governed entirely by the effective friction angle and ambient effective stresses.

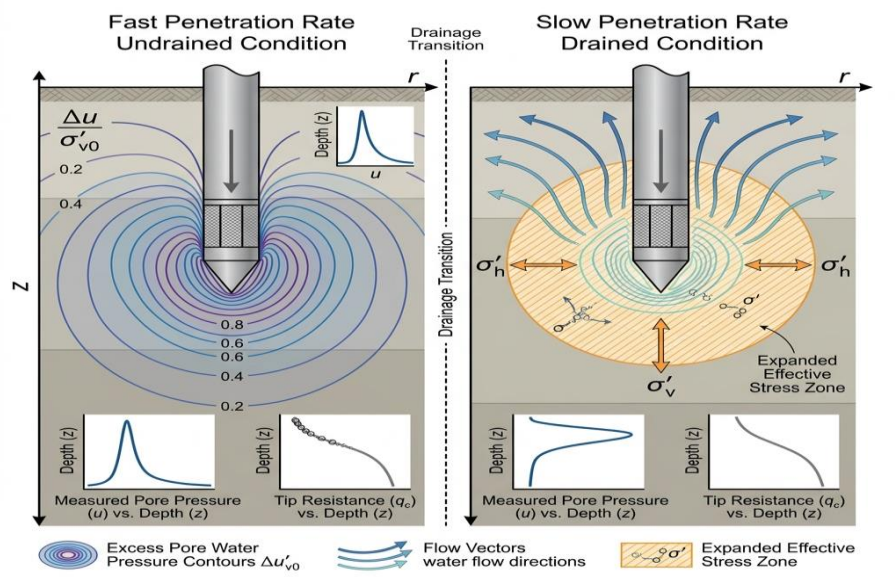


Figure 1: Schematic representation of the drainage transition during variable

3.2 Consolidation and Pore Pressure Dissipation

The transition through these drainage states is governed by the coefficient of consolidation of the soft clay. The consolidation process around an advancing cone is highly complex due to the continuous moving boundary and the large strain destruction of the soil structure. The soil immediately adjacent to the cone is severely remolded, which drastically reduces its permeability compared to the undisturbed state. The variable-rate test effectively acts as a continuous spatial and temporal consolidation experiment. At any given velocity, a steady-state excess pore pressure field is established around the cone. The magnitude of the pore pressure measured at the cone shoulder is a direct function of the degree of consolidation that has occurred during the time it takes for the cone to pass a given point in the soil profile. By plotting the measured pore pressure against the penetration velocity on a logarithmic scale, an S-shaped transition curve is typically observed. The inflection point of this curve is highly sensitive to the in situ coefficient of consolidation and the effective stress strength parameters, providing the critical data points required for the subsequent numerical inversion process.

3.3 Transition from Undrained to Partially Drained States

The transition from undrained to partially drained states is accompanied by a fundamental shift in the failure mechanism surrounding the cone tip. In the undrained state, the failure mechanism is typically modeled as the expansion of a spherical or cylindrical cavity, where the ultimate cavity pressure is governed by the undrained shear strength. However, as partial drainage initiates, the increasing effective stresses enhance the frictional resistance of the soil. The failure zone transitions from a predominantly contractive, plastic shear zone to a more complex state involving both shear-induced dilation and consolidation-induced hardening. This mechanical transition is reflected in the continuous measurements; the tip resistance begins to climb asymptotically toward its drained maximum, while the pore pressure ratio drops. The mathematical representation of this transition requires the coupling of fluid flow equations with an advanced elasto-plastic soil constitutive model capable of capturing effective stress changes. The inversion framework developed in this study leverages these coupled mechanical relationships to back-calculate the fundamental strength parameters that dictate the shape and bounds of this transition curve.

4. Analytical Methodology for Inversion

4.1 Conceptual Framework for Parameter Extraction

The core of the proposed variable-rate piezocone inversion framework relies on establishing a mathematically robust mapping between the continuous field measurements and the desired effective stress parameters. The conceptual framework is built upon the premise that if the backbone curves relating normalized velocity to tip resistance and pore pressure can be empirically or numerically defined for a given soil deposit, then the theoretical end-members (fully drained and fully undrained states) can be extrapolated from variable-rate data that only captures the partially drained regime. In soft clays, it is often impractical to achieve fully drained penetration due to the extremely slow velocities required, which can take days to advance a single meter. Therefore, the inversion algorithm must operate on the partially drained transition data. The framework utilizes a coupled Eulerian-Lagrangian numerical simulation space to pre-calculate hundreds of theoretical transition curves for various combinations of effective friction angle, effective cohesion, rigidity index, and lateral stress coefficient. These pre-calculated curves form a high-dimensional reference matrix. The inversion process then becomes an optimization problem, seeking the specific set of effective stress parameters that minimizes the residual error between the field-measured variable-rate data and the theoretical curves. For a broader comparison, related research addresses benthic foraminiferal morphogroups at the end-Guadalupian extinction in eastern Sichuan basin, china [6].

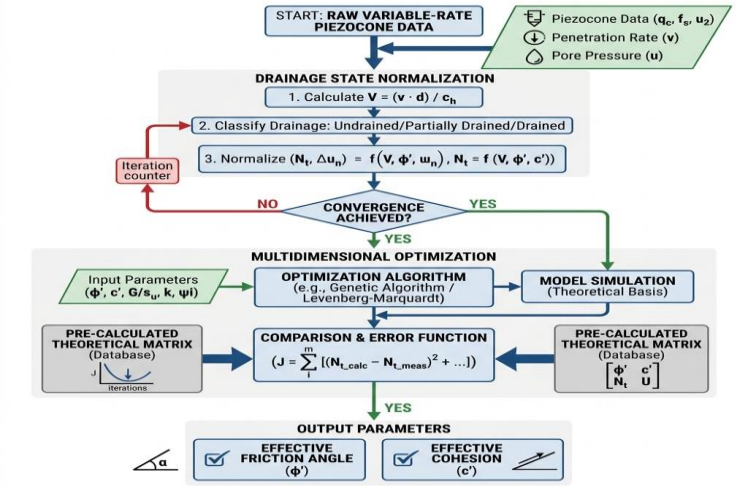


Figure 2: Algorithmic flowchart of the proposed inversion methodology for effective stress parameter extraction

4.2 Variable-Rate Inversion Algorithms

The specific inversion algorithm developed for this research employs a gradient-descent optimization technique combined with a nonlinear least-squares fitting approach. The input data stream consists of matched pairs of penetration velocity and the corresponding steady-state tip resistance and pore pressure measurements. To ensure stability, the raw data undergoes a filtering process to remove high-frequency noise and sudden anomalies caused by localized soil heterogeneity, such as shell fragments or thin silt lenses. The filtered data is then normalized against the in situ vertical effective stress. The algorithm initializes by assuming a baseline set of effective stress parameters derived from standard empirical correlations. It then iteratively adjusts the effective friction angle and cohesion, generating a new theoretical transition curve at each step by querying the pre-calculated reference matrix. A cost function is evaluated at each iteration, defined as the sum of squared differences between the measured data points and the theoretical curve. The gradient of the cost function directs the subsequent parameter adjustments. This iterative process continues until the change in the cost function drops below a predefined convergence tolerance, at which point the final effective stress parameters are extracted and recorded for that specific depth interval.

4.3 Calibration and Validation Procedures

To ensure the reliability of the inversion algorithm, a rigorous calibration and validation protocol was established prior to field implementation. The calibration phase utilized synthetic piezocone data generated from highly controlled numerical simulations of penetration into a virtual soil deposit with known effective stress properties. The algorithm was challenged to blindly invert the synthetic variable-rate data and recover the original input parameters. This synthetic testing allowed for the fine-tuning of the optimization hyperparameters, such as the learning rate and convergence criteria, ensuring that the algorithm did not become trapped in local minima. Furthermore, the sensitivity of the inversion output to uncertainties in secondary input parameters, such as the coefficient of earth pressure at rest, was systematically evaluated. Following the successful numerical calibration, the validation phase involved comparing the algorithm's predictions against high-quality reference data obtained from undisturbed laboratory testing. This step is critical, as it bridges the gap between theoretical mechanics and actual soil behavior, demonstrating that the inversion framework can account for the complex effects of soil structure, anisotropy, and remolding that occur during in situ testing.

5. Experimental Setup and Field Investigations

5.1 Site Characterization and Soil Profiling

The field investigations to validate the variable-rate inversion methodology were conducted at a well-documented national geotechnical experimentation site. The site is characterized by a deep, homogeneous deposit of soft, normally consolidated marine clay, extending from immediately below the superficial desiccation crust down to a depth of approximately thirty meters. The groundwater table is located near the ground surface, ensuring that the clay deposit is fully saturated. Prior to the piezocone testing program, extensive site characterization had been performed, including rotary core drilling and high-quality thin-walled tube sampling. The laboratory characterization program provided a comprehensive baseline of the soil's index properties, consolidation behavior, and triaxial shear strength. The clay is classified as having high plasticity, with a natural water content slightly exceeding its liquid limit, indicative of a sensitive soil structure. The initial void ratio is exceptionally high, which contributes to its high compressibility and very low initial undrained shear strength. This extensive background data makes the site an ideal candidate for testing advanced in situ interpretation methodologies, as the fundamental effective stress parameters are well-established.

Table 1: Baseline geotechnical properties of the soft clay at the experimental test site

Depth Interval (m)	Natural Water Content (%)	Plasticity Index	Initial Void Ratio	Vertical Effective Stress (kPa)
2.0 - 5.0	78.5	42.1	1.95	18.4
5.0 - 10.0	75.2	40.5	1.88	32.6
10.0 - 15.0	72.1	38.2	1.81	48.2
15.0 - 20.0	69.4	36.8	1.74	64.5

5.2 Equipment and Variable-Rate Testing Protocol

The field testing was conducted using a state-of-the-art, ten square centimeter piezocone penetrometer equipped with highly sensitive strain gauges for measuring tip resistance and sleeve friction, and a porous ceramic filter located immediately behind the cone tip for pore pressure measurement. The penetrometer was pushed into the ground using a heavily ballasted, track-mounted twenty-ton capacity rig. To achieve the required precise control over the penetration velocity, the standard hydraulic feed system of the rig was bypassed and replaced with a specialized, computer-controlled servomotor pushing system. This customized setup allowed for accurate, continuous variation of the penetration rate from a maximum of ten centimeters per second down to extremely slow rates of zero point zero one centimeters per second. The variable-rate testing protocol involved advancing the cone to a target depth at the standard rate, pausing momentarily to allow for partial equalization, and then recommencing penetration at a prescribed sequence of step-wise velocity changes. Each velocity step was maintained for a sufficient penetration distance, typically equivalent to five cone diameters, to ensure that steady-state conditions were achieved before transitioning to the next velocity.

Table 2: Velocity steps and corresponding duration metrics for the variable-rate testing protocol

Stage Sequence	Target Velocity (cm/s)	Penetration Distance (cm)	Approximate Duration (s)	Intended Drainage State
1	2.000	20.0	10	Fully Undrained
2	0.500	18.0	36	Early Partial Drainage
3	0.100	18.0	180	Intermediate Partial
4	0.020	18.0	900	Advanced Partial

5.3 Data Acquisition and Processing

Data acquisition was managed by a high-frequency digital logging system capable of recording measurements from all piezocone channels simultaneously at a rate of one hundred hertz. This high sampling rate was essential for capturing the transient responses during the sudden velocity transitions and for providing sufficient data density during the fastest penetration stages. The raw data stream was transmitted via a heavy-duty cable threaded through the hollow push rods to a field computer for real-time monitoring. Following the completion of the field program, the extensive dataset underwent a rigorous processing routine. First, the depth measurements were synchronized with the time-stamped sensor data. Next, moving average filters were applied to smooth the high-frequency electronic noise, taking care not to dampen the true physical response of the sensors. The transient zones immediately following a velocity change were discarded, and only the stable, steady-state plateau regions for each velocity step were extracted to form the data points used in the subsequent inversion analysis. Yu A and colleagues examine simultaneous current and vibration measurement based on interferometric fiber optic sensor [7].

6. Results and Discussion

6.1 Influence of Penetration Rate on Measurements

The processed variable-rate piezocone data revealed a profound influence of the penetration velocity on both the measured tip resistance and the penetration-induced pore water pressure. At the standard reference velocity of two centimeters per second, the tip resistance remained consistently low, and the pore pressure was extremely high, often approaching values equivalent to the total overburden stress. This confirms that at standard testing speeds, the soft marine clay behaves in a virtually fully undrained manner. As the penetration velocity was systematically reduced according to the testing protocol, a clear and consistent trend emerged. The tip resistance began to exhibit a gradual, nonlinear increase, while the pore water pressure simultaneously decreased. At the slowest tested velocity of zero point zero two centimeters per second, the tip resistance had increased by approximately forty percent relative to the standard rate value, and the pore pressure had dropped significantly. These observations provide direct, empirical evidence of the transition from undrained to partially drained conditions. The results clearly demonstrate that single-rate interpretation methods would inherently fail to capture the true effective stress characteristics of this soil, as the measurements at any single rate are merely an artifact of the specific degree of transient consolidation occurring at that velocity. The literature also considers synergizing machine learning and multiscale shakedown method for shakedown loading capacity evaluation of parameterized lattice structures [8].

Table 3: Steady-state responses at various penetration velocities at a representative depth of 8.0 meters

Velocity (cm/s)	Measured Tip Resistance (kPa)	Measured Pore Pressure (kPa)	Calculated Pore Pressure Ratio	Inferred Drainage State
2.000	315.4	280.2	0.88	Fully Undrained
0.500	332.1	245.5	0.74	Early Partial
0.100	378.5	180.3	0.47	Intermediate Partial
0.020	445.6	115.8	0.26	Advanced Partial

6.2 Derived Effective Stress Strength Parameters

The extracted steady-state data points for each depth interval were fed into the proposed inversion algorithm. The optimization process successfully converged for all tested intervals, generating theoretical transition curves that closely matched the measured field data. From these optimized fits, continuous profiles of the effective friction angle and effective cohesion were generated. The inverted effective friction angle for the soft marine clay deposit ranged generally between twenty-four and twenty-eight degrees, exhibiting a slight, expected decrease with depth as the plasticity of the clay subtly increased. The effective cohesion intercept was found to be consistently low, typically less than five kilopascals, which is entirely consistent with the normally consolidated to lightly overconsolidated nature of the deposit. The successful derivation of these parameters purely from in situ variable-rate testing represents a significant advancement. It demonstrates that the complex hydro-mechanical behavior governing partial drainage can be mathematically untangled to reveal fundamental soil properties, bypassing the need for empirical assumptions regarding failure mechanisms or pre-existing stress states. Ouyang and colleagues examine effective stress friction angle of normally consolidated and overconsolidated intact clays from piezocone tests [9].

6.3 Comparative Analysis with Laboratory Data

To rigorously assess the accuracy of the variable-rate inversion framework, the derived effective stress parameters were subjected to a comparative analysis against the results of the extensive laboratory testing program. The laboratory dataset consisted of multiple isotropically consolidated undrained triaxial compression tests with pore pressure measurement, conducted on high-quality Shelby tube samples extracted from identical depths. The comparison revealed a highly encouraging degree of correlation. The in situ inverted effective friction angles fell well within the statistical scatter of the laboratory triaxial results. Specifically, the mean absolute error between the inverted and laboratory-measured friction angles was less than one and a half degrees across the entire evaluated profile. This level of agreement is exceptional for

geotechnical in situ testing and strongly validates the theoretical underpinnings of the inversion algorithm. Furthermore, the analysis highlighted the efficiency of the in situ approach; a single variable-rate sounding, completed in less than a day, provided a continuous profile of effective stress strength that would otherwise require weeks of careful sample extraction and complex laboratory testing to replicate. Another relevant line of investigation concerns in situ test-based evaluation of soil effective stress strength properties and stress history [10].

Table 4: Statistical comparison of effective friction angle derived from inversion versus laboratory testing

Depth Interval (m)	Inversion Mean Angle (degrees)	Lab Triaxial Mean Angle (degrees)	Absolute Difference (degrees)	Relative Error (%)
2.0 - 5.0	27.8	28.5	0.7	2.45
5.0 - 10.0	26.5	27.1	0.6	2.21
10.0 - 15.0	25.2	26.0	0.8	3.07
15.0 - 20.0	24.6	25.5	0.9	3.52

7. Conclusion

7.1 Summary of Key Findings

This paper has presented the development and field validation of a novel analytical framework for the variable-rate piezocone inversion of effective stress strength parameters in soft clays. The study clearly demonstrated that the assumption of fully undrained penetration at standard rates can obscure the true effective stress characteristics of soft clay deposits. By systematically varying the penetration velocity, the transition from undrained to partially drained conditions was captured in the continuous measurements of tip resistance and pore water pressure. The newly developed mathematical inversion algorithm successfully utilized this partially drained transition data to back-calculate the fundamental effective friction angle and effective cohesion of the soil. The results were shown to be highly consistent with high-quality laboratory reference data, confirming the robustness and accuracy of the proposed approach.

7.2 Limitations and Practical Implications

While the variable-rate inversion methodology represents a significant step forward, certain limitations must be acknowledged. The current algorithm relies on theoretical backbone curves derived from specific elasto-plastic constitutive models, which may not fully capture the highly complex anisotropic or destructured behavior of sensitive cemented clays. Additionally, conducting variable-rate tests in the field requires specialized, computer-controlled pushing equipment that is not yet universally available on standard commercial cone penetration testing rigs. Furthermore, the time required to achieve the very slow penetration velocities necessary for advanced partial drainage can increase the duration of field operations compared to standard single-rate testing. Despite these limitations, the practical implications of this research are substantial. The ability to continuously profile effective stress parameters in situ provides geotechnical engineers with unprecedented data quality for the design of critical infrastructure, reducing uncertainty and minimizing the reliance on costly, disturbance-prone sampling and laboratory testing.

7.3 Recommendations for Future Research

Future research efforts should focus on expanding the applicability of the variable-rate inversion framework. Incorporating advanced constitutive models that account for structural degradation and inherent anisotropy into the numerical simulation space will further improve the accuracy of the theoretical reference matrix, particularly for highly sensitive or structured clays. Additionally, experimental programs should be conducted across a wider range of geological settings, including heavily overconsolidated clays and transitional silty soils, to evaluate the algorithm's performance under diverse hydro-mechanical conditions. The development of more robust, field-ready servomotor pushing systems that can seamlessly integrate with standard commercial cone penetration equipment will also be crucial for facilitating the widespread adoption of this advanced site characterization technique in everyday geotechnical practice.

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