Advancing geotechnical engineering education: proposing an AI/ML-integrated curriculum for enhanced soft soil-structure interaction analysis

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Abstract. Soft marine clay deposits along coastal regions present significant challenges in geotechnical engineering due to their high compressibility and long-term consolidation behaviour. Regions such as Kerala in India are vulnerable to settlement and subsidence issues arising from infrastructure development on under-consolidated marine deposits. While classical soil mechanics provides the theoretical basis for analysing such behaviour, modern geotechnical projects increasingly generate monitoring datasets requiring systematic interpretation beyond conventional analytical approaches. This paper proposes a data-driven geotechnical education framework aimed at bridging the gap between traditional soil mechanics training and emerging data-centric engineering practices. A review of undergraduate and postgraduate geotechnical curricula highlights limited emphasis on interpretation of field monitoring data and large geotechnical datasets. The study identifies key educational gaps and proposes a specialised postgraduate course focused on interpretation of monitoring data related to soft soil behaviour and long-term settlement. The proposed curriculum integrates geotechnical instrumentation, monitoring data interpretation, and data-driven modelling concepts to enable students to evaluate soil–structure interaction in soft clay environments. The framework is relevant for coastal regions characterised by extensive soft deposits and long-term ground deformation. The study highlights the importance of evolving geotechnical education to prepare engineers capable of integrating field observations with analytical and data-driven approaches.

1 Introduction

Geotechnical engineering has evolved significantly over the past century as the understanding of soil behaviour has progressed from empirical practice to theoretically based engineering analysis. Early foundation design relied largely on observational methods and field experience. The development of modern soil mechanics, particularly through the pioneering work of Terzaghi, established the theoretical framework for analysing soil behaviour and predicting foundation settlement and stability [1, 2].

Despite their widespread application, classical analytical models rely on simplified assumptions regarding soil behaviour, material homogeneity, and drainage conditions. Natural soils frequently exhibit spatial variability, anisotropy, and time-dependent deformation behaviour that cannot be fully captured by deterministic formulations [3]. These limitations are particularly significant in soft cohesive soils where long-term consolidation and creep deformation govern performance. Secondary compression behaviour, commonly represented using the $C\alpha/Cc$ relationship [5], further complicates prediction of long-term settlement.

Such conditions are prevalent in coastal regions, including the southwest coast of India. Large areas of Kerala are underlain by soft marine clay deposits formed in lagoonal and estuarine environments. These soils typically exhibit high natural water content, low undrained shear strength, and high compressibility, often resulting in substantial consolidation settlement under structural loading.

Modern geotechnical projects increasingly employ instrumentation systems such as settlement plates, piezometers, and inclinometers, generating large time-series datasets that provide insight into consolidation behaviour and soil–structure interaction. However, systematic interpretation of these datasets, including correlation with theoretical predictions, is rarely addressed within conventional geotechnical education.

In recent years, geotechnical engineering has evolved towards a data-centric discipline. Modern infrastructure projects routinely generate large volumes of digital geotechnical data through site investigations, field instrumentation, and long-term monitoring programs.

These datasets include settlement monitoring, pore pressure dissipation records, inclinometer measurements, and construction-stage observations. While advances in data analytics and machine learning provide opportunities for extracting meaningful patterns from such data [8, 9], their integration into geotechnical education remains limited.

Engineering education in Kerala follows an outcome-based framework incorporating Programme Outcomes (PO), Programme Educational Objectives (PEO), and

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Course Outcomes (CO). While this framework enables systematic evaluation of curriculum effectiveness, a critical review of postgraduate geotechnical subjects indicates limited alignment with emerging requirements related to monitoring data interpretation and data-driven analysis. This paper therefore proposes a specialised postgraduate curriculum framework aimed at integrating data-driven approaches into geotechnical engineering education.

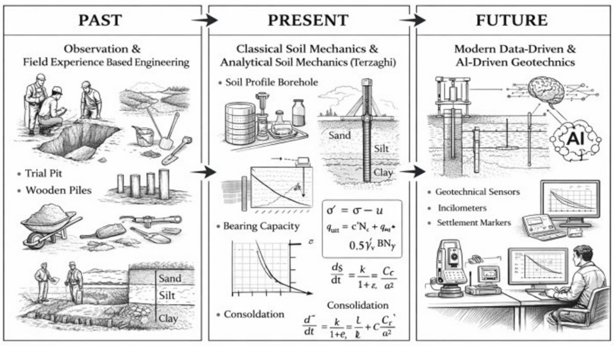

Fig. 1. Past, present and future of Geotechnical Engineering.

2 Review of relevant literature

2.1 Behaviour of soft marine clays

Soft marine clays represent one of the most challenging geomaterials encountered in geotechnical engineering due to their high compressibility, low undrained shear strength, and pronounced time-dependent deformation behaviour. These soils typically possess high natural water content and low permeability, resulting in significant consolidation settlement under structural loading.

The analytical framework for understanding time-dependent settlement in saturated soils was first established through Terzaghi's theory of consolidation [1]. However, subsequent research has demonstrated that long-term deformation cannot be explained by primary consolidation alone. Bjerrum [4] highlighted delayed compression, while Mesri and Castro [5] formalised secondary compression through the C_α/C_c relationship.

Despite these developments, prediction of settlement behaviour remains difficult due to spatial variability, sampling disturbance, and complex stress–strain interactions in natural deposits [3].

2.2 Limitations of conventional geotechnical modelling

Traditional geotechnical analysis relies on deterministic models with simplified assumptions. However, soil properties exhibit inherent variability due to geological formation processes, measurement uncertainties, and transformation errors.

Phoon and Kulhawy [8] demonstrated that geotechnical uncertainty arises from multiple sources, making deterministic predictions inherently limited. Additionally, long-term settlement predictions based on limited laboratory data often deviate from field observations due to heterogeneity and construction effects [5, 6].

2.3 Monitoring-based geotechnical engineering

Instrumentation plays a critical role in understanding soil behaviour. The observational method [7] emphasises adapting design based on monitored performance.

Modern instrumentation systems generate continuous time-series datasets that capture soil response under loading [10]. However, systematic interpretation and integration with analytical models remain limited.

2.4 Data-driven approaches in geotechnics

Machine learning techniques have increasingly been applied in geotechnical engineering for settlement prediction, soil classification, and parameter estimation [9]. These methods allow identification of complex relationships within large datasets and provide improved predictive capability when combined with conventional approaches.

Furthermore, probabilistic and data-driven frameworks enable explicit consideration of uncertainty and variability in soil properties [8]. Despite these advancements, such techniques are rarely incorporated into geotechnical curricula.

3 Soft soil behaviour and subsidence challenges in coastal Kerala

The coastal plains of Kerala are characterised by extensive deposits of soft marine and estuarine soils formed through lagoonal and backwater depositional processes. These deposits predominantly consist of normally consolidated to lightly overconsolidated clay layers with high natural water content, low undrained shear strength, and high compressibility. Such soil conditions result in significant primary consolidation settlement under structural loading, followed by long-term secondary compression effects that continue well beyond the construction phase.

Geotechnical investigations across the Kerala coastal belt consistently indicate thick strata of soft clay with low permeability, leading to slow dissipation of excess pore water pressures. As a result, consolidation behaviour in these soils is highly time-dependent and sensitive to loading rate, drainage conditions, and stress history. The presence of organic content and loose microstructure further contributes to high compressibility and creep susceptibility.

Infrastructure development in these regions—including embankments, approach roads, and foundation systems—frequently encounters challenges related to excessive settlement, differential deformation, and serviceability issues. In several cases, discrepancies between predicted settlement based on conventional consolidation theory and observed field performance have been reported, highlighting the limitations of relying solely on laboratory-derived parameters [3, 5].

These challenges are compounded by the geomorphological characteristics of the Kerala coastline, which include low elevation, proximity to tidal influences, and exposure to environmental factors such as seasonal groundwater fluctuations and coastal erosion. Regional studies and coastal vulnerability assessments have identified significant susceptibility to subsidence and long-term ground deformation in these areas [12, 13].

Modern geotechnical practice in such environments increasingly relies on instrumentation systems—such as settlement plates, piezometers, and inclinometers—to monitor ground response during and after construction. These systems generate continuous time-series data that provide valuable insights into consolidation behaviour, rate of settlement, and soil–structure interaction mechanisms. However, effective utilisation of such data requires systematic interpretation and integration with analytical models, which remains a challenge in practice.

The complexity of soft soil behaviour in coastal Kerala therefore underscores the need for approaches that combine classical soil mechanics with monitoring-based interpretation and data-driven analysis techniques. This requirement forms a key motivation for the educational framework proposed in this study.

4 Gap between modern geotechnical practice requirements and conventional civil engineering curriculum

Modern geotechnical engineering practice has evolved significantly with the increasing adoption of field instrumentation, digital data acquisition systems, and long-term monitoring strategies. Contemporary projects routinely generate large volumes of time-dependent data related to settlement, pore pressure dissipation, and lateral deformation, which are essential for evaluating soil–structure interaction and validating design assumptions.

Despite these developments, conventional civil engineering and geotechnical engineering curricula continue to be largely centred on theoretical soil mechanics and deterministic analytical methods. Core subjects such as consolidation theory, foundation design, and soil behaviour provide strong fundamental knowledge; however, they offer limited exposure to the interpretation of real-world monitoring data or the variability inherent in field conditions.

One of the primary gaps lies in the lack of training in handling and analysing geotechnical monitoring datasets. While students are introduced to laboratory testing and basic field investigations, they are rarely exposed to continuous time-series data obtained from instrumentation systems. As a result, graduates often lack the ability to interpret settlement trends, assess pore pressure dissipation behaviour, or correlate field observations with analytical predictions.

Another critical limitation is the absence of structured learning related to digital geotechnical data formats and data management practices. Modern projects frequently utilise digital databases, geotechnical information systems, and structured data formats such as AGS, yet these aspects are seldom included in academic training. This creates a disconnect between academic preparation and industry practices.

Furthermore, the integration of monitoring observations with analytical soil models is not systematically addressed in existing curricula. In practice, engineers must reconcile differences between predicted and observed behaviour by considering soil variability, construction sequencing, and environmental influences. Such interpretative skills require exposure to real datasets and iterative analysis, which are currently underrepresented in formal education.

In addition, emerging data-driven approaches—including statistical analysis and machine learning techniques—are gaining importance in geotechnical engineering for interpreting complex datasets and improving predictive capability. However, these methods are rarely introduced within traditional coursework, limiting awareness and application among graduates.

Table 1: Existing geotechnical curriculum overview.

Subject Area	Topics and Focus	Limitations in Modern Context
Soil Mechanics	Soil classification, permeability, consolidation theory, shear strength behaviour and laboratory testing	Strong theoretical foundation but limited integration with long-term field monitoring datasets
Foundation Engineering	Bearing capacity analysis, shallow and deep foundation design, settlement estimation	Settlement prediction often relies on simplified assumptions with limited observational validation
Geotechnical Investigation	Borehole logging, sampling, in-situ tests such as SPT and laboratory testing	Limited exposure to instrumentation-based monitoring and long-term geotechnical data interpretation
Ground Improvement	Preloading, vertical drains, compaction and stabilization techniques for weak soils	Performance evaluation rarely linked with monitoring datasets and time-dependent soil response
Advanced Geotechnical Engineering	Constitutive soil models, advanced testing, slope stability and earth retaining structures	Focus remains largely theoretical with limited emphasis on data-driven interpretation
Research Methodology	Experimental planning, analysis and technical reporting	Limited introduction to modern data processing or large monitoring datasets

The combined effect of these limitations results in a clear gap between the competencies required in modern geotechnical practice and those developed through conventional civil engineering education. This gap is particularly critical in soft soil environments, where accurate assessment of long-term behaviour depends on the ability to interpret monitoring data alongside theoretical models.

Table 2: Educational gap in current geotechnical engineering curriculum.

Emerging Practice Requirement	Current Curriculum Coverage	Identified Educational Gap
Interpretation of monitoring datasets from field instrumentation	Rarely addressed explicitly	Students lack training in handling real monitoring data
Analysis of long-term settlement and time-dependent ground behaviour	Covered theoretically through consolidation theory	Limited practical exposure to real settlement monitoring data
Handling of digital geotechnical datasets	Not formally included	Limited familiarity with data formats and geotechnical databases
Integration of monitoring observations with engineering interpretation	Not systematically taught	Students lack experience in linking field observations with analytical models
Data-driven interpretation of geotechnical behaviour	Not included in traditional courses	Limited awareness of emerging data-centric approaches

Addressing this gap requires a structured curriculum that integrates classical soil mechanics with monitoring-based learning, digital data handling, and data-driven analytical techniques. The proposed framework presented in this study aims to bridge this divide by equipping students with the necessary skills to interpret complex geotechnical datasets and support engineering decision-making.

5 Proposed data-driven curriculum framework for soft-soil behaviour analysis

The preceding sections highlight the increasing importance of monitoring-based interpretation and data-driven analysis in modern geotechnical engineering practice, particularly in soft soil environments where long-term settlement behaviour is difficult to predict using conventional analytical models alone. Addressing these challenges requires educational frameworks that extend beyond classical soil mechanics and incorporate systematic interpretation of geotechnical monitoring datasets.

The proposed curriculum framework therefore focuses on developing competencies in data-driven interpretation of soft soil behaviour, while retaining the theoretical foundations of soil mechanics. The objective is not to replace classical analytical methods but to enhance their applicability through integration with monitoring data and modern data analysis techniques. Similar approaches have been suggested in emerging studies on data-centric geotechnical engineering and probabilistic soil modelling, which highlight the importance of incorporating field observations and uncertainty analysis in geotechnical decision-making [8, 9].

The framework is designed as an advanced postgraduate elective course structured around five core modules, as summarised in Table 3. The course begins with an overview of soft soil monitoring systems and instrumentation used in geotechnical engineering practice. Instruments such as settlement plates, piezometers, and inclinometers provide essential datasets for understanding consolidation behaviour and soil–structure interaction [10]. Familiarity with such instrumentation and the datasets they generate forms the foundation for subsequent analytical work.

The second module introduces geotechnical data management and digital data structures commonly used in geotechnical investigations. Modern infrastructure projects increasingly produce large volumes of digital geotechnical data, including site investigation records, monitoring datasets, and construction performance observations.

Understanding how such data are structured, stored, and processed is essential for meaningful interpretation. The third module focuses on processing and interpretation of geotechnical monitoring data, including time-series analysis of settlement and pore pressure measurements. Particular emphasis is placed on soft soil consolidation behaviour, where continuous monitoring data can provide valuable insight into the evolution of ground deformation over time.

The fourth module introduces data-driven approaches for interpreting geotechnical behaviour and developing predictive models based on monitoring observations. Machine learning methods have increasingly been applied in geotechnical engineering to analyse complex datasets and identify relationships between soil properties and performance indicators [9]. In the context of soft soil engineering, such approaches can assist in refining settlement predictions and improving understanding of long-term ground behaviour.

The fifth module focuses on engineering interpretation and decision support, enabling students to evaluate infrastructure performance using monitoring data and develop informed engineering judgement.

The overall structure of the proposed curriculum framework is illustrated in Figure 2, which presents the workflow for data-driven interpretation of soft soil behaviour. This structured approach integrates classical soil mechanics with modern data-driven analysis methods within geotechnical engineering education.

6 Implementation strategy and expected learning outcomes

The proposed curriculum is designed as an advanced postgraduate elective course that can be integrated into existing geotechnical engineering programs without major restructuring of current syllabi. The course builds upon foundational knowledge of soil mechanics and consolidation behaviour typically acquired in undergraduate and early postgraduate coursework [2, 3].

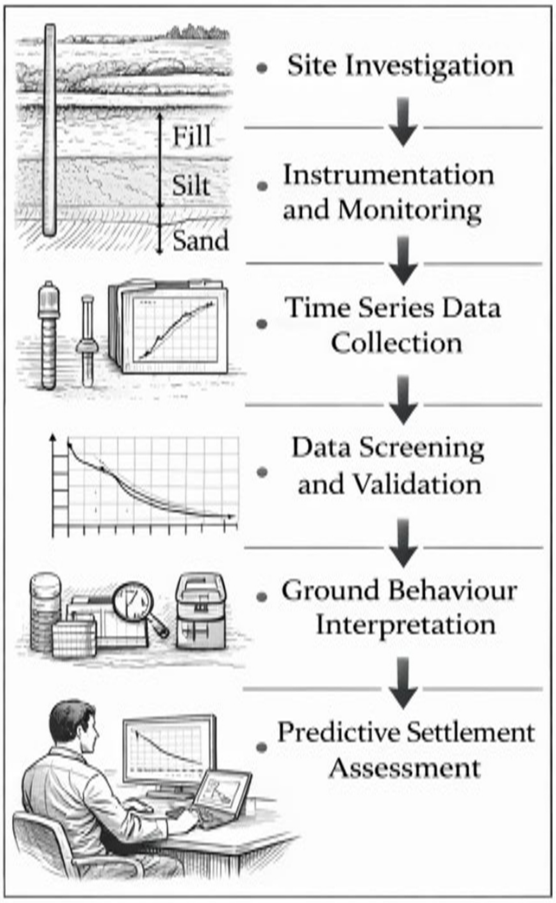

Fig. 2. Data-driven soft soil analysis workflow.

By focusing on interpretation of geotechnical monitoring datasets, the course introduces students to emerging data-driven approaches while maintaining continuity with established geotechnical principles.

As part of the proposed curriculum, students may analyse monitoring datasets obtained from embankments, foundations, or infrastructure projects constructed on soft soils. For example, settlement-time measurements obtained from settlement plates installed in soft clay deposits can be used to evaluate consolidation trends and compare observed behaviour with theoretical predictions derived from consolidation theory. Such exercises allow students to connect theoretical models with real field behaviour and develop practical interpretation skills relevant to engineering practice.

Implementation requires representative monitoring datasets from infrastructure projects on soft soils. Typical datasets include settlement, pore pressure, and deformation measurements obtained from settlement plates, piezometers, and inclinometers. These datasets enable students to examine the evolution of ground behaviour under loading and to relate observed responses to classical consolidation concepts.

The curriculum emphasises practical data interpretation exercises using commonly available computational tools for data analysis and visualisation. Students are expected to develop skills in handling geotechnical monitoring data, identifying trends in time-series datasets, and interpreting soil behaviour in the context of analytical models and field observations. In addition, the course introduces basic concepts of data-driven modelling and machine learning for interpreting complex geotechnical datasets [9].

Upon completion of the course, students should be able to integrate monitoring observations with classical soil mechanics concepts to evaluate soft soil behaviour and settlement trends. This capability is particularly important for engineering practice in regions characterised by extensive soft clay deposits, where long-term ground deformation and subsidence require continuous monitoring and interpretation.

The structure of the proposed elective course is organised into five modules that progressively introduce students to geotechnical monitoring systems, data processing, and interpretation of soft soil behaviour. The key course modules and the major topics covered in each module are presented in Table 3.

Table 3: Proposed course modules.

Module	Course Component	Key Topics Covered
Module 1	Geotechnical Monitoring and Instrumentation	Settlement plates, piezometers, inclinometers, monitoring strategies for soft soil deposits, instrumentation planning for infrastructure projects
Module 2	Geotechnical Data Acquisition and Processing	Monitoring data formats (AGS, JSON, GeoJSON), time-series geotechnical datasets, data cleaning, filtering erroneous data, validation of monitoring measurements
Module 3	Interpretation of Soft Soil Behaviour	Consolidation trends, settlement–time behaviour, interpretation of monitoring data, linking field observations with classical consolidation theory
Module 4	Data-Driven Interpretation of Soil Behaviour	Statistical analysis of geotechnical monitoring datasets, predictive interpretation methods, identification of settlement trends and behaviour patterns
Module 5	Engineering Interpretation and Decision Support	Evaluation of infrastructure performance on soft soils, monitoring-based engineering judgement, interpretation of case study data

The corresponding practical exercises and expected learning outcomes are presented in Table 4. Together, these modules are designed to combine theoretical understanding with hands-on analysis of geotechnical monitoring datasets, enabling students to develop practical skills relevant to modern geotechnical engineering practice.

Table 4: Module outcomes.

Module	Practical Exercises	Expected Learning Outcomes
Module 1	Review of monitoring instrumentation used in soft soil projects	Understand how geotechnical instrumentation systems generate monitoring data
Module 2	Processing real monitoring datasets and identifying anomalous measurements	Ability to clean and organise geotechnical monitoring datasets
Module 3	Analysis of settlement-time curves from monitored projects	Ability to interpret consolidation behaviour from field data
Module 4	Development of simple data driven predictive settlement models using monitoring data	Understanding of data-driven interpretation methods in geotechnical engineering
Module 5	Case study analysis of infrastructure constructed on soft soils	Ability to use monitoring data for engineering decision making

7 Discussion and conclusions

The findings of this study highlight a growing mismatch between conventional geotechnical engineering education and the evolving demands of modern geotechnical practice. While classical soil mechanics provides the theoretical basis for analysing soil behaviour [2, 3], contemporary projects—particularly those involving soft marine clays—generate extensive monitoring datasets that require systematic interpretation. The increasing use of field instrumentation and long-term settlement monitoring has reinforced the importance of integrating observational data with analytical models [7, 10].

As geotechnical engineering increasingly incorporates digital monitoring systems and large geotechnical datasets, educational programs must evolve to equip engineers with the ability to interpret and utilise such data effectively.

This study proposes a data-driven curriculum framework aimed at bridging this gap by equipping postgraduate students with the ability to interpret geotechnical monitoring data and evaluate soft soil behaviour using modern data-analysis approaches. The proposed framework emphasises integration of field observations, monitoring datasets, and predictive interpretation methods. Such educational initiatives may contribute to improving engineering decision-making in regions characterised by extensive soft soil deposits and long-term ground deformation challenges.

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