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INTEGRATING INFORMATION TECHNOLOGY IN ENGINEERING GEOLOGY: CASE STUDIES AND EDUCATIONAL APPROACHES FOR ENHANCED GEO-LOGICAL ANALYSIS FOR INFRASTRUCTURE DEVELOPMENT

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ABSTRACT

The paper critically investigates the indispensable geotechnical knowledge crucial for effective engineering practice and proposes innovative approaches to seamlessly incorporate it into the education and training of geotechnical engineers. It initiates by scrutinizing the core responsibilities of geotechnical engineers, encompassing exploration, analysis and design, management, and construction, subsequently delving into the principal reservoirs of this knowledge, such as engineering sciences, models, software, codes of practice, judgment, and heuristics, and their pragmatic applications. Furthermore, it anticipates and discusses forthcoming trends poised to impact the profession in the foreseeable future. The paper concludes with a strong emphasis on rectifying the current disjunction between academic knowledge and practical application in the field, underscoring the paramount importance of augmenting the comprehension of geotechnical knowledge within engineering practice. It advocates for the integration of this understanding into the education and training of geotechnical engineers, fostering mutual benefits for both academia and practitioners.

Keywords: *Decision Tree, Risk Management, Geological Uncertainties, Tunneling.*

1. INTRODUCTION

The high demand for infrastructure facilities motivates engineering innovation to explore novel technologies, concepts, materials, and spatial possibilities, aiming to deliver safer and more dependable infrastructure. Meeting such demand typically involves underground excavation technology, which is associated with comparatively large investments, relatively long construction phases, various combinations, and the coordination of multiple contractors. Despite detailed geological investigations, most underground excavations face geological and hydrological surprises in actual ground conditions. These surprises, combined with inappropriate excavation methods and unfavorable surface and sub-surface conditions such as busy traffic, existing facilities, and a lack of efficient construction management, can lead to accidents or hazards [1]. Consequently, owners and contractors incur significant losses, making the management and minimization of risks in underground excavation a critical factor in tunnel or cavern construction work.

Since the 1970s, the recognition of underground excavation risks has led to subsequent research, with a focus on qualitative measurement and reliability analysis [2, 3]. However, the majority of research has centered on reliability analysis of geotechnical risks, presenting inherent difficulties. Geotechnical risk management has become challenging due to the increased use of underground space. According to Michael Latham, "No construction project is devoid of risk. Risk can be managed, reduced, shared, transferred, or acknowledged. It cannot be disregarded." [4].

Over the years, a variety of risk analysis techniques have evolved, including the Influence Diagram Method, Monte Carlo Simulation Method, Expected Value Method, Decision Tree Method, and Fault Tree Method, as well as their combinations [5]. Each method has its merits and demerits, making them suitable for specific civil

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construction processes. In the context of underground excavation, risk is primarily related to geological surprises, and entropy serves as a measure of the uncertainty of the excavation process. Therefore, risk in underground excavation is defined as the probability of the occurrence of a hazard. A decision tree, a simple and powerful method for inferring classification rules, provides an advantage over the neural network method due to its easy-to-follow sequence of decisions [6]. However, developing a decision tree with the minimum number of leaves poses challenges [6].

In the Indian context, underground structures play a pivotal role, given the anticipated land use density of 403 persons/km², surpassing that of even the most populous country, China, by 2.5 times [7]. The urban population concentration in towns and cities, where tall buildings are commonplace, necessitates an expanded network of mass transit systems and various facilities. However, this urban growth and densification pose substantial challenges to the earth's crust due to the uncertainties associated with complex geological conditions and rock mass responses. These uncertainties manifest as potential risks of rock mass instabilities, underscoring the imperative for risk management measures encompassing elimination, mitigation, acceptance, or transfer. Nonetheless, a standardized method for quantifying underground engineering risk analysis is currently lacking. Therefore, the quantification of risk emerges as a critical component of risk management [8]. This paper introduces an interval entropy measurement method rooted in expert investigation, built upon the principles of entropy and its generalization and extension.

Each underground construction endeavor entails a unique level of risk contingent upon its site-specific conditions. This paper systematizes the procedure for risk identification and consequence assessment, culminating in the formulation of a predictive model grounded in suitable strategies [9]. A systematic methodology entails scrutinizing and comprehending the hazards of structures under analogous conditions and functional specifications to devise a predictive model adept at recognizing risks in forthcoming projects. This research introduces a straightforward approach for crafting a risk assessment-driven predictive model, leveraging data from two completed projects and implementing this model to forecast outcomes for a prospective project.

The research gap in the present context revolves around the imperative need to analyze the geotechnical knowledge essential for the burgeoning infrastructure sector and the subsequent demand for skilled professionals. The challenge lies in determining what constitutes this knowledge explicitly and identifying the most effective methods for educating and training engineers to endure successfully in this evolving field. Unfortunately, the absence of clear-cut answers hinders the establishment of optimal approaches to acquire, store, and transmit geotechnical knowledge for practical application. With anticipated technological developments on the horizon, understanding the pertinent geotechnical knowledge for both education and practice becomes even more crucial. Despite considerable recent interest in the education and training of geotechnical engineers, a distinct separation persists between the approaches adopted by practitioners and academicians. This research seeks to fill this gap by presenting a collaborative approach to nurture geotechnical engineers, drawing on decades of experience to identify key aspects of geotechnical knowledge crucial for future practitioners. The paper introduces a novel approach to both education and training, outlining the main activities of geotechnical engineers and discussing key sources of knowledge, including engineering sciences, models, codes of practice, uncertainty, heuristics, and engineering judgment, with a focus on practical application. The study also briefly addresses broad trends expected to impact the profession in the coming decades, concluding with essential requirements for the education and training of geotechnical engineers.

2. MAIN ACTIVITIES OF GEOTECHNICAL ENGINEERS

The main activities of geotechnical engineers:

2.1. Exploration, Testing and Interpretation

These initial activities serve as the foundation for all geotechnical endeavors, many of which are exclusive to the field of geotechnical engineering. The assessment of geology and ground conditions, coupled with the measurement of material properties, marks the outset of the process. Consequently, the formulation of a ground engineering model becomes paramount, serving as the fundamental framework for all subsequent engineering endeavors. It's important to acknowledge that the ground, being a product of historical geological processes, is inherently complex and only approximately understood. Ge-otechnical engineers must gather and interpret data to develop this ground model, relying on limited investigations including surface mapping, drill-ing, geophysics, field, and laboratory testing. However, it's crucial to recognize that this model is likely to be a simplified interpretation of actual conditions, thus encompassing significant uncertainties.

Exploration serves as a valuable tool for those proficient in its utilization. The objectives of the exploration plan, along with the anticipated outcomes, should be clearly defined and understood before its execution. It necessitates a comprehensive understanding of geology, coupled with investigation procedures. Moreover, engineers often find themselves collaborating closely with geologists to pinpoint areas potentially posing future challenges. However, engineers' and geologists' differing traditions and practices can sometimes lead to complications due to a mutual lack of understanding.

2.2. Analysis and Design

Geotechnical analysis and design rely on a combination of the strength of materials ap-proach derived from soil and rock mechanics in engineering sciences, as well as empirical methods. Additionally, various heuristics and codes of practice are utilized, drawing from past successful experiences. Moreover, design considerations are tailored to accommodate available construction equipment and technologies.

Typically, a simplified ground engineering model, derived from the exploration phase and supplemented with empirical correlations for ground parameters, serves as the basis for analysis and design. However, these models involve considerable simplifications, be-ing approximate interpretations of reality. Consequently, the initial uncertainties inherent in the ground engineering model are compounded by uncertainties in material properties and loadings, with implications for project time cycles and cost estimates. Moreover, civil engineering projects are inherently unique, making comprehensive testing of the entire system impractical.

Geotechnical design is seldom a straightforward step-by-step process. It encompasses conceptual design, feasibility studies, investigations, basic and detailed design phases, followed by construction and monitoring. Each stage requires significant experience and judgment, often drawing from past projects with similar geological contexts. Furthermore, the design must not only meet technical requirements but also consider the owner's preferences, regulatory standards, legal and economic constraints, as well as functional utility for the intended usage. Achieving a successful design often involves balancing conflicting re-quirements, resulting in compromises that may leave stakeholders less than completely satisfied. Ultimately, the design must be translated into practical implementation through draw-ings, specifications, and bills of quantities. Errors at this stage, along with inherent uncer-tainties, frequently lead to changes during construction, potentially carrying contractual implications. It's crucial to recognize that uncertainties evolve throughout the project, and different objectives may need to be addressed at different stages, necessitating an adaptive and flexible approach to geotechnical design.

2.3. Management

This includes planning, contracting, costing, engineering, and project management and these activities are common to all civil engineering works. However, because of the variability and uncertainty in all geotechnical works, specific changes are required in the contract and management of these works. For example, today geotechnical risk management is used in many large geotechnical projects [3]. These activities along with legal and ethical issues will not be discussed further, but it should be noted that most engineers spend a major portion of their time in these activities. Another very important factor for the successful execution of projects lies in the need to interact with specialists from related fields such as geology, geophysics, hydro-geology, structures, etc as projects become in-creasingly complex requiring multi-disciplinary teams working closely with each other.

2.4. Construction and Monitoring

Engineers are responsible for overseeing and managing construction to ensure the faithful implementation of the design. This entails a comprehensive understanding of construction equipment and technologies, as well as ensuring adherence to necessary testing and quality control standards. Geotechnical projects often encounter

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unforeseen geological conditions or unexpected system behaviors during execution, necessitating design modifications that may impact time and cost. Such occurrences are common due to factors like insufficient investigations, flawed data interpretation, lack of experience, poor judgment, and inherent uncertainties inherent in these projects.

In addition to meeting construction requirements and quality control standards, many geotechnical projects require ongoing monitoring to validate and update the design during construction, exemplified by the application of the observational method. Geotechnical monitoring is increasingly recognized as a crucial aspect of underground projects, with engineers needing to grasp its significance as a tool for validating designs during construction.

The successful execution of an engineering project involves various activities to be managed throughout its duration. These activities can be succinctly summarized in a typical flowchart, exemplified in Fig. 1 for an underground cavern project.

This flowchart delineates the different project stages and their associated main activities, providing a structured overview of the essential considerations for engineers to manage and execute the project successfully, from conceptualization to completion.

3. KEY ASPECTS OF GEOTECHNICAL KNOWLEDGE

This section delves into several essential sources of geotechnical knowledge and their practical application in engineering practice. While some of these sources are shared across various disciplines within civil engineering, others are distinct to geotechnical engineering. Each of the topics discussed below encompasses a broad and intricate subject matter, thus only the most pertinent features will be highlighted herein.

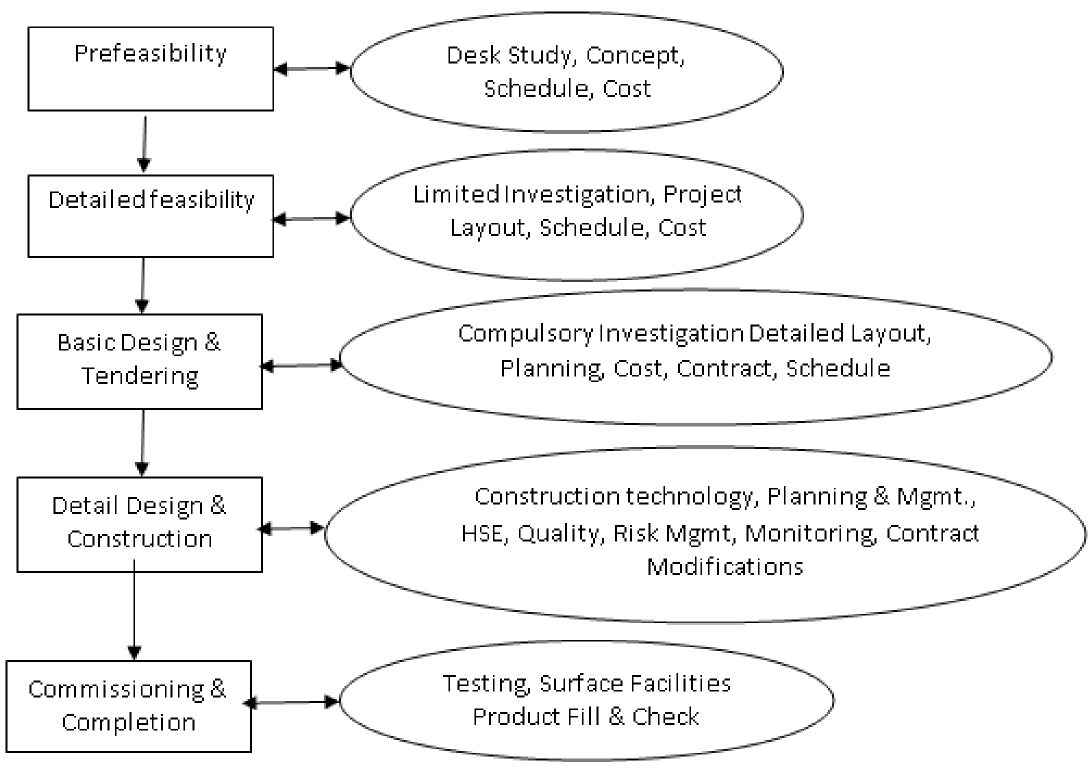

Figure 1: Flow chart of a typical underground cavern project.

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3.1. Engineering Sciences

As any seasoned engineer can attest, engineering diverges from applied science. While science plays a minor role in engineering practice, the essence of engineering lies in the creation of tangible structures and systems. This encompasses conceptual development, analysis, design, specification, management, planning, costing, contracting, construction, and eventual operation.

Fundamentally, our engineering knowledge draws from the disciplines of soil and rock mechanics, coupled with engineering geology [6, 7]. However, unlike pure science, which seeks to understand nature, geotechnical engineering sciences primarily focus on the analysis, design, and construction of structures within geological environments. These sciences encompass foundational principles such as the effective stress principle and the application of mechanics to geological materials, as well as classification systems, material behaviors, and foundation concepts. While engineering sciences provide a framework for understanding and analyzing the ground, they only constitute a portion of geotechnical knowledge.

Achieving proficiency in geotechnical engineering requires not only knowledge of codes of practice, heuristics, and engineering judgment but also substantial experience in investigations, interpretation, analysis, design, construction, and management of geotechnical projects. As highlighted by [8], the educational challenge in geotechnical engineering lies not only in imparting a strong theoretical foundation but also in equipping students with the ability to apply risk management throughout the entire design process.

3.2. Models

Typically, geotechnical engineering projects rely on two main types of models. The first is the ground engineering model, which stems from comprehensive investigations and testing. This model encompasses various factors such as topography, soil or rock layers, a range of key ground parameters derived from field and laboratory tests, groundwater levels, and other pertinent variables. In rock engineering projects, this is often referred to as a geological model, encompassing descriptions of different rock types and major geological features. Developing this model necessitates a solid understanding of geology, proficient investigation techniques, and meticulous field and laboratory testing. Accurate interpretation of exploration data is crucial for creating a representative model of the ground.

The second model is the geotechnical or analysis model, typically a simplified version of the ground engineering model. It incorporates observed and measured parameters along with values derived from correlations. Average values of critical analysis parameters like strength and stiffness are estimated for each layer or zone. In some cases, more sophisticated constitutive models may be utilized, requiring additional testing to obtain parameters. Rock engineering projects estimate rock mass parameters within this model. A comprehensive introduction to geotechnical modeling is provided in the book by [9]. Ultimately, this model facilitates mechanical analysis to estimate stresses and deformations, leading to the development of final design configurations. Empirical factors may be incorporated into the analysis, such as skin friction parameters for piles or rock support for tunnels, often combining mechanical analysis with empirical design.

Regardless of the specific engineering challenge, numerical modeling serves as a common tool for engineers and scientists. Numerical modeling aids in understanding the behavior of geo-materials under various conditions and loads, optimizing performance in terms of project cost and schedule. However, it's important to recognize that model development is rarely straightforward, involving numerous assumptions, interpretations, and reliance on experience. Once developed, analyses may range from simple hand calculations to complex numerical methods with advanced constitutive models. The complexity of the analysis typically correlates with the number of parameters required, introducing more uncertainty. Often, a simpler analysis suffices, prioritizing approximate correctness over exact precision. It's crucial to approach models with caution, ensuring suitability for the intended problem and validating them whenever possible through observation, testing, and monitoring during construction.

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3.3. Codes of Practice

Today, various codes of practice cover nearly every aspect of geotechnical engineering, such as those referenced in [9-13]. These codes draw upon engineering sciences and ac-cumulated knowledge from years of geotechnical work. They encompass guidelines for investigations, testing, analysis, and design, specifying not only testing methodologies but also analysis procedures and acceptable values for factors of safety and settlements. Most codes are presented in a format readily usable by engineers. While some codes may carry legal weight, others are widely accepted within the profession, ensuring a minimum standard by providing essential procedures and allowable values for safety and perfor-mance. However, unlike other fields of civil engineering, geotechnical codes afford considerable flexibility in selecting ground parameters and designing structures.

In addition to codes of practice, various guidelines are issued by organizations such as the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), and the International Society of Rock Mechanics (ISRM), among others. These guidelines originate from engineering societies, academic and research institutions, as well as governmental and private entities. While codes of practice distill substantial professional knowledge into engineer-friendly formats, they alone may not suffice. Constant advancements often lead to codes lagging behind the lat-est technologies, and in some cases, they may prove overly restrictive, requiring engineers to possess a thorough understanding of the subject matter to navigate effectively. Design codes in geotechnical engineering must be structured to ensure structures are both adequately safe and constructed cost-effectively. Effective codes should be developed on a risk-based framework capable of accommodating the heightened uncertainty inherent in geotechnical engineering projects.

3.4. Heuristics and Judgment

A heuristic refers to any tool or guideline that offers a plausible direction or assistance in solving a problem, yet ultimately lacks justification, cannot be justified, and may be fallible [14]. These may include rules of thumb, factors of safety, performance parameters, and design procedures, among others, which have proven effective in previous applications. Design procedures, in particular, could be viewed as overarching rules of thumb that have demonstrated success in the past. Much of engineering knowledge is rooted in heuristics, given that engineering is predominantly an empirical discipline. Many of these heuristics are acquired through practical experience on the job [15].

Furthermore, engineers rely on judgment throughout every stage of a project, from conception to completion, to meet project requirements. Engineering judgment defies clear defini-tion but is a skill familiar to experienced engineers, enabling them to swiftly and adeptly address complex situations [16]. It's worth noting that engineering education imparts rules that young engineers initially follow, but with experience, they develop the ability to identify key issues and provide practical solutions. Engineering judgment evolves through on-the-job experience. Researchers acknowledge that the tacit knowledge possessed by expert engineers is intricate and challenging to capture. However, if suc-cessfully captured and articulated, tacit knowledge serves as a driving force behind innovation, whether in the form of new technology, processes, or techniques. The significance of heuristics and judgment is amplified in geotechnical engineering, where codes and guidelines afford considerable flexibility in parameter selection and design. Moreover, substantial uncertainty exists in ground conditions and our understanding of facility response. Given the uniqueness of each project's design, experience coupled with engineer-ing judgment is indispensable for the successful execution of geotechnical projects.

3.5. Uncertainty

While uncertainty is inherent in all branches of engineering, its magnitude and scope are particularly pronounced in geotechnical engineering. Nearly every geotechnical endeavor grapples with significant uncertainty, posing a primary challenge for geotechnical engineers [17,18].

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These uncertainties can be broadly categorized into two types: aleatory, related to chance occurrences, and epistemic, related to our knowledge limitations. Aleatory uncertainty often arises from randomness in factors such as loading and material properties, while epistemic uncertainty stems from factors like limited investigations, material behavior, and the accuracy of models and analyses. Addressing epistemic uncertainty involves acquiring additional information about the geological conditions of a site, which can aid in achieving a more controlled project execution.

Engineers typically manage uncertainty through conservative design approaches, quality control measures, heuristics, adherence to codes of practice, the observational method, and risk management strategies. In recent times, reliability techniques have also gained traction. However, it's important to recognize that none of these methods are foolproof or universally applicable. Experienced engineers working in familiar geological settings with well-established foundation systems can often navigate many of the uncertainties arising from known factors (referred to as "known unknowns"). Nevertheless, nature also presents "unknown unknowns," or geological surprises, which geotechnical engineers must learn to anticipate and adapt to.

4. FUTURE TRENDS

While predicting the future is inherently challenging, certain general observations can be made regarding the evolution of the geotechnical profession. Historically, the profession has been influenced by advancements in technologies developed outside its realm, nota-bly computing and new materials. Moreover, the profession has adeptly responded to emerging challenges, such as those posed by geo-environmental issues. Similar trends are anticipated to shape the future of the field. While specific developments cannot be fore-seen, the following trends are expected:

- Complex Projects with Stringent Technical and Non-Technical Requirements:

Future projects are likely to entail intricate technical specifications and broader non-technical considerations. Addressing these challenges will demand both the adapta-tion of existing methodologies and the development of novel technical and management approaches. Key areas of focus may include sustainable engineering, carbon reduction, brownfield site remediation, underground space utilization, and energy exploration and storage. Collaboration with specialists from related fields will be essential to tackle these multifaceted challenges effectively.

- Large-Scale Problems Arising from Global Environmental Factors:

Growing environmental concerns on a global scale will give rise to complex challenges requiring innovative solutions. These may encompass issues such as climate change mitigation, environmental conservation, and resilience to natural disasters. Geotechnical engineers will play a crucial role in devising strategies to address these pressing environmental issues.

- Integration of New Technologies:

The emergence of new technologies from external domains will necessitate their adaptation and integration into geotechnical practice. These technologies could span a wide range, including advancements in materials science, ground improvement techniques, investigation technologies, modeling and computing tools, sensor technologies, big data analytics, and artificial intelligence. Engineers will need to stay abreast of technological advancements and continuously update their skillsets to remain competitive in the field.

Given these anticipated changes, the traditional approach of learning theory in academic settings and gaining practical experience on the job may no longer suffice. Today's young engineers are expected to demonstrate proficiency in their roles early on, while experienced professionals must prioritize continuous learning and skill development throughout their careers to remain relevant in an evolving landscape.

5. EDUCATION AND TRAINING

The discussion above underscores the diverse array of sources contributing to geotechnical knowledge and highlights the indispensable role of experience and judgment in its application. However, this discussion merely scratches the surface, and substantial effort is

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needed to gain a comprehensive understanding of the key issues surrounding geotechnical knowledge. Such understanding is crucial for improving approaches to engineer education and training, research and development, and the practice of geotechnical engineering. Additionally, addressing issues such as geotechnical expertise, quality, and ethics is paramount.

In light of the aforementioned points, there is an urgent need to equip both aspiring and practicing engineers with the skills to navigate the challenges that lie ahead. While academic institutions effectively teach engineering sciences and analytical techniques, enhancements can be made to geotechnical engineering programs to better prepare young engineers. This could involve incorporating elements discussed earlier, such as emphasizing the empirical nature of engineering, enhancing the interpretation of exploration data, clarifying assumptions and modeling bases, and instilling a deep understanding of codes and guidelines. Moreover, greater academia-industry collaboration is essential to expose students to real-world geotechnical practice.

A two-year master's degree is deemed the minimum educational requirement for geotechnical engineers. Unlike a four-year undergraduate program, which provides only a cursory introduction to geotechnical engineering, a master's program should offer a comprehensive curriculum spanning four semesters. This curriculum should encompass a broad range of courses covering theoretical soil and rock mechanics, engineering geology, laboratory testing, exploration and investigation techniques, foundation engineering, soil dynamics, and various specialized topics.

Furthermore, the master's program should culminate in a practical project of significance, focusing on data interpretation, analysis, design, and constructability considerations. This practical project should steer clear of purely research-oriented endeavors, aiming instead to produce engineers ready for immediate integration into the workforce. Exposure to practical geotechnical engineering practice would also benefit students aspiring to pursue careers in research and academia.

To keep pace with evolving technology and industry demands, students should receive hands-on training in the use of key geotechnical engineering software packages. They should also gain experience in deriving input parameters for numerical problems from field and laboratory investigations, as well as tackling various field problems requiring two- and three-dimensional analysis.

While traditional teaching formats suffice for theoretical courses, design-oriented courses could benefit from the incorporation of case study methods and project-based learning. These methodologies foster teamwork, leadership, and independent thinking among students, preparing them for the challenges of real-world engineering practice. Engineering societies also play a vital role in engineer training by organizing conferences, workshops, and training programs to keep members abreast of industry developments and foster interdisciplinary skills.

Overall, a concerted effort involving academic institutions, industry partners, and engineering societies is essential to cultivate a new generation of comprehensive geotechnical engineers equipped to tackle the complexities of future challenges.

6. IN PRACTICE

Some of the above observations on the education system were implemented in the Master of Technology of Geotechnical Engineering scheme at Visvesvaraya National Institute of Technology-Nagpur having an intake of twenty students. Based on the comment received during the academic audit in the year 2020, the syllabus of the core course i.e. Design of Underground Structures having course code CEL 581 was updated. Case studies are made essential part of this course and will also be incorporated in the evaluation process in 2021.

Most of these case studies are presented by professionals who is involved in the work. The performance of the students in the years 2020, 2021, and 2022 for Design of Underground Structures were presented in Figure 1.

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In Cumulative Grade Point Average (CGPA) evaluation systems for theses consecutive years, the cut off of each grade remained same. The grade pointer was for AA-10, AB-9, BB-8, BC-7 and CC-6. There was a significant increase of a number of students in AA grade was observed in the years 2021 and 2022. This increased number of students in AA grade is mainly due to a reduction in AB grade students. This indicates that the modification in syllabus significantly helps serious students to enhance their performance. It was also observed that those practical examples create interest among CC grade students. As most of them have improved their performance in the year 2021 and 2022. This explanation is based on the assumption that the quality of students remains same as they were admitted through the all-India examination i.e. Graduate Aptitude Test in Engineering (GATE).

7. CONCLUSIONS

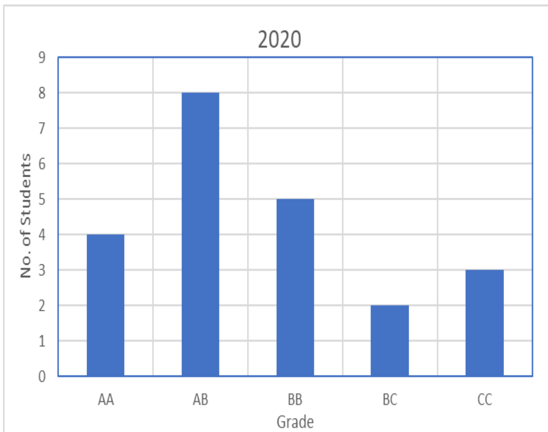
This paper presents a distinctive approach to understanding the geotechnical knowledge essential for engineering practice and the education and training of geotechnical engineers. Commencing with an examination of the primary activities undertaken by geotechnical engineers, encompassing exploration, analysis and design, management, and construction, the paper proceeds to explore key sources of geotechnical knowledge, including engineering sciences, models, codes of practice, judgment, and heuristics, elucidating their applications in engineering practice. Subsequently, the paper delves into a discussion on anticipated broad trends likely to impact the profession in the forthcoming decades. Finally, it concludes with an exploration of the education and training of geotechnical engineers.

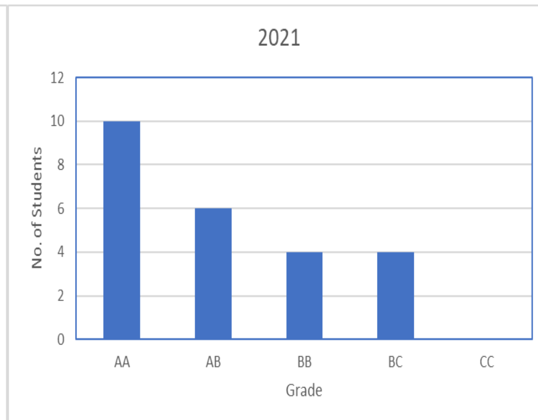
Presently, a significant gap exists between academic theory and practical application in the field. This paper aims to bridge this divergence by advocating for a better integration of practical geotechnical knowledge into academic curricula. By enhancing the understanding of geotechnical knowledge essential for engineering practice and incorporating this knowledge into the education and training of aspiring geotechnical engineers, both academia and practice stand to benefit. Achieving this entails fostering continuous academia-industry collaboration, where industry experts actively contribute to student education and teachers are exposed to real-world practice. Moreover, ongoing training programs should be provided to practicing engineers to ensure they remain updated on the latest developments in geotechnical engineering.

Furthermore, the adoption of case study methodologies and project-based learning models within academic programs holds promise for significantly enhancing the education of young engineers. These approaches foster practical problem-solving skills, critical thinking, and a deeper understanding of real-world challenges. Through concerted efforts to integrate practical knowledge and experiential learning into academic curricula, the field of geotechnical engineering can better prepare future engineers for the complexities of professional practice.

The study underscores a significant finding concerning the educational efficacy of systematically presenting case studies. This pedagogical approach proves to have a considerable impact on both students' understanding and their level of interest. The discernible enhancement in comprehension directly correlates with an augmented investment of time by students in the covered topics, thereby positively shaping their performance evaluations. This positive influence is particularly conspicuous among students classified as above-average and average in proficiency levels, as manifested by their exemplary performances in subsequent analyses.

The discerned positive correlation between systematic case study presentation and improved academic outcomes suggests that this method holds promising potential for educational enrichment. In the realm of infrastructure projects, where practical application and theoretical knowledge intersect, the adoption of structured case studies emerges as a valuable strategy. By incorporating such pedagogical tools, educators can effectively narrow the gap between theoretical training and real-world application. This is especially pertinent in fields where hands-on experience and theoretical understanding are pivotal, as is often the case in the intricate landscape of infrastructure development. In essence, the implementation of structured case studies stands out as a proactive measure to foster a more seamless transition from academic training to practical proficiency in the realm of infrastructure projects.





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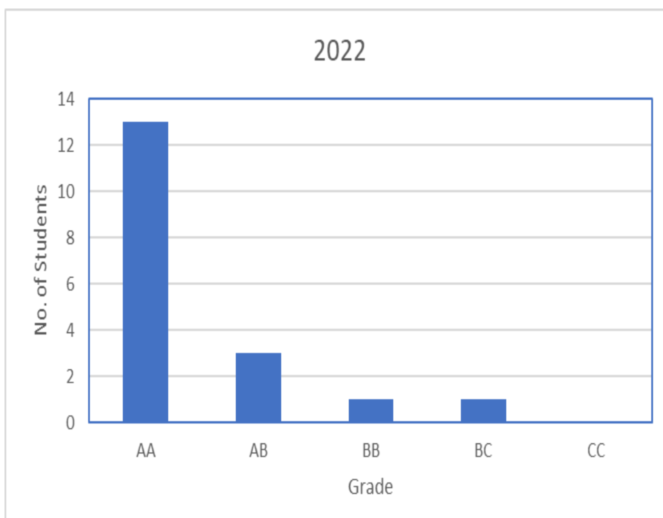

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Figure 2: Students' performance in a) for 2020 b) for 2021 c) for 2022

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