Indian Geotechnical Society

ISSMGE Technical Committee

Time Capsule Reports

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Convener SC 5 International
Cooperation (TC Activities)

INDIAN GEOTECHNICAL SOCIETY

ISSMGE Technical Committee

Time Capsule Reports

Acknowledgment

We are delighted to present the International Society for Soil Mechanics and Geotechnical Engineering Technical Committee (ISSMGE TC) Time Capsule, a result of the collaborative efforts of esteemed IGS members from the ISSMGE TCs. The diverse expertise and unwavering commitment of each member have played a crucial role in shaping the comprehensive content of this book.

We would also like to express our heartfelt thanks to the Indian Geotechnical Society (IGS) President, Dr. Anil Joseph and IGS Honorary Secretary, Dr. A. P. Singh, for their invaluable support and encouragement throughout this initiative. Their leadership has been instrumental in facilitating the realization of the ISSMGE TC Time Capsule.

Our sincere gratitude goes to the members of the SC5 committee who embraced the idea of creating a time capsule to capture the Achievements and Challenges faced by the Technical Committees in India. A special acknowledgment is extended to the Convenor of the SC5 committee, Prof. Neelima Satyam D., for her exceptional leadership, guidance, and steadfast commitment to the success of this endeavour.

The meticulous compilation and organization of the report were made possible by the dedicated efforts of the IGS staff, and we express our appreciation for their valuable contributions. We would also like to recognize and thank the National Executive Members of IGS for their persistent support and cooperation throughout the entire process.

This Time Capsule serves as a testament to the collaborative spirit and shared dedication to advancing the field of geotechnical engineering within our community. We extend our heartfelt appreciation to each contributor for their efforts in turning this project into a reality.

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1 TC 102 Ground Property Characterization from In-Situ Tests

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1.1 Abstract:

Technical Committee 102 (TC 102) of the ISSMGE focuses on geotechnical and geophysical exploration, playing a vital role in ground property characterization in different parts of the world. The committee led by Prof. Jason T. De Jong of USA aims to advance geotechnical engineering practices through research, knowledge sharing, and collaboration. Prof. Kaushik Bandyopadhyay of Jadavpur University and Dr. P. Anbazhagan, Associate Prof. of IISC Bangalore are the nominated members of this TC 102 committee from India along with the corresponding members, Dr. J. K. Shukla of Geodynamics and S. K. Garg of IGS Infra Pvt. Ltd. This document has been prepared by Prof. Bandyopadhyay with active assistance from Dr. P. Anbazhagan and their research scholars. TC 102 promotes excellence, innovation, and standardization in ground property characterization techniques, including in-situ tests such as Standard Penetration Test (SPT), Cone Penetration Test (CPT), Dilatometer Test (DMT), Pressuremeter Test (PMT), Vane Shear Test (VST), Cross Hole Test (CHT), Down Hole Test (DHT), and more. By facilitating international and national collaborations, advocating for accurate ground data, and developing guidelines and standards, TC 102 drives the improvement of geotechnical designs, ensuring safer and resilient infrastructure development in India.

Keywords: TC 102, ground property characterization, in-situ tests.

1.2 Introduction:

The Technical Committee 102 (TC 102) of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) is dedicated to Ground Property Characterization and its relevance to Geotechnical Engineering Practice. TC 102 focuses on the study and dissemination of knowledge related to the characterization of soil and rock properties, including laboratory testing, field testing and interpretation of test results.

The history of TC 102 can be traced back to the early years of ISSMGE. The ISSMGE was founded in 1936, and over time, it formed various technical committees to address specific areas of geotechnical engineering. During its inception, this committee was named TC 16. Later on, it was renamed so. Presently, host member Society of this committee is United States. TC 102 was established to specifically address ground property characterization and its importance in geotechnical practice.

- **Knowledge exchange:** TC 102 has organized conferences, workshops, and technical sessions in India, providing a platform for researchers, practitioners, and academicians to share knowledge and advancements in ground property characterization.

- **Guidelines and technical reports:** TC 102 has developed publications, guidelines, and technical reports that serve as valuable resources for geotechnical engineers in India in various forums. Some of these reports are documented and some are not. More or less, these resources provide guidance on soil investigation techniques, laboratory testing, and interpretation of test results in India.

- **Training and education:** TC 102 has organized workshops, seminars, and short courses in India to enhance the skills and knowledge of geotechnical professionals and students. These initiatives contribute to the overall improvement of geotechnical engineering practices in the country.

- **Research collaboration:** TC 102 promotes research collaboration among its members and geotechnical professionals in India. Collaborative research projects and studies on ground property characterization help advance the understanding of soil behavior and improve design methodologies.

- **Professional networking:** TC 102 provides networking opportunities for professionals in India to connect with geotechnical experts worldwide. This networking fosters the exchange of ideas, experiences, and best practices in ground property characterization, contributing to professional growth and development.

1.3 Overview of the Timecapsule Document

In this section an overview of what the Time Capsule document contains, the reason for creating it has been discussed.

The Time Capsule document on TC 102 contains a comprehensive overview of the committee's activities, achievements, and contributions in the field of geotechnical in-situ testing. It serves as a historical record and knowledge repository for future generations. The document includes the following key components:

- **Introduction:** The document begins with an introduction to TC 102, providing background information on its establishment, purpose, and objectives. It highlights the significance of the committee's work in advancing geotechnical in-situ testing practices in India.

- **Milestones:** The Time Capsule document outlines the initiation and advances of Geotechnical in-situ testing practices in India, along with the involvement and contribution from TC 102 nominated Indian members in the field of in-Situ testing for the past two decades have been discussed.

- **Case Studies and Projects:** The document features case studies and projects where TC 102's expertise and recommendations were applied. It provides an overview of notable geotechnical engineering projects in India, showcasing the committee's involvement, challenges faced, and successful outcomes. This section demonstrates the practical application of TC 102's research and guidelines.

- **Challenges and Lessons Learned:** This section discusses the key challenges faced by the nominated Indian members of TC 102 during their journey and the lessons learned from those experiences. It provides insights into the obstacles encountered in implementing geotechnical in-situ testing practices in India and offers recommendations for addressing future challenges.

- **Future Outlook and Recommendations:** The Time Capsule document concludes with a forward-looking perspective. It presents the committee's vision for the future of geotechnical engineering in India and provides recommendations for further advancements, research priorities, and policy considerations. This section serves as a guide for future initiatives and developments in the field.

Overall, the Time Capsule document on TC 102 is a comprehensive compilation of the committee's activities, technical contributions, and lessons learned. It serves as a valuable resource for knowledge preservation, reference, and inspiration for the geotechnical engineering community in India.

Overall, the creation of a time capsule document on TC 102 ensures the preservation, accessibility, and celebration of the committee's knowledge, experiences, and contributions. It acts as a valuable resource for the geotechnical in-situ testing practices in India for the future researchers and policymakers, fostering continuous growth and development in the field of geotechnical engineering in India.

1.4 Milestones in TC 102

The Technical Committee TC 102 of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) focuses on Ground Property Characterization from In-Situ Tests. Here are some notable milestones:

> **Research Initiatives:** TC 102 nominated Indian members have undertaken various research initiatives to enhance the understanding and implementation of in-situ testing methods and guide lines for ground property characterization in India in various forums. These initiatives are expected to move way forward the development of improved testing techniques and methodologies.
>
> **Publications:** TC 102 nominated Indian members have contributed to scientific publications, research papers, and technical reports on ground property characterization. These publications will add to the gamut of knowledge in the field and help in disseminating valuable information to the geotechnical community as a whole.
>
> **Collaboration and Networking:** TC 102 has facilitated collaboration and networking among geotechnical professionals, researchers, and academicians in India. Joint collaboration between academicians and researchers of IISc, Bangalore and Jadavpur University has already been developed. A workshop was organized jointly by these two Institutes at IISc Bangaore in the year 2019. This has fostered an environment of knowledge sharing, interdisciplinary cooperation, and research partnerships not only between these two institutes but also among other participating members of other elite academic and industrial institutions of India.
>
> **Training and Capacity Building:** TC 102 has been involved in organizing training programs and capacity-building initiatives to enhance the skills and knowledge of geotechnical engineers in the field of ground property characterization. These activities with further encouragement and participation from Government bodies and industry will contribute to a great extent to the professional development of practitioners in India.

Overall, TC 102 nominated Indian members have been sincerely endeavouring to make significant strides in advancing the field of ground property characterization through research, knowledge dissemination, collaboration, and capacity building. These milestones are expected to play a crucial role in enhancing geotechnical practices and promoting the use of reliable and accurate in-situ testing methods for ground property assessment.

1.4.1 Projects involving Geotechnical in-situ testing in India

Along with this list of some remarkable engineering projects which involved a great deal of geotechnical in-situ testing in India is given below.

- Golden Quadrilateral: A network of highways connecting Delhi, Mumbai, Chennai, and Kolkata, spanning over 5,846 kilometers.

- Delhi Metro: The largest metro network in India, reducing traffic congestion and improving public transportation in Delhi.

- Bandra-Worli Sea Link: An iconic cable-stayed bridge in Mumbai, connecting Bandra to Worli.

- Chenani-Nashri Tunnel: India's longest road tunnel, reducing travel time between Chenani and Nashri in Jammu and Kashmir.

- Sardar Sarovar Dam: One of the largest dams in the world, providing irrigation, hydroelectric power, and drinking water supply.

- Konkan Railway: A railway line along the Konkan coast, improving connectivity and boosting tourism.

- Statue of Unity: A colossal statue dedicated to Vallabhbhai Patel, standing at a height of 182 meters.

These projects have had a significant impact on India's infrastructure, transportation, and tourism, contributing to its overall development and growth.

1960-1980

The projects in this time span significantly contributed to the development of irrigation, power generation, and transportation infrastructure in India during the period from 1960 to 1980.

- Bhakra Dam: High gravity dam in Himachal Pradesh, facilitating irrigation, hydroelectric power, and flood control.

- Nagarjuna Sagar Dam: Massive masonry dam on the Krishna River, enabling irrigation and hydroelectric power generation.

- Tarapore Atomic Power Station: India's first nuclear power plant, pivotal in advancing the country's nuclear energy sector.

- Mettur Dam: Key dam on the Cauvery River, providing irrigation and hydroelectric power to Tamil Nadu.

- Trombay Thermal Power Station: Mumbai's prominent thermal power plant, operational since 1956.

- Rihand Dam: Multipurpose dam on the Rihand River, contributing to irrigation, hydroelectric power, and flood control.

- Nehru Bridge: Iconic bridge in Ahmedabad, connecting the city's eastern and western regions across the Sabarmati River.

1980-2000

The projects in this time span significantly contributed to transportation, irrigation, and water management, fostering economic growth and development in India.

- Konkan Railway: 741-km coastal railway line connecting Maharashtra, Goa, and Karnataka, boosting connectivity and tourism.
- Kolkata Metro: Oldest metro network in India, easing congestion with underground tunnels.
- Delhi Metro: Largest metro network in India, providing reliable transportation and alleviating traffic congestion in Delhi.
- Durgapur Barrage: Crucial irrigation and flood control structure in West Bengal, supporting agricultural development.
- HVJ Gas Pipeline: Extensive natural gas pipeline system supplying western to northern India for industrial, commercial, and domestic use.
- Farakka Barrage: Diversion structure on the Ganges River, ensuring river flow and navigation to Kolkata Port.
- Indira Gandhi Canal: 650-km irrigation project in Rajasthan, bringing water to arid regions and promoting agriculture.
- Vidyasagar Setu: Cable-stayed bridge connecting Kolkata and Howrah, facilitating transportation across the Hooghly River.

2000-2020

These projects have significantly impacted transportation, connectivity, tourism, and economic growth in India.

- Delhi Metro Phases I, II, and III: Expanded metro network enhancing connectivity in Delhi and NCR.
- Yamuna Expressway: 165 km highway reducing travel time between Greater Noida and Agra.
- Mumbai-Pune Expressway: Six-lane expressway improving connectivity and fostering economic growth.
- Metro Rail Projects in Various Cities: Kolkata, Bengaluru, Chennai, Hyderabad, and Kochi metro systems improving urban transportation.
- Chenani-Nashri Tunnel: 9.2 km tunnel enhancing connectivity in Jammu and Kashmir.
- Mumbai Trans Harbour Link: Under-construction sea bridge connecting Mumbai and Navi Mumbai.
- Statue of Unity: Tallest statue honoring Sardar Vallabhbhai Patel, a popular tourist attraction.

1.4.2 Publications on Ground Property Characterization

Along with this the contributions of TC 102 Indian members in the field of scientific publications, research papers, and technical reports on ground property characterization are listed below.

1.4.2.1 Dr. P. Anbazhagan, IISc Bangalore

2006:

Remote sensing techniques were utilized to gather information about the physical characteristics of the area, including land cover, topography, and geological features.

- Seismotectonic parameters, which described the regional tectonic activity and the potential for earthquake occurrence, were considered in the analysis.
- The correlation between remote sensing data and seismotectonic parameters was explored to assess the seismic hazard in Bangalore.
- Integration of these datasets aimed to identify areas of higher seismic risk within the city, providing valuable information for urban planning and disaster management.
- The findings of the analysis contribute to an improved understanding of the seismic hazard in Bangalore and aid in the development of mitigation strategies.

The combined use of remote sensing and seismotectonic parameters offered a comprehensive approach for assessing seismic hazards in urban areas like Bangalore.

2007:

- Conducted a seismic hazard analysis specifically for the Bangalore region in India.
- The study utilized various seismological data, including historical earthquake records, geophysical data, and seismotectonic information, to assess the seismic hazard in the area.
- Different probabilistic methods and models were employed to estimate the potential occurrence of earthquakes and their associated ground shaking levels.
- The analysis took into account the specific geological and tectonic characteristics of the Bangalore region to provide accurate assessments of seismic hazard.
- The findings of the study can contribute to improving the understanding of earthquake risks in Bangalore and help in developing effective strategies for disaster preparedness and mitigation in the region.

2008:

- Seismic microzonation analysis conducted for Bangalore, India, characterizing seismic response based on geological, geotechnical, and geophysical properties.
- Utilized geotechnical investigations, geological surveys, and geophysical measurements to assess site-specific seismic hazards.
- Provides detailed maps and zonation schemes indicating ground shaking levels and vulnerability across Bangalore.

- Findings aid in urban planning, infrastructure design, and emergency response preparedness for seismic safety measures in Bangalore.
- Spatial variability of weathered and engineering bedrock depth analyzed using the MASW method.
- MASW method employs seismic surface waves to estimate shear wave velocity profile and correlate with subsurface layers' depth.
- Study provides insights into depth distribution of weathered and engineering bedrock, benefiting geotechnical and civil engineering projects.

2009:

- Probabilistic seismic hazard analysis conducted for Bangalore, India, assessing earthquake likelihood and impact.
-
- Provides probabilistic seismic hazard maps illustrating spatial distribution of shaking intensities and occurrence probabilities.
- Calculated peak ground acceleration and spectral acceleration considering local site effects in South India.
- Developed a ground motion equation combining recorded and simulated data for improved predictions.
- Site classification and response studies conducted using shear wave velocity, enhancing understanding of site-specific seismic behavior.

2010:

- Conducted a comprehensive assessment of seismic hazards in Bangalore city using multiple evaluation criteria.
- Considers various factors such as geological, geotechnical, and seismological parameters to evaluate the hazard potential.
- Incorporates advanced techniques and models to analyze the seismic hazard, including probabilistic approaches and ground motion prediction equations.
- Provides insights into the vulnerability of structures and the potential impact of earthquakes in Bangalore.
- Aims to support urban planning, infrastructure development, and disaster management strategies by identifying high-risk areas and improving seismic resilience.

2011:

- Investigated the condition of fouled ballast in railway track formations through the use of ground penetrating radar (GPR) and multichannel analysis of surface wave (MASW) methods.
- Applies GPR to detect and assess the presence of contaminants and fouling materials within the ballast layer.

- Utilizes MASW to analyze the surface wave characteristics and evaluate the stiffness properties of the ballast layer.
- Provides valuable insights into the extent of ballast fouling and its effects on track stability and performance.
- Offers a practical approach for assessing ballast condition and supports maintenance and management strategies for optimizing railway track performance.

2012:

- Comprehensive review of correlations between SPT N values and shear modulus, identifying limitations.
- Proposes a new correlation accounting for regional variations in geotechnical properties.
- Demonstrates effectiveness through comparisons with field data.
- Investigates ballast fouling in railway track formations, analyzing its impact on stability and drainage.
- Provides insights into mechanisms and facilitates development of mitigation strategies and maintenance practices.

2013:

- Focuses on seismic site classification in Lucknow City, an active seismic region.
- Determines SPT N values and shear wave velocities through geotechnical investigations.
- Classifies seismic sites based on obtained data, aiding earthquake-resistant design and planning.
- Investigates rock depth influence on site classification and seismic response in shallow bedrock regions.
- Provides insights into geotechnical factors affecting seismic site classification in such areas.

2016:

- Focuses on the probabilistic evaluation of soil liquefaction potential, which is the susceptibility of soils to lose strength during earthquakes.
- Utilizes Standard Penetration Test (SPT) data, a commonly used geotechnical investigation method, to assess soil properties relevant to liquefaction.
- Develops a probabilistic framework to quantify the likelihood of soil liquefaction based on SPT data, considering factors such as cyclic stress ratio and soil properties.
- Incorporates statistical analysis and geotechnical modeling to estimate the liquefaction potential and associated uncertainties.

- Provides valuable information for assessing and managing the seismic hazards associated with soil liquefaction, aiding in the development of resilient infrastructure and land-use planning in seismically active areas.

2017:

- Investigated the spatial variability of rock depth in Bangalore, focusing on understanding the distribution and characteristics of the underlying bedrock.
- Utilizes geostatistical methods, neural network models, and support vector machine models to analyze and predict the variations in rock depth across the study area.
- Integrates geological data, geotechnical investigations, and remote sensing techniques to develop accurate and reliable models for estimating rock depth.
- Provides insights into the subsurface conditions and geological features of Bangalore, which are crucial for various engineering and construction projects.
- Offers valuable information for urban planning, infrastructure development, and geotechnical engineering applications in the region, aiding in better decision-making and risk assessment.

2018:

- Focuses on the identification of ballast fouling in railway track formations using ground-coupled ground-penetrating radar (GPR) antennas.
- Utilizes GPR technology to collect subsurface data and assess the type and degree of fouling in the railway ballast.
- Develops a methodology to analyze GPR data and identify different types of fouling, such as mud, fines, or vegetation, present in the ballast layer.
- Quantifies the degree of fouling based on the GPR data, providing valuable insights into the condition and performance of railway tracks.
- Offers a non-destructive and efficient approach for assessing ballast fouling, aiding in maintenance planning, track performance evaluation, and overall safety of railway infrastructure.

2019:

- Focuses on the evaluation of dynamic properties and ground profiles using the Multichannel Analysis of Surface Waves (MASW) method.
- Utilized MASW to determine the shear wave velocity (Vs) profile of the subsurface, which is an important parameter for assessing soil behavior during seismic events.
- Investigated the correlation between Vs and the N60 value, which represents the standard penetration resistance of the soil.

- Established a relationship between Vs and N60, enabling the estimation of Vs profiles using the readily available N60 data.

Provided insights into the geotechnical properties of the subsurface, aiding in seismic hazard assessment, site characterization, and geotechnical engineering design.

1.4.2.2 Prof. Kaushik Bandyopadhyay, Jadavpur University

2006:

- Focused on combining Seismic Dilatometer Test (SDMT) and Cone Penetration Test (CPT) for soil analysis.
- Aimed to compare SDMT and CPT results and evaluate the suitability of SDMT.
- Found good correlation between SDMT and CPT results.
- SDMT provided additional benefits such as determining shear wave velocity profiles and calculating shear modulus (G_0) for studying liquefaction. Concluded that SDMT is well-suited for detailed soil exploration work.

2015:

- Compared sub-soil profiles obtained by Seismic Dilatometer Test (SDMT) and Standard Penetration Test (SPT) for settlement analysis in post-earthquake conditions.
- Provided recommendations on the suitability of both methods for liquefaction potential and post-earthquake settlements.

2016:

- Investigated the behavior of laterally loaded piles in layered cohesive soil.
- Utilized the OASYS Alp 19.2 software and field data for analysis.
- Emphasized the importance of considering non-linear behavior and plastic analysis in pile design for lateral loads.

2017:

- Analyzed the failure of stone columns and suggested rectification measures for tank foundations over soft soil deposits.
- Addressed settlement issues and identified causes of failure.

2018:

- Conducted a comparative study on slope stability analysis using different approaches.
- Used Geo-studio software for numerical simulations.

- Found that Geo-studio software provided better results compared to traditional methods like the limit-equilibrium method.

- Concluded that Geo-studio software can potentially reduce project costs in embankment construction.

- Examined erosion hotspots and drivers of erosion along the West Bengal coast in India.

- Emphasized the importance of data collection and construction methods for seawalls to mitigate erosion.

- Assessed rainfall thresholds for rain-induced landslides in the North Sikkim Road Corridor.

- Established thresholds based on intensity-duration and antecedent rainfall models for landslide prediction and early warning systems.

2020:

- Predicted settlement of the High Court building in Kolkata, India, using the flat dilatometer.

- Utilized the Marchetti Flat Dilatometer Test (DMT) for computing settlement and other geotechnical parameters.

- Found accurate results with the DMT and recommended its use for determining engineering properties and estimating settlement in ground improvement work.

1.4.2.3 Dr. Jaykumar Shukla, Principal Engineer and Senior Consultant, Geo Dynamics

2011:

- Analyzed the probability of earthquake occurrence and studied recurrence models for Gujarat state in India.

- Utilized historical data and considered factors such as seismic activity and tectonic settings.

- Investigated various earthquake recurrence models to understand patterns and frequencies.

- Provided insights into the likelihood of earthquakes in Gujarat state.

- Implications include enhancing earthquake preparedness and risk assessment strategies.

- Contributes to the development of mitigation measures to minimize potential damages caused by seismic events.

- Supports decision-making processes related to earthquake preparedness and mitigation in Gujarat, India.

2012:

- Conducted seismic hazard assessment and site-specific ground motion studies for ports and cities in Gujarat, India.

- Developed ground motion equations specific to each location, aiding in seismic design and retrofitting of structures.

- Provided valuable information for enhancing the resilience of ports, buildings, and infrastructure against earthquakes.
- Supported the development of seismic design guidelines, building codes, and safety measures in the region.
- Contributed to informed decision-making in construction practices and maintenance of ports and structures in Gujarat.
- Showcased advancements and best practices in geotechnical engineering through a collection of research papers and case studies.
- Promoted knowledge sharing, collaboration, and innovation in the geotechnical engineering community.
- Served as a valuable resource for geotechnical engineers, researchers, and professionals in the field.

2013:

- Conducted a study on slope stability and settlement analysis for a dry bulk terminal project in Mozambique.
- Investigated geotechnical conditions, evaluated slope stability, and provided recommendations for risk mitigation.
- Valuable reference for geotechnical engineers and project managers in coastal infrastructure projects.
- Explored the design and performance of a breakwater for a sea water intake facility on the southeast coast of India.
- Utilized numerical modeling and wave-structure interaction studies to optimize the breakwater design.
- Addressed challenges in coastal environments and provided practical recommendations for construction.
- Studied the estimation of ultimate socket friction capacity for micropiles in different rock strata.
- Developed empirical correlations and mathematical models for accurate load-bearing capacity predictions.
- Useful for geotechnical engineers in ensuring the structural integrity of foundation systems.

2015:

- Focuses on seismic design of pile foundations for oil tanks using PLAXIS3D software.
- It aims to assess the response of pile foundations under seismic loading conditions and ensure their stability and safety.
- The analysis considers dynamic properties of soil and pile materials, simulating different design scenarios and loading conditions.
- Parameters such as pile spacing, length, soil properties, and seismic input are evaluated for their impact on foundation response.

- PLAXIS3D analysis provides insights into stress distribution, displacement, and deformation patterns during seismic events.

- The study offers recommendations to optimize design parameters and enhance seismic resistance of pile foundations for oil tanks.

- Findings are valuable for engineers involved in seismic design, ensuring structural integrity and safety of critical infrastructure.

2016:

- Aims to establish a correlation between the SPT N-value and shear wave velocity, which is crucial for geotechnical and seismic analyses.

- Field data from various locations are collected, including SPT N-values and corresponding shear wave velocities.

- Statistical analysis and regression techniques are employed to develop a reliable correlation equation between the SPT N-value and shear wave velocity.

- The correlation equation provides a convenient and practical approach for estimating shear wave velocity in regions where direct measurements may not be available.

- The study contributes to the understanding of soil properties and enables accurate seismic analysis and site-specific design considerations.

- Examines the effects of trench excavation on the performance and stability of buried pipes.

- Detailed field measurements and monitoring data are collected during the excavation process to assess the deformation and behavior of the pipes.

- The findings contribute to the understanding of the interaction between large-diameter buried pipes and surrounding soil during excavation activities.

- The study provides insights into the design and construction considerations for large-diameter buried pipes, ensuring their stability and performance in similar scenarios.

2019:

- Presents case studies and practical approaches to address geotechnical challenges in industrial construction, focusing on foundation design, soil-structure interaction, ground improvement, and seismic assessment.

- Emphasizes the importance of sustainability in foundation design for long-term performance and resilience against seismic events.

- "IGS NEWS" publication provides updates and news from the International Geosynthetics Society, covering various geotechnical engineering topics and promoting knowledge sharing.

- Highlights the significance of learning from past failures in large infrastructure projects, analyzing case studies to identify geotechnical issues and lessons learned.
- Advocates for comprehensive site investigations, advanced geotechnical analysis, and risk assessment to mitigate failures in large-scale projects.
- Explores opportunities for innovative geotechnical solutions and technologies to enhance performance and safety in large infrastructure projects.
- Aims to improve understanding of geotechnical challenges and promote effective strategies for successful implementation.

2020-Present

1.4.3 Civil Engineering projects in India

Here is a summary of the previous write-up regarding notable civil engineering projects in India:

- Mumbai Coastal Road Project: 29.2 km freeway improving connectivity in Mumbai.
- Delhi-Mumbai Expressway: 1,250 km expressway reducing travel time between Delhi and Mumbai.
- Chennai Peripheral Ring Road: Proposed 128 km orbital road to ease congestion in Chennai.
- Mumbai-Ahmedabad High-Speed Rail: Ongoing construction of high-speed rail between Mumbai and Ahmedabad.
- Chennai Metro Rail Phase 2: Expansion of Chennai's metro rail network by 118 km.
- Jewar International Airport: Construction of India's largest airport near Noida, UP.
- World One: On-hold residential skyscraper in Mumbai, intended to be the world's tallest.
- Char Dham Expressway: Proposed highway linking holy places in Uttarakhand.
- GIFT City: Development of a financial district in Gujarat.
- INSTC: Transport route linking India, Russia, Iran, Europe, and Central Asia.
- Freight Corridors: Dedicated rail lines for efficient freight transportation.
- Shiv Smarak: Monument dedicated to Chhatrapati Shivaji Maharaj in Mumbai.
- Sethu Bharatam Yojana: Railway bridges on national highways.
- Bharatmala Project: Construction of 34,800 km of new roads across India.

- Sagarmala Program: Development of coastlines, waterways, and ports for logistics.
- High-Speed Rail Project (Mumbai-Ahmedabad): 509 km high-speed rail corridor between Mumbai and Ahmedabad.

Along with this the contributions of TC 102 Indian members in the field of scientific publications, research papers, and technical reports on ground property characterization has been listed.

1.4.3.1 Dr. P. Anbazhagan, IISc Bangalore

2020:

- Focuses on seismic site classification and the correlation between shear wave velocity (VS) and standard penetration test blow count (SPT-N) for deep soil sites in the Indo-Gangetic Basin.
- Conducts field investigations and collects data on VS and SPT-N from various sites in the region.
- Performs statistical analysis to establish correlations between VS and SPT-N, considering the specific characteristics of deep soil sites in the Indo-Gangetic Basin.
- Develops site classification criteria based on VS values, allowing for the categorization of sites into different seismic hazard levels.
- Enhances understanding of soil behavior and its relationship with seismic response, facilitating more accurate seismic hazard assessments and geotechnical design in the Indo-Gangetic Basin.

2021:

- Focuses on assessing seismic hazard in the Patna district, India, by considering seismotectonic parameters and local geological conditions.
- Utilizes probabilistic seismic hazard analysis techniques to estimate ground motion parameters for different return periods.
- Generates seismic hazard maps that depict the spatial distribution of seismic hazard levels in the region.
- Provides information on the magnitude and frequency of potential earthquakes, aiding in mitigation strategies and engineering design considerations.
- Applies a logic tree approach to capture uncertainties in seismic hazard assessment and incorporates data on historical earthquakes, fault characteristics, and site-specific geotechnical information.
- Provides valuable information for seismic risk management, emergency planning, and resilient infrastructure development in the Patna district.

2022:

- Focuses on estimating the maximum magnitude of earthquakes considering the regional rupture characteristics in a specific area.

- Analyzes geological and tectonic data, including fault distribution, historical earthquake records, and stress accumulation patterns, to understand the potential for large-magnitude earthquakes.

- Incorporates statistical and probabilistic methods to assess the likelihood of future earthquakes and estimate their maximum magnitudes.

- Considers factors such as fault length, slip rates, and recurrence intervals to determine the upper bound of earthquake magnitudes that can occur in the region.

- Provides valuable information for seismic hazard assessment, infrastructure design, and risk mitigation strategies, helping to ensure the resilience and safety of the affected area.

2023:

- Utilizes the Horizontal-to-Vertical Spectral Ratio (HVSR) method for seismic site classification in the Himalayan region, providing insights into site conditions and seismic hazards.

- Investigates equations for estimating soil water content using Ground Penetrating Radar (GPR) technology, comparing their accuracy and reliability under various soil conditions and GPR settings.

- Conducts a comprehensive investigation on ground response characteristics in the deep Indo-Gangetic Basin, analyzing seismic behavior, amplification effects, and ground motions through advanced analysis techniques and simulations.

- Investigates amplification characteristics of seismic waves in shallow engineering bedrock sites, comparing empirical relations for estimating amplification factors and conducting site response analyses.

- Focuses on the seismic characterization and dynamic response analysis of a municipal solid waste landfill in Bangalore, assessing stability, liquefaction susceptibility, and seismic performance for appropriate design and mitigation strategies.

- Presents a reconnaissance report on the geotechnical effects and structural damage from the Tripura Earthquake in India, assessing infrastructure impact, geotechnical aspects, and spatial distribution of damages for post-disaster response and future mitigation measures.

1.4.3.2 Prof. Kaushik Bandyopadhyay, Jadavpur University

2022

- Analyzes landslide distribution in the North Sikkim Road Corridor using geospatial techniques, considering both rain-induced and earthquake-triggered landslides.

- Integrates remote sensing, GIS tools, and geospatial datasets to identify landslide-prone areas based on factors like slope, lithology, land cover, and rainfall.

- Reveals the contributions of rainfall and seismic activity to landslides in the region, identifying vulnerable zones along the road corridor.

- Findings are valuable for disaster management and planning measures to mitigate landslide impacts.

- Emphasizes the use of the dilatometer as an in situ soil exploration tool for assessing ground conditions and optimizing construction activities.

- Highlights the importance of understanding soil behavior before construction, with the dilatometer providing real-time measurements and data on soil strength and compressibility.

- Enables informed decisions, cost savings, and reduced construction time through accurate assessment of soil properties.

- Emphasizes the significance of the dilatometer for geotechnical engineers and construction professionals.

2021

- Overview of geosynthetics as a ground improvement technique in civil engineering.

- Benefits of geosynthetics in bearing capacity increase, soil reinforcement, stabilization, and erosion control.

- Case studies demonstrating successful utilization of geosynthetics in construction projects.

- Design considerations, installation techniques, and quality control for geosynthetics.

- Evaluation of liquefaction potential in Kolkata's Rajarhat area using empirical methods, CPT, and Vs-based methods.

- Field investigations, laboratory testing, and seismic hazard analysis for liquefaction susceptibility assessment.

- Comparison and evaluation of different methods for predicting liquefaction potential with recommendations for site-specific conditions.

- Contribution to understanding liquefaction and informing future geotechnical studies and earthquake hazard mitigation strategies.

- Subsoil parameter estimation and settlement analysis for a construction project in Kolkata.

- CPT and DMT tests to collect data on soil behavior and properties.

- Detailed analysis of subsoil parameters and settlement predictions for the project.

- Comparison and evaluation of CPT and DMT test results, discussing advantages and limitations.

- Recommendations for improving subsoil parameter estimation and settlement analysis accuracy.

- Importance of CPT and DMT tests for accurate geotechnical analysis and guidance for engineers in Kolkata.

1.4.3.3 Dr. Jaykumar Shukla, Principal Engineer and Senior Consultant, Geo Dynamics

2021:

- Focuses on the analysis and design of piled raft foundations, which are composite foundation systems combining the benefits of both pile foundations and raft foundations.
- The study investigates the behavior and performance of piled raft foundations under various loading conditions and soil types.
- It explores the interaction between the piles, raft, and surrounding soil, considering factors such as settlement, load distribution, and soil-structure interaction.
- The work includes numerical analyses, field investigations, and case studies to provide insights into the design considerations, construction techniques, and performance evaluation of piled raft foundations.
- The findings of the study contribute to the understanding of the structural behavior and efficiency of piled raft foundations, offering guidance for their optimal design and implementation in geotechnical engineering projects.

2022:

- Focuses on assessing the stability of a stacker-reclaimer embankment considering the presence of an adjacent stockpile.
- The study investigates the influence of the stockpile on the stability of the embankment, considering factors such as slope geometry, soil properties, and loading conditions.
- Numerical modeling techniques, such as finite element analysis, are employed to simulate the behavior of the embankment and evaluate its stability.
- The findings highlight the importance of considering the presence of adjacent stockpiles in slope stability analysis and provide insights into the factors that affect the stability of such embankments.
- Focuses on the analysis and design of pile groups and piled rafts as foundation systems.
- The study investigates the load-carrying capacity, settlement behavior, and interaction mechanisms between the piles, raft, and surrounding soil.
- Numerical analyses, field investigations, and case studies are employed to evaluate the performance and efficiency of pile groups and piled rafts under various loading and soil conditions.
- The findings contribute to the understanding of the behavior and design considerations of pile groups and piled rafts, providing guidance for their optimal implementation in geotechnical engineering projects.

1.5 Key Challenges and Practices in TC102

India uses several modern in-situ tests for site characterizing during and after 2010, which is essential for quality geotechnical practice in the country. At the same time, some major issues such as standards, equipment, knowledge and practice aspects make in-situ characterizing very weak in India. Key Challenges and Practices in TC102 are highlighted here.

Code & Standards

Internationally recognized codes & Standards are developed based on testing and difficulties in their regional condition. However, most of the codes and Standards in India are reproduced from Western countries without accounting for regional soil and subsurface condition. Many of these reproductions remove some part, section, or suggestion based on implementing practical difficulties without knowing its importance. For example, hammer energy is not part of SPT testing in IS2131, as the county has limited SPT equipment with energy measurement. Another example, IS1893, gives hammer energy correction based on the type of SPT hammer without any measurement and verification in the different parts of the country.

Besides, there is no code on Dilatometer test (DMT) which is a very popular test in the western countries given its accuracy and results being obtained within the same day of the test. Almost similar scenario is seen for Cone Penetration Test (CPT). Though there is some mention of this test in IS code, this is not sufficient. It should include variety of soils and more detailed discussions are necessary.

Improper In-Situ Testing Cost: Tendering & Pricing

The quality of testing and interpretation is mainly controlled by the price paid for the same. In India, most in-situ testing works are allotted through tendering instead consulting. In current practice, this tendering process allows assigning projects to L1 (Lowest quoted) agencies, which ends up with low-quality in-situ & lab testing in the country.

Lack of Multiple Techniques

Mother Earth is very complex, which requires proper testing and profiling using multiple in-situ testing techniques to capture its variation of subsurface and account for them in design. In India, the practice of subsurface exploration using multiple method testing at the same location or site is minimal. Most of the time, design is done based on one in-situ test, i.e. SPT, rather than multiple tests e.g., DMT, CPT etc. There is a need to make multiple in-situ testing mandatory in project values of more than 100 lakhs with minimum number and cost.

Lack of Knowledge about modern Tests

The technical teams of most of the originations do not have proper knowledge and experience on modern in-situ tests; because of this, modern in-situ tests are not carried out, and even if tests are done, proper interpretation is not done and hence these are not adequately accounted in the design.

Low-Quality Equipment and Testing

Some agencies are interested in characterizing sites using multiple in-situ tests. But due to the lack of knowledge, they hire agencies with low-quality and non-standard equipment for in-situ characterization. Sometimes equipment is used without any proper calibration and even if calibration was done, that too much older. As a result, low-quality and non-standard equipment are still widely used because of a lack of standards and awareness. Since agencies are not aware or are unclear about data and results, these substandard in-situ testing are still predominantly practised in India. All the more, these agencies are averse to sharing all the test data owing to these faulty testing procedure and doubtful results. This is another reason why it is difficult to create a data bank of test results of various locations of the country with authenticity.

Improper Support & Service and Lack of Indigenous Products in In-situ testing

Many foreign companies selling quality in-situ testing equipment keep changing their sales and service dealers. So, often these equipment are sold for a higher cost when compared to other regions of the world (Price in India is several times higher than those in other countries for the same equipment and supplier). Change of Indian agencies results in poor service & support and also higher service/spare parts cost. Moreover, manufacturing of quality indigenous in-situ equipment in India is very limited.

Accreditation and Issues

Recently accreditation has been taken country level to check the quality of results. As per in-situ site characterization test results and data, very limited experimental quality data and results are referenced/available for different subsurface conditions in India as pointed earlier. Many of the ranges of properties (minimum and Maximum) are taken from Western countries studies or textbooks and used for accreditations. Many times these results are not applicable and lead to biases in in-situ tests, interpterion and inference.

1.6 Way Forward for TC102

Based on expertise and experience in the variety of quality in-situ characterization testing, the following suggestions are made as Way Forward for TC102.

Preparation of Codes & Standards

Best Code & Standards must be prepared based on state-of-the-art knowledge and practice at the international level without omitting any section or parts due to cost factors or non-availability. Many Indian codes give correlations or charts developed elsewhere without verifying their applicability to Indian conditions.

Any correlation or chart required for geotechnical design, their correlation & chart must be developed using respective soil, verified and validated for Indian conditions through more than two committees and then incorporated in the code. Last but not the least, these committees should include experts from the respective TCs.

Change of Work Allotment for In-Situ Investigation

It may be appropriate to treat in-situ testing as consulting project rather than tendering work. This can help to get quality in-situ testing reports from well-trained agencies.

Multiple Techniques in the Same Site/project

It should be mandatory to carry out a minimum number of multiple in-situ tests in the same site/project and need to provide comparison and correlation to account for the design.

Increase Knowledge about modern Tests.

Indian Geotechnical Society & TC 102 should periodically arrange knowledge workshops and keep increasing modern in-situ testing techniques with case studies. Agencies that are selling these modern in-situ testing should come forward to arrange such workshops in collaboration with the leading institutes in academia so that gaps between academics and industry can be bridged.

Increase Outreach to the Students

The students in graduate and postgraduate programs in Civil/ Geotechnical engineering should be considered as future engineers and practitioners who will be working in field using these methods. They should be given enough exposure so that they understand the need and importance of these exploration methods.

Support & Service and Indigenous Product

Government should make a policy to ensure the service of in-situ testing equipment even if the Indian agent is changed, and government should also promote indigenous manufacturing of modern equipment.

Establishing Accreditation Parameters

The accreditation agency should appoint multiple committees to measure and benchmark each soil & rock's minimum and maximum properties for different geometrical parameters, which should be used for accreditation instead of using textbook values.

By focusing on these aspects, TC 102 in India can progress towards its objectives of promoting excellence in ground property characterization, improving geotechnical practices, and contributing to the overall advancement of the geotechnical engineering field.

1.7 Remarks

The collection of works presented covers various aspects of geotechnical engineering, seismic hazard assessment, and foundation design. These studies contribute valuable insights into understanding the behavior of soil and rock under different conditions and provide practical solutions for engineering projects. Along with these all the mega civil engineering projects of India for last 63 years have been listed.

The distinguished Indian members of TC 102 have employed a range of methods and techniques, including numerical modeling, field investigations, and case studies, to investigate topics such as seismic site classification, ground motion estimation, slope stability analysis, foundation design, and seismic hazard assessment. The works demonstrate a comprehensive understanding of geotechnical principles and their application in real-world scenarios.

The studies focus on vast regions in India, such as West Bengal, Gujarat, Sikkim, Karnataka and cities like Kolkata, Bangalore, Patna, Lucknow and the Himalayan region, highlighting the importance of site-specific analysis and considering regional geotechnical factors. They address challenges specific to these areas, such as seismic activity, soil conditions, and infrastructure development.

The research papers provide practical guidance and recommendations for engineers and practitioners working in geotechnical in-situ testing and seismic engineering fields. The findings from these studies can be used to enhance the design, construction, and safety of infrastructure projects in the respective regions.

Overall, the works demonstrate the significance of geotechnical investigations, seismic hazard assessments, and appropriate foundation design in ensuring the stability and resilience of structures in various geological and geotechnical contexts. The research conducted by the authors contributes to the core of knowledge in geotechnical engineering and serves as a valuable resource for future studies and engineering practices.

Last but not the least, India started using several modern in-situ tests for site characterizing around 2010and this is very much essential for quality geotechnical practice in the country. At the same time, some major issues such as lack of standards, equipment, knowledge and practice aspects make in-situ characterizing very weak in India. These activities with further encouragement and participation from Government bodies and industry will contribute to a great extent to the professional development of practitioners in India.

1.8 Disclosure Statement

The authors report there are no competing interests to declare.

2 TC 104 Physical Modelling in Geotechnics

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Understanding Seepage and Pseudostatic Stability of Earthen Dam using Centrifuge Modelling Technique

2.1 Abstract

This paper aims to present the performance of a small-scale earthen dam model subjected to pseudo-static loading along with inertial loading in a high gravity environment using a custom-developed tilt table-based setup in a geotechnical centrifuge. The base of the earthen dam model, when tilted by a small inclination of α° above the horizontal, will impart an inertial force. The developed setup consists of a screw jack based lifting mechanism with a hinge that can produce a maximum horizontal inertial acceleration of 0.36g to mimic the seismic response of a prototype geotechnical structure. The setup also consists of a water pumping system for simulating upstream filling, flooding, and drawdown conditions. The various components and working principle of the developed setup are discussed. Further, calibration and performance of the setup were demonstrated in a high gravity environment on an earthen dam section subjected to upstream flooding and pseudo-static loading. The centrifuge tests were conducted at 30 g-level in a 4.5 m radius large beam geotechnical centrifuge facility available at the National Geotechnical Centrifuge Facility at the Indian Institute of Technology Bombay, Indi

Keywords: Physical Model, Centrifuge Test, Flooding, Pseudo-Static, Earthen Dams

2.2 Introduction

Due to anthropogenic and natural factors, the instability of geotechnical structures, including earthen dams, tailings storage facilities, levees, etc., is a common problem worldwide posing threat to the built environment besides causing enormous financial implications. Several cases of catastrophic dam failures have been witnessed in the past (Seed 1979), including the Mount Polley dam in Canada in 2014, the Cadia dam failure in Australia in 2018, and the Brumhadino dam failure in Brazil in the year 2019. The failure causes include slope instability, earthquake loading, overtopping, seepage, piping, etc. The official database on dam failures doesn't exist, but independent studies record more than eight incidents of tailings dam failure per year out of nearly 30,000 tailings dams for the decade 2011 to 2020 compared to 1 in 10,000 for earth dams storing water (CSP^2 database 2022). India accounts for more than 7% of the world’s dams of which nearly 90% of the dams are earthen dams. Of the total earthen dams 90% of this lie in low to moderate seismic zones (NRLD, 2019).

The preliminary seismic design of earth dams is based on the pseudo-static method (Terzaghi 1950, Seed 1979). This approach does not consider the cyclic nature (i.e., the effects of time, frequency, and body waves) of an earthquake. The appropriate value of the seismic coefficient is decisive for the safe design of the dam (Jibson 2011, Andrianopoulos et al. 2014). The deformation behavior of an earthen dam subjected to seepage and inertial loading conditions is stress dependent; therefore, centrifuge-based model studies in enhanced gravity environment (Saran and Viswanadham 2018) or full-scale studies at 1g (Jeong et al. 2020) can provide decisive information compared to small-scale studies at 1g. Here, centrifuge test is viewed as a practical substitute for full-scale testing due to the time and cost of model construction and test repeatability.

Several researchers have developed and utilised tilt table-based setups to induce pseudo-static loading at 1g and Ng environment in the past such as rotating drum type (Saitoh et al. 1995, Izawa and Kuwano 2011), electric winch-based (Koseki et al. 1998), inclined base type (Kitazume et al. 2003), and hydraulic-jack based (Richardson and Lee 1975). Very recently, Wolinsky and Take (2019) developed a tilting table setup for studying instability in loose dry sand for landslide investigation. However, these studies had limited to no facility for studying the response of geotechnical structures like earthen dams and levees subjected to seepage and inertial loading simultaneously, which is critical to their design. Hence, the necessity was felt to design and develop a robust setup for water retention type geotechnical structures subjected to upstream filling, flooding, steady-state seepage, and pseudo-static loading simultaneously in a high gravity environment.

2.3 Development of Test Setup for Pseudo-static Loading

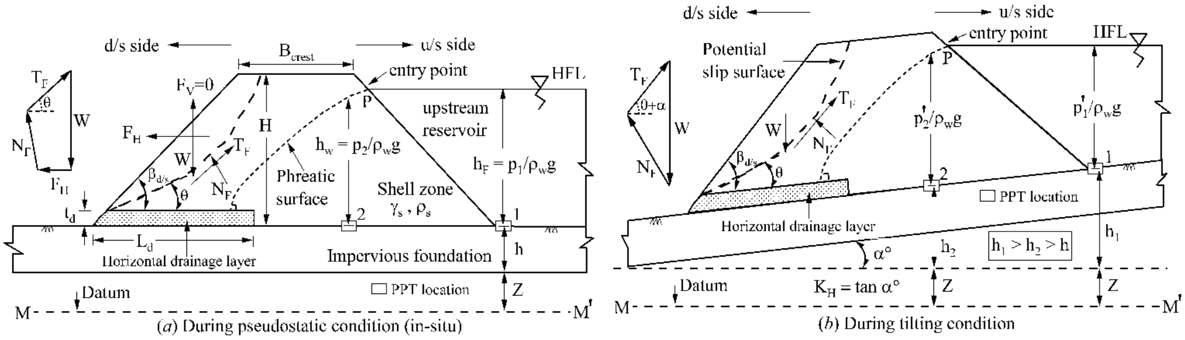
2.3.1 Basic Principle

The developed setup induces tilting of the small-scale centrifuge model by angle (α°) at high gravity level that is analogous to the pseudo-static loading condition. Fig 2.1 illustrates the earthen dam section subjected to inertial loading while in-situ and laboratory tilting and subsequent variation of force vector diagram. The pseudo-static force here is defined by the product of horizontal seismic coefficient (K_H) and weight of the sliding mass (W). From the resolution and comparison of normal and tangential forces in both the cases and solving for K_H, equation (1) is obtained.

$$K_H = \tan\alpha \tag{2.1}$$

2.3.2 Scaling Laws for Modeling Flooding and Pseudo-static Loading in a Geotechnical Centrifuge

The response of the soil model at Ng in a geotechnical centrifuge depend upon identical stress fields attained for both model and prototype (Madabhushi 2014). For this, appropriate scaling laws are developed using set of governing differential equations or dimensional analysis (Langhaar 1951). Table 2.1 summarizes pertinent scaling laws for modelling flooding and pseudo-static loading in a geotechnical centrifuge.



(*a*) During pseudostatic condition (in-situ)
(*b*) During tilting condition

Fig. 2.1. Earthen dam section under inertial loading (after Kumar and Viswanadham, 2022)

Pseudo-static loading is characterized by seismic coefficients and pseudo-static forces. In the present study, the centrifuge model is subjected to a tilting angle (α°) to simulate the pseudo-static condition, as depicted in Fig 2.1b. Its scale factor is considered unity. Further, flooding or rising of water towards the upstream side in an earthen dam in a geotechnical centrifuge at high gravities leads to changes in total stresses and hydraulic boundary conditions, having transient nature and affects the performance of the model. At the onset of flooding, several parameters viz. coefficient of permeability of the soil (k), discharge through the soil (Q), seepage velocity (v_s), seepage time (t_s), porewater pressure (u), upstream water head (h_F) or high flood level (HFL), duration of water rising (t_F), and water rising rate (R_f) play an important part in comprehending the seepage phenomenon inside earthen dams (Saran and Viswanadham 2018, Kumar and Viswanadham 2022).

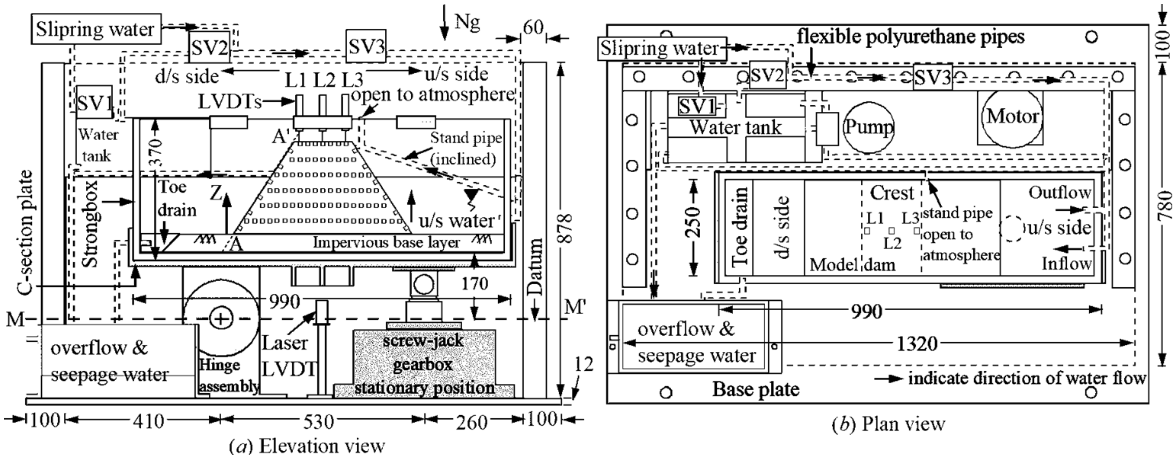
Table 2.1. Summary of scaling laws used in the present study

Parameters	Units	Prototype	Model
		Tilting parameters	
Tilting angle (α)	Degree (°)	1	1
Pseudo-static coefficient	-[a]	1	1
Pseudo-static force (F_H)	kN	1	$1/N^2$
		Flooding parameters	
Upstream water head (h_F)	m	1	1/N
Duration of water rising	day	1	$1/N^2$
Rising rate (R_F)	m/day	1	N
		Seepage parameters	
Porewater pressure (u)	kN/m^2	1	1
Seepage time (t_s)	sec	1	$1/N^2$
Coeff. of permeability (k)	m/sec	1	N
Seepage velocity (v_s)	m/sec	1	N

Note: N is scale factor or g-level attained in centrifuge experiment; -

2.3.3 Various Components and Operating Procedure of the Developed Setup

As shown schematically in Fig. 2.2a, the developed setup is primarily made up of a screw-jack, a two-stage helical gear train system, a hinge assembly, and a C-section plate. Machine design handbooks like Shigley and Mischke (1996) documents the procedure adopted for the setup design. A key design parameter is the amount of torque needed for the screw to overcome friction and raise and lower the design load.



(*a*) Elevation view

(*b*) Plan view

Fig. 2.2. Details of model test package (After Kumar and Viswanadham, 2022)

To facilitate vertical motion and smooth translation of the C-section plate, and load distribution to the screw, a swivel joint including a clevis joint, a pin, and four sets of linear needle roller bearings are provided at the screw head. The helical gear train assembly is powered by a permanent magnet direct current motor, which produces high torque for lifting the screw at high gravity (Kumar and Viswanadham 2022). For soil model construction, an Aluminum container with internal dimensions of 950 mm × 250 mm × 350 mm and a front wall of 20 mm thick Perspex sheet is used. The container is placed on a C-section type base supported by hinge assembly at one end and a screw-jack on the other, like a uniformly loaded overhang beam. An axial pump is used for pumping water at the desired rate. A reservoir tank situated at the rear serves as a water source for the pump (Fig. 2.2b). The operation of the motor and pump is facilitated by a relay arrangement. A digital camera records the experimental observations by capturing one photo every 5 sec. The front wall of the container is illuminated with LED lights.

The developed setup is tested for the functionality of its components at normal and high gravity levels. A 4.5 m radius large beam geotechnical centrifuge at the National Geotechnical Centrifuge Facility, Indian Institute of Technology Bombay, India, is used for centrifuge model tests. During the tilting stage, water is fed directly to the upstream side of the centrifuge model through sliprings. The input voltage (V_{in}) to the motor and the pump can be facilitated from the control room. The tilting angle is measured with a laser LVDT placed beneath the C-section plate. Calibration tests indicate that the inclination (α) varies linearly with the tilting duration (t_α) and V_{in}. The tilting rate varies between 0.2°/min to 0.8°/min depending on the motor V_{in}. The variation of water head on the upstream is observed to vary from 0.01 mm/min to 0.06 mm/min (model dimensions), non-linear variation due to the shape of the reservoir.

2.4 Salient Characteristics of the Developed Setup

The setup can be operated remotely during in-flight conditions (maximum 60g) while being robust and versatile. It can induce a maximum K_H of 0.36 (≈ tilting of 20°) at tilting rates between 0.2°/min to 0.8°/min analogous to experiencing low to high seismicity in-situ. The lightweight Aluminum container for housing the soil models can accommodate gentle slopes (1V:1.5H and 1V:2H) in both sides of a dam. The setup is secured with an external strong box with extension walls to protect from outside interference while in-flight. These features also make the setup of the largest tilting table developed to date for centrifuge-based studies. The setup can simulate upstream filling, steady-state seepage, and drawdown conditions simultaneously with the pseudo-static condition at user-controlled rates by adjusting the input voltage. The setup is equipped with a camera assembly that rotates with the centrifuge model upon tilting. As a result, the digital camera is always in a stationary position with respect to the centrifuge model, making it possible to capture any small instability signature in the model. Further, the setup is useful in studying the behaviour of geotechnical structures on inclined plane or natural hill, for soil-geosynthetic interface studies, and for inducing eccentric loads like that in buried pipelines.

2.5 Centrifuge Model Tests on Earthen Dam Section

To evaluate the effectiveness of the developed setup, a series of centrifuge model tests on earthen dams (with and without internal drain) were carried out at 30g. The earthen dam model had a height (H) of 240 mm (7.2 m), a top width of 150 mm (4.5 m), side slope inclinations of 45° (1H:1V) and was supported by an impermeable firm base layer that was 50 mm (1.5 m) thick, as shown schematically in Fig 2.3. The earthen dam model without drainage provisions has a factor of safety just above one (numerically) close to the HFL condition, so 30g was chosen.

2.5.1 Model Preparation and Test Procedure

The soil used to construct the shell zone of the earthen dam resembles silty sand material available locally in most parts of India. The model material has 20% fines content and a coefficient of permeability of 1.54×10-6 m/sec. The maximum dry unit weight ($\gamma_{d,max}$) of 19.75 kN/m^3 and optimum moisture content (OMC) of 7.5% (standard Proctor compaction). The effective cohesion (c') and angle of internal friction (ϕ') for the soil are 8 kPa and 33° obtained by conducting consolidated-undrained triaxial compression tests. The horizontal drains are made of fine sand having coefficient of permeability of 1.5×10-4 m/s (at a relative density of 85%). The internal friction angle from the direct shear test was observed as 33° with zero cohesion. The Aluminum container mentioned earlier was used for model preparation and subsequent testing. A rectangular grid of permanent markers was pasted firmly at regular intervals to serve as reference points during digital image analysis (DIA). A thin film of white petroleum grease was applied on the inner sides to minimize friction between the walls and model material. Thin polyethylene sheets strips were used to simulate plane-strain conditions. Four centrifuge model tests on homogeneous earthen dam were conducted with the developed setup. Model TD1 had no provision for seepage control (or fully clogged horizontal drain), whereas models TD2, TD3 and TD4 were provided with horizontal drain, having normalized lengths (L_d/H) of 0.5, 1.31, and 1.31, respectively and normalized thicknesses (t_d/H) of 0.083, 0.083, and 0.125, respectively.

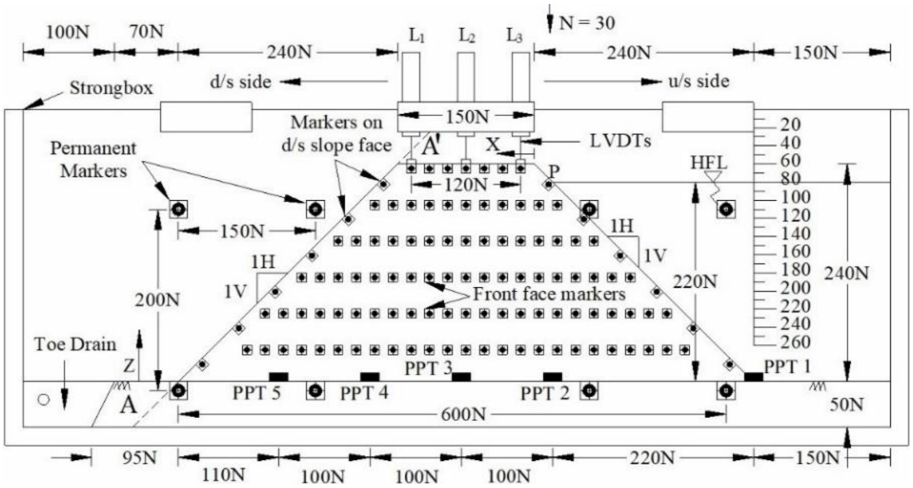


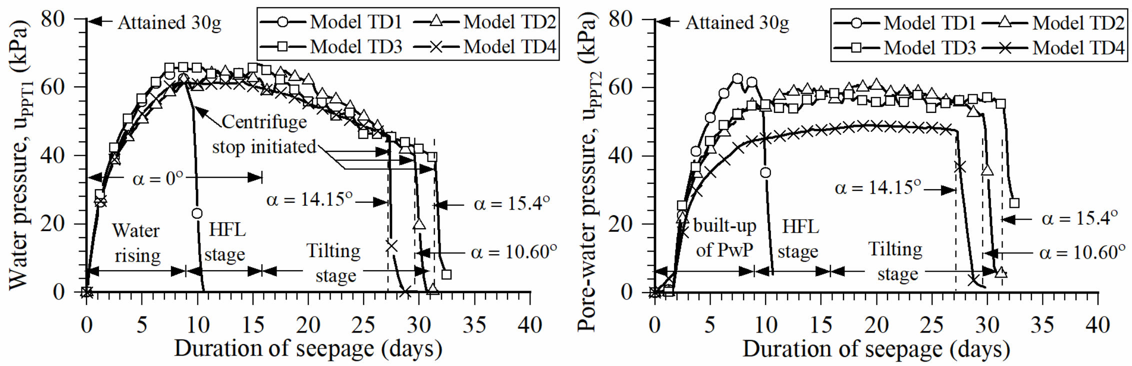
Fig. 2.3. Cross-sectional details of earthen dam model

After compaction of the impermeable base layer, five pore pressure transducers (PPTs) were placed such that PPT 1 monitors the development of upstream head and other PPTs records the porewater pressures within the shell zone. The models were constructed in six equal layers of 40 mm thickness with the soil moist-compacted at $\gamma_{d,max}$ and OMC. The horizontal drain was constructed by raining dry sand at 85% relative density. Further, L-shaped plastic markers (20×10 mm) were embedded after each soil layer within front elevation and along the slope faces to determine relative displacements with respect to permanent markers. After completion, the Aluminum container was placed firmly on the C-section plate. The linear variable differential transformers (LVDTs) were mounted on fixtures placed along the container width to register surface settlements (L1: at crest towards the downstream side, L2: at middle, and L3: at crest towards the upstream side). Finally, the test package was mounted on the swing basket of the centrifuge, and necessary connections were established.

After reaching 30g and establishing stable equilibrium conditions, the pump was activated at V_{in} of 18 V. Development of upstream head was monitored and high flood level (HFL $\approx$ 0.9H) was maintained. The steady-state seepage condition was maintained for a minimum of 5 minutes (in model dimensions) and the pump was stopped by reducing the V_{in} to zero. After this, model was subjected to tilting by operating the motor at V_{in} of 18 V. HFL was maintained by the constant water supply through the slip ring (Fig. 2.2b). The centrifuge was stopped as soon significant distress was observed or $\alpha = 20°$ was attained, whichever occurs earlier. The model test package was then brought to 1g by stopping the centrifuge followed by a thorough post-test examination. The analyses and interpretation of the earthen dam model centrifuge test results are provided in the following sections.

2.5.2 Development of Upstream Head and Porewater Pressure

Fig 2.4a shows the development of the upstream water pressure with seepage time (in prototype dimensions) for earthen dam models TD1, TD2, TD3, and TD4. It is observed that the water pump could induce flooding varying from 0.5 m/day to 2.5 m/day (prototype dimensions) at a constant input voltage of 18 V at 30g. Further, repeatability of the development of water pressure on the upstream side could be registered with good reproducibility till three days in all the centrifuge models; thereafter, minor variation is attributed to seepage owing to the presence of horizontal drainage layer towards the downstream side. The maximum operating reservoir level (or high flood level) was attained after seepage time of 7.24 days, 8.53 days, 7.5 days, and 7.7 days for Models TD1, TD2, TD3 and TD4, respectively. As can be seen from Fig 2.4a, the HFL stage was maintained for a minimum of 5 days, ensuring steady-state seepage conditions at the onset of tilting ($\alpha = 0°$) and during the tilting stage.



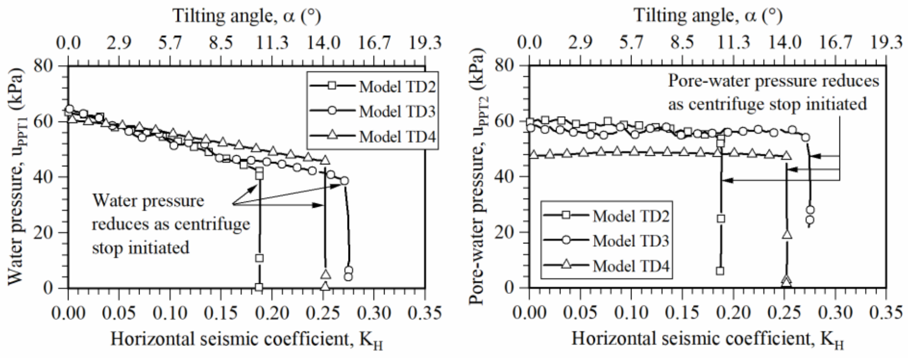
(a) Upstream water pressure v/s duration of seepage (b) Pore-water pressure, u_{PPT2} v/s duration of seepage

Fig. 2.4. Variation of porewater pressure with seepage time

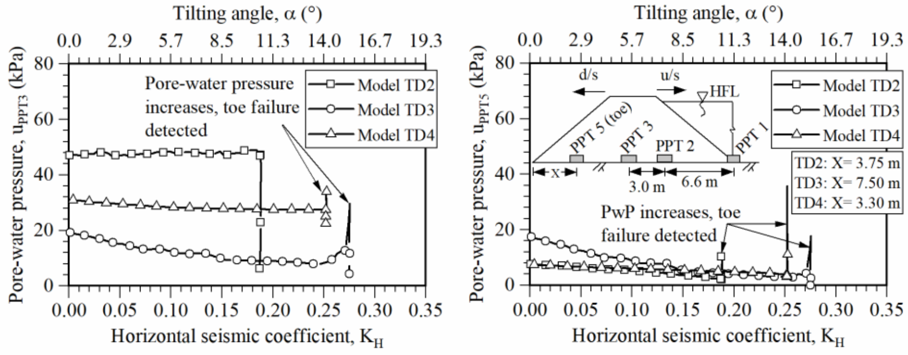
Fig 2.4b depicts the variation of pore pressure at entry point P with seepage time for all earthen dam models. The development of upstream water head and porewater pressures were in tandem. For the earthen dam model having clogged drain (model TD1), the centrifuge test was terminated after attaining the HFL due to excess porewater pressure buildup and localized sloughing at the downstream toe. The downstream slope failed catastrophically at HFL at the end of nine days of seepage. Contrary to this, the earthen dam models TD2, TD3, and TD4 with horizontal drain were stable during HFL, and steady-state seepage conditions continued up to 18 days, 16 days, and 14.5 days of seepage, respectively. The maximum pore pressure registered by downstream side PPT for model TD1 was 30.48 kPa, which is attributable to a fully clogged drain, but was lowered by five times in other models due to the presence of horizontal drain. Additionally, the horizontal drain led to reduction in the porewater pressure at the entry point P (PPT 2). The average porewater pressures registered by PPT 2 after attaining and during the HFL condition ($\alpha = 0°$) were 58.5 kPa, 58.4 kPa, and 46.9 kPa for models TD2, TD3, and TD4, respectively. During this stage, negligible surface settlements were registered in all the models. More details about the porewater pressure variation in the earthen dam body are available in Kumar and Viswanadham (2022).

2.5.3 Variation of Porewater Pressure During Tilting

After ensuring steady-state seepage conditions, the earthen dam models TD2, TD3, and TD4 with horizontal drain were subjected to tilting at a constant rate of 0.7°/min up to failure. Figs 2.5a-2.5d present the variation of porewater pressures with tilting angle and horizontal seismic coefficient. As evident by the horizontal variation of the recorded porewater pressures, the steady-state seepage condition was maintained even during the tilting stage. The differential porewater pressure measured by PPT 2, PPT 3, and PPT 4 was within 5%. In the case of PPT 4 and PPT 5, a marginal decrease in porewater pressure was observed with the increasing tilting angle. This is attributed to the increased performance of the horizontal drain in dissipation of porewater pressure owing to its long length ($L_d/H = 1.31$). A sudden increase in the porewater pressure near the downstream slope (u_{PPT5}) was observed at $\alpha_{max} = 10.60°$ for the earthen dam model with horizontal drain having $L_d/H = 0.5$ and $t_d/H = 0.083$ (Model: TD2), followed by failure of the slope towards the downstream side. A catastrophic reduction in the water pressure on the upstream side and the porewater pressures at point P and below the crest was also observed, indicating failure of the downstream slope. Similarly, for model TD3, the downstream slope failed at $\alpha_{max} = 15.40°$. This is attributed to a horizontal drain with $L_d/H = 1.31$ in model TD3. Whereas model TD4 (with thicker horizontal drain) witnessed failure of the downstream slope at $\alpha_{max} = 14.15°$.



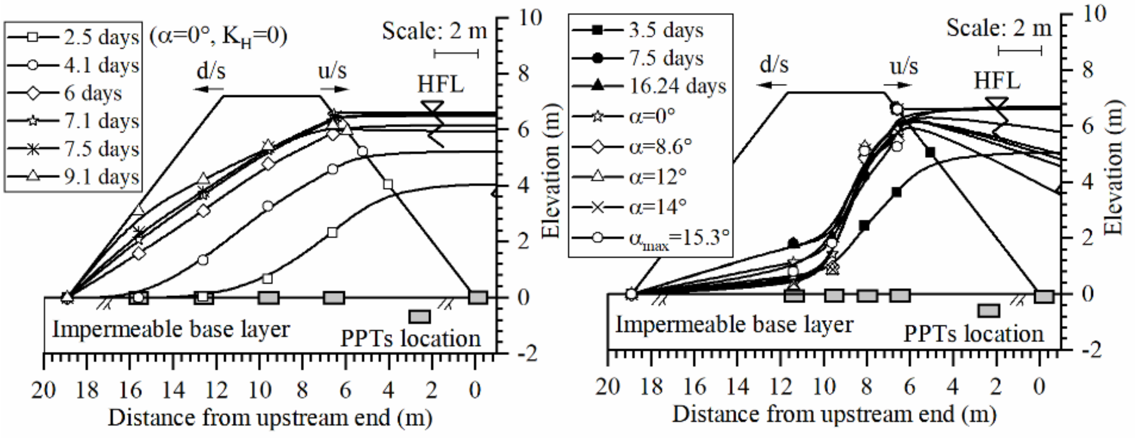
(a) Upstream water pressure v/s seismic coefficient K_H (b) Pore-water pressure, u_{PPT2} v/s seismic coefficient K_H



(c) Pore-water pressure, u_{PPT3} v/s seismic coefficient K_H (d) Pore-water pressure, u_{PPT5} v/s seismic coefficient K_H

Fig. 2.5. Variation of porewater pressure with tilting

Figs 2.6a-2.6b show the variation of phreatic surfaces for models TD1 and TD3. The rise in phreatic surfaces during the filling stage was rapid for model TD1. After 5 to 6 days of seepage, the phreatic surface intercepted the downstream slope face. The porewater pressure registered by downstream PPT ranged from 24 kPa to 30 kPa, just before HFL was reached. A horizontal drain decreased the excess porewater pressure inside the dam body for models TD2, TD3, and TD4. The phreatic surface shifted to the upstream side as the length of the horizontal drain increased. During the tilting stage, the elevation of the phreatic surfaces below crest and upstream slope remained unaffected. This also agrees with the pore water pressures recorded by PPTs. This implies that phreatic surfaces were contained well within the earthen dam body, demonstrating the significance of a horizontal drain in preventing seepage and ensuring long-term stability.



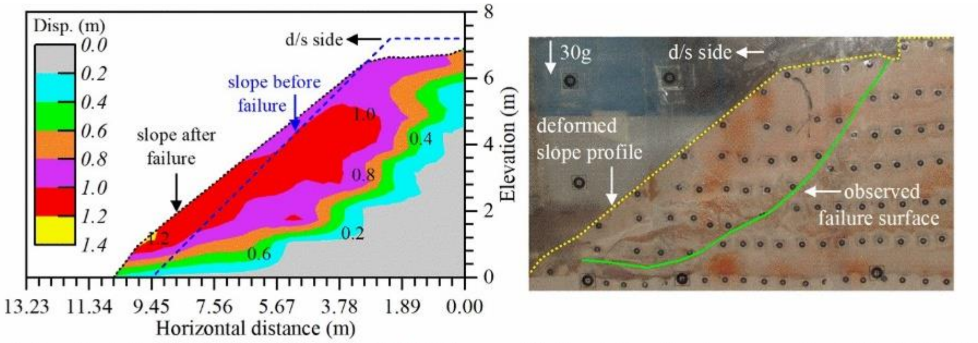
(*a*) Model TD1 (*b*) Model TD3

Fig. 2.6. Development of phreatic surfaces during various stages of centrifuge model test

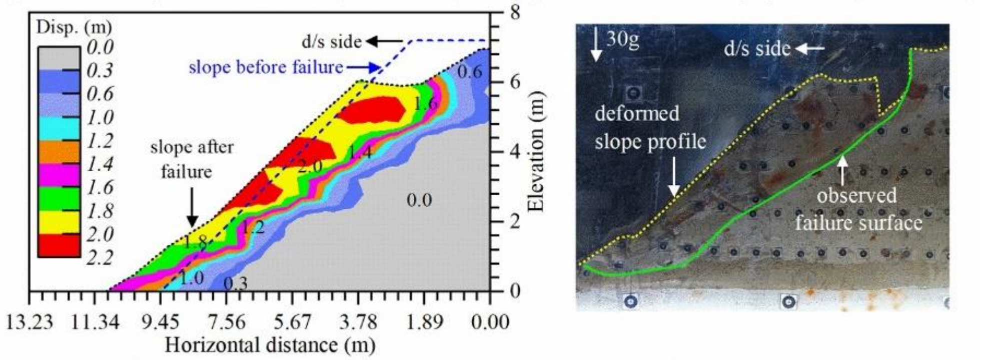
2.5.4 Digital Image Analysis of Centrifuge Models

The deformations due to seepage and/or tilting were deduced from DIA using Image-J software (Image J, 2012) at various intervals of seepage time and tilting angles. The high-resolution front elevation images of the earthen dam model that were taken while in flight at different loading stages served as the input for DIA. Figs 2.7a and 2.7c depict the resultant displacement contours for models TD2 and TD4. The relative displacements were obtained for computing face movements and surface settlements. The coordinates of markers before the onset of filling serve as reference points for relative movements. At the onset of tilting, the model experienced high porewater pressure development and softening of the slope near the toe region towards the downstream side, resulting in sudden movement and global failure, as shown in Figs. 2.7a and 2.7b. The slip surface was observed to originate from the toe towards the downstream side and progressed towards the crest of an earthen dam (Figs. 2.7b and 2.7d). The maximum crest surface settlement recorded for model TD1 was 0.03 m at the end of 8.6 days of seepage. The maximum surface settlement of 0.69 m for Model TD2, 1.46 m for Model TD3, and 1.2 m for Model TD4 was registered. The data recorded by LVDTs agree with the DIA, registered porewater pressures and phreatic surfaces.

As the tilting progressed, for some value of K_H, the available resisting force along the failure plane of the sliding mass equals the pseudo-static driving force (Fig. 2.1b), resulting in a factor of safety of unity. The minimum K_H that corresponds to the pseudo-static factor of safety of unity is called the yield coefficient ($K_{H\ yield}$), and the tilting angle is referred as the tilting angle at yield (α_{yield}) (Jibson 2011).



(a) Resultant displacement contour (Model:TD2) (b) Front elevation image post-test (Model:TD2)



(c) Resultant displacement contour (Model:TD4) (d) Front elevation image post-test (Model:TD4)

Fig. 2.7. Digital image analysis results obtained for the penultimate stages of the centrifuge tests.

The onset of yielding is indicated by visible signs of distress at the crest and along the slope face. Likewise, $K_{H\ max}$, corresponds to the global stability failure of the slope on the downstream side of the earthen dam, beyond which centrifuge test is terminated. For centrifuge models subjected to pseudo-static loading the following were deduced,

$K_{H\ yield}$ = 0.12 for model TD2, $K_{H\ yield}$ = 0.18 for model TD3, and $K_{H\ yield}$ = 0.21 for model TD4, respectively. The centrifuge models failed when subjected to $K_{H\ max}$ = 0.18 for model TD2, $K_{H\ max}$ = 0.27 for model TD3, and $K_{H\ max}$ = 0.25 for model TD4, respectively.

2.6 Conclusions

In the present study the details about the design and development of an in-flight setup for simulating flooding and pseudo-static loading conditions for use in a geotechnical centrifuge is presented. Further, an attempt has been made to investigate an earthen dam's response when subjected to flooding and tilting operations through centrifuge model tests. As observed, the developed setup can simulate seepage and pseudo-static conditions for an earthen dam. It could ensure a flood rate of 0.01 mm/min to 0.06 mm/min (model dimensions) and tilting rate of 0.2°/min to 0.8°/min. The centrifuge model test on the earthen dam having a fully clogged drain witnessed slope failure before high flood level. The porewater pressure of more than 20 kPa was registered near the downstream toe and downstream slope face movement greater than 1 m. When the earthen dam has provision for a horizontal drain, the models were stable during filling stage with insignificant deformations. The development of pore pressure within the dam shell zone was per the upstream head. Compared to a fully clogged drain model, porewater pressures registered within the earthen dam body with horizontal drain were lower in magnitude. The horizontal drain also ensured containment of phreatic surfaces well within the dam body. During pseudo-static loading stage, the earthen dam models with horizontal drain witnessed face movements post $K_{H\ yield}$, and slope failure at $K_{H\ max}$. With the increase in the drain length, the porewater pressure within the dam section lowered. An increase in the horizontal drain thickness increased the risk of slope failure. It can be concluded that the developed setup can effectively model flooding and inertial loading conditions in earthen dam and similar structures in a geotechnical centrifuge environment.

2.7 Acknowledgements

The authors acknowledge the support during model testing from the members and staff of the NGCF at IIT Bombay. The authors also acknowledge the financial support received for the present study vide grant no. 36(2)/15/07/2016-BRNS/36007 from BRNS, Mumbai, India.

Conflict of interest: The authors declare that they have no conflict of interest.

Data Availability: The data will be made available on request.

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3 TC 105 Geo-Mechanics from Micro to Macro

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3.1 Abstract

This document is being submitted to the Indian Geotechnical Journal to provide an overview of the activities and outcomes of TC105-Geo-Mechanics from Micro to Macro. Micro to macro is an emerging new field of Geotechnical Engineering and the researchers from India have significantly contributed to the development and evolution of this area in recent years. This time capsule document provides the details of the history and evolution of TC105, milestones of the activities, with a specific focus on the research contributions of the Indian members of TC105 and provides the vision of the committee members from India

3.2 Introduction

Multi-scale understanding of engineering processes in geomaterials was ignored for several years by the researchers. Intrinsic heterogeneity, natural processes responsible for their formation and unique physical, mechanical, and topographical features of geomaterials are responsible for their multi-scale interactions among themselves and with other materials in contact. These interactions are responsible for the evolution of their response from microscale to macroscale – from asperities to grains, from force chains to shear bands, and from element tests to prototype applications. Knowledge of fundamental mechanisms at finer scales is imperative for all fields of geotechnical engineering to explain the failures or improve the overall response. Hence a separate Technical Committee (TC) on Micro to Macro of Geomechanics was conceived and formed by the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE).

The conceptualization of Geo-Mechanics from micro is closely related to the musings of Karl Terzaghi (1920):

"Coulomb purposely ignored the fact that sand consists of individual grains. Coulomb's idea proved very useful as a working hypothesis, but it developed into an obstacle against further progress as soon as its hypothetical character came to be forgotten by Coulomb's successors… The way out of the difficulty lies in dropping the old fundamental principles and starting again from the elementary fact that sand consists of individual grains."

TC105 of ISSMGE is an international technical committee under the category of fundamentals. The committee was formed during the 15th ICSMGE organized in Istanbul in 2001, which was initially TC35 and currently TC105, to fundamental research on the behavior of geomaterials at multiple scales. The committee aims at studies carried out with measurements at micro scale, to explain the behaviour of geomaterials at a macroscale. The knowledge of the microscopic mechanisms responsible for the response of these materials at bigger scales provides evidence to the fundamental scientific interpretations of geotechnical engineering, while throwing light on the ways to improve the response by considering these mechanisms. Hence the field of micro to macro has received a lot of attention and spread quickly into all fields of geomechanics. The major advances in experimental, digital and computational tools have brought revolutionary progress to the micro to macro research along with growing awareness towards the need for integrating different scales while understanding and explaining the geomechanical processes.

3.2.1 The objectives of TC105 are listed below.

- To promote co-operation and exchange of information about the behaviour of soil particles (clays to gravels) and the interactions among themselves and with pore fluids (air, water and other liquids).
- To clarify the fundamental micro-mechanisms of macroscopic soil behavior.
- To encourage microscopic particle-scale understanding of significant macroscopic behaviours of gravel, sand, clay and their mixtures, such as compressibility, anisotropy, yielding, creep, cyclic liquefaction, shear failure and tensile fracture.
- To promote discussions on the use of micro-scale measurements and simulations to enhance soil characterization procedures (grading, plasticity index, CPT / SPT etc) and to clarify the selection and use of continuum parameters in geotechnical engineering practice.
- To promote better practice of Discrete Element Modelling (DEM) of soil aggregates, through simulations of laboratory tests and round-robin tests.
- Encourage preparation of keynote lectures, state-of-the-art lectures including new technology, round robin tests, blogs, general reports for conferences organized by the International Society, regional conferences and conferences organized by Member societies.
- Interact with industry and overlapping organizations working in areas related to the TCs specialist area: - ASCE Granular Materials committee - ALERT (Europe) - GM3 (UK) - National research group - Korean Geotechnical Society - National research group - Chinese Geotechnical Society - National research group - Japanese Geotechnical Society
- The present TC105 has 73 members from different countries, including Kenichi Soga (Chair), Mingjing Jiang (Vice-Chair) and Yukio Nakata (Secretary). India is represented by its four members, Gali Madhavi Latha (nominated member), Arghya Das (nominated member), Prashanth Vangla (corresponding member) and Tarun Naskar (Corresponding member).

3.3 Milestones of TC105-Geo-Mechanics from Micro to Macro

The TC105 was formed in 2001. Milestones of the committee are outlined as follows.

2000-2020:

The committee organized focused quadrennial international conferences in the years 2006 in Yamaguchi, 2010 in Shanghai, 2014 in Cambridge, 2018 in Atlanta. Furthermore, a themed issue for Géotechnique (entitled "Soil mechanics at the grain scale") appeared in 2010, followed by a themed issue for Géotechnique Letters (entitled "Geomechanics across the scales") in 2012. A TC105 special session was organized during the China-Europe Conference on Geotechnical Engineering during Aug 13-16, 2018 in Vienna, Austria.

A day-long Mini-Symposium on "Geo-mechanics from Micro to Macro" was held on December 12, 2019, in IIT Mandi, India. The symposium was jointly organized by the Technical Committee (TC105) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) and ICCMS-2019 in collaboration with IGS-Bangalore Chapter and ITASCA Consulting Group, Inc. The symposium was chaired jointly by the then Indian members of TC 105, Dr. Mousumi Mukherjee of IIT Mandi and Dr. Arghya Das of IIT Kanpur. A total of 7 invited lectures and 4 contributory papers were delivered. Prof. Amit Prashant of IIT Gandhinagar delivered the inaugural lecture on the topic, "Macro to Micro Insights on Instabilities: Across 'Length-scales' in Granular Media." Prof. Prashant Vangla (IIT Delhi), Prof. Anurag Tripathi (IIT Kanpur), Prof. Arghya Deb (IIT Kharagpur), Prof. Tejas G Murthy (IISc Bangalore), Prof. Arghya Das (IIT Kanpur), and Dr. Jay Aglawe (ITASCA) delivered invited lectures on experimental, numerical and theoretical aspects of micro-mechanics based research. The lectures encompass topics like discrete element modelling of cemented granular rocks and concrete, application of image analysis for examining sand-geosynthetic interface, experimental studies on weakly cemented sand, calibration of micro parameters, and through nano-pores, etc. Besides the invited lectures, the contributory talks also cover diverse topics like anisotropy in granular materials, particle shape effects, molecular dynamics, and particle breakage.

TC105 organized a workshop on "Emerging Scales in Granular Media" in Hong Kong, during 14-16 January 2020.

2020-Present:

In 2022, TC105 organized five webinars on "Discrete Element Method (DEM) in geotechnical engineering education". The video links for the lectures are given below.

Lecture 1: Teaching granular mechanics with Discrete Element Method
Francois Guillard and Benjy Marks (University of Sydney)
Youtube link - https://youtu.be/D6TRok1s_4g

Lecture 2: Virtual laboratory testing using DEM to understand soil behaviour
Benjy Marks and Francois Guillard (University of Sydney)
Youtube link - https://youtu.be/YwmGq7Rc5fA

Lecture 3: Let's code the discrete element method for a deeper understanding
Vincent Richefeu (Université Grenoble Alpes)
Youtube link - https://youtu.be/n7NWEpIKbJE

Lecture 4: Using open source DEM in teaching
Shiwei Zhao (Hong Kong University of Science and Technology)
Youtube link - https://youtu.be/i3odF7qU7kk

Lecture 5: Building a real-time interactive playground with in-situ viz and deep learning
Krishna Kumar (University of Texas, Austin)
Youtube link - https://youtu.be/1g_S5THxhvs

Several meetings of the committee were held online. An in-person meeting was held during the International Conference of Soil Mechanics and Geotechnical Engineering at Sydney in 2022.

With Madhavi Latha Gali from India as the lead guest editor, a special issue on “Digital Imaging Techniques Applied to Geosynthetics” is published in Geotextiles and Geomembranes in August 2023. This issue covered a wide variety of digital imaging techniques applied to geosynthetics, including X-ray computed tomography (CT), Digital Image Correlation (DIC), Particle Image Velocimetry (PIV), Scanning Electron Microscopy (SEM), and image segmentation in transparent soils (Latha and Mukunoki, 2023).

3.4 Key Challenges and Practices in TC 105

However, the progress and developments in this field are not accessible to the masses, particularly in India. The major challenges are the unavailable access to the microscopic measurements in experiments and modelling facilities, lack of training in using the central facilities in different sensing Departments of academic Institutes and unavailability of expertise for complex computational modelling.

With all the challenges in this field, a good amount of research related to micro to macro was published from India during the last decade. A few important studies published in the last five years can be categorized into the following three groups:

Micromechanical characterizations:
Khan and Latha (2023), Matsumura et al. (2023), Kandpal and Vangla (2023), Singh et al. (2023), Anusree and Latha (2023), Gayathri et al. (2022), Hegde and Murthy (2022), Singh and Murthy (2022), Pandey et al. (2022), Sarate et al. (2022), Roy et al. (2021), Prashant et al. (2010), Vangla et al. (2018)

Application of digital image analysis in micro to macro:
Lakkimsetti and Latha (2023a, 2023b, 2023c, 2023d), Jayanandan and Viswanadham (2023), Venkateswarlu et al. (2023a, 2023b), Pillai and Latha (2023), Selvam et al. (2023), Latha and Lakkimsetti (2022b), Chaduvula et al. (2022), Pillai and Latha (2022a, 2022b, 2023a, 2023b), Naskar and Kumar (2022), Kundu and Viswanadham (2021), Tiwari et al. (2020, 2021), Bhattacharya and Prashant (2020, 2021), Yadav et al. (2018)

Computational models:
Das and Barma (2023), Mufti and Das (2023a, 2023b), Iyer et al. (2023), Bhaumik and Naskar (2023), Kalyan and Kandasami (2023), Alam et al. (2022), Mufti and Das (2022), Das et al. (2022), Das and Das (2022), Bisht and Das (2021), Bhattacharya et al. (2021), Mukherjee et al. (2021), Naiyyalga and Mukherjee (2021), Kumar and Das (2019), Naskar and Kumar (2019), Sisodiya and Das (2018).

3.5 Way Forward

To improve the awareness on the importance and advantages of micro to macro studies, TC105 is committed to conduct various activities to disseminate the knowledge on this field. The committee will work towards these ambitious objectives. Developing models capable of integrating information at multiple scales is the need of the hour, for which TC105 will provide a forum for synergistic collaborations and active interactions.

3.6 Remarks

As it is well established that all fields of geotechnical engineering can gain much from an accurate understanding of the mechanisms at finer scales, networking people working in this field and promoting active collaborations can help in spreading the footprint of this important domain and in applying the knowledge to practice.

3.7 Disclosure Statement

This is a time capsule document and there is nothing to disclose.

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4 TC 106 Unsaturated Soils

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4.1 Introduction

Sustainability of geostructures is one of the major concerns in the field of geotechnical engineering. Recurring evaluation and maintenance related to geotechnical infrastructure can often lead to faulty decisions due to errors in analysis. Terzaghi's [1] effective stress equation not only provided a rational framework for explaining the mechanical behavior of saturated soils but was also used as a tool in the design of various geostructures. Inspired by Terzaghi's work, Bishop [2] has put forward the effective stress equation for explaining the behavior of the unsaturated soil, which is more widely distributed over many regions in the world. Since then, there has been significant research interest all over the world towards better understanding the behavior of unsaturated soil. However, the focus of most of these studies was directed towards understanding the hydraulic and mechanical properties of unsaturated soils. These studies and other recent innovations are used as tools in the design of several geotechnical and geo-environmental infrastructures which include pavements, foundations/ earthworks, retaining walls, waste containment facilities to list a few. The concepts of unsaturated soils are also being extensively used in societal relevant projects like agriculture, forestry, ecological practices, bioengineering, and reversing land degradation.

4.2 Milestones in TC106

1960-1980:

The basic principles related to the understanding of unsaturated soil mechanics were formulated mainly in 1970-80. Prior to that, most of the attention was given to unsaturated soil related to capillary flow, leading to the development of capillary tube rise model. Terzaghi [1] revealed the importance of air-water interface in assessing the behavior of soils. These research works acted as a catalyst for the development of principles and practices in unsaturated soils. The need for the development of unsaturated soil mechanics was strengthened when the strength and deformation response of expansive soils were not able to be captured with the help of traditional saturated soil mechanics principles. Several eminent researchers from India have contributed to understanding the deformation response of expansive soils.

1980-2000:

In the year 1987, India hosted Sixth International Conference on Expansive Soils. Several research works on partially saturated soils were presented. Most of the research works were focused on volume change and the shear strength of expansive soils. However, from 1990, focus shifted to the determination and estimation of soil suction and unsaturated shear strength of soil at various geoenvironmental conditions [3-4]. Laboratory studies reported during this period revealed fundamental differences between the response of saturated and unsaturated soils [3]. Later, research focus got diverted towards obtaining unsaturated material property functions from conventional geotechnical index property tests. In parallel, methodology for measuring soil suction, and the development of soil water characteristics curve (SWCC) of soils were standardized. Debate on adopting either independent or dependent stress state variables in describing the phenomenon were exchanged. A book on "Soil mechanics for unsaturated soils" by Fredlund and

Rahardjo [3] provided a deep insight into unsaturated soil concepts, which has motivated several budding researchers to work on unsaturated soils.

2000-2020:

The development of numerical modelling of saturated and unsaturated soils leading to a better prediction of the response of geostructures was witnessed during this period due to the growing computing power of computers. Several researchers from India have contributed to establish the thermal and electrical properties of soils, SWCC/SWRC of challenging soils, numerical models for predicting heave of expansive soils using unsaturated material parameters, shear strength of compacted soils, effect of adsorption, diffusion and dispersion behavior of chemicals in unsaturated soils [5-12]. Special emphasis was placed on hydro-mechanical behavior of unsaturated soils, especially for landfill and mining applications. Few institutions in India have developed a postgraduate level course on unsaturated soils, thereby students were exposed to both saturated and unsaturated soil mechanics concepts to handle complex field problems [13].

2020-Present”:

Several researchers from India are contributing to establish the thermo-chemo-hydro-mechanical behavior of unsaturated soils, especially for the analysis and design of hazardous waste disposal, solid waste disposal using engineered landfill, ash tailing, mining applications etc. Addressing the hydraulic and gas flow transfer mechanisms through porous media is also gaining importance to tackle various geoenvironmental issues and challenges [15-16]. Attempts are also being made to adopt concepts and framework of unsaturated soil in the analysis and the design of geostructures [17-20]. Recently, a workshop on the “Relevance of unsaturated soil mechanics in practice” was organized by TC 106 (India) in association with Indian Geotechnical Conference 2021 on 15 Dec 2021 (online). Several eminent Indian and International speakers working in the area of the TC-106 Theme were invited to deliver lectures, followed by Panel discussion highlighting the state-of-the-art research at present, practical relevance and way forward. The preconference workshop has attracted a huge audience and has ignited research interest in young minds.

4.3 Key Challenges and Practices in TC 106

With the recent advancement in multi-disciplinary research, unsaturated soil mechanics is becoming increasingly complex. The experimentation and numerical modelling schemes required to understand the response of unsaturated soils is becoming complex as the concepts were derived from several disciplines of engineering and science such as geotechnical engineering, geoenvironmental engineering, agricultural science, soil physics, and hydrology [21]. Such difficulties will delay engineers applying unsaturated soil mechanics in engineering practice [22]. There is also a need for a statistical framework to quantify the variability of the fitting parameters of unsaturated material property functions. Moreover, understanding the governing mechanism for rainfall-induced landslides requires concepts of unsaturated soil mechanics, which may later be used for the designing of early warning systems.

4.4 Way Forward

A standard protocol for various geotechnical engineering problems associated with unsaturated soil mechanics may need to be established for smooth transfer of knowledge from theory to laboratory to field. Establishing unsaturated soil mechanics as a course for graduate / post-graduate students in universities and colleges in India will strengthen the research in the domain of unsaturated soils. Simplified analytical formulations incorporating unsaturated soil mechanics principles may need to be developed and standardized for the analysis and design of geostructures. Such formulations will attract the use of unsaturated soil mechanics in routine geotechnical engineering practices. An efficient sensor design and installation approach for field monitoring of geostructures (pore pressure, water content, soil suction, pressure sensor, thermal sensors, etc) will optimize system reliability.

4.5 Remarks

The report was drafted as per the author's field of research. There is a need to involve other TC 106 members (served earlier and now) to attain comprehensive time capsule of TC 106 (Unsaturated soils)

4.6 Disclosure Statement

As the domain of research on unsaturated soils is vast, this report covers some of the scope of the unsaturated soil mechanics in the field of geotechnical engineering. Research work related to other scopes of unsaturated soil mechanics was not covered due to certain limitations.

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5 TC 107 Tropical Residual Soils

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5.1 Abstract

Residual soils are found in abundance in the tropics; mainly between the tropics of Cancer and Capricorn. These soils are extensively used as construction or foundation materials. In the tropical region, residual soils constitute major type of soils found. These soils are formed at the site and hence they vary in characteristic and behaviour as compared to transported or deposited soils. These soils remain in situ since they are formed due to rock weathering which predominates soil transport by the various natural agencies like wind, water, etc. These are formed because of natural weathering and their properties depend upon extent of weathering, parent rock, topography, drainage, and age. The challenges and practices of Engineering with tropical residual soils is presented in this article..

5.2 Introduction

Residual soils as the name suggest are formed from rock and remain in situ. The weathering process depends upon the environmental conditions in which soil is found. Formation of residual soils largely depends upon parent rock, climatic conditions, topography, vegetation, and time. The tropical high temperatures and humid conditions provide a favourable environment for heavy weathering. Hence, a thorough study of its nature is necessary. The unconsolidated upper cover is termed as regolith, which constitutes upper 0.3–2.0 m or more. The lower portion which progressively grades into the bedrock is known as saprolite (Bland and Rolls, 1998).

Figure 5.1 shows the geological rock cycle and how these residual soils are formed. The thickness of residual soils above the parent rock may vary up to 30m or even more, which depends upon the degree of weathering (Tan, 2004). The different horizons are visible due to leaching action of rainwater and precipitation of dissolved minerals in the lower layers. The parent rock can be granite, basalt, limestone, sandstone, schist and others. Identification of such parent rock sometimes becomes difficult for these soils which are formed many years ago and also in the case of higher degrees of weathering (Huat et al., 2012).

Lateritic soils found in various parts of India are the typical residual soils observed in India. Figure 5.2 shows the distribution of lateritic soils in India.

The time capsule presented here contains a brief overview of the genesis and characteristics of tropical residual soils. It presents some of the challenges in engineering practice with these soils. Possible future activities of TC 107 for improving the understanding about tropical residual soils and to have better engineering practices with these soils are suggested.

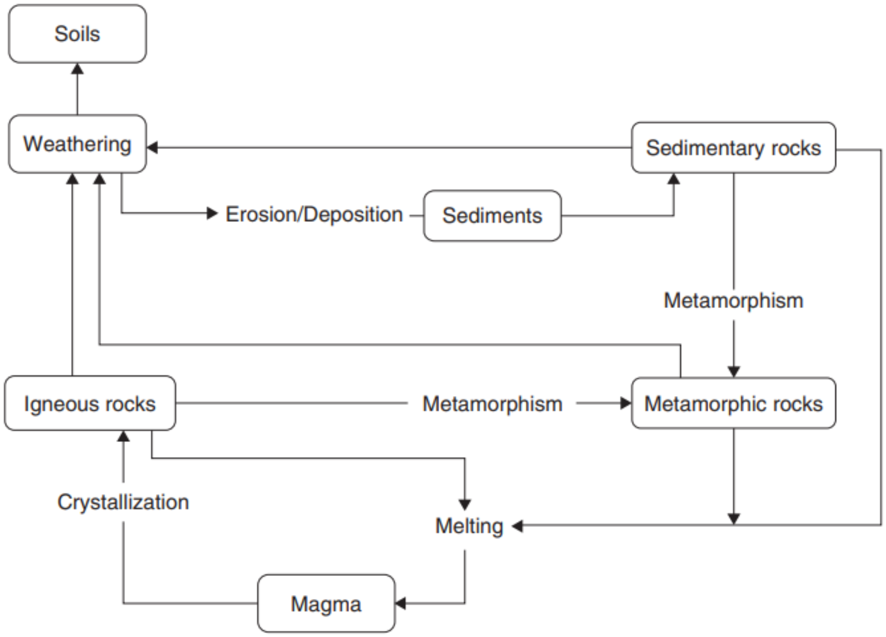

Fig 5.1: The geologic rock cycle and formation of residual soil.

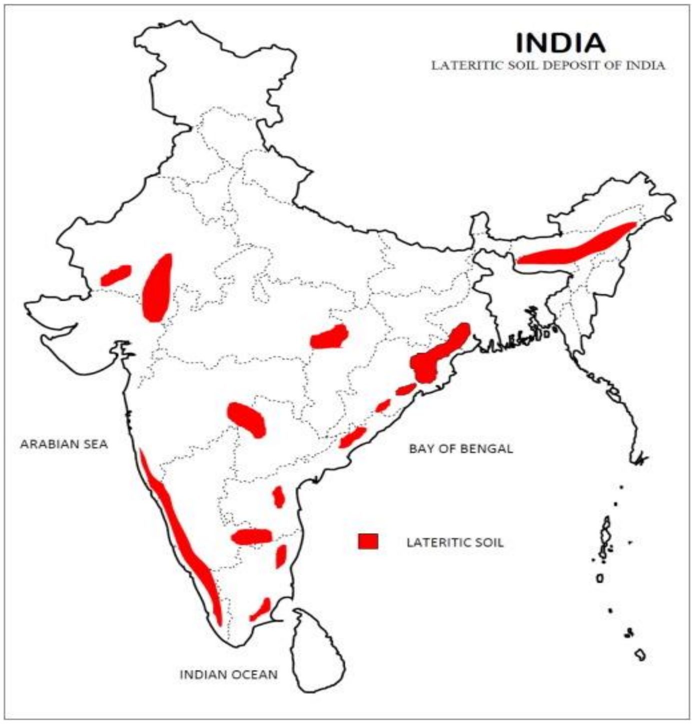

Fig. 5.2. Distribution of lateritic soils in India (www.ScienceDirect.com)

5.3 Milestones in TC 107 Tropical Residual Soils

Buchanan (1807) coined the term laterite, to describe ferruginous, vesicular, un-stratified and porous soil with yellow ochres due to high iron content in Malabar, India. Later in Latin means brick. Laterites occur in many parts on the globe such as Africa, South America, Arabian Peninsula and Australia. Lateritic soils contain iron and aluminum, formed in hot and humid tropical areas and are generally in rusty-red colour due to the presence of iron oxides.

Since ancient laterites were used for construction of monuments by cutting them in the form of bricks. After 1000 CE, construction at Angkor Wat and other south-east Asian sites changed to rectangular temple enclosures made of laterite, brick, and stone.

Field investigations in tropical region started in 1905 through the Soil Research Institute in Bogor, Indonesia. In 1910, Mohr divided the soils of Java in six groups based on a combination of parent material, temperature, moisture regime and stage of weathering (Dudal, 2003).

1950-1960: Initially, European soil scientists worked on the tropical soils using the available knowledge on temperate soils. Lateritic soils were termed as “Latosol” comprising of high degree of aggregate stability and low activity clays and oxides of iron and aluminium. The ferruginous (lateritic) gravel was termed as gravel layer in geological profile by the Belgian scientists in 1960, separating the layer of superficial deposits and the saprolite. The term "Plinthite" replaced "Laterite" to explain the iron-rich clay materials (Dudal, 2003).

1960-1980: During the period 1960 to 1970, the term laterite and lateritic soils was not in much use. Lateritic soils were then classified as Kaolisols, Ferralsols, Ferrisols. Soil maps of Africa were prepared in 1964 with lateritic soils as Ferrallitic soils, Ferrisols, Ferruginous tropical soils (D’Hoore, 1964). Later on in 1968, the soil units for the Soil Map of the World were defined with Ferralsols, Acrisols, Nitisols with Plinthic groups (Dudal, 1968). In mid 1970s, laterites were used as base course for lighter bitumen-surfaced roads. Deep lateritic layers which were generally porous and permeable were used as aquifers in rural areas. Phosphorus and heavy metals in sewage-treatment plants were removed by using lateritic rock in an acid solution, followed by precipitation.

1980-2000: Origin, formation and distribution of laterites in India were presented by Bruckner & Bruhn (1992) and Widdowson & Gunnell (1999). Sahasrabuddhe & Deshmukh (1981), Widdowson & Cox (1996), Widdowson (1997) classified the laterites with reference to western ghats where the basaltic rocks were classified as high level laterites and those between the coastal plateaux of outer Konkan and Kanara coastal plains as low level laterites. A typical weathering profile of laterites is shown in Fig. 5.3.

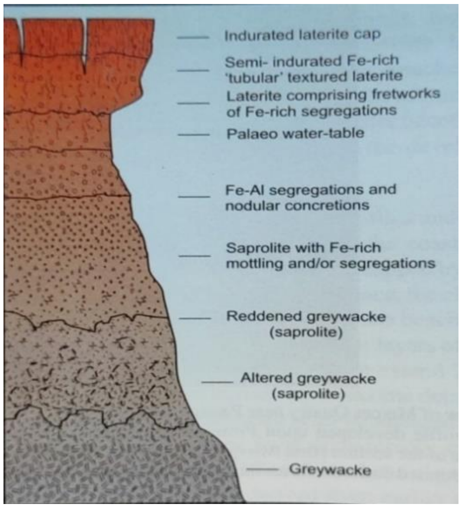

Fig. 5.3. Typical weathering profile of laterite (Widdowson, 2009)

2000-2020: During this period of time, the theme of TC-107 was Laterites and Lateritic Soil. This soil type is the major residual soil in the tropical areas. Typical mineral content of lateritic soils is depicted in Table 5.1.

Table 5.1. Typical mineral content of lateritic soils

Mineral	Sulawesi, Indonesia (Saing et al., 2018)	Tamshui (Andesite), Pingchen, Loupi, Sopa (Shale), Tungwei (Basalt), Taiwan (Ko, 2014)	SW Nigeria (Adebisi et al., 2013)	Kerala (Chandran et al., 2005)
Hematite	1-13 %	less		
Kaolinite	8-67 %	medium	52.3 – 75.5 %	medium
Illite	18-80 %	-	2.3 – 17.6 %	
Montmorillonite	1-11 %	-		
Rutile		-		
Magn. Sillicate	3-6 %	-		
Gibbsite		medium		more
Goethite		medium		
Quartz		more		more
Mica		more		more

Lateritic soils in many places were used as a rich source of aluminum and iron ores and sometimes the early major source of nickel. Lateritic soils are softer when wet and harder when dried. They are rich in iron and aluminium content and hence, mostly red in colour.

2020-Present: The theme of the TC-107 was changed to Tropical Residual Soils, which is a more generic term. Many workshops and symposiums on this topic are being organized by various members of TC-107 to disseminate knowledge about the engineering behaviour of tropical residual soils.

5.4 Key Challenges and Practices in TC-107 Tropical Residual Soils

Under temperate conditions (without extremes of temperature and precipitation), low chemical and soil forming activity continues up to the clay-forming stage. In tropics, where higher temperature and rainfall is observed, the clay minerals decompose into various forms of aluminous and iron oxides, depending on the extent of weathering. The behaviour of some lateritic soils is different from the conventional soil mechanics developed for temperate-zone soils. It is due to the free iron oxide content and the state of alumino-ferruginous complexes and the granular nature of lateritic soils.

The weathering action results in leaching of silica, formation of colloidal sesquioxide, precipitation of the oxides and dehydration in the case of higher weathering action on rocks. The parent rock containing primary feldspars, quartz, and ferromagnesian minerals gets converted to a porous clayey system containing kaolinite, sesquioxide, and residual quartz. The primary feldspars are transformed to kaolinite first which then gets converted to gibbsite. The primary ferromagnesian minerals are transformed to diffused goethite, well-crystallized goethite, and finally to hematite. The crystallization leads to the formation of iron and/or aluminium oxide concretions, coalescence of concretions and their cementation by iron and/or aluminium colloids.

Development of different minerals such as montmorillonite, kaolinite, goethite, hematite and ilmenite in lateritic soil depends on the climate, topography, vegetation, weathering condition and drainage system. Mineral kaolinite is found in lateritic soil when soil is formed from the parent rock which contains primary feldspars, quartz, and ferromagnesian minerals. The kaolinite content is higher in regions receiving small amount of annual rainfall in the range of 0.65 to 0.90m. With the increase in rainfall, the kaolinite content reduces. Presence of kaolinite as the clay mineral within the lateritic soil profiles results in relatively low plasticity. The increase in kaolinite results in higher cohesion while the friction angle increases with increasing sesquioxide content. Lateritic soil with high kaolinite content exhibits poor soil aggregation. Permeability of soil with montmorillonite as predominant clay mineral is less as compared to soil having illite and kaolinite minerals. Lateritic soil with montmorillonite as predominant mineral is highly plastic in nature having very high plastic limit, liquid limit and also high activity. Lateritic soil having goethite as predominant clay mineral has high specific gravity. Specific gravity of soil increases with increasing amount of goethite. Illite are intermediate between kaolinite and montmorillonite. Soils with illite are generally non-expansive type.

For designing engineering structures in tropical residual soils, the conventional principles of soil mechanics, which is developed for the soils in temperate zones, is still being followed today. The behavior of tropical residual soils is very different from that od temperate zone soils. This necessitates the development of new theories for tropical residual soils taking into account their chemical composition, morphology. Degree of hardening etc.

5.5 Way Forward

The members of TC-107 may initiate more research for gaining more understanding about the engineering behavior of tropical residual soils. They should be encouraged to organize technical workshops and seminars to disseminate the knowledge gained about the engineering behaviour of these soils. Mineral content of laterites vary based on climatic conditions and degree of laterization, and so is its colour. The lateritic soils are observed in different colours due to presence of different minerals. Typical lateritic soils observed in Goa are shown in Fig. 5.4.

It is advisable to characterize the lateritic soils for its mineralogical content vis-à-vis its geotechnical properties. Strength characteristics of lateritic soil, variation of stiffness modulus of lateritic soils need to be studied in depth. The typical geotechnical issues with lateritic soils are cavities, settlement issues and rainfall induced landslides. Hence, a detailed study of macro and micro level properties of laterites and lateritic soils is very important.

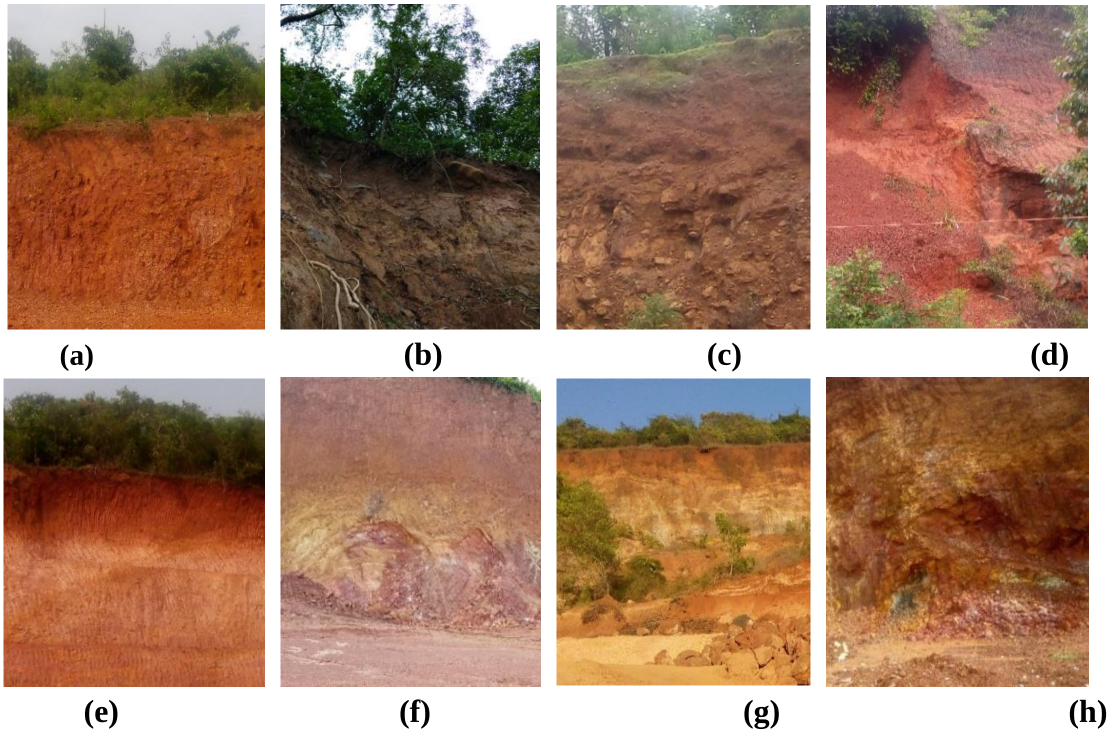

Fig. 5.4: Typical laterite soil/rock profiles in Goa : (a) Bambolim Goa, (b) Chorla Ghat, (c) Kadamba Plateau, Ribandar, (d) Mardol Goa, (e) Ponda Goa, (f) Sancoale Goa, (g) Margao Goa and (h) Verna Goa (Photo courtesy: Leonardo Souza).

5.6 Remarks

Research to assess the influence of various parameters like mineralogy, chemical composition etc. on shear strength and other engineering parameters of tropical residual soils may be promoted by TC 107. In tropical regions many slope failures have been observed recently especially during monsoon. New theories for the prediction of engineering behaviour of these soils are to be developed. Study of lateritic soils, its mineralogy, stiffness characteristics, soil water characteristic curves will throw more light on its engineering behavior and will help in finding solutions to the problems associated with lateritic soils such as cavities, settlement issues and rainfall induced landslides.

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6 TC 206 Observational Method

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6.1 Abstract

TC206 started as "Interactive Design". Good work was done in the early 2000's but did not progress much and therefore TC206 has been reactivated and the name changed to Observational Method (OM). The 4 OM approaches have been recognised to OM. The key developments are now (i) Contracts, (ii) Codes, (iii) Monitoring interpretation and (iv) RTBA. Experience is being sort from Tunnelling where OM is very strong. Peck (1969) Observational Method emphasized on “Learn-as-you-go” which means as the construction progress, any change in the sub-strata should immediately be brought to the notice and necessary adjustment or accommodation in the design of substructure should be made. Euro Code 7 (CEN 2007) has already adopted the observational method as one of the verification approach for the geotechnical design of structures. Peck's work on the Observation Methods was based on Most Probable parameters. Current limit state design is developed around characteristic parameters. Numerical modelling predictions have developed. Monitoring methods have improved. These features have been incorporate into the Observational Method. The manuscript provides brief background, introduce the approach to geotechnical fraternity, milestones achieved since 1960s till date, identifying key challenges and practices, and way forward for future research and development in the field of observational method in the field of geotechnical engineering.

Keywords: Observational method, Euro code 7, Geotechnical engineering, subsurface investigation, case studies

6.2 Introduction

A structure erected on ground has many stakeholders, such as, Client, Consulting companies & designers, Contractors or builders, users or occupants of the built environment and the society at large. Every structure has a foundation and a strong foundation can ensure the stability, safety, durability and serviceability requirements of a structure to be fulfilled. Additionally, the economical, environmental and sustainability aspects cannot be ignored and all efforts are made to ensure the same. Buried underground, a foundation act as interface element to transfer all the loads of the superstructure to the ground in a safe manner and it requires a detailed subsurface exploration program uncertainty in the ground. In complex geology the site investigations are inevitably limited by sampling volume. Hence, sometimes the important information is missed and there comes the role of observational method to be adopted and executed in a timely manner before it is too late.

The observational method was formally introduced by Peck in 1969 during his 9th Rankine Lecture (Peck,1969). The method uses subsurface profiles and geotechnical properties which are often limited. The analytical and empirical tools for analysis and design of foundation system are also limited. Uncertainty is handled with engineering judgment, experience and confidence level of the designer. There was no option left but to be on the conservative side to ensure safe design which was sometimes proved to be very uneconomical. Dealing with measurement uncertainty, model transformation and uncertainty associated with inherent variation in the soil profile was a measure challenge. Geotechnical Engineering was considered to be more an ART rather than being a SCIENCE. With the development of geotechnical field and better understanding of soil behavior, Terzaghi and Peck developed the "observational Method" with the background that designing on over conservative side, with excessive factor of safety, is always not a good option and sometimes lead to uneconomical design or otherwise accepting the risk knowing the fact that achieving a complete safety is practically impossible and suggest some early warning system. Peck (1969) however cautioned that the observational approach should not be used in every circumstance, unless the project allows making changes during the construction and at the same time designers has complete knowledge of alternatives to suggest for every unexpected outcome during the execution of the work. Since the formal introduction of the observational approach, extensive work is done in the field of geotechnical engineering and the following section discuss some of the major contributions recently made in the field.

6.3 Milestones in TC206 Observational Method

1960 – 1980	Peck (1969)	The observational method was formally introduced by Peck in 1969 during his 9th Rankine Lecture
1980 – 2000	Commission of the European Communities (1989) Draft Eurocode 7	This was the first code to recognise the Observational Method Process. It recommended that limits of behaviour be established and the actual behaviour be assessed. A monitoring plan with designed contingency plans be established
	Powderham (1994)	Highlighted the advantages of incorporating observational method in cut& cover and bored tunneling projects in the light of OM criteria set by Peck (1969). He mentioned that situations like complex soil-structure interaction problems and complicated geometry as well as variable ground condition warrant the use of OM. Savings in cost and time along with safety assurance are the major advantages of OM and it should have wider applications. He was also able to establish a connect between observational method and value engineering
	ICE (1996) The Observational Method in Geotechnical Engineer	Proceeding of the Geotechnique Symposium in Print on the Observational Method with eleven papers. This symposium summarized information on the observational method. It highlighted the difference that Peck used where design was based on "Most Probable" parameters and the Eurocode 7 approach based on "Characteristic" parameters
	Nicholson et al, (1999) Ciria R185	provided a definition of the observational Method. It explained it place within limit state design. It summarized many practical applications of OM. It discussed the need for clear contractual frameworks
	Fell et al (2000)	while reviewing the method of stability analysis of cut, fills and natural slopes emphasized that Observational and risk assessment approach can be a better option over traditional factor of safety approach. Factors

		considered were site characterization, Geology and Hydrogeology inputs, material properties, pore pressure development, sliding mechanics, and their integration to assess the stability and deformation pattern and ultimately to manage the slope failure hazards
2000 – 2020	ISSMGE TC37 (2001) - Interactive Geotechnical Design	This technical committee was set up in 2001 and renamed TC206 in 2011. The term interactive design was used. This incorporated the observational method process.
	Powderham (2002)	Presented 3 case studies which used “progressive modification approach” through simple measurements and helped in handling complexities as well as controlling risk. Author stated that OM provided an opportunity to remove those barriers normally encountered in traditional approach. Observational approach provides a greater learning opportunity, team work, to address uncertainty and it has greater applications in temporary work and underground construction where time, cost and safety are of paramount importance
	Sakurai et al (2003)	Stated that observational method is evolving since its inception and with the advent of computer based simulation techniques; it is possible to integrate back analysis procedures with outputs of modern measuring instruments. The technique was implemented in a tunneling project.
	Finno and Calvello (2005)	implemented observational method in a 12.2 m deep supported excavation. To predict the deformation, inverse modeling procedure backed with field measurement, through inclinometer, was used. With the objective to optimize FEM model by minimizing error between field measurement and computed displacement, model was constantly calibrated for every predefined construction stage to ensure good “predictions” of soil behavior are made.
	Patel et al (2007)	thoroughly reviewed the seven case studies available on GeoTechNet (2006) website in which OM was applied on various projects across Europe and highlighted the shortcomings of OM approach of EC7 and at the same time suggested to define more precisely the “acceptable limits” of behavior for further improvement. It was highlighted that the OM approach in EC7 is silent on “design and contractual framework of a project” and clearly stated that UK CIRIA guide 185 (1999) is complete in all aspects and should be used in European projects when it comes to applying OM. They also raised the concern over less

		visibility of UK CDM regulations as legal requirements for safe design in construction projects to benefit the European countries
	Yeow et al (2014)	implemented OM to achieve greater success in eliminating the temporary propping and achieving 13 m deep prop-free excavation. This required not only defining the trigger criteria, comprehensive review and predefined contingency measures but also a great coordination and collaborative efforts of all the stakeholders. Major achievement was saving in cost and programme time due to the implementation of OM approach
	Spross and Johansson (2017)	stated that the observational method is rarely used in the field of geotechnical engineering in spite of its several advantages and potential of achieving savings during the execution of the work. Major concerns were related to “safety definition” and “lack of guidelines” on when and under what circumstances observational method should be adopted. Authors advocated that probability based approach to deal with uncertainty and help designer in decision making while selecting between conventional approach and observational approach and managing the associated risk
	Calvello (2017)	coined “observational modeling” in which inverse modeling techniques are used to update the boundary value numerical model with the help of monitoring data. Author presented two case studies of deep excavation problem and slows moving active landslide in which OM was effectively implemented in coordination with the predicted displacement
	CIRIA C760, (2017) and Hardy et al (2017)	the new OM framework was introduced with approaches A-D . The Approaches A and B follow Ab Initio principles. In Approach A construction starts with most probable parameters (as Peck,1969). In Approach B construction starts with Characteristic parameters with progressive modification contingency plans to change to Most Probable designs. (As CIRIA R195, 1999). In Approaches C and D the the OM is introduced during construction of a traditional design. In approach C the back analysis of instrumentation led an assessment of most probable parameters used in a redesign with contingencies (as CIRIA C760,2017). In approach D unforeseen conditions develop and Peck’s best way out approach is used
	Fuentes et al (2018)	advocated the application on OM as per the guidelines of EC7. By presenting a case study of a deep excavation in over consolidated clay, authors discussed the implications of observational method considering

		corner effects and time dependent movement. Also, field observations and 3D numerical simulation procedure can greatly help in implementing the OM. A set of design parameters were also suggested to helputure projects of similar kind
2020 – Present	ISSMGE TC206 (2020) name to Observational Method	New terms of referenee were developed. The following working groups are being developed:- Contracts Group –Tony O'Brien Code Development –Johan Spross Monitoring and databases- Daniele Fornelli Real Time Back Analysis –Franz Tschuchnigg Tunnelling – Chris Menkiti
	Mitelman et al (2023)	Coupled Numerical Analysis with Machine Learning algorithms to improve the decision making in Observational Method Projects and demostrated the effectiveness of the approach through case study

The following sections provide a brief discussion on observational method in the light of traditional or conventional method along with the limitations of originally proposed Peck OM approach and highlights of CIRIA approach which is an up gradation of the existing EC7 OM approach.

6.4 Traditional vs. Observational Method (OM) Design

In traditional geotechnical designs, everything is fixed in advance based on robust design from the available input information and set of data. The design is based on characteristic parameters. There is no plan for the change during the construction. Triggers are often identified for instrumentation and monitoring as passive inclusion. This is to ensure that predictions are better than actual measurements. This is also termed as Predefined Design (CIRIA, 1999). On the other hand, for an OM design instrumentation and monitoring plays a very important and active role during the construction. In approach C the monitoring can back analysed and parameters improved. If required and agreed upon by all the project stakeholders design modification can be proposed within the agreed contractual framework.

6.5 Observational Method – Peck Approach

The following flowchart shows the step by step procedure adopted in observational approach as explained by Peck in his 9th Rankine lecture. As per the suggestions, it is not necessarily to follow each and every step in all projects, but everything depends on the nature and complexity of the project and underground conditions. Note that Peck's approach was based on most probable parameters rather than characteristic parameters used by current codes. The idea is to close the gap between the outcome of the knowledge based on anticipation and actual measurements made during the construction and execution of the work. Peck (1969) suggested two OM approach, i) Ab Initio and ii) Best Way out. The former starts from the inception and later takes over when some unexpected occur after the commencement of the project and OM is required to be implemented to get rid of the difficulties. The step by step approach explained is adopted by EC7 (2004). Some of the issues raised in EC7 OM approach are highlighted below (Fig 6.2). To overcome these limitations, in 1999, Construction Industry Research and Information Association's

Report 185 (CIRIA, 1999) discussed OM approach which was different from the Peck approach and authors advocated that CIRIA approach is a complete guide to OM.

6.6 Observational Method – CIRIA Approach

As per CIRIA, the following definition of OM was given

"*The Observational Method in ground engineering is a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising safety.*" CIRIA 185 (1999).

Fig 6.3 depicts the difference between Peck OM approach and CIRIA OM approach. It is to be understood that observational method is based on most probable design parameters and not on the characteristic value parameters. Hence, a margin of safety is reduced that necessitates greater control on project execution, extensive instrumentation and monitoring as well as well defined contingency plan in the event when triggered criteria is exceeded. When meticulously planned and executed, OM gives greater flexibility and cost savings.

Fig. 6.4 provides operational framework of implementation of OM as per CIRIA R185, (1999) report. It is suggested that OM should be implemented in the framework of national / corporate policy, design codes, specifications, QA/QC policy as per quality management system document, safety and health guidelines and so on. Then comes the role of stakeholders, client, consultant, builder/contractor, owner, and users / society at large. Their commitment to implementation of OM approach is very important. Once decided to implement OM with identified associated risk and contingency measures, rest is the management of implementing OM at every design and construction stage. Activities like instrumentation and monitoring, regular audit, third party assessment are some of the key areas to focus to achieve the desired results. For details, readers may refer CIRIA 185, (1999) document.

6.7 Remarks on OM & Way Forward

Some of the potential benefits of OM are highlighted below (CIRIA 1999):

- Saving of Time and Money
- Improved Construction Control and Management
- Flexibility, if change anticipated
- Team Work
- Better control on handling uncertainties

Some of the issues that need to be addressed or require more details in the existing OM documents are:

- Understanding Contracts

- Choice of design soil parameters
- Factor of safety
- Traffic Light system
- Behavior and planned modification

Some of the limitations of OM approach are identified as

- When Brittle failure is anticipated as it does not give enough time to respond
- Assessment of “most probable” soil parameters, that requires high quality data
- Engineering judgment, experience and good knowledge still plays a major role

6.8 TC206 Observational Method- Planned developments

The main objects for the current TC206 group are

Contracts	A guide is being produced on contracts procedures that would enable OM to be introduced. The also includes the use of Baseline Report and value Engineering clauses
Code Development	The new Eurocode 7 will be introduced shortly. The text will be reviewed and a guide may be produced on the is planned. The definitions of trigger values is planned
Monitoring and databases	The quality of instrumentation is important. The precision or repeatability of the instrumentation must be linked to the trigger value requirements. Data bases are increasing for site wide access to data. This links with TC220
Real Time Back Analysis	Work is in progress to speed up the back analysis of site data. Probabilistic tools and machine learning is being used. This links with TC103 and 309
Tunnelling	NATM tunnelling has long been an important application of the OM. This is because the ground conditions are often complex and it is difficult to undertake a sufficient site investigation. It is important to assess the contractual, design and construction framework that has evolved and lessons that can be leant and applied to other forms of construction. This links with TC204

6.9 Conclusion

- Importance of observational approach in the field of geotechnical engineering is advocated through literature survey and case studies presented.

- Comparative study of EC7 OM approach and CIRIA OM approach is presented. Shortcomings of EC7 OM approach and its up gradation through CIRIA 185 report is presented.
- OM provides several advantages over Traditional approach and major achievements are in terms of savings in cost and time with enhanced safety.

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6.11 List Of Figures

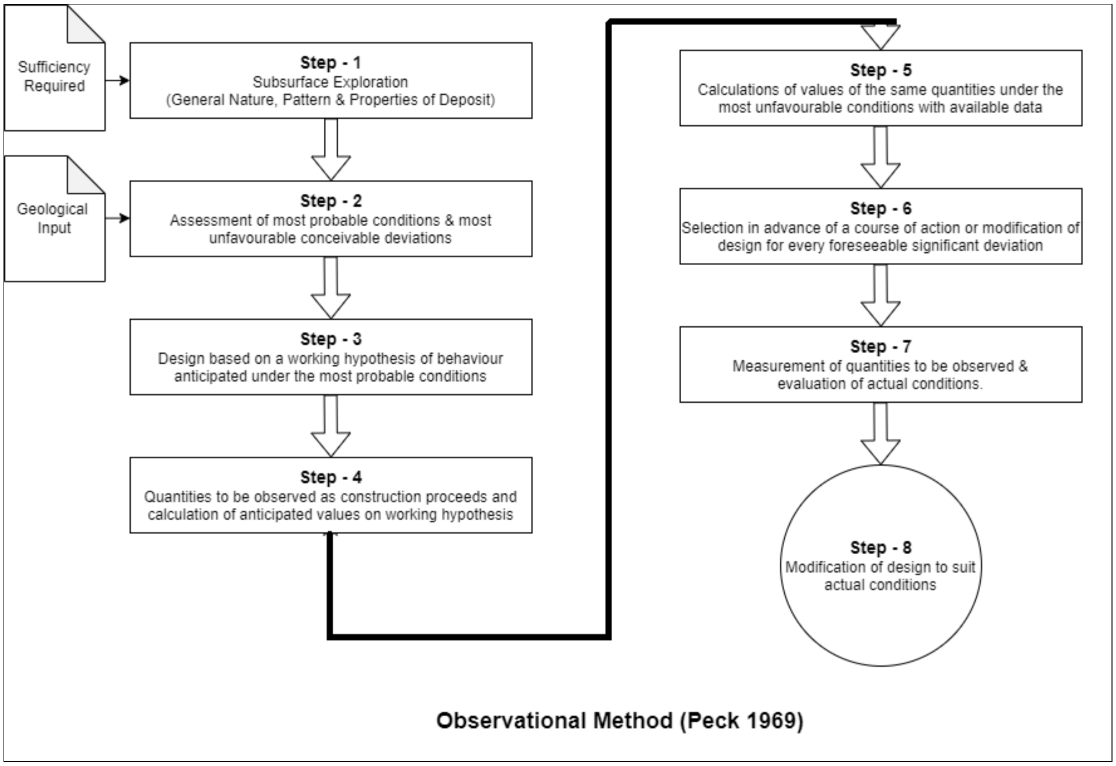

Figure 6.1 Step by step procedure to be adopted in observational method

Figure 6.2 Identified Limitations of EC 7 OM approach (patel et al 2007)

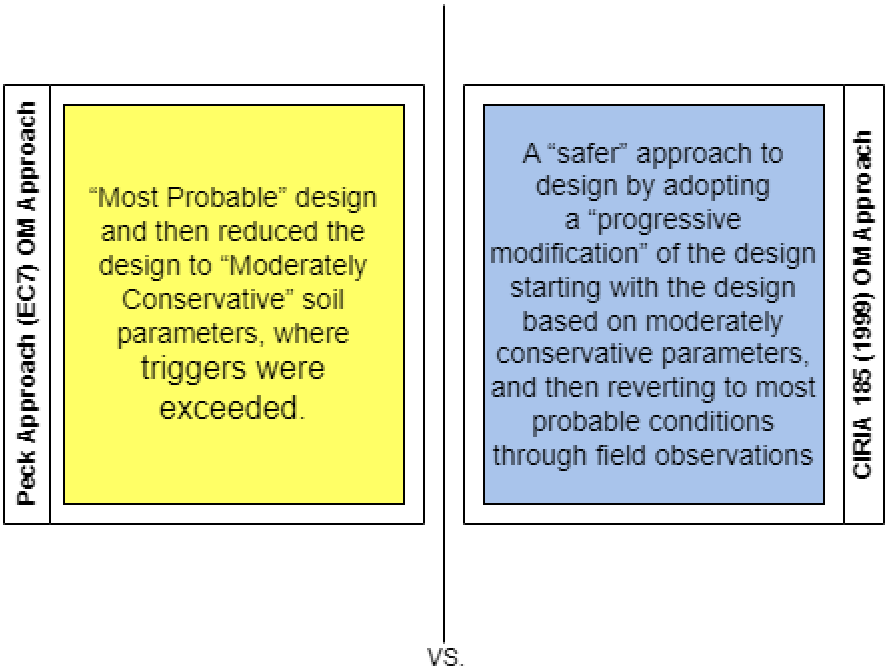

Figure 6.3 Peck OM vs. CIRIA OM approach [CIRIA R185, 1999)

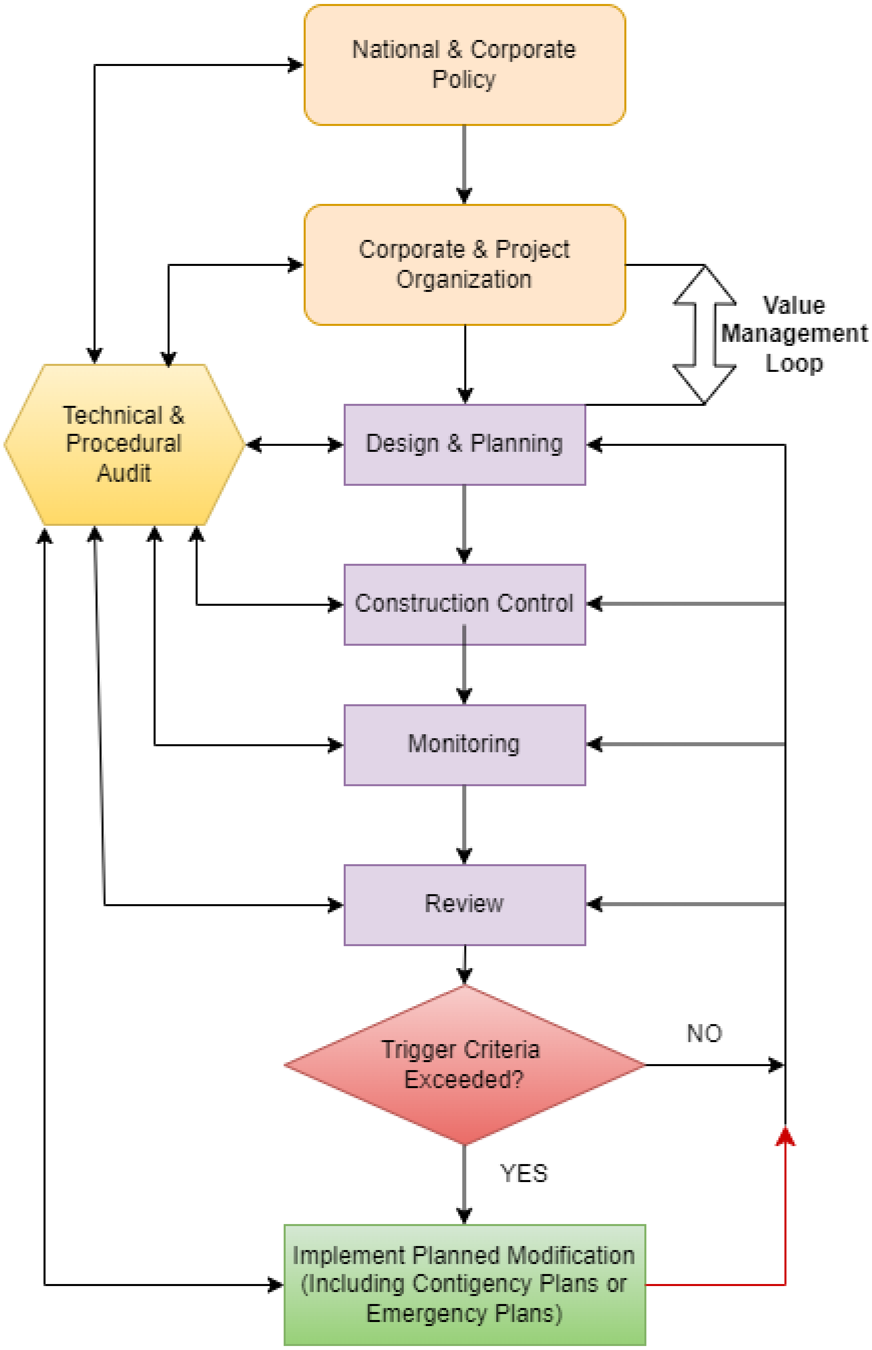

Figure 6.4 CIRIA 185 (1999) Approach on Observational Method (OM)

6.12 Statements and Declarations

6.12.1 Funding

“The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.”

6.12.2 Competing Interests

“The authors have no relevant financial or non-financial interests to disclose.”

6.12.3 Author Contributions

“All authors contributed to the study conception and design. Material preparation, data collection and analysis, manuscript writing were jointly performed

6.12.4 Data availability statement:

No data set associated with the paper

7 TC 210 Embankment Dams

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METHODS OF ASSESSING SHEAR STRENGTH OF ROCKFILLS AND SOIL-ROCK MIXTURES: APPLICATION OF ROCK MECHANICS

7.1 Abstract

Rockfills and soil-rock mixtures are abundantly encountered in dams, slopes, abutments and foundations of civil engineering structures. These materials are treated to be cohesionless and their peak shear strength is represented through friction angle. The friction angle varies non-linearly with increase in normal stress or confining pressure. Assessment of the friction angle of these materials in laboratory or field is extremely difficult due to the scale of the mass to be tested. As an alternative, indirect approaches are used to assess the shear strength response. The present article discusses some major indirect approaches that have been suggested to obtain the friction angle. The approaches are divided into two main categories. Firstly, the approaches based on classical dilatancy theories developed in late forties and fifties are discussed. In later part, the recent approaches, manly from Rock Mechanics literature are presented. Keywords: Rockfill, Soil-Rock Mixture, Friction Angle, Dilatancy, Joint, JRC-JCS, Non-linear strength

7.2 General

Rockfills are frequently used as a construction material in dams due to their strength and higher flexibility. In earthquake prone area these materials are preferred over the other materials (Fig.7.2.1). One of the major engineering attributes of rockfills is their shear strength. It is well known that shear strength of rockfills depends on normal stress and has highly nonlinear variation with normal stress. Soil-Rock Mixtures (S-RM) are abundantly encountered at many sites in foothills of mountains especially the lower Shivalik region of the Indian Himalayas. These coarse-grained materials often include a mixture of soils (clay, silt, and sand) and rock particles (gravel, cobbles, and boulders). A great deal of similarity is observed in shear strength behaviour of rockfills and S-RM, especially when S-RM has high fraction of rock particles. Substantial understanding has been developed by geotechnical engineers and geologists towards engineering behaviours of sands and clays, however engineering response of rockfills and S-RM is still not well understood. On the other side of geological materials, substantial advancement has been made on understanding the engineering response of rocks and rocks masses. With greater extent of fracturing, the behaviours of jointed rocks tend to become quite similar to those of rockfills or R-SM. As a consequence, the investigators have attempted to extend the shear strength models developed for rock joints to model the shear strength of rockfills and R-SM. The present article presents state of art on the shear strength models used for rockfills and R-SM. Special emphasis of given to recent developments which have originated for Rock Mechanics research

Fig 7.2.1. Tehri dam (India). The dam is one of the highest rockfill dams in the word and is loacted in seismic zone-V (Bureau of Indian Standard, 2016) . Loacted on river Bhagirathi, the dam is a part of pumpred storage scheme with Tehri being the main dam on upstram, and Koteshwar dam (gravity dam) about 22 km donstrem (Jazayeri & Moeini, 2020).

7.3 Factors Affecting Shear Strength of Rockfills and S-RM

The shear strength of rockfills and S-RM in the field is influenced by many factors. The most influencing factors may be summarised as (Holtz & Kovacs, 1981; Hawley, 2001; McLemore et al., 2009):

- **Parent rock origin and strength:** It is understood that the material originating from stronger rock materials like granite and quartzites are likely to exhibit higher friction angle as compared weaker rocks like shale.

- **Grain size distribution:** A well graded material is likely to be more competent as compared to poorly graded material if all other attributes are same.

- **Largest grain size:** Size of the particles influences the shear strength of the rockfills and S-RM. The strength may increase or decrease with change in grain size.

- **Shape of particles:** Presence of angular particles results in higher strength as compared to rounded particles.

- **Surface roughness of particles:** A rough surface results in higher strength.

- **Porosity and state of packing:** A dense packing with low porosity indicates much higher competent rockfill or S-RM.

- **Confinement:** The friction angle tends to become lower at high confining stress levels due to constrained dilatancy and higher possibility of particle breakage.

- **Moisture content:** A higher moisture content tends to reduce the shear strength of rockfill/ SR-M.

7.4 Shear Strength Criteria Originated from Soil Mechanics

For obtaining shear strength parameters for geological materials, there is no better alternative, than to perform tests in the field or laboratory. It is relatively easy to perform tests on soils; however, it is extremely difficult to conduct tests on rockfills and S-RM. As an alternative, different shear strength criteria are used to assess the shear strength of these materials. These shear strength models have mainly been derived from studies conducted on granular materials.

7.4.1 Mohr-Coulomb failure criterion

The Mohr-Coulomb failure criterion is the most widely used criterion in the geotechnical engineering field. The criterion assumes that the failure occurs along a planar slip surface; the shear strength along the slip surface is treated as a linear function of normal stress acting on the surface. The criterion is expressed as:

$$\tau_f = c + \sigma_n tan\phi_p \qquad (7.1)$$

Where c is the cohesion and ϕ_p is peak friction angle. The analysis is done in terms of total or effective shear strength parameters.

Generally, the rockfills and S-RM are considered as cohesionless materials. Hence, the Mohr-coulomb equation simplifies to:

$$\tau_f = \sigma_n tan\phi_p \qquad (7.2)$$

Granular materials are discrete in nature, and exhibit ‘dilatancy’ during shear. It was shown by Reynolds (1885) that dense sands expand at failure, whereas loose sands contract during shear to failure. The dilatant behaviour indicates that particle movements during deformation and failure plane deviates from the direction of the applied shear stress. The peak friction angle ϕ_p is a function of ‘dilatancy’ angle which is credited to dilatant behaviour caused due to sliding, overriding of large size particles and rotation (K. L. Lee & Seed, 1967). The shear strength can be expressed as:

$$\tau_f = \sigma_n \tan(\phi_b + \psi) \qquad (7.3)$$

where ϕ_b is basic friction angle, which is constant for a given rock type, and ψ is dilatancy angle. At considerably high stresses, the materials can experience breakage. To take this into account the breakage, the angle ϕ_p can be written as a combination of three components; ϕ_p, the basic friction angle, plus dilation component ψ, and subtracted by an amount caused by particle crushing.

$$\phi_p = \phi_b + \psi - \phi_{crush} \qquad (7.4)$$

7.4.2 Stress-Dilatancy Relationships

Stress-dilatancy relationships form the basis of majority of approaches that are used for explaining shear strength of granular materials. Many investigators have studied stress- dilatancy relationships of granular materials and contributed towards better understanding of their shear strength. Taylor (1948) used energy principles and proposed a stress-dilatancy relationship for standard size direct shear as given below:

$$\frac{\tau}{\sigma_n} = tan\phi_r + \frac{\delta h}{\delta s} \tag{7.5}$$

Where, τ is shear stress at failure, σ_n is normal stress, ϕ_r is the friction angle at the residual state, δh is vertical displacement and δs is horizontal/shear displacement.

Newland & Allely (1957) proposed a model to explain the dilatant behaviour of granular material such as sand. The researchers highlighted the fact that the shear strength of a granular mass is dependent on frictional properties of the particle, and the average angle of deviation of particle displacement from the direction of the applied stress. The peak friction angle ϕ_{max} was expressed as:

$$\phi_{max} = \phi_f + \theta \tag{7.6}$$

Where the angle θ is defined as:

In shear box test, $\tan\theta = d\dot{V}/V\dot{\varepsilon}_1$ (7.7)

In triaxial test, $\tan\theta = \frac{\sqrt{}(\sigma_1'/\sigma_3')_{max.}\ d\dot{V}/V\dot{\varepsilon}_1}{\{1+(\sigma_1'/\sigma_3')_{max.}+d\dot{V}/V\dot{\varepsilon}_1\}}$ (7.8)

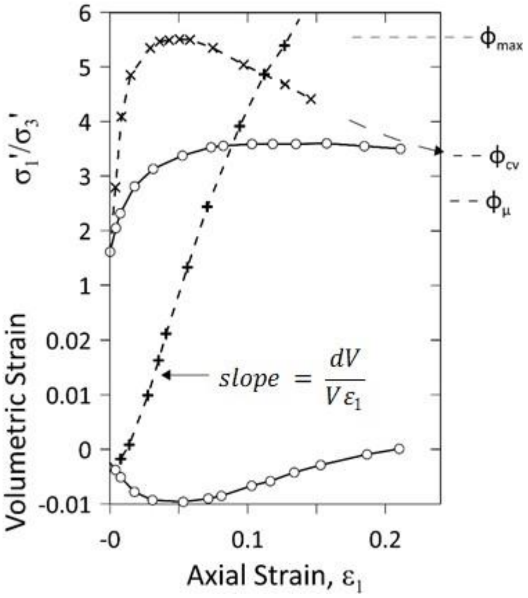


Figure 7.4.1. Stress-dilatancy relationship (Rowe, 1962). The plot shows the three forms of friction angles namely ϕ_{max}, ϕ_{cv} and ϕ_μ representing shear strength of granular materials for different stages

Rowe (1962) studied stress-dilatancy relationship in detail. An excellent discussion on dilatational aspects of shear strength is presented by the author. Quoting from Taylor (1948), Rowe (1962) stated that, the peak shear strength could be represented through three types of angles of friction, namely, ϕmax, ϕcv and $\phi \mu$ (Fig. 7.4.1). It was stated that *"At observed peak- stress ratio (ϕmax), the sand increases in volume during shear. At considerably greater strains, shearing occurs at constant volume where the corresponding angle of friction may be denoted by ϕcv."* It was also stated that the true angle of friction ϕ_μ between the mineral surface is the minimum out of all the angles of friction discussed. The following stress-dilatancy equation was suggested:

$$\frac{\sigma'_1}{\sigma'_3} = k(1 + \frac{d\epsilon_v}{d\epsilon_1}) \tag{7.9}$$

The following expressions were reported between ϕ_μ and ϕ_{cv} (Rowe, 1962):

Caquot (1934) $tan\phi_{cv} = \frac{1}{2}\pi\ tan\phi_u$ (7.10)

Bishop (1954) $sin\phi_{cv} = \frac{15tan\phi_u}{10+3tan\phi_u}$ (7.11)

Stress-dilatancy relationship for granular materials was also studied by Bolton (1986). It was emphasized that: *"a) secant, rather than tangent, ϕ' values should be the basis for discussion, b) that dilatancy towards critical states is central to an understanding of soil behaviour, c) that both effective stress and soil density affect the rate of dilatancy of soils and thereby their strength parameters"*. Bolton (1986) stated that *"The critical state angle of shearing resistance of soil which is shearing at constant volume is principally a function of mineralogy and can readily be determined experimentally within a margin of about 1° using triaxial test data"*. The secant value of ϕ_{cv} was expressed as:

$$sin\ \phi_{cv} = (\frac{\sigma'_1 - \sigma'_3}{\sigma'_1 + \sigma'_3})_{cv} \tag{7.12}$$

Bolton (1986) expressed peak friction angle under plain strain as:

$$\phi_p = \phi_{cv} + 0.8\psi \tag{7.13}$$

The maximum angle of dilation was expressed as:

For plain-strain, $\phi_{max}' - \phi_{cv}' = 5I_R = 0.8\psi_{max},$ (7.14)

For triaxial, $\phi_{max}' - \phi_{cv}' = 3I_R,$ (7.15)

Where, I_R is a relative dilatancy index that can be determined using the correlation given below:

$$I_R = D_r\{10 - \ln(p')\}\text{-}1 \tag{7.16}$$

Where, D_r is relative density and p' is mean effective pressure in kPa.

Xu & Song (2009) modified Rowe's stress-dilatancy relationship to extend its applicability to rockfill materials. The main limitations of Rowe's stress-dilatancy relationship were stated to be:

a. Irregular packing of the uniform rods was considered. The particle size distribution for rockfill materials is considerably different.

b. Particle slip was considered as one of the primary mechanisms and the validation was done using test results of sands and steel balls, which are more difficult to crush, and no breakage of particle occurred.

The modified equation (M. Xu & Song, 2009) was expressed as:

$$sin\psi_m = R_d \frac{sin\phi_m - sin\phi_{v0}}{1 - sin\phi_m sin\phi_{v0}} \quad (7.17)$$

Where, R_d is a reduction factor less than unity, ϕ_{v0} is the mobilised friction angle in the characteristic state or phase transformation state at which the increment of the volumetric strain is zero.

Simoni & Houlsby (2006) performed laboratory tests on gravelly materials and proposed a correlation between the relative dilatancy index of sands (I_R) and gravel mixtures ($I_{R,mixture}$) as stated below:

$$I_{R,mixture} = 5D_{r,mixture} - \{1 - 4.3(e_{min,sand} - e_{min,mixture})\} \quad (7.18)$$

Where, $D_{r,mixture}$ is relative density of gravel mixture. The above-mentioned equation can be used for surcharge pressures lower than the particle breakage threshold.

Hamidi et al. (2009) also proposed the following form to relate shear strength characteristics of sandy soil and poorly graded sand-gravel mixtures under surcharge pressures (σ_v') greater than the particle crushing limit:

$$I_{R,mixture} = 5D_{r,mixture} - \{1 + (4.5 - 0.006\sigma_v') \times (e_{min,sand} - e_{min,mixture})\} \quad (7.19)$$

Szypcio (2017) proposed stress-dilatancy relations for simple shear conditions. The following expressions were proposed:

$$\frac{\tau}{\sigma_n} = \frac{\eta cos\phi cos\theta\sqrt{3}}{3+\eta(sin\theta - sin\phi cos\theta\sqrt{3}} \quad (7.20)$$

where, $\eta = Q - AD,$

$$Q = M^O - \alpha A^o \quad (7.21)$$

$$M^O = \frac{3sin\phi}{-sin\phi sin\theta + cos\theta\sqrt{3}} \quad (7.22)$$

$$A^o = \frac{1}{\cos(\theta - \theta_i)}\{1 - \frac{2}{3}M^o \sin\left(\theta + \frac{2}{3}\pi\right)\} \quad (7.23)$$

$$A = \beta A^0$$

$$\theta_i = \tan^{-1}\left\{\frac{1}{\sqrt{3}} \frac{\frac{\delta h}{\delta v}}{\sqrt{1 + (\frac{\delta h}{\delta v})^2}}\right\} \quad (7.24)$$

$$D = -\sqrt{3}\,\frac{\frac{\delta h}{\delta v}}{\sqrt{1+\frac{4(\frac{\delta h}{\delta v})^2}{3}}} \tag{7.25}$$

Where, ϕ is the friction angle at critical state, α and β are the parameters of fictional state theory and θ is Lode angle. For plane strain conditions, the Lode angle for stress may be assumed to be θ = 15 degrees. The 'h' is the growth of sample height during shearing and s is the horizontal shear displacement.

7.4.3 Dilatancy Angle (ψ)

The dilatancy angle ψ of granular materials is a characteristic parameter like the internal friction angle ϕ (Hansen, 1958). At low stresses, volume generally increases. Dilatancy can be estimated from the volumetric strain versus axial strain curve of a material subjected to triaxial with the following expression (Bolton, 1986):

$$\sin\psi = -\frac{d\epsilon_v}{d\gamma} = -\left\{\frac{d\epsilon_1}{d\epsilon_3}+1\right\} / \left\{\frac{d\epsilon_1}{d\epsilon_3}-1\right\} \tag{7.26}$$

Where, ϵ_v is volumetric strain, γ is shear strain, ε_1 and ε_3 are major and minor principal strains. Variation of dilation angle during direct shear test can be computed, considering horizontal displacement u and vertical displacement v as

$$tan\psi = \frac{dv}{du} \tag{7.27}$$

Based on the critical state concept for soils, Collins & Muhunthan (2003) defined the dilation angle as:

$$\psi_p = \tan^{-1}\frac{\delta\epsilon_p}{\delta\epsilon_q} \tag{7.28}$$

Where, ψ_p is dilatancy angle at peak stresses and $\delta\epsilon_p$ and $\delta\varepsilon_q$ are volumetric strain and deviatoric strain, respectively.

Based on plasticity concepts, Vermeer & De Borst (1984) defined the dilation angle by:

$$\psi = \sin^{-1}\frac{\delta\epsilon_p}{-2\delta\epsilon_1+\delta\epsilon_q} \tag{7.29}$$

Where, $\delta\epsilon_p$ is incremental volumetric strain, $\delta\varepsilon_1$ is incremental strain in principal direction and $\delta\varepsilon_q$ is incremental deviatoric strain.

Based on Rowe's theory (1962) and Bolton's theory (1986), Schanz & Vermeer (1996) developed the following empirical relationship to define the dilation angle:

$$sin\psi = \frac{I_R}{6.7+I_R} \tag{7.30}$$

Where, I_R Is a relative dilatancy index.

7.5 Shear Strength Models Originated from Rock Mechanics

During last few decades, phenomenal growth has occurred in understanding the engineering response of intact rocks, rock joints and jointed rock masses. Striking similarities have been observed between the shear strength behaviour of rock joints and jointed rock masses with those of rockfills and S-RM. It has been observed that shears strength models for rock joints and jointed rock masses have great potential in becoming handy in estimating the non-linear strength behaviour of rocks fills and S-RM in the field. Some of the approaches are reproduced in the following section.

7.5.1 Patton’s (1966) shear strength criterion for rough rock joints

The observations made on dilatational behaviour granular materials (Newland & Allely, 1957) were found to be quite similar to the shear behaviour of perfectly matching rough rock joints. Using this analogy, Patton (1966) proposed a shear strength model for rough rock joints. The model was suggested based on direct shear tests on 'saw-tooth' artificial joints under constant normal load (CNL) condition. It was observed that, the asperities of the rough surface of joints begin to ‘slide’ at low normal stress; while at higher normal stresses, ‘shearing’ was encountered through the asperities. The joints have high dilation at low normal stress and the dilation is suppressed at higher normal stress. As per Patton’s model, there is a normal stress level, at which the failure mode shifts from ‘sliding-up’ to ‘shearing through’ (Fig. 7.5.1). The shear strength along the joint plane is expressed as:

For low normal stress (asperity sliding) $\tau = \sigma_n \tan{(\phi_b + i)}$ (7.31)

For high normal stress (asperity shearing) $\tau = c + \sigma_n\, tan(\phi_r)$ (7.32)

Where ϕ_b and ϕ_r are the basic and residual friction angle of the joint surface, and i is the angle of the saw-tooth surface.

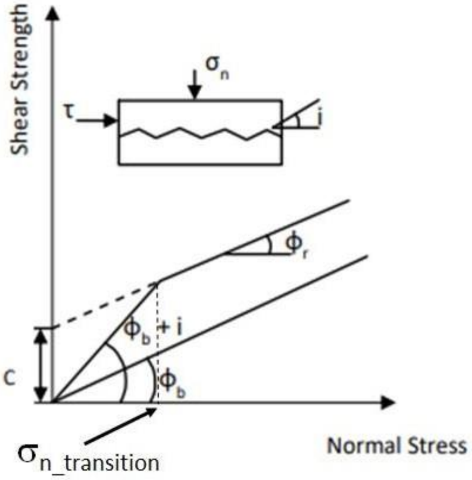


Figure 7.5.1. Patton (1966) shear strength criterion for rough rock joints. Note the transition normal stress, which represents the boundary between two failure modes sliding and shearing. The transition normal stress is obtained from tests.

7.5.2 JRC-JCS (Barton & Choubey, 1977) criterion for rough rock joints

The Patten model suggests two distinct failure modes for shear strength along the joint plane depending on normal stress level. In reality, the failure mode is always a mixed mode without any abrupt shift at a particular normal stress level; and there is gradual and continuous shifting from 'sliding' to 'shearing' modes. Barton's model is an extension of the Patton's model and considers simultaneous occurrence of sliding and shearing. The model was derived based on extensive laboratory studies in which morphology of potential failure surface, strength of joint walls, normal stress levels and dilation interacted with each other. The roughness angle 'i', was assumed to be constant for low normal stress range in Patton's model. It was observed by Barton (1973) that the roughness i varies with normal stress level as given below:

$$i = JRC \log_{10} \frac{JCS}{\sigma_n} \qquad (7.33)$$

Where, JRC is joint roughness coefficient (geometrical component representing initial roughness of the joint surface in degrees); JCS is joint wall compressive strength (ratio of JCS to σ_n represents asperity failure component; Hoek & Bray (1981) have reported that the criterion is valid for a range of $0.01 < \sigma_n / JCS < 0.3$.

The peak friction angle of the joint can be expressed as:

$$\phi_p = \phi_b + JRC \log_{10} \left(\frac{JCS}{\sigma_n} \right) \qquad (7.34)$$

Where, ϕ_b is basic friction angle (fundamental parameter of intact rock). The angle ϕ_b can be estimated by conducting tilting tests using dry, flat, non-dilatant, i.e., sawn, surfaces of the rock (Barton & Kjaernsli, 1981). It is suggested that a cap of 70° be imposed on the estimated value of ϕ_p. The shear strength for a rough rock joint is thus expressed as (Barton, 1973):

$$\tau_f = \sigma_n \tan \left(\phi_b + JRC \, log_{10} \frac{JCS}{\sigma_n} \right) \qquad (7.35)$$

The basic friction angle ϕ_b, for different rock types are reproduced in Table 7.1. Graphical representation of the Barton (1973) model is shown in Fig. 7.5.2.

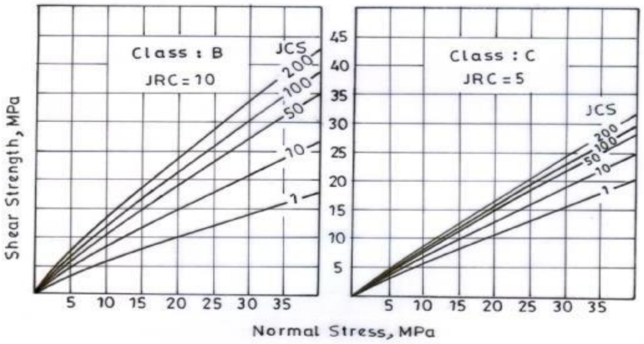


Figure 7.5.2. Barton's shear strength model for rough rock joints (Barton, 1973). The model represents continuous degradation of rough asperities with increasing normal stress across the joint surface

Table 7.1. Typical values of basic friction angle, ϕ_b for various unweathered rocks (Barton & Choubey, 1977)

Rock type	Moisture condition	ϕ_b°	Rock type	Moisture condition	ϕ_b°
A. Sedimentary			**B. Igneous**		
Sandstone	Dry	26–35	Basalt	Dry	35–38
Sandstone	Wet	25–33	Basalt	Wet	31–36
Sandstone	Wet	29	Fine-grained granite	Dry	31–35
Sandstone	Dry	31–33	Fine-grained granite	Wet	29–31
Sandstone	Dry	32–34	Coarse-grained granite	Dry	31–35
Sandstone	Wet	31–34	Coarse-grained granite	Wet	31–33
Sandstone	Wet	33	Porphyry	Dry	31
Shale	Wet	27	Porphyry	Wet	31
Siltstone	Wet	31	Dolerite	Dry	36
Siltstone	Dry	31–33	Dolerite	Wet	32
Siltstone	Wet	27–31	**C. Metamorphic**		
Conglomerate	Dry	35	Amphibolite	Dry	32
Chalk	Wet	30	Gneiss	Dry	26–29
Limestone	Dry	31–37	Gneiss	Wet	23–26
Limestone	Wet	27–35	Slate	Dry	25–30
			Slate	Dry	30
			Slate	Wet	21

Later the shear strength equation was revised on the basis of experimental results performed on rock joints with different weathering conditions (Barton & Choubey, 1977). The revised equation to estimate the shear strength τ_f along a joint plane subjected to a given normal stress σ_n was expressed as:

$$\tau_f = \sigma_n \tan\left\{\phi_r + JRC\ log_{10}\left(\frac{JCS}{\sigma_n}\right)\right\} \tag{7.36}$$

Where, $\left\{\phi_r + JRC\ log_{10}\left(\frac{JCS}{\sigma_n}\right)\right\}$ is peak friction angle of joint plane (ϕ_p), and ϕ_r is the residual friction angle of the joint corresponding to large shear displacements. In practice, ϕ_r may vary between 15° to 30°, whereas the values of ϕ_b generally vary between 25°-35° (Barton & Choubey, 1977).

The joint roughness coefficient (JRC) is a dimensionless number that represents the initial roughness of the joint surface in degrees. The most reliable method to get the JRC is to conduct tilt tests, preferably with rock blocks of natural size containing through going joints. If sliding occurs at angle α, the is back-calculated as (Barton & Choubey, 1977):

$$JRC = \frac{\alpha - \phi_r}{\log_{10}(\frac{JCS}{\sigma_{no}})} \tag{7.37}$$

Where σ_{no} is normal stress across the joint when sliding occurs.

Barton & Choubey (1977) have published standard profiles (Fig 7.5.3) for estimating JRC. An approximate value of the JRC can be estimated by comparing the appearance of the discontinuity surface with standard profiles.

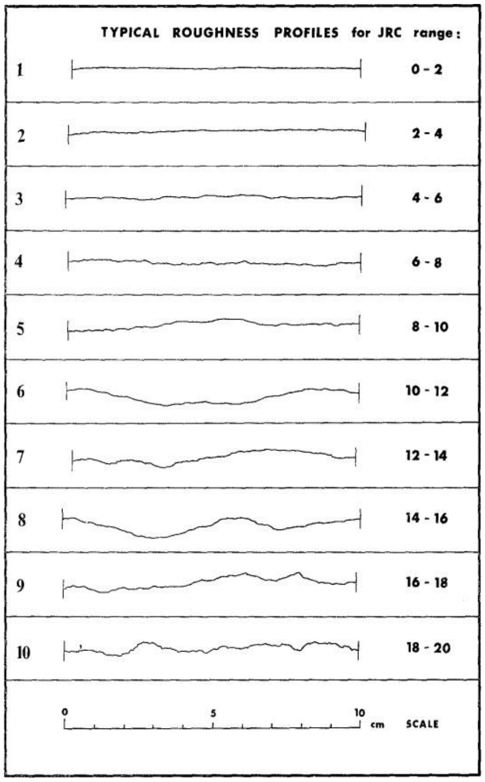


Figure 7.5.3. Roughness profiles to estimate JRC (After Barton & Choubey, 1977)

Figure 7.5.4 shows how peak friction angle of rock joints varies with normal stress as per JRC- JCS model. For this plot, the computations were done for $\phi_r = 28°$ and normal stress was varied upto a maximum of half the JCS. Four different values of JRC i.e., 5, 10, 15 and 20 were considered in this analysis. The plots indicate that peak friction angle varies non-linearly with increasing normal stress. At low normal stress, the ϕ_p values are very high due to higher dilation. At higher normal stress the dilation is suppressed resulting in lower values of peak friction angle. As normal stress approaches JCS, the dilation is completely suppressed and peak friction angle, irrespective of roughness, will be equal to residual friction angle ϕ_r r. At higher normal stress values, the plots of shear strength tend to merge with each other irrespective of the initial roughness of the joints.

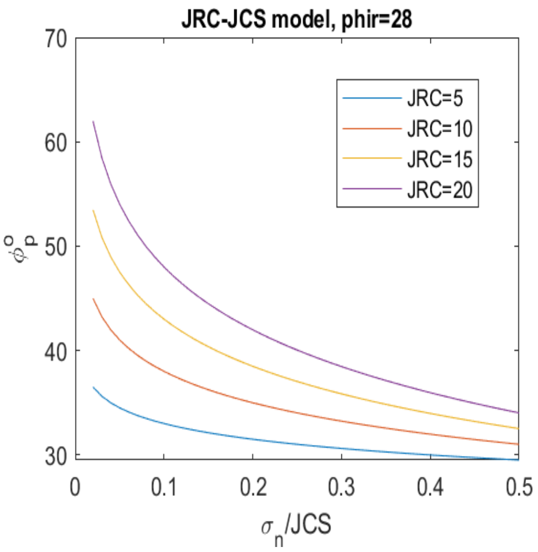


Figure 7.1.4.Variation of peak friction of joint with increasing normal stress as per JRC-JCS model

Venkateswarlu (2022) conducted large number direct shear tests on S-RMs using direct shear test apparatus of large (1000x1000x750mm height) and medium (300x300x250mm height) size (Fig. 7.5.5a and b). Tests were performed by varying gravel fraction in the soil-rock mixture. It was observed that gravel content in soil rock mixtures has substantial influence on shear strength of the mixture. Earlier, Irfan & Tang (1993) had shown that the effect of coarse particles on shear strength was substantial when coarse fraction varies between about 30 to 70%. The following relation was suggested by Irfan & Tang (1993):

$$\phi_{mass} = \phi_{sand\ fines} + \Delta\phi \tag{7.38}$$

Where, ϕ_{mass} is the friction angle of soil mass containing large size rock particles, $\Delta\phi$ is the increase in friction angle of rock soil mixture resulting from the addition of coarse fraction content and $\phi_{sand\ fines}$ is the friction angle of sand fines matrix without coarse particles.

Venkateswarlu (2022) worked out the values of Δϕ for different S-RMs based on laboratory tests as shown in Table 7.2.

(a)

(b)

Figure 7.5.5. Direct shear test apparatus (a) Large size (1000mm x 1000mm x 750 mm) (b) Medium size (300mm x 300mm x 250 mm) (After Venkateswarlu, 2022)

Table 7.2. Increase in peak friction of soil-rock mixture due to increase in gravel fraction (Venkateswarlu, 2022)

Rock soil mixtures	Observation	$\Delta\phi°$ (per 10% increase in gravel fraction)
Phyllitic	$\phi_{S\text{-}RM}$ increases linearly	1.1
RBM	$\phi_{S\text{-}RM}$ increases linearly up to gravel content of 65% beyond which it almost constant	1.7
Dolomitic limestone	$\phi_{S\text{-}RM}$ increases linearly between 20 and 50% of gravel content, beyond which it is almost constant	4.3
Quartzitic limestone	$\phi_{S\text{-}RM}$ increases linearly up to gravel content of 60%, beyond which it is almost constant	3.4

In addition to gravel fraction, Venkateswarlu observed that the shear strength of soil-rock mixture is influenced by maximum particle size and particle gradation in the mixture. Applicability of JRC-JCS model was examined and it was observed that JRC-JCS models can be utilised to explain the non-linear strength behaviour of S-RMs. Equivalent values of JCS and JRC were expressed in terms of UCS of parent rock, gravel fraction, maximum particle size (represented by d_{90}), and mean particle size, d_{50} as follows:

Equivalent JCS, $\mathrm{JCS_{eq}} = \frac{\sigma_{ci}}{10} \times \frac{G\%}{100}$ (7.39)

Equivalent JRC, $\mathrm{JRC_{eq}} = \alpha \times \left(\frac{d_{50}}{d_{90}}\right)$ (7.40)

$\alpha = 0.3 \times d_{90} + 16$ (for maximum particle size ranging from 40 to 125 mm) (7.41)

Where, σ_{ci} is the UCS of the parent rock; G% is gravel fraction in percent in the S-RM. The above expressions were derived from tests on S-RMs having maximum particle size ranging from 40 to 125mm, d_{50}/d_{90} =0.1 – 0.5, Gravel= 0 to 100 (20 to 80), porosity = 24 to 40%. The author (Venkateswarlu, 2022) considered four components i.e. UCS of parent rock, maximum grain size, percent gravel content and ratio d_{50}/d_{90} to extend JRC-JCS shear strength criterion for estimating shears normal stress dependent peak friction angle of S-RMs. Figure 7.5.6 shows how these components affect the shear strength. The plots were drawn by taking UCS=10000kPa, d_{90}=100mm; ratio d_{50}/d_{90} = 0.3 and percent gravel =50. For each plot, one component was varied, and others were kept constant, and shear strength for a range of σn = 0 to 500 kPa were obtained. The peak friction angle is found to reduce non-linearly with increasing normal stress. Positive correlations of peak friction angle are observed for all the components i.e., UCS of parent rock, maximum grain size, gravel content and the ratio d_{50}/d_{90}.

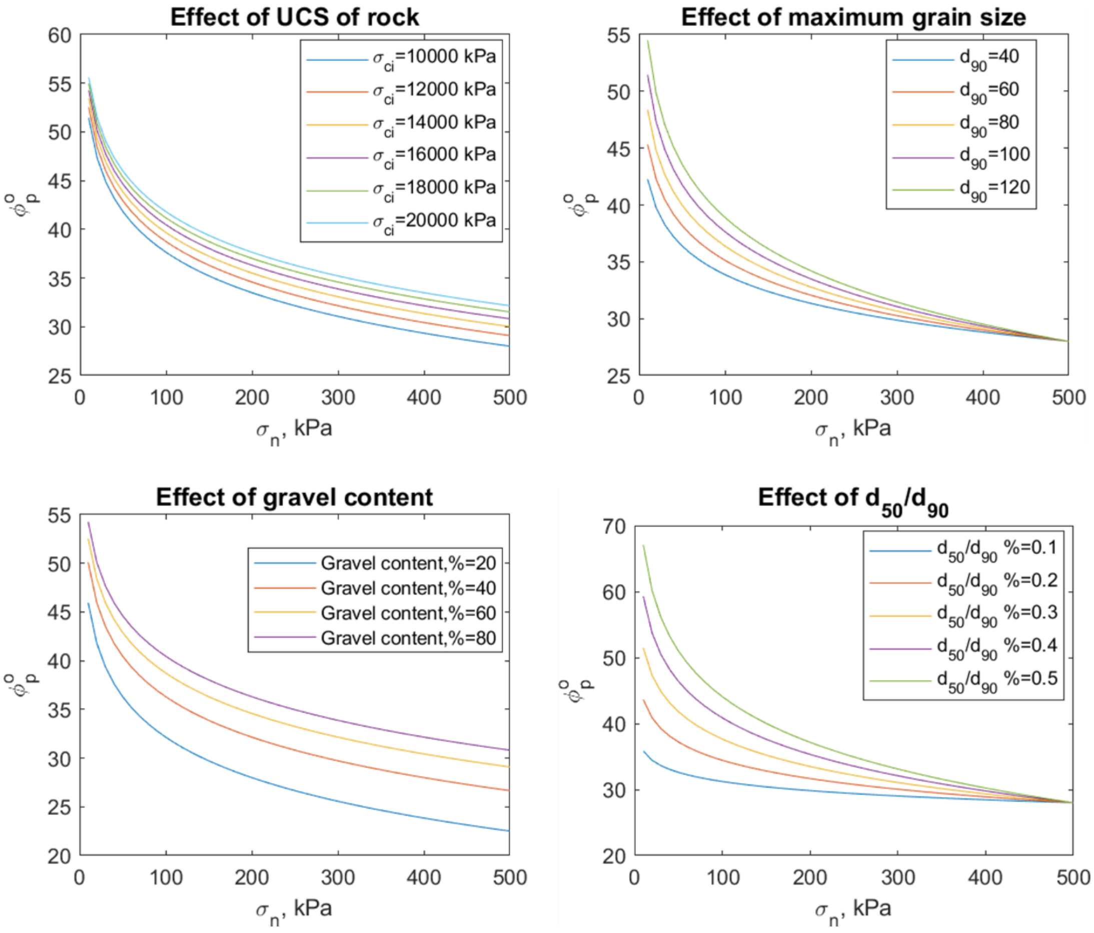


Figure 7.5.6. Effect of variation of UCS, maximum grain size, gravel content and d_{50}/d_{90} on the shear strength of S-RM as per Venkateswarlu (2022).

7.5.3 Barton & Kjaernsli (1981) model for rockfills

Barton & Kjaernsli (1981) reviewed test data of rockfills and compared strength behaviour of rockfills with that of rock joints. It was argued that the variation of peak friction angle of rockfills and rock joints is closely related to each other. The peak friction angle of both the materials is reported to be dependent on sample size, stress level, surface roughness and uniaxial compressive strength of the rock. It was shown that the friction angle of rockfills can be estimated from the following four parameters of rockfill: a) the uniaxial compressive strength of parent rock, b) the mean particle size d_{50}, c) the degree of particle roundness and d) the porosity of the rockfill. An equivalent roughness (R) of the rockfill was defined to be used in place of JRC of rock joints. The equivalent roughness R was expressed in terms of porosity, degree of particle roundedness and surface smoothness. Also, JCS of rock joints was replaced with equivalent strength S of rockfill. The peak friction angle of the rockfill was expressed as:

$$\phi_p = R \log_{10}(\frac{S}{\sigma_n}) + \phi_b \tag{7.42}$$

Where, R is equivalent roughness of rockfill; S is size dependent equivalent strength of rockfill particles and ϕb is the basic friction of the rock.

Empirical charts (Barton & Kjaernsli, 1981) were suggested to estimate R and S. R is a function of porosity of the rockfill, particle origin, roundedness, and smoothness (Fig 7.5.7). S is estimated empirically through reduction factor (S/σ_C) depending on mean particle size of the sample (Fig. 7.5.7). The value of σ_C can be estimated from laboratory UCS, point load strength index or Schmidt hammer test. The value of ϕ_b can be estimated from tilt tests of sawn surfaces of the rock. Depending on rock type, the ϕ_p value usually ranges from 25°-35° (Barton and Choubey, 1977). While constructing rockfill dams, strength investigations are usually performed on rockfills for triaxial and plane strain conditions. Barton & Kjaernsli (1981) recommend extrapolating the tests data and back calculate equivalent roughness, R from available test data, and estimate the values of S and ϕ_b from simple index tests. It is also recommended that for occasions where estimation of R through suggested charts is found to be adequate, the equivalent particle strength S would be back calculated as a basis for extrapolating available test data. The equivalent strength S would be back calculated as:

$$S = \sigma_n \, 10^{\{(\phi_p - \phi_b)/R\}} \tag{7.43}$$

Laboratory shear strength investigations have limitations especially with regard to the size of rock particles. A robust rectangular open box test was suggested by Barton & Kjaernsli (1981) for actual rockfill dam site (Fig. 7.5.8). The tilt angle obtained from these tests can be extrapolated to design stresses by estimating values of S and ϕb from index tests, and back calculating the value of R.

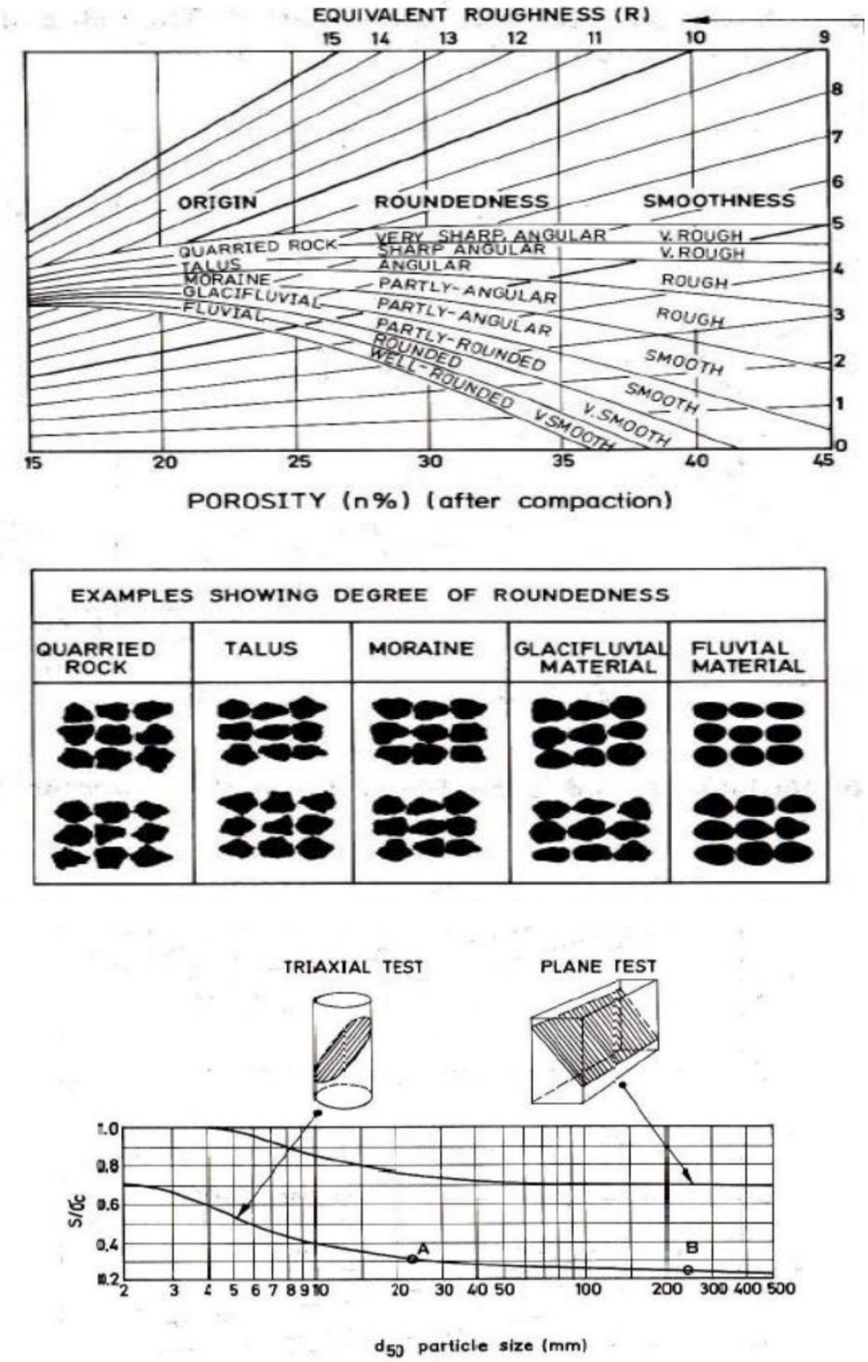


Figure 7.5.7. Empirical chart for the estimation of equivalent roughness (R) and equivalent strength (S) (After Barton & Kjaernsli, 1981)

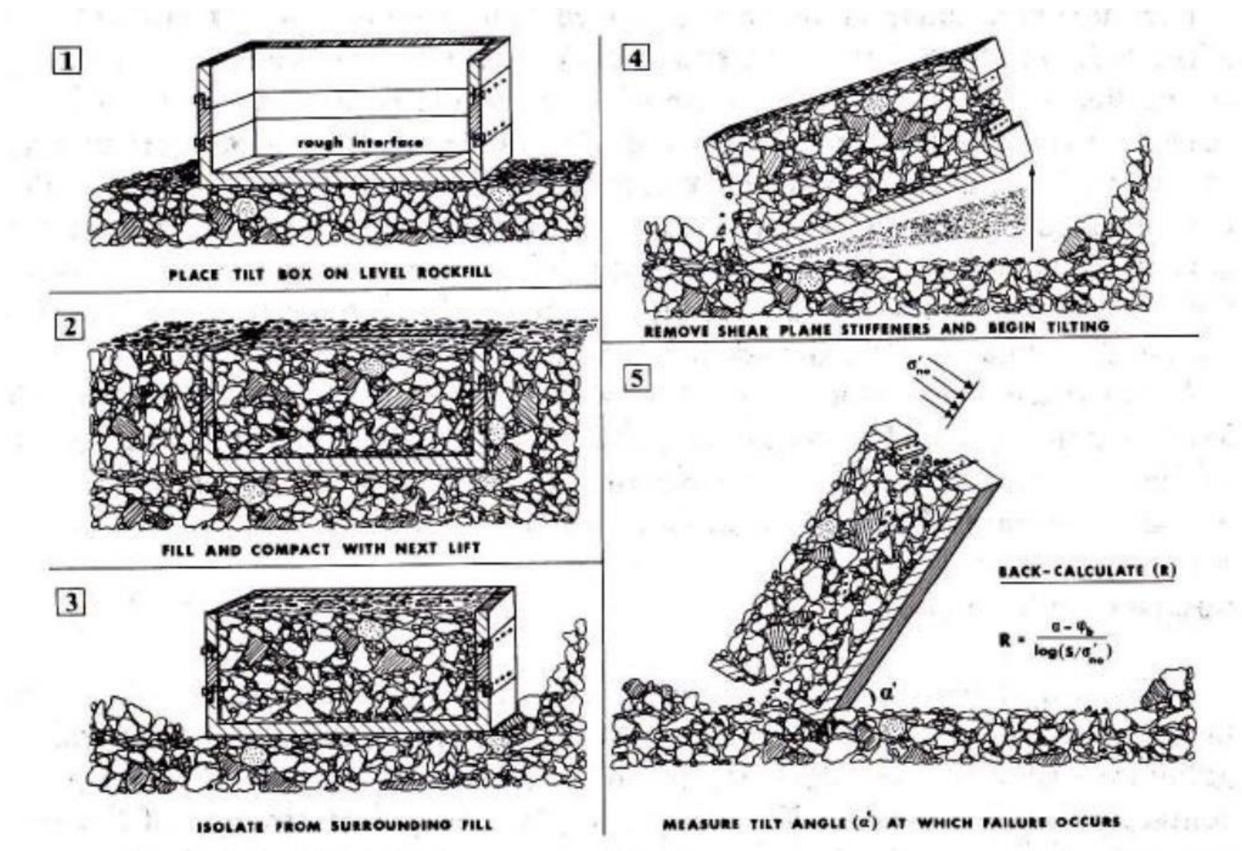


Figure 7.5.8. Full scale strength tests for rockfill (after Barton & Kjaernsli, 1981)

Venkateswarlu & Singh (2023) have suggested modification to R value for applicability of Barton-Kjernsli model to S-RMs. Based on extensive laboratory tests, corrections are suggested for gravel content, mean particle size d_{50} and normal stress σ_n (Fig. 7.5.9). It was recommended that the maximum value out these be used as correction factor to obtain modified R as:

$$R_{mod} = CF_{max} \times R \tag{7.44}$$

Where CF_{max} is the maximum value of correction factor obtained from the Charts (Venkaeswarlu and Singh, 2023) and R is equivalent roughness from Barton-Kjernsli charts.

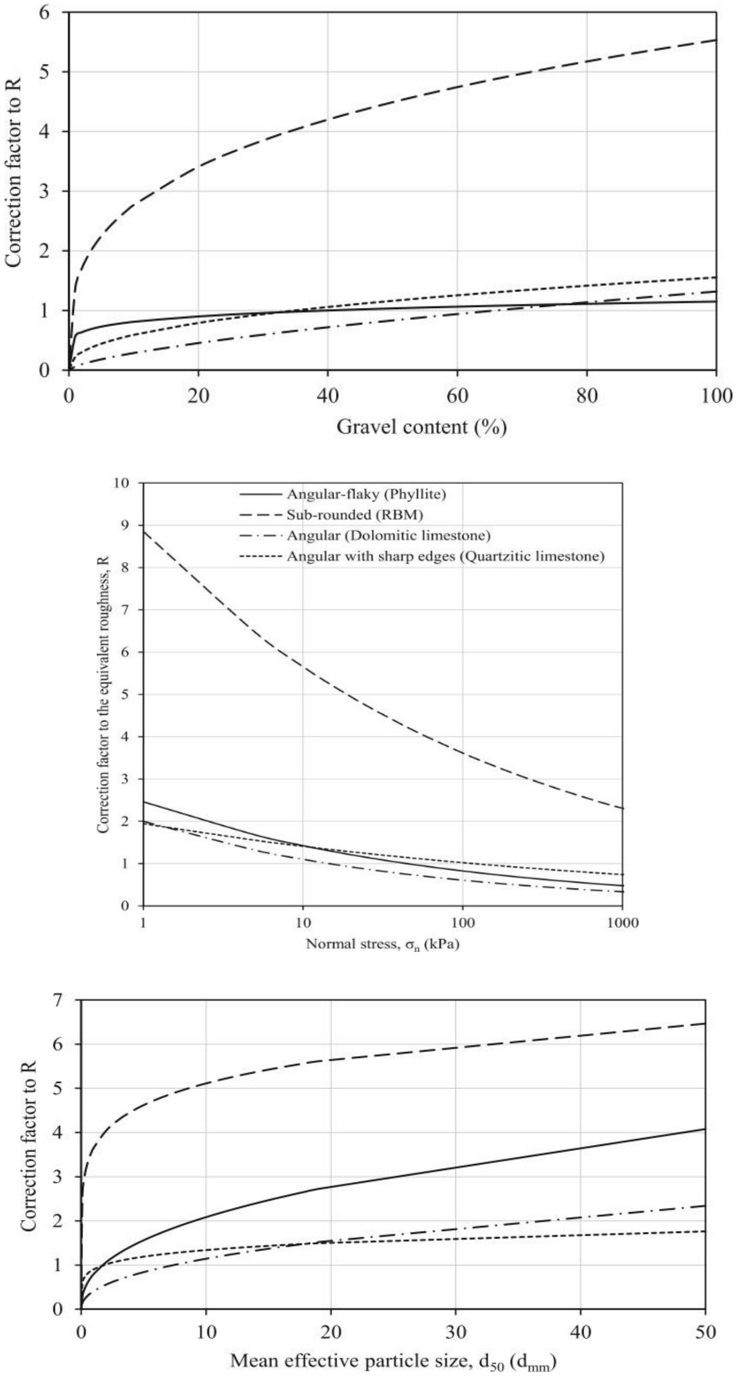


Figure 7.5.9. Correction factors suggested by Venkateswarlu & Singh (2023) for Barton-Kjernsli shears strength model for rockfills. The maximum value out of the three is used for modifying equivalent roughness, R.

7.5.4 Non-linear strength criterion of jointed rocks (Singh & Singh, 2012)

Jointed rocks and rock masses exhibit highly non-linear strength behaviour quite similar to rockfills and S-RMs. Several non-linear strength criteria are available in literature. A non-linear strength criterion for jointed rock mass has been proposed by Singh & Singh (2012). The criterion was suggested based on critical state of rocks (Barton, 1976). Barton's critical state concept for rocks postulates *"critical state for any intact rock is defined as stress condition under which Mohr envelope of peak shear strength of the rocks reaches a point of zero gradient. This condition represents the maximum possible shear strength of the rock. For each rock, there will be a critical effective confining pressure above which the shear strength cannot be made to increase.*" Singh & Singh (2012) observed that jointed rocks and rock masses also follow critical state concept. The non-linear strength criterion (Singh & Singh, 2012) is expressed as:

$$(\sigma_1 - \sigma_3) = \sigma_{cj} + \frac{2sin\phi_{j0}}{(1-sin\phi_{jo})}\sigma_3 + \frac{1}{\sigma_{crtj}}\frac{sin\phi_{j0}}{(1-sin\phi_{jo})}\sigma_3^2 \quad for\ 0 \leq \sigma_3 \leq \sigma_{crtj} \tag{7.45}$$

$$(\sigma_1 - \sigma_3) = \sigma_{cj} + \frac{2sin\phi_{j0}}{(1-sin\phi_{j0})}\sigma_{crtj} \qquad for\ \sigma_3 \geq \sigma_{crtj} \tag{7.46}$$

Where σ_1 and σ_3 are major and minor principal stresses at failure; σ_{cj} is the UCS of jointed rock; ϕ_{j0} is the limiting friction angle of the rock mass at $\sigma_3 \to 0$; σ_{crtj} is critical confining pressure of jointed rock. Fig 4.5.10 shows the physical significance of angle ϕ_{j0}. On σ_1 vs σ_3 plot, a tangent to the failure envelope, where it intersects y axis, will have gradient of $\pi/4+\phi_{j0}/2$. The friction angle ϕ_{j0}may be deduced from triaxial tests conducted on intact rock and UCS of the jointed rock σ_{cj} as follows:

$$sin\phi_{j0} = \frac{(1-SRF)+\frac{sin\phi_{i0}}{(1-sin\phi_{i0})}}{(2-SRF)+\frac{sin\phi_{io}}{(1-sin\phi_{i0})}} \tag{7.47}$$

Where, SRF= strength reduction factor= σ_{cj}/σ_{ci}; Φ_{i0} is the limiting friction angle of the intact at $\sigma_3 \to 0$ (Singh et al., 2011). The value of Φ_{i0} is obtained by conducting few triaxial strength tests on intact rock specimens. If $\sigma1$ is the triaxial strength of the rock at confining pressure $\sigma3$, the following expressions are used step-by-step to obtain Φ_{i0}.

$$A_i = \frac{\Sigma(\sigma_1 - \sigma_3 - \sigma_{ci})}{\Sigma(\sigma_3^2 - 2\sigma_{ci}\sigma_3)}\ ;\ \ 0\ <\ \sigma_3\ \leq\ \sigma_{ci} \tag{7.48}$$

$$B_i = -2A_i\sigma_{ci} \tag{7.49}$$

$$sin\phi_{i0} = \frac{B_i}{2+B_i} \tag{7.50}$$

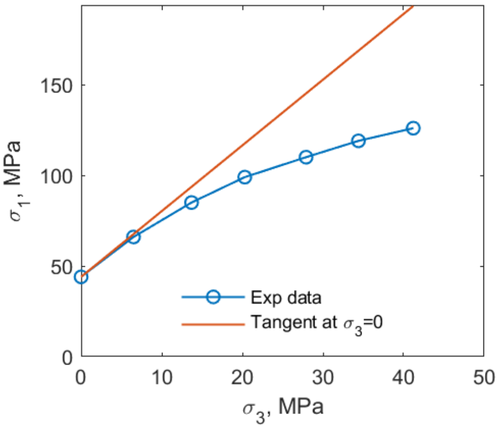


Figure 7.5.10. Modified Mohr-Coulomb criterion for jointed rocks (Singh & Singh, 2012). The friction angle ϕ_{j0} may be obtained by drawing tangent to the curved envelope at a point where it intersects y axis ($\sigma_3 \rightarrow 0$).

One of the most important parameters for applying this criterion to jointed rocks is the UCS of the jointed rock, σ_{cj}. Several approaches are available in rock mechanics literature to estimate the UCS of jointed rock, σ_{cj}. A reliable estimate of σ_{cj} in the field strength may be obtained by adopting procedure suggested by Singh & Rao (2005). The approach is based on the argument that strength and deformability of rock are closely related to each other. It is recommended that deformability tests (e.g. cyclic plate load tests) be performed by loading the rock mass upto a pre-decided load and rock mass modulus may be obtained. The following correlation may be used to get the σ_{cj}.

$$SRF = (MRF)^n \tag{7.51}$$

Where, MRF= modulus reduction factor $= E_j/E_i$; E_j and E_i are the moduli of the jointed rock and the intact rock respectively; index n varies from 0.5 to 1 (Zhang, 2010). An average value of 0.63 may be taken for jointed rocks. Intact rock modulus E_i may be obtained from UCS tests conducted on intact rock specimens in the laboratory.

Venkateswarlu (2022) evaluated the applicability of the above strength criterion (Singh & Singh, 2012) to the test data generated from direct shears test performed on S-RMs. He obtained correlations of the inputs namely σ_{cj}, ϕ_{j0} and σ_{crtj}. The following step-by-step procedure was suggested for obtaining peak friction of SR-Ms in the field:

a. Perform deformability test (cyclic plate load test, IS:5248 - 1992) in the field to get deformation modulus Ej, and obtain hypothetical (apparent) strength σ_{cj} using following expression:

$$\sigma_{cj}/\sigma_{ci} = \left(E_j/E_i\right)^n \tag{7.52}$$

The index n has been suggested to be between 0.94 to 1.1 with an average value of 0.92 for S-RMs.

b. Compute ϕ_{j0} as follows:

$$\phi_{j0} = 16.5\left(\frac{G\%}{100}\right) + 16.54\log_{10}\left(\frac{JCS}{5\,kPa}\right) - 10.3 \tag{7.53}$$

Where $JCS = \frac{\sigma_{ci}}{10} \times \frac{G\%}{100}$

c. Compute triaxial strength of SR-M as:

$$(\sigma_1 - \sigma_3) = \sigma_{cj} + \frac{2sin\phi_{j0}}{(1-sin\phi_{jo})}\sigma_3 + \frac{1}{\sigma_{crtj}}\frac{sin\phi_{j0}}{(1-sin\phi_{jo})}\sigma_3^2 \quad for\ 0 \leq \sigma_3 \leq \sigma_{crtj} \tag{7.54}$$

$$(\sigma_1 - \sigma_3) = \sigma_{cj} + \frac{2sin\phi_{j0}}{(1-sin\phi_{j0})}\sigma_{crtj} \quad for\ \sigma_3 > \sigma_{crtj} \tag{7.55}$$

Where $\sigma_{crtj} = 4 \times \sigma_{cj}$ (7.56)

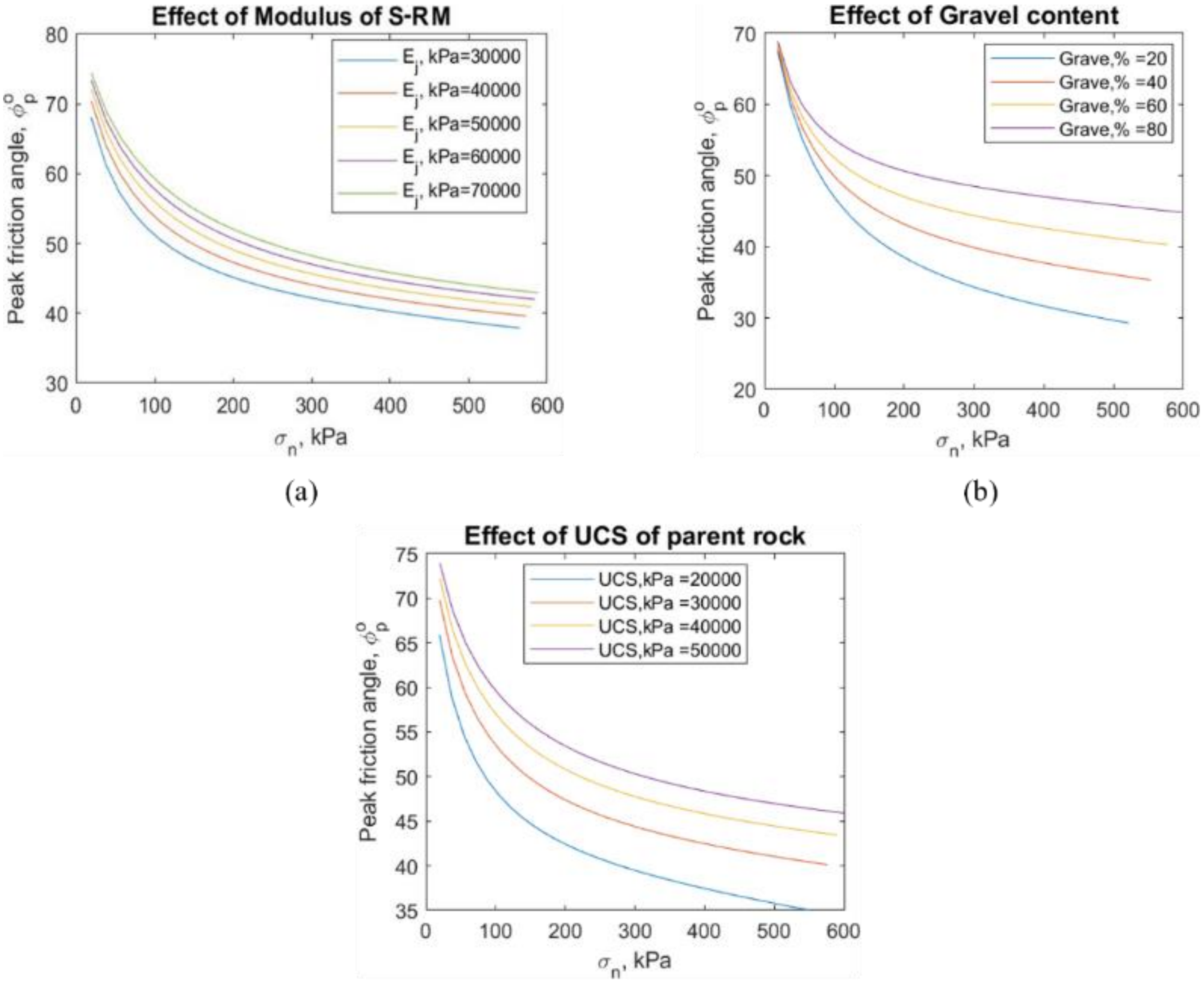
d. For a given confining pressure obtain peak friction angle of S-RM as:

$$sin\phi_p = (\sigma_1 - \sigma_3)/(\sigma_1 + \sigma_3) \tag{7.57}$$

Figure 7.5.11 show plots to indicate how estimated value of friction angle ϕ_{j0} varies with various parameters viz. modulus of S-RM, Gravel content and UCS of parent rock.

7.6 Concluding Remarks

Assessment of shear strength of rockfills and soil-rock mixtures is important for design of dams and other structures. Generally, the cohesion component of shears strength of these materials is negligibly small and the strength represented through peak friction angle. The friction angle is found to have great stress dependence, and it reduces non-linearly with increase in normal stress across failure plane. Some of the most important parameters that influence the friction angle are: parent rock strength, basic friction angle, gravel content, grain size distribution, mean particle size, porosity and state of packing. Obtaining friction angle of rockfills and soil-rock mixture through laboratory or field tests is costly, time consuming and sometimes not feasible also. As a consequence, indirect approaches are used to assess the friction angle in the field. Present article has discussed some of the most commonly used approaches used for assessing the stress dependent friction angle. Two broad categories of the approaches are discussed. The first category of approaches is mainly derived from classical stress-dilatancy theories that were developed for granular materials in late forties and fifties. Of late, a substantial research has been done in the field of Rock Mechanics to better understand the dilatational behaviour rock joints and jointed rock masses. The second category of approaches are derived from these Rock Mechanics studies. It is relatively easy to get the deformability as compared to strength for rockfills and soil-rock mixtures in the field. It is envisaged that the approach for assessment of strength through deformability will be found to be serve better.



(a)

(b)

(c)

Figure 7.5.112. Effect of modulus, gravel content and UCS of parent rock on stress dependent peak friction angle ϕ_p of S-RM

7.7 References

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8 TC 215 Environmental Geotechnics

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8.1 Abstract

This time capsule presents a brief background of the objectives and activities of ISSMGE Technical Committee 215 on Environmental Geotechnics. It provides a detailed list of events and activities held in India since the mid-1990s till date (in chronological order) in the area of Environmental Geotechnics (also referred to as Geoenvironmental Engineering) held under the umbrella of the Indian Geotechnical Society (IGS) or by members of IGS at various institutions associated with it. It summarises the challenges and the way forward.

8.2 Introduction

The area of Environmental Geotechnics evolved in the 1970s through the adoption of geotechnical engineering knowledge to produce solutions for problematic situations relating to the subsurface environment. The term Environmental Geotechnics is sometimes combined or replaced with the more broad-based term Geoenvironmental Engineering. TC215 is one of the Technical Committees of the International Society of Soil Mechanics and Geotechnical Engineering focusing on Environmental Geotechnics. It promotes the dissemination of knowledge, research findings and practice in the following areas:

- Pollutant barriers, waste containment and cut-off walls
- Waste mechanics
- Stability of liners & covers in landfills
- Stability of tailings dams
- Surface containment of lagoon and ponds
- Soil remediation, contaminated and damaged land reclamation
- Geosynthetics in subsurface pollution containment
- Biological soil improvement
- Environmental geochemistry
- Underground energy exploitation
- Carbon dioxide sequestration
- Nuclear waste disposal
- Others

8.3 Objectives Of TC215

The objectives of TC215 (https://sites.google.com/site/tc215issmge/) are:

- Dissemination.
- Guidelines and recommendations.
- Conference assistance.
- Industry links

8.4 Membership of TC215

8.4.1 ISSMGE

The International Society for Soil mechanics and Geotechnical Engineering (ISSMGE) currently has 71 members on TC215 (2023) representing geotechnical societies of over 30 countries. Each country has one (or more) nominated member and corresponding member. The TC is headed by Prof. Andrea Dominijanni (Italy) as Chair, Prof. Takeshi Katsumi (Japan) as Vice-Chair, and Prof. Kristin Sample-Lord (US) as Secretary. Indian Geotechnical Society currently has two nominated members and two corresponding members on TC215.

8.4.2 IGS

Indian Geotechnical Society (IGS) has 4 members nominated to TC215 for the period 2022-2025 – Prof. Manoj Datta (IIT Delhi), Prof. H.N. Ramesh (UVCE, Bangaluru), Prof. K. Ravi (IIT Guwahati), Prof. Anumita Mishra (IIT Roorkee). Earlier members of TC215 include Prof. D.N Arnepalli (IIT Madras), Prof. G.V. Ramana (IIT Delhi), Prof. D.N. Singh (IIT Bombay) and Prof. R.K. Srivastav (MNNIT Allahabad), and others.

8.5 International Activities/Milestones (1990 - 2023) of TC215

1. Quadrennial premier conference - International Congress on Environmental Geotechnics (ICEG):

1994	1st ICEG, Edmonton Canada
1996	2nd ICEG Osaka Japan
1998	3rd ICEG Lisbon Portugal
2002	4th ICEG Rio de Janeiro Brazil
2006	5th ICEG Cardiff UK
2010	6th ICEG New Delhi India

2014 7th ICEG Melbourne Australia

2018 8th ICEG Hangzhou China

2023 9th ICEG Chania Greece

2027 10th ICEG Kyoto Japan (forthcoming)

2. International Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG):

2013 1st CPEG Torino Italy

2017 2nd CPEG Leeds UK

2021 3rd CPEG Kyoto Japan (online)

2025 4th CPEG Denver Colorado (forthcoming)

3. R. Kerry Rowe Lecture: At every ICEG from 2012 onwards.

2014 1st lecture by Prof. Charles D. Shackelford

2018 2nd lecture by Prof. Mario Manassero

2023 3rd lecture by Prof. Abdelmalek Bouazza

4. Special sessions and joint sessions with other TCs of ISSMGE and sister societies at regional and international conferences
5. Workshops and educational courses
6. Special issues on specific themes in scientific journals
7. Others

8.6 National Activities/Milestones (1990 - 2023) of TC215

8.6.1 Academic Initiatives

1995 Course Syllabus developed for undergraduate elective and post-graduate elective courses on "Environmental Geotechnology" through national Curriculum Development Workshop, 23-24 Nov 1995, IIT Delhi

2003 M.Tech Program at IIT Delhi modified to "Geotechnical and Geoenvironmental Engineering", Aug 2003

2003 M.Tech Program in "Geoenvironmental Engineering" started at MNNIT Allahabad

2006 M.Tech Program in “Environmental Geotechnology” started at NIT Calicut

2017 Course on “Geoenvironmental Engineering (Environmental Geotechnology)” launched by IIT Delhi under National Program on Technology Enhanced Learning (NPTEL) (noc17-ce27) and 42 video lectures uploaded for users on NPTEL website, https://nptel.ac.in/courses/105102160

8.6.2 International Conferences, Symposia, and Webinars

2010 “6th International Congress on Environmental Geotechnics”, 10-14 Oct 2010, New Delhi. Quadrennial Congress of ISSMGE TC-215. Attended by 400 delegates including 200 from abroad

2015 International Conference on Geo-Engineering and Climate Change Technologies for Sustainable Environmental Management (GCCT-2015) 9-11 Oct 2015, MNNIT Allahabad

2018 International Conference on “Environmental Geotechnology, Recycled Waste Materials and Sustainable Engineering”, 29th – 31st March, 2018, NIT Jallandhar

2020 Geoenvironment 2020: International Seminar cum Conference on “Contaminated Sites”, and “Geoenvironment & Sustainability”, 17-19 Feb 2020, IIT Delhi

2021 International Webinar on “Landfill Mining: Experiences in India and Global Perspectives”, 4-6 Aug 2021, IIT Delhi

2023 4th International Conference on “Environmental Geotechnology, Recycled Waste Materials and Sustainable Engineering”, Oct 25-27, 2023 (forthcoming), NIT Jallandhar

8.6.3 National Conferences, Workshops, and Webinars

1992 A Theme Session dedicated to Environmental Geotechnology was introduced in Indian Geotechnical Conference (IGC) in 1992 for the first time and it has been held in every subsequent annual IGCs over the past 30 years

1997 National Workshop on “Waste Disposal in Engineered Landfills” 1-3 Feb 1997, IIT Delhi

1998 Indian National Conference on Geo-Environment, 10-12 April 1998, MNREC Allahabad

1998 National Workshop on “Industrial Solid Waste Management and Landfilling Practice”, Oct 1998, IIT Delhi

1999 National Seminar on “Geotechnical & Environmental Aspects of Managing Municipal Solid Waste”, 30 Oct 1999, MNREC Allahabad

2000 National Workshop on “Disposal and Utilization of Coal Ash”, 12-15 April 2000, IIT Delhi

2001 National Seminar on “Geotechnical Perception of Environmental Challenges”, 30 June 2001, MNREC Allahabad

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2017 National Workshop - Geoenvironment 2017: “Landfills and Waste – to – Resources”, 28 Mar and 19 April 2017, IIT Delhi

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2020 National Field Demonstration Workshop on “Environmental Subsurface Investigations”, 17-21 Feb 2020, IIT Delhi

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8.7 Key Challenges and the Way Forward

The activities of TC215 have consolidated over the years with widespread dissemination of information in various sub-areas of the Technical Committee. The key challenge for the IGS in the future is to prepare documents useful for designers and field engineers working in this area. The way forward is to set up several working groups, each of 4 to 6 experts, in all the prominent sub-areas of Environmental Geotechnics and publish guidelines, design manuals & field handbooks for all practitioners (scientists and engineers) who are involved in solving national level problems in Environmental Geotechnics.

8.8 Concluding Remarks

Activities relating to TC-215 in the areas of Environmental Geotechnics and Geoenvironmental Engineering started in mid 1990s in India and have progressed steadily over the years. These activities received a major thrust in 2010 through the organization of the quadrennial international congress, 6th ICEG at New Delhi, which was attended by over 400 delegates, including 200 from abroad. The IGS and its members in association with various institutions have spearheaded the growth of the activities through organization of conferences, seminars, webinars, workshops along with the publication of design manuals /guidelines. The focus should now shift towards publishing user-friendly material for practitioners in this area.

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9 TC 216 Frost Geotechnics

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9.1 Abstract

Frost geotechnics is an essential subfield within geotechnical engineering, focusing on the complex interactions between freezing temperatures and soil properties. Soil is said to be in a frozen state when its temperature falls below its freezing point and possess relatively high strength. However, an overlying structure may sustain damage because of issues caused by the alternate freezing and thawing of ground. The near-surface soil freeze/thaw state of the in-situ ground is related to the variation in temperature, which induces frost heave and frost thaw as the main geotechnical problems of frozen soils. In cold regions, these seasonally frozen soils are subjected to freezing–thawing cycles and undergo significant volumetric changes, which have caused considerable damage to the structures such as road, railroad, pipeline, and buildings built on, in or with them. Generally, the fine grained soils undergo significant impact of freezing-thawing cycles compared to coarse grained soil and show drastic changes in water content, volume, compressibility, strength, bearing capacity and microstrucrural arrangement of soil grains/particles during pre-and-post freezing-thawing cycles. Therefore, this manuscript presents a comprehensive overview of the key concepts, challenges, and advancements in frost geotechnics. The manuscript explores the geotechnical consequences of frost action, including frost heave, thaw weakening and changes in soil strength and stiffness due to thawing permafrost. The existing literature has been presented in the form of milestones. Further, this manuscript highlights the need for advanced modelling approaches, improved climate change impact assessments, and advanced monitoring systems to address the evolving challenges posed by freezing environments.

Keywords: Frost geotechnics, Frozen soil engineering, Frost heave, Fermafrost, Frozen ground

9.2 Introduction

Frost geotechnics, also known as frozen ground engineering, is a specialized discipline within geotechnical engineering that focuses on the complex interactions between frozen ground and engineering structures. Frozen ground, is defined as soil or rock that is at or below its freezing temperature. This distinctive geological phenomenon presents unique challenges and implications for infrastructure development and construction in cold regions, such as polar areas, high mountain regions, and northern latitudes. The behavior of frozen ground is influenced by the freezing and thawing processes, which significantly alter the mechanical and thermal properties of soils and rocks. As moisture within the ground freezes, it undergoes volumetric expansion, leading to frost heave and subsequent ground uplift. Conversely, during thawing, the ground contracts, causing ground subsidence and the potential settlement of infrastructure. These dynamic processes can exert considerable stresses on engineering structures, impacting their staility, integrity, and serviceability.

The challenges in frozen ground engineering are multifaceted and demand innovative engineering solutions. Frost heave and thaw settlement can induce differential movements in the ground, posing risks to foundations, pavements, and utilities. Infrastructure built on permafrost is also subject to climate change-induced permafrost degradation, as rising temperatures cause the ground to thaw and weaken. This phenomenon further increases the complexity of designing resilient structures in permafrost regions. This time capsule document on frost geotechnics is created to encapsulate the essential knowledge, advancements, and challenges related to frost geotechnics at present. This document would serve as a concise summary of the state of the field, aimed at informing and enlightening future generations about the complexities and significance of dealing with frozen ground.

9.3 Milestones in TC216 on "Frost Geotechnics"

The available research and literature on Milestones in TC216 on frost geotechnics starting from 1960 to date has been briefly described as below:

9.3.1 Milestones in TC216: 1960-1980

Cook (1963) showed that some clays show little or no heave especially when water supply is restricted but also exhibit segregation of ice during freezing resulting in weakening during thawing. When determining a soil's frost susceptibility, both the characteristics of frost-heave as well as thaw-weakening are taken into account. It is important to understand that both these phenomena can prove detrimental for engineering structures and that one is not necessary for the other to occur (Cook 1963).

Morgenstern and Nixon (1971) came up with a consolidation parameter called the thaw-consolidation ratio from a one-dimensional consolidation theory, to predict the behavior of thawing permafrost. The thaw consolidation ratio (R) is defined as:

$$R=\frac{\vec{x}}{\vec{S}}=\frac{\alpha}{2\sqrt{C_v}} \tag{9.1}$$

Where: $\bar{x}$ is the rate of progression of the thaw front, $\vec{S}$ is the rate of settlement, C_v is the coefficient of consolidation and α is a constant depending on thermal conditions and is given by:

$$\alpha = \sqrt{L\frac{2\lambda_u}{}T_s} \tag{9.2}$$

Where: λ_u is the thermal conductivity of unfrozen soil, L the volumetric latent heat of unfrozen soil, T_s is the surface temperature (Morgenstern & Nixon 1971).

Sykes et al. (1974) extended the one-dimensional theory into three-dimensional conditions, allowing for accurate simulation of the complex stress state as well as the water and heat migration.

The total settlement caused during spring thaw has three consequential causes, vis., volume decrease due to the phase change, consolidation due to self-weight of the thawing soil and consolidation due to external loads. Therefore, the settlement of thawing soil (S) can be determined by the following empirical equation (Wang et al. 2019; Tsytovich 1975):

$$S = A_o h + \alpha P h \tag{9.3}$$

Where: A_o is the thaw-settlement coefficient, h is the thawed depth of soil, α is the coefficient of compression of soil and P is the overburden pressure. Figure 9.1 represents the empirical equation as defined by Tsytovich (1975).

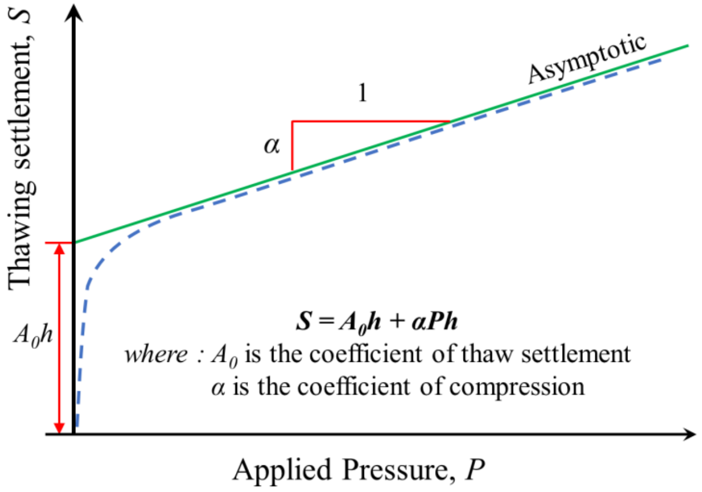

Fig. 9.1. Thaw-settlement coefficient as defined by Tsytovich (1975)

A one-dimensional frost heave model indicative of unidirectional freezing as suggested by Konrad and Morgenstern (1980) proposed that as the formation of ice lens at a site takes place, the soil above it does not contribute to the development of ice lens as the soil freezes from top downwards. The migration of water from the below towards the ice lens takes place through a partially frozen layer of soil immediately below the ice lens. This thin layer has been called as frozen fringe (Konrad & Morgenstern, 1980). Segregation potential (SP), as defined by Konrad in 1999, is the slope of the linear correlation between the velocity of pore water (v_u) moving into the unfrozen soil and the steady-state temperature gradient of the frozen fringe (Konrad, 1999). The estimation of segregation potential can help to uniquely characterize the soil for its frost-heave susceptibility (Konrad & Morgenstern 1980).

9.3.2 Milestones in TC216: 1981-2000

Frost heaving is the upward movement of the ground because of expansion of soil pore-water as it turns into ice and the development of ice lenses (segregated ice) when freezing temperatures exist in a region (Sheng, et al. 1995). The prerequisite for such an occurrence of heave is sub-freezing temperature, availability of free water and a frost-susceptible soil (Andersland & Ladanyi 1994). With sub-freezing temperature attained, the rate of freezing is a crucial factor that affects the total amount of heave produced. If a saturated sample is frozen rapidly the pore water freezes in-situ and a rich textured soil-ice matrix is obtained without any segregation of ice taking place (Wijeweera & Joshi, 1990) and the heave produced is low (not more than 9% of the water present in the sample). On the other hand slow freezing creates ideal condition for maximum ice lens formation (Simonson & Isacsson, 1999) and if external water source is available a large heave (>9%) will be produced (Andersland & Ladanyi 1994).

The availability of free water to migrate towards the freezing front consequences the development of large ice lenses (Andersland & Ladanyi, 1994). The effect on freezing behavior of soils due to the availability of free water can be explained using Fig 9.2 (Terzaghi, 1952).

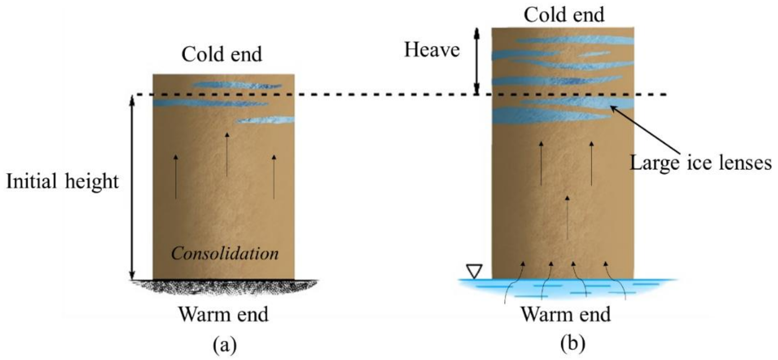

Fig. 9.2. Ice lens formation in soils. (a) Closed and (b) open system freezing

The two samples (a and b) are saturated with ‘a’ having no access to free water and ‘b’ having lower part immersed in water. The temperature of top surface is gradually lowered so that top-down freezing takes place. Temperature gradients cause moisture to migrate through the soil (Liu et al. 2019). The direction of moisture migration is controlled by the soil matric potential, which results in a change in total water content of the soil (Wen et al. 2012). The likelihood of ice lens development increases with water movement towards the freezing front (Bai, et al. 2020). There are little ice lens formations near the top surface in sample ‘a’ due to migration of water from the bottom part of the sample towards the freezing front as the freezing progresses. Due to this migration of water, the lower part consolidates while the upper part heaves. The total increase in the volume of the sample is not more than 9+% of the sample pore water content (Andersland & Ladanyi 1994). In sample ‘b’, as the water from the lower part migrates towards the freezing front and results in the initial ice lens formation. The suction thus produced draws water from the free water available at the bottom of the sample. In this way there is a continuous supply of water to the freezing front. Theoretically, ice lens formations in this case can be of several meters in thickness (Andersland & Ladanyi 1994). The use of the segregation potential for estimation of frost-heave susceptibility in geotechnical problems involving freezing is favorable as it normalizes the effect on the soil due to the intensity of freezing. It, thus, helps to evaluate the relative frost heave susceptibility of a given soil and could at the same time permit various variations in test standards (Andersland & Ladanyi 1994; Jessberger et al., 1988; Konrad 1999). Another advantage is that SPfield enables the estimation of frost heave for particular climatic and geological conditions with the chance of equating an expected value with an acceptable value of the possible frost heave based on the project constraints and the acceptable risk by the designer (Konrad, 2005). The expensive frost-heave tests, however, may not be feasible for the determination of SP and the use of readily available soil index properties may become more economical for linear projects and feasibility studies (Konrad 1999).

Chamberlain in 1981 reviewed over one hundred methods of frost susceptibility classification of soils which were based on mostly the particle-size characteristics, some on frost heave and some were based on soil-water/ice-soil-water interactions. Out of these the most commonly adopted are those based on particle size distribution because of the simple basic testing involved. Some of these tests include determination of Atterberg limits in addition to gradation of soil while others involve determination of permeability, CBR and the effects of mineralogy (Brandl 1980) in their criteria for frost-susceptibility classification. However, grain size characteristics-based methods are often not idle because they do not address the whole problem. Although most of these methods prove dependable in discarding frost-susceptible soils, non-frost-susceptible soils would also get rejected frequently thus making it a conservative approach.

To check the overall reliability of these methods, Chamberlain (1981) compared 64 grain-size criteria for frost susceptibility determination with laboratory-based freeze-thaw tests of sixteen soils reported by Kaplar (1974). Laboratory scale freeze-thaw tests, which simulate frost action in soils involve exposing the surface of an insulated cylindrical sample to freezing or thawing temperature. Based on the reliability analysis, Chamberlain (1981) reported that the most unfailing of the criteria were the ones adopted by the Association of Swiss Road Engineers (1976) and the US Army Corps of Engineers (1965) method. The American Society for Testing and Materials has proposed a standard (ASTM D5918-13) for frost-heave and thaw-weakening susceptibility tests. The test is based on the US Army Corps of Engineers (1965) method. This test is an index test to estimate the relative degree of frost-susceptibility of soil used in pavement systems. The amount of frost heave or thaw weakening in the field cannot be predicted by the ASTM method. The method is not applicable to permafrost conditions and is only recommended for seasonal frost conditions. A schematic diagram of the ASTM apparatus is illustrated in Fig 9.3. The result of thawing of frozen ground is the rearrangement of soil skeleton as the volume change occurs due to both phase change of ice into water and drainage of that water causing consolidation (Jhonson et al. 1984).

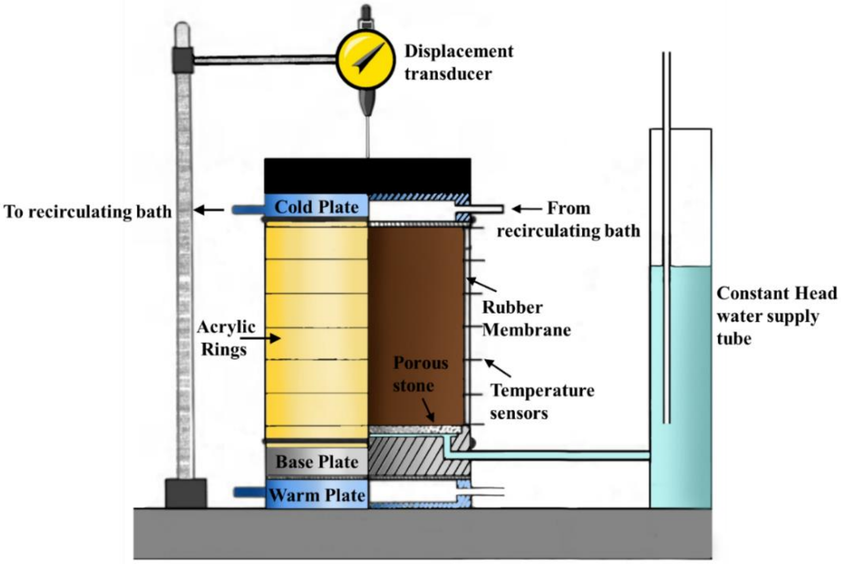

Fig. 9.3. Schematic diagram of ASTM freezing test equipment. (After Johnson et al., 1986.)

9.3.3 Milestones in TC216: 2001-2023

A criterion for the development of ice lens is presented by Zhou et al. (2014), according to which the volumetric water content must be equal to (or greater than) one for an ice lens to form (or grow). The freezing point of pure water is zero-degree Celsius. The soil pore water usually freezes below that temperature which is primarily due soil grain matrix effects and osmotic effects (Wang et al. 2021). While matrix effect encompasses the effects of soil structure, fabric, grain size and pore size distribution (Kozlowski 2009; Wen et al. 2012; Wan & Yang 2020; Wan et al. 2021), the osmotic effect includes the effect of solutes in the pore water (Ming et al. 2020). Presence of solutes in soil pore water depresses the freezing point of soil and this depression is greater for lower water contents (Arenson & Sego 2006; Bing & Ma 2011).

Figure 9.4 shows a typical cooling curve of soil. The temperature usually drops below the soil's freezing point (T_f) to a point where the pore water exists in a metastable supercooled state (T_{sc}), without changing into ice (**Error!**

Reference source not found.4). Soil particles may clump together and act as nucleating agents promoting the formation of ice crystals. Due to the latent heat produced by the development of ice, the temperature rises to T_f. The soil remains at this temperature till the free pore water in the soil freezes. The soil temperature may drop even further subject to the ambient temperature of the soil (Ming et al. 2020). The freezing point of soil is lowered by the presence of solutes in soil pore water, and this depression is larger for lower water contents (Arenson & Sego 2006; Torrance & Schellekens 2006; Shah & Mir 2022). The addition of salt lowers the overall potential of soil water while lowering the molecular interactions. As the salt content rises, the water activity drops resulting in the drop in freezing point of the soil (Ming, et al., 2020). As the pore solution freezes, the formation and growth of ice crystals is associated with the rejection of solute molecules into the unfrozen water. This results in increased solute concentration in unfrozen water, lowering the freezing point further (Bing & Ma, 2011; Arenson, et al., 2006a). The impact of common salt ions (Cl^-, CO_3^{2-} , SO_4^{2-} , K^+, Na^+, and Ca^{2+}) on freezing temperatures, as well as the impact of different solutes (NaCl, KCl, and $MgCl_2$, etc.) on the unfrozen water content in various types of frozen soils, have been the focus of a considerable research (Banin & Anderson 1974; Watanabe & Mizoguchi 2002; Bing & Ma 2011; Zhou et al. 2018; Ming et al. 2020; Wang et al. 2020). These investigations revealed that sulfate salts have a little effect on a soil's freezing temperature, whereas chloride-salt content had the greatest influence (Zhang et al. 2019; Wan et al. 2021).The characteristics of soil such as structure, grain size (Shah & Mir 2022) and pore size distribution (Xiao et al. 2018), water activity (Ming et al. 2020) and the temperature (Watanabe & Mizoguchi 2002) also affect the quantity of unfrozen water in the frozen soil in addition to the type of solute in pore water. Since the amount of unfrozen water content in frozen saline soil, compared to non-saline soil, is more, the creep and strength behavior of saline permafrosts is greatly affected. The loss of strength of frozen soil due to salinity is well studied and has been directly related to the amount of unfrozen water content in the frozen state (Ladanyi 1989). However, in regions experiencing seasonal frost, the presence of unfrozen water content and the delay in freezing of soil caused by the presence of solutes can reduce the detrimental heaving of the ground that is otherwise unfrozen.

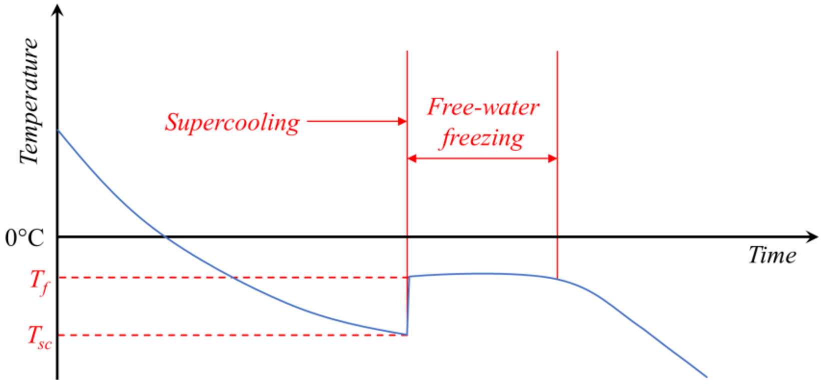

Fig. 9.4. A typical cooling curve of soil

Thaw weakening is the substantial reduction in the bearing capacity of frozen ground as it thaws. The weakening is significant in case of presence of ice lenses in the frozen state. Melting of the segregated ice saturates the soil, increasing the pore water pressure, if drainage is not permitted, and reducing the effective stress. This can result in substantial settlements and pavement failures (Saarelainen 2005). A less permeable soil which cannot drain at an adequate rate gets saturated (Simonson & Isacsson 1999). Therefore, high pore-water pressure is generated resulting in reduction of strength. On the other hand, with a relatively more permeable soil, the water produced due to thawing will get drained off quickly. As such, the pore water pressure will not increase due to saturation and the loss of soil strength will be restricted. The rate at which the segregated ice thaws has a significant consequence on the development of pore water pressure. A rapid increase of ground surface temperatures with the onset of spring will result in top-down thawing (**Error! Reference source not found.**5). This leads to a serious drainage condition in which the water produced at the surface does not find way to drain off (even in a more permeable soil) as the ground underneath is still frozen. Only transverse or upward drainage is possible in that case. However, if the temperature during spring transits slowly to higher temperature with moderate temperature occurring for longer time, thawing can occur mostly from bottom upwards, if the frozen zone is of limited thickness.

Guy Doré in 2004 proposed a mechanistic index to measure thaw-weakening of pavements. The index known as the thaw weakening index (TW_{in}) calculates the probable weakening of frozen subgrade from the observed heave and frost penetration depth at the site. The index associates the weakening potential with the thaw-consolidation ratio (R) as under:

$$TW_{in} = \frac{h}{D} * R \qquad [4]$$

Where: h is the observed/expected frost heave at the site and D is the frost penetration depth.

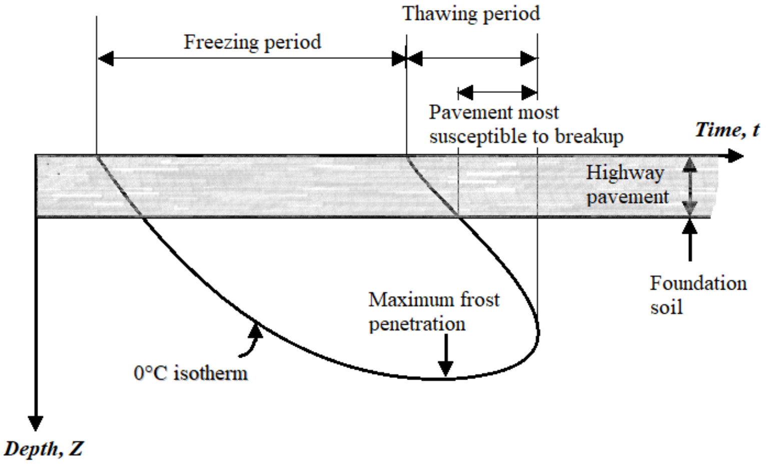

Fig. 9.5. Active layer under seasonal frost

Shoop and Affleck (2005) simulated large scale freeze-thaw test in ABACUS to study the thawing behavior of a frost susceptible soil under traffic load. Yao et al. (2012) conducted a three-dimensional analysis of the large-strain consolidation of thawing permafrost to estimate the thawing settlement of an embankment on the Qinghai-Tibet highway, taking volume and shape change into account. Wang et al. (2019) studied the effect of soil salinity on coefficient of thaw-settlement and proposed an empirical equation for calculation of thaw settlement coefficient that takes both water and salt contents into account. Conclusively, post-thaw settlement is a composite process which is affected by three aspects: the extent of heave produced, the rate of thawing and the rate of consolidation. All the three aspects are either based on the characteristics of soil or the climatic and geological conditions of the region.

9.3.3.1 Stabilized soils under freeze-thaw conditions

Various stabilization techniques have been used in the past few decades to improve the mechanical properties of problematic soils. Stabilizers such as lime, cement, fly ash, fiber reinforcements have been widely studied and implemented in field in many cases. The performance of stabilized soils under freeze-thaw conditions, has also been explore the recent time, though not much. It can be ascertained from available literature that freezing and thawing of stabilized soils greatly affects the strength and permeability of stabilized soils. Table 1 summarizes the key observations of various researchers who studied the behavior of stabilized soils under alternate freezing and thawing conditions (2010-2022).

Table 9.1 Summary of key observations on the behaviour of stabilized soils under freeze-thaw conditions

Researcher	**Additive used**	**Type of soil**	**Property studied**	**Key observations**
Hazirbaba & Gullu (2010)	Geofiber; synthetic fluid	ML (Low plasticity silt)	CBR	The value of post-freeze-thaw CBR improved. There was 58% to 60% reduction in the value of CBR post freeze-thaw.
Yıldız & Soğancı (2012)	Lime	High plastic clay; low plastic clay	Permeability, unconfined compressive strength	Permeability of stabilized soil increased 10 to 20 times, while UCS decreased 10% to 15% after 3 freeze-thaw cycles
Jamshidi & Lake (2015)	Portland cement	Silty sand and silt	Hydraulic conductivity, unconfined compressive strength	Hydraulic conductivity increased up to 5250 times after exposure to 12 freeze-thaw cycles. UCS strength decreased by 58%.
Zhang, et al. (2016)	Cement; class C fly ash; fibers	Sandy lean clay (CL) subgrade	Frost heave and thaw CBR	Frost heave susceptibility reduced to ‘negligible’ (as per ASTM-D5918) using cement but remained ‘high’ using fly ash and fibers. Post-thaw CBR, however improved using all three additives.
Bozbey, et al. (2017)	Lime and class F fly ash	CH (high plasticity clay)	Unconfined compressive strength, Initial modulus	Both UCS and Initial modulus of the treated samples reduced due to freeze-thaw conditioning and the reduction was more for samples with coarse pulverization
James, et al. (2018)	Lime, Jaggery, and Gallnut Powder	Expansive soil (CH)	Unconfined compressive strength	The most durable combination of the three additives (LJG821) lost 12.3% of its strength due to three freeze-thaw cycles.
Lu, et al. (2020)	Cement	Expansive soil	Unconfined compressive strength, resilient modulus	Despite increase in UCS, addition of cement indicated to aggravate the deterioration under F-T cycles; Increasing cement content retarded the degradation of Resilient modulus due to freeze-thaw cycles
Liu, et al. (2021)	Cement	Silty soil	Triaxial compressive strength and resilient modulus	Regardless of increase in static properties due to addition of cement, the percentage reduction in the strength and resilient modulus due to freeze-thaw cycles was almost similar to that of non-stabilized soil.
Changizi, et al. (2022)	Nano-silica	CL (low plastic clay)	Unconfined compressive strength, elastic modulus,	The reduction in UCS due to freeze-thaw cycles was restricted by the use of nano-SiO_2. However, decrease in the values of

			resilient modulus	Elastic (E_{50}) and resilient modulus (M_r) after freeze-thaw cycles was more for treated soil.
Kalkan, et al. (2022)	Quartzite	Expansive clay	Unconfined compressive strength	All the quartzite stabilized samples suffered the loss of UCS comparable to un-stabilized sample.

9.4 Key Challenges and Practices in Frost Geotechnics

Frost geotechnics, a specialized branch of geotechnical engineering dealing with frozen ground, presents unique challenges that demand innovative practices to ensure the safety and longevity of infrastructure in cold regions. This section delves into the key challenges and prevailing practices in frost geotechnics.

9.4.1 Key Challenges:

9.4.1.1 Frost Heave and Thaw Settlement:

Frost heave, caused by the expansion of moisture during freezing, and thaw settlement, resulting from soil contraction during thawing, pose significant challenges for engineering structures. The differential movements induced by these processes can lead to distress and damage, impacting the stability of foundations, pavements, and utilities.

Climate Change Impact on Permafrost Stability:

As global temperatures rise due to climate change, permafrost degradation becomes a pressing concern. The increasing frequency and intensity of thawing events can weaken permafrost, compromising its bearing capacity and creating uncertainties in engineering design.

9.4.1.2 3.1.3. Groundwater Flow Alteration:

Freezing and thawing processes in frozen ground can alter the hydrological behavior, changing groundwater flow patterns and leading to soil erosion, slope instability, and the formation of thermokarst features.

9.4.1.3 3.1.4. Thermal Insulation and Energy Efficiency:

Adequate thermal insulation of structures is critical to prevent the penetration of heat into permafrost, which can accelerate thawing. Balancing thermal insulation with energy efficiency becomes a delicate engineering challenge.

9.4.1.4 3.1.5. Construction and Maintenance Difficulties:

The construction and maintenance of infrastructure in frozen ground environments are arduous tasks due to limited construction windows, remoteness of sites, and challenging logistics.

9.4.2 Prevailing Practices:

9.4.2.1 Thermosyphons and Heat Exchangers:

Thermosyphons and heat exchangers represent innovative techniques in permafrost engineering that play a crucial role in regulating ground temperature and mitigating the effects of frost heave and thaw settlement. Thermosyphons are passive heat transfer devices that capitalize on the phase change of a working fluid to facilitate thermal energy transport. Comprising a hermetically sealed tube partially filled with a volatile liquid, thermosyphons operate based on the principles of evaporation and condensation. When the lower portion of the tube, buried within the permafrost, absorbs heat from the surrounding ground during warm periods, the liquid inside vaporizes, rising to the upper section of the tube where it condenses due to lower temperatures, releasing heat to the colder environment. The condensed fluid then returns to the lower section by gravity, creating a continuous loop. This cyclical process enables the transfer of heat from the ground surface to deeper permafrost layers, thus regulating ground temperature and reducing the risk of frost heave. In permafrost engineering, heat exchangers are employed to maintain the temperature of the infrastructure's foundation within a range conducive to permafrost preservation. During cold periods, heat is extracted from the ground and dissipated into a warmer fluid stream, preventing permafrost from thawing. Conversely, during warm periods, heat is removed from the infrastructure and transferred into the cooler ground, preventing excessive ground temperatures that could lead to thaw settlement. Thermosyphons and heat exchangers in foundation designs can regulate the ground temperature, preventing frost heave and minimizing the impact of seasonal temperature variations.

9.4.2.2 Flexible and Insulating Building Materials:

Employing flexible building materials and incorporating thermal insulation in infrastructure designs can help accommodate ground movements and reduce heat transfer to the permafrost. For mitigating the effects of seasonal frost using thermal insulation and capillary cut-off barrier such as a gravel blanket or waterproof geomembranes to effectively cut off water movement towards the freezing front can be utilised. This is, however, subject to economic feasibility of the project and the quantity of soil involved.

9.4.2.3 Ground Improvement Techniques:

Techniques like dynamic compaction and thermal stabilization are employed to enhance the mechanical properties of frozen ground, mitigating the impacts of frost heave and thaw settlement. Various stabilization techniques using additive such as lime, cement, flyash, etc have been used in past few decades to improve the performance of soils under freeze-thaw conditions. In the recent times, bio-stabilization using microbially induced calcite precipitation (MICP) or bacterial enzyme-induced calcium carbonate precipitation (BEICP) has been used as an efficient and environmentally friendly method of soil stabilization.

9.4.2.4 Advanced Monitoring and Prediction Systems:

Utilizing advanced monitoring systems, such as borehole thermistors and remote sensing technologies, enables real-time data collection and predictive modeling of permafrost behavior, facilitating proactive decision-making. Borehole thermistors and sensors are extensively deployed in permafrost regions to measure ground temperatures at varying depths. These instruments provide crucial data on thermal profiles and seasonal temperature fluctuations. The collected data aids in assessing the stability of permafrost and identifying potential areas of concern (Romanovsky et al. 2010). Remote sensing techniques, including satellite imagery, LiDAR (Light Detection and Ranging), and aerial surveys, offer valuable insights into permafrost conditions over large geographic areas. These technologies provide information on surface topography, ground temperature, and permafrost distribution. Integration with geographic information systems (GIS) facilitates data analysis and mapping (Bartsch et al. 2016).

9.5 The Way Forward

The challenges in frost geotechnics necessitate continuous research, innovation, and adaptive engineering practices. Robust numerical modeling and data-driven analyses should be employed to better understand the complex behavior of frozen ground under changing climatic conditions. Interdisciplinary collaboration between geotechnical engineers, climatologists, and environmental scientists is vital to develop comprehensive strategies that address both engineering and environmental aspects.

Furthermore, investment in long-term monitoring networks is essential to track permafrost conditions and assess the efficacy of engineering solutions. Integration of climate change scenarios into design standards and codes can ensure that infrastructure projects are resilient to future climatic conditions. Additionally, the dissemination of best practices, lessons learned from past projects, and case studies among practitioners will contribute to collective knowledge and foster better engineering practices in frost geotechnics.

By embracing a holistic and proactive approach to frost geotechnics, engineers can overcome the challenges presented by frozen ground environments and contribute to the sustainable development of infrastructure in cold regions.

9.6 Concluding Remarks

Based on the literature survey, it is concluded that:

1. As climate change continues to exert its influence, the study of frozen ground engineering assumes ever-increasing significance. It can be concluded from the literature that the problem of frost heave and thaw weakening has been addressed be many researchers in cold regions of the world.

2. The point remains of reducing the frost susceptibility of soils because replacement of such soils in the field or providing proper insulation to reduce heat loss from the ground may not always be feasible.

3. The use of chemical stabilizers and recycled materials (such as lime, fly ash, cement kiln dust, polymer fibers, etc.) have not proven much useful when it comes to reducing frost susceptibility except cement, which produced negligible frost heave and high thaw-CBR value in case of sandy lean clay (CL) subgrade.

4. The cement content also retarded the degradation of resilient modulus due to freeze-thaw cycles. The overall effect of freeze thaw cycles on stabilized soils is highly deteriorating. The observed loss of strength, development of cracks and manifold increase in permeability destroys the whole purpose of stabilization.

5. The pursuit of knowledge in frozen ground engineering is essential for the sustainable development of infrastructure in cold regions, ensuring its resilience in the face of a changing climate and contributing to the overall progress of geotechnical engineering as a whole.

6. Ongoing research and development efforts focus on improving our understanding of frost susceptibility, long-term permafrost behavior, and the broader implications of climate change on frozen ground stability.

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10 TC 218 Reinforced Fill Structures

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10.1 Abstract

Henri Vidal in 1963 modified the old concept of earth reinforcement and invented a new structure called Reinforced Earth (RE) walls. These structures are known for its impressive qualities like low weight, quick construction, economic, less space requirement and environmentally friendly. Due to these properties, RE walls are replacing the traditional concrete retaining walls. With the advent of geosynthetic products, these walls become more popular in the civil engineering field. In India, the construction of geosynthetic reinforced earth wall started in 1986. In the last four decades, the country has built hundreds of reinforced earth walls in different areas with inclusion of new material and techniques. In 2014, the Indian Road Congress has published the guidelines for design and construction of reinforced earth walls in IRC: SP:102. Although reinforced earth walls have evolved a lot with time, still there is scope for research to explore the use of marginal backfills and understand its performance in severe environmental conditions. This manuscript highlights historical developments, present challenges and future prospects in the field of RE walls specific to Indian scenarios.

Key words: Reinforced earth; Geosynthetics; Backfill; Infrastructure; Time capsule

10.2 Introduction

The concept of reinforcing the soil and improving its properties is not new. Back in older period, tree logs and plant straws were used as a reinforcement. It was Henri Vidal who gave theses old technique a modern form with the name “reinforced earth”. Henri Vidal a French architect-engineer has invented Reinforced Earth (RE) or Mechanically Stabilized Earth wall (MSE)in 1963. Reinforced Earth is a composite material, in which horizontal reinforcing elements are provided in between the compacted layer of granular backfill.

Mainly, reinforced earth walls consist of three elements, namely, reinforcement, backfill and the facing panels. A typical cross section of reinforced earth wall is shown in Figure 10.1. It is desirable that the backfill used in the reinforced earth walls should have higher shear strength and the adequate drainage properties. Therefore, granular backfill is considered to be best suited backfill material as it satisfies the above requirements. The desired gradation requirement for the fill material is given by IRC: SP: 102 (2014) and FHWA-NHI-10-025 are shown in Table 10.1. In addition to gradation requirement, it is desired that the plasticity index should be less than or equal to six. Further, according to the FHWA recommendation, the acceptable range of pH value lies between 3 and 9 for backfill with geosynthetic reinforcement.

Initially, metallic reinforcement was used as a reinforcement in RE walls. However, these reinforcements are vulnerable to corrosion in the presence of moisture. To use the metallic reinforcement in reinforced earth walls, IRC: SP: 102 [16] recommends the zinc coating of minimum thickness of 140 microns. With the advent of geosynthetics, various products like geogrid, geotextile and geostrips are being used as reinforcements in RE walls. These materials have significant tensile strength and are not susceptible to the corrosion. However, the strength of these polymeric geosynthetic products is significantly affected by temperature and creep effects. To account these factors, partial factor of safety is used to assess the long-term design strength [16].

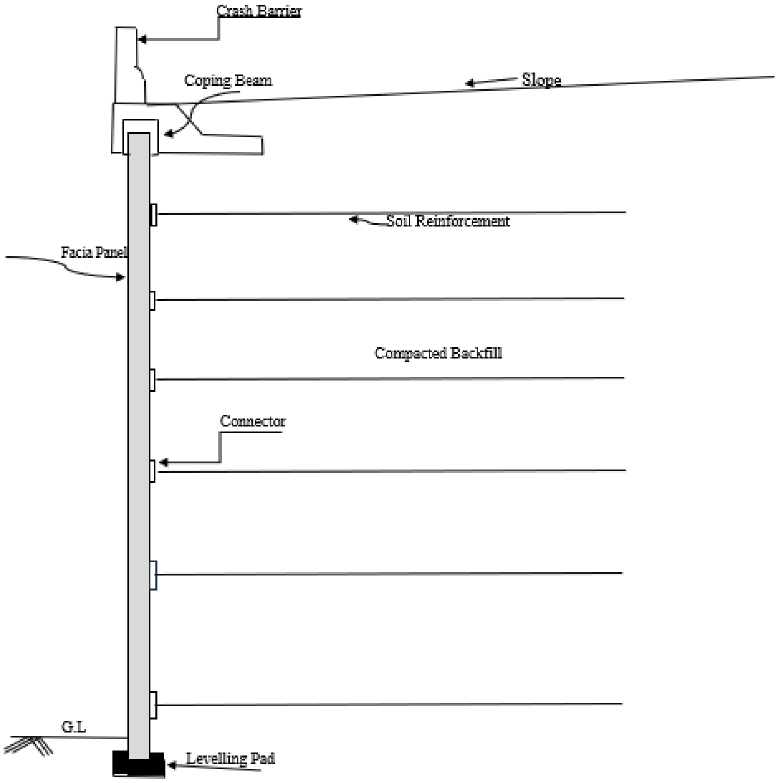

Figure 10.1. Cross section of reinforced earth wall structure

Table 10.1. Comparison of particle size gradation requirement given by IRC [16] and FHWA [17]

Sieve Size	Percentage finer (%) IRC: SP:102 [16]	Percentage finer (%) FHWA-NHI-10-025 [17].
75 mm	100	100
4.75 mm	85-100	100
425 µ	60-90	0-60
75 µ	<15	0-15

For facing element, generally pre-cast concrete panels are used. The other type of facing element includes the precast concrete blocks, gabion facing, and warp around facing with geosynthetics. The purpose of these facing panels is to hold and prevent the spilling of backfill material. With the help of connectors, the reinforcements are attached to the facing panels and extended up to few meters into the backfill as per design requirement. The reinforcement has a dual role; first is to hold the facing elements in position and second is to resist the lateral active earth pressure coming from the backfill soil. The lateral active earth pressure is resisted by the frictional resistance of the reinforcement generated due to interaction between the backfill soil and the reinforcement [18]. The length of the reinforcement should be such that it should extend to the resisting zone of the reinforced earth wall system.

Initially, the application of reinforced earth walls was limited to roads; but nowadays, it has been widely used in waste containment, river bridge abutment, seawalls, dikes etc. It has many advantages in comparison of traditional concrete retaining walls such as low cost, less space requirement, less construction time, less weight etc. More than 200 000 MSE walls had been constructed by 2018 worldwide [21]. India has built its first geosynthetic reinforced wall in 1986. In the past three decades, our country has built several reinforced earth walls by adopting modern techniques. In 2021, tallest reinforced earth of height 102.8 m was built in Darjeeling district of West Bengal [15].

10.3 Overview of the time capsule project

This paper is motivated by the time capsule project (TCP) of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The historical developments in the field of reinforced fill structures in India has been covered over the past four decades (1980-2023). Key milestones in the construction of reinforced earth walls with brief insights into technical aspects of the projects are discussed in the subsequent sections. At the end, the present challenges and the future prospects are discussed.

10.4 Milestones in reinforced fill structures in India

This section covers the key milestone in the applications of the reinforced earth walls in India since 1980s.

1980-2000:

The first geosynthetic reinforced earth wall in India was built in 1986 for road over rail bridge approach on NH-1 near Ludhiana. The height of this wall was 8 m and concrete panel was used as a facing element. Geostrip was used as a reinforcing element [1]. Further in 1995, a 60 m long reinforced earth wall was constructed for the Okhla flyover in New Delhi. The height of the wall varies from 7.3 m to 5.9 m. Uniaxial geogrids were used as a reinforcement. Instead of granular backfill, fly ash was used as a backfill material [2].

2000-2020:

In 2002, reinforced earth walls were constructed on Bypass Road in Kanpur on NH-2. PET geogrids were adopted as the reinforcing element with precast concrete panels were used as facia elements. Doing so, India became the first country in the world to have adopted PET geogrids as a reinforcement in the reinforced earth walls [3]. Next, on Vijayawada -Vishakhapatnam section of NH-5 in Andhra Pradesh, one road over bridge and three vehicle underpasses were constructed with REwalls. The limited time frame was one of the main challenges in the project. Secondly, the cost available for the project was also less. Considering the situations, reinforced earth walls were constructed. Geogrids were adopted as a reinforcement and precast concrete panel as a facia element. The maximum height of the wall was 13.6 m and the project was completed in February 2005. The oblique view of the constructed wall is shown in Figure 10.2.

Figure 10.2. Oblique frontal view of geogrid reinforced segmental retaining wall at NH-5, Bypass near Kanpur [4]

Next, a reinforced earth wall with wrap around with vegetative facia was constructed in July 2008 near tunnel no. 1 at Katra Jammu and Kashmir. The height of the wall was 10 m and TechGrid knitted & PVC coated polyester Geogrids was used as a reinforcing element. The facing comprised of a geogrid wrapped face supported by L-shaped galvanized welded wire mesh panels. The RE wall acted as an impact resistance pad on both sides of the tunnel taking the load of the slush/ muck which may come over the tunnel with high momentum endangering the foundation [5].

In 2008, on NH-7, a reinforced earth wall was constructed for trumpet interchange. The height of the wall was about 15 m and galvanized steel strips were used as a reinforcement. The whole project was completed in only 5 months. The same type of interchange was constructed in Hyderabad of height around 17 m. Two types of reinforcement were used in this reinforced earth wall at the interchange. For height up to 11 m, Geostrap9 and from 11 to 17.5 m, galvanized steel strips was used as reinforcements [6]. In 2010, a RE wall was constructed as part of the highway approach to the railway over bridge in Hyderabad-Bangalore highway in Anantapur in Andhra Pradesh. The total height of RE wall is 13.85 m with 9.5 m above ground level. The steel strips were used as the reinforcements in the construction. Precast concrete panels were used as the facing elements. The length of the wall was more than 100 m [25]. Figure 3 shows the photograph of the RE wall. Further in 2013, a reinforced earth wall of height varying from 2 to 11 m was constructed to support a villa on the top of hill at Kumne village Lonavala. Geogrid was used as a reinforcing element and steel wire mesh with non-woven geotextile as a facia. The total constructed length of the wall was 120 m [7].

Figure 10.3. Photograph of the RE wall in Hyderabad-Bangalore highway in Anantapur [25]

Due to the rapid increase in the number of constructions of reinforced earth walls over past decades, there was a need to standardize the design methodologies for the reinforced earth walls. Due to this reason, on 19th January 2014, the council of Indian Road Congress in its 201st meeting at Assam approved the guidelines for the design and construction of reinforced earth walls and the same has been published in IRC: SP: 102 [16].

In 2015, reinforced earth wall was constructed on NH-24 for wing wall and abutment closure at Moradabad-Bareilly section. The height of the wall was 10 m [8]. A new methodology 'TerraLink' was used in thes construction. This technique involves the linking the wall with the existing structure when the enough space is not available for the construction. The reinforcements are connected to the existing structures due to the reinforced fill zone is not wide enough to accommodate conventional lengths of reinforcements due to space constraints. Using this technique in 2016, an elevated service road in Bengaluru was constructed at the toe of a hill. Considering the safety of structures at the hilltop, TerraNails with grouting was used to connect nails with existing slope. The constructed height of the wall varies from 3 m to 10 m [9].

Next, in Kaljani West Bengal, reinforced earth wall was constructed for a bridge approach way with a 70-degree slope. The major challenges in the project were the limited construction time and less space availability. Considering all the problem, GeoStrap reinforced earth wall with wire mesh as a facia was constructed in 2017. The maximum height of the wall was 9 m. In addition, the soil on the site was very soft, which would not have withstand the load of the conventional retaining wall. The detailed cross-sectional drawing of the constructed GeoTrel wall is shown in Figure 10.4.

The next milestone in the field of reinforced earth wall in India was in 2017 at Vapi, Gujrat. The country's first vertical landfill was constructed with the use of the reinforced earth wall of 15 m height. The existing landfill at Vapi needed the vertical expansion to store more wastes as the horizontal expansion was having certain constraints. To overcome the problem, the reinforced earth wall was constructed for containment purposes using 'StarGrid' as a reinforcement and 'StarBlock' as a facia element. After the vertical expansion, the storage capacity was increased two times as compared to conventional technique [11].

On NH-48, along the six-lane road stretch connecting Ahmedabad to Vadodara, India's largest reinforced earth wall was constructed in 2018. 'StrataGrid' polyester knitted geogrids as soil reinforcement and precast segmental concrete blocks were used as a facia element. There were 46 crossovers in between the road stretch. By constructing the reinforced earth wall, a huge cost saving was achieved [12]. Further in 2019, a composite gabion reinforced soil was constructed at New Mumbai international airport near Gadhi River. The purpose of the wall was to train the river stream and reclaim the land for the construction of the airport. Polyester uniaxial geogrid was used for the reinforcement. The metal gabion was used as a facia element. Non-woven geotextile was installed in between gabion and backfill to retain soil particles. The maximum height of the wall was 12 m [13].

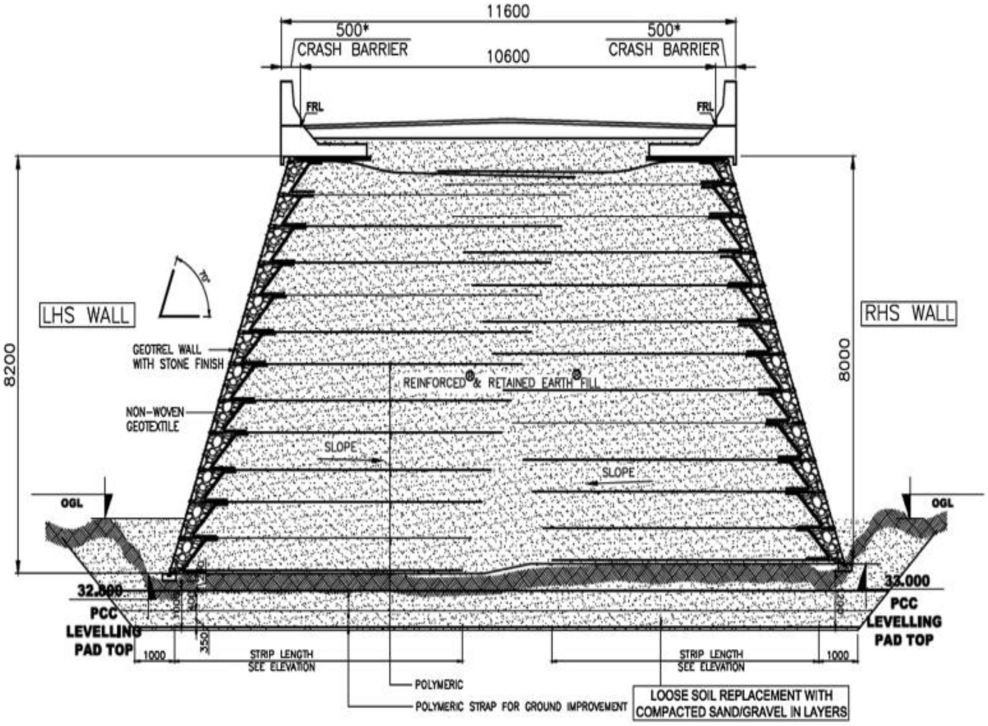

Figure 10.4. The cross-sectional drawing of reinforced earth wall at Kaljani West Bengal [10].

2020-Present:

In 2020 for the Gondal railway portion road over bridge in Gujarat, reinforced earth wall was constructed to ease the heavy traffic in the area. The project requirement was to restrict the acquisition of adjacent private lands and to design a lightweight structure due to the poor geotechnical condition of the site. The maximum height of the wall was approximately 11 m in which GeoStrap polymer was used as a reinforcing element [14]. The major milestone in the area of reinforced earth wall was achieved in India was in year 2021. World's tallest reinforced earth wall with a height of 102.8m was constructed in Darjeeling district of West Bengal on NH-110. GeoStrap made from high tenacity polyester encased in LLDPE sheeting was used as a reinforcement. TerraLink technique was adopted for building the wall in a limited base space of only 2 m [15].

10.5 Key challenges and practices in reinforced fill structures

The first major challenge in the construction of reinforced earth walls is the availability of good quality granular backfill. Conventionally, sand has been the preferred choice for backfill material in RE walls. However, with the growing concern over the depletion of natural resources, finding the suitable alternative is a key challenge. The good quality sand, which is suitable for the backfill is only available in some parts of India. Hence, the transportation of these materials from one place to another can be expensive and cumbersome. Second, the challenge is related to the performance of polymeric reinforcement under the UV rays. Polymeric products can undergo degradation with time when exposed to UV rays. Due to which, the interface friction angle reduces resulting in increased deformation in the walls. The third challenge is associated with the construction companies. There are only few Indian companies having required expertise in the design and construction of reinforced earth wall. Lastly, the performance of reinforced earth wall under the extreme events like earthquakes, tsunamis and cloudbursts are not fully understood and needed further research.

10.6 Way forward

The need of the hour is to explore the options of using marginal fills as an alternative to standard backfills in RE wall. Marginal fills are those materials which may not necessarily meet the requirements laid down by various codal provisions. Examples of marginal fills include recycled waste materials like steel slag, copper slag, fly ash and construction demolition waste (CDW) etc. Also, the granular soil with significant fines content can also be termed as marginal fills. Use of the marginal fills not only reduce the dependency on sand but also help to address the disposal issues with some of the aforesaid waste materials. Sarkar and Hegde [19] conducted laboratory studies to explore the utilization of steel and CDW in RE wall backfill applications. The study revealed that the performance of the aforesaid waste materials is comparable to the performance of the sand backfill materials. Similarly, Mandloi and Hegde [20] and Mandloi et al. [23] conducted the numerical investigations on prototype RE walls to study the efficacy of the steel slag and construction waste in backfill applications. The results demonstrated a significant reduction in the horizontal facing displacement at the top of the wall in the presence of aforesaid waste materials. Santos et al. [22] investigated the performance of a full-scale instrumented MSE wall model with CDW backfill and reported satisfactory performance.

Another material which could be potentially used as an alternate backfill material is sand-rubber mixtures. Waste tires have evolved as one of the leading recycled lightweight materials that can be used in several civil engineering applications. Bandyopadhyay et al. [24] conducted the shake table studies to evaluate the seismic performance of MSE wall constructed with sand-rubber mixtures of varying proportions as backfill material. The use of the crumb rubber in the backfill found to reduce the lateral earth pressure on the wall. Crumb rubber- sand mixture with a rubber content of 30% showed optimum values and thus recommended to be used as a backfill in MSE walls.

Although the field of reinforced earth wall has evolved a lot, still there is a need for developing the closed form solutions for determining the stress and displacements under different load combinations. These solutions can be used for not only design the structures but also to validate and train the numerical models. Further, the available design guidelines have not fully complied to design the structures under extreme events like earthquake, Tsunami, and cloudbursts. Therefore, the research activities need to be taken up to study the behaviour of RE walls under the extreme events. Further, there is a need for the preparation of design guidelines and codal provisions for designing the walls under extreme events. More and more case studies should be documented to create a database on the application of the MSE walls under different practical scenarios. These case studies can help the designers, practitioners and the researchers to gain the necessary insights for implementing RE wall solutions in challenging geotechnical problems.

10.7 Summary

The manuscript summarized the development of the reinforced earth walls in India in last 4 decades. Since building the first RE wall in 1986, India has witnessed significant growth in the applications of RE wall for various infrastructure projects. The study of the historical developments suggests that the RE wall construction in Indian is continuously evolving by embracing the new techniques and materials. The significant growth in the RE wall sector was witnessed between the year 2000-2020. Mainly, the space, time and the budget constraints were the main reasons for opting for the RE wall as compared to conventional retaining walls. The construction of the word’s tallest RE wall in Darjeeling district of West Bengal has certainly put India on the global map of the RE wall construction. However, in order to tackle the future challenges, a significant research and development activities need to be taken up in the areas of use of the marginal fills, seismic response and performance in extreme environmental conditions. Constant interactions between the industries and academia are the need of the hour to invent new applications and advance the current knowledge on the reinforced earth walls.

10.8 Data availability statement

All data underlying the results are available as part of the article and no additional source data are available with authors.

10.9 Funding details

No specific funding details are available.

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11 TC 220 Field Monitoring in Geomechanics

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11.1 Abstract

Field monitoring in geomechanics is an indispensable practice that enables engineers to unravel the complex behaviour of geotechnical structures buried beneath the Earth's surface. This abstract encapsulates the essence of field monitoring, highlighting its significance, methodologies, and key findings. The primary goal of field monitoring is to collect real-time data from geotechnical constructions such as foundations, slopes, retaining walls, and tunnels to validate design hypotheses and projections. Engineers may acquire a thorough understanding of how these structures respond to different loading circumstances by continuously monitoring crucial metrics like stresses, strains, deformations, groundwater levels, and environmental factors. A major component of field monitoring is the choice and installation of the proper devices. The kind of structure, projected loads, deformations, and desired precision are all factors considered while selecting instrumentation. Field monitoring data represent a wealth of knowledge that necessitates expert analysis. Engineers create correlations between various parameters, compare measured values to design predictions, and look for patterns and anomalies that point to problems with structural performance. The accuracy of forecasts and design choices is improved by using this data to calibrate and validate numerical models used for geotechnical analysis.

Keywords: Field monitoring, Geomechanics, Real-time data, Instrumentation, Numerical modelling

11.2 Introduction

Geomechanics is the study of soil, rock, and their interactions with engineering structures such as foundations, slopes, tunnels, and retaining walls. Field monitoring in geomechanics is critical for understanding the behaviour of geological materials and structures under real-world situations. It entails the systematic observation, measurement, and analysis of various parameters to evaluate the performance, stability, and integrity of geotechnical systems. It entails the gathering and analysis of data from actual geotechnical projects, which is essential to geotechnical engineering research. It offers insightful information about the functioning of geotechnical structures, the behaviour of soil and rock masses, and the verification of design presumptions. We can obtain crucial data through field monitoring to strengthen design processes, increase understanding, and guarantee the dependability and safety of geotechnical projects. It aims to collect precise and thorough data directly from the field measurements of several geotechnical parameters, such as soil characteristics, groundwater levels, stresses, deformations, and environmental factors; typically, specialised instrumentation strategically positioned in the right places is used to capture this data. We can examine the performance of geotechnical constructions, evaluate the behaviour of the soil and rock masses under various loading and environmental circumstances, and detect any problems or dangers by using the data gathered during field monitoring. The efficiency of numerous geotechnical approaches, such as ground improvement techniques, slope stabilisation measures, and foundation systems, can also be studied. Researchers can validate the performance of these methods in the field and make the required alterations or enhancements to increase their efficacy. In geomechanics, numerous instruments and measuring systems are used in field monitoring procedures. Installation of sensors, such as strain gauges, piezometers, inclinometers, settlement gauges, and seismometers, may be one of these. These sensors can be used to measure a variety of characteristics, including stress, deformation, groundwater pressure, slope movements, and vibrations.

LiDAR, GPS, and satellite images are a few examples of remote sensing tools that are used for extensive monitoring and geographical analysis. Field monitoring in geomechanics plays a crucial role in understanding and managing complex geological and geotechnical conditions prevalent in India. The vast geographic expanse of India encompasses diverse landscapes from the Himalayas in the north to the coast in the south. These diverse terrains present a variety of geotechnical challenges, including slope stability, landslides, seismic hazards, foundation design, and groundwater management. The use of field monitoring is indispensable for understanding the dynamic behaviour of these geotechnical systems and making informed decisions. Data from field monitoring can be used to create accurate models of the geotechnical systems. These models can then be used to predict future behaviour and develop mitigation strategies.

By combining field data with advanced modelling, engineers can ensure the safety and effectiveness of infrastructure in India's diverse landscapes. Urbanisation and industrial growth in India further exacerbate the need for effective field monitoring. Large-scale infrastructure projects require comprehensive monitoring to ensure safety, structural integrity, and longevity. To assess risks, monitor ground movements, and implement appropriate mitigation measures, robust field monitoring systems are needed in India due to its vulnerability to natural disasters. Field monitoring can also help to identify potential hazards and provide early warning systems. This can help reduce the effects of disasters and minimise the cost of damage. A reliable field monitoring system is crucial for Indian development. The introduction of advanced monitoring technologies in India, including remote sensing, geophysical surveys, satellite imaging, and real-time monitoring systems, has revolutionised geomechanics. As a result, these technologies provide detailed information for analysis, early warnings, and informed decision-making on geotechnical systems. Geomechanics allows interdisciplinary collaborations between geotechnical engineers, geologists, seismologists, and environmental scientists. Such collaborations facilitate the exchange of knowledge, expertise, and best practices, leading to the development of innovative monitoring techniques.

This time capsule preserves and disseminates information for the benefit of future academics, practitioners, and decision-makers. It will highlight the achievements, difficulties, best practices, and possibilities of field monitoring in geomechanics in India.

11.3 Overview of the Time Capsule Document

This document is a compilation of 40 research papers from journals that address various aspects of field monitoring in the discipline of geotechnical engineering. These publications have been chosen with care to show the developments, difficulties, and creative methods in monitoring soil, rock masses, geotechnical constructions, and associated phenomena. The goal of the time capsule document is to provide future researchers, engineers, and professionals with useful information about the state of field monitoring over the specified period.

11.4 Reason for Creating a Time Capsule Document

The main goal of this Time Capsule document is to exhibit and preserve the collective knowledge and advancements made in the area of field monitoring in geomechanics. The document summarises the state of the art. It offers insights into the methodology, case studies, difficulties, and developments associated with field monitoring in geomechanics by bringing together a broad collection of academic papers. The document also seeks to serve as a source of inspiration and learning for future researchers and practitioners. By reviewing the research papers included in the Time Capsule, readers can gain a comprehensive understanding of the field, identify emerging trends, and build upon the existing knowledge to further advance field monitoring techniques in geomechanics.

11.5 Background

Geomechanics field monitoring is essential for determining the behaviour, effectiveness, and stability of geotechnical systems. It entails systematically observing, measuring, and analysing variables like vibrations, groundwater pressure, stress, and deformation. Field monitoring gathers data under actual settings and offers priceless insights into how geotechnical systems react to outside forces, environmental changes, and time-dependent processes. The rapid developments and increasing significance of field monitoring in geomechanics have necessitated the creation of a Time Capsule document. Significant advancements have been made in the sector in terms of instrumentation, data-gathering methods, data processing, and integration into design and decision-making processes. The Time Capsule intends to record and preserve the information produced by these developments by combining the research articles into a single document.

Researchers, engineers, and industry professionals in the subject are acknowledged in the Time Capsule paper for their interdisciplinary work, knowledge, and commitment. To ensure that their contributions continue to motivate and educate future generations, it emphasises the importance of sharing and protecting them.

11.6 Milestones

Year	Author	Paper	Journal	Significance
1997	B. Singh et al., 1997	"Rock Mass Strength Parameters Mobilised in Tunnels"	Tunnelling and Underground Space Technology	Analysed mobilised strength parameters and modulus of deformation have been deduced from back analysis of the field experience.
1999	V. K. Singh & Singh, 1999	"Geotechnical study of the optimum design of the Chandmari Coppermine, Rajasthan, India "	Engineering Geology	The limit equilibrium method is developed for measuring structural discontinuities.
2006	C. Richard Donnelly, 2006	Engineering and Construction of Tunnel Portals in Chamera, India	Canadian Dam Association Annual Conference	The study highlights the introduction of state-of-the-art tunnelling, excavation, and rock support techniques, providing valuable insights and knowledge to engineers

				and contractors encountering similar projects for the first time.
2008	Sivakumar et al., n.d.	“RealTime Microseismic Monitoring to Study Geomechanics of Underground Structures”	International Association for Computer Methods and Advances in Geomechanics (IACMAG)	Integrated Seismic System (Strata behaviour in real-time)
2008	R Dharmaraju et al., 2008	Evaluation of Landslide Behaviour Based on Geological and Geotechnical Investigations in Sikkim Himalaya – a Case Study	International Association for Computer Methods and Advances in Geomechanics (IACMAG)	It focuses on applying geotechnical field and laboratory investigations and some simple devices used for surface and sub-surface movement monitoring of landslide areas. Based on such assessment, prediction of probable failures of the slide area can be made.
2010	Latha & Garaga, 2010	Stability analysis of a rock slope in the Himalayas	Geomechanics and Engineering	Numerical slope analysis used the equivalent continuum approach using commercial numerical tools like FLAC and SLOPE/W of GEOSTUDIO, pseudo-static, and kinematic analyses.
2011	Hayden & Puleo, 2011	Near Real-Time Scour Monitoring System: Application to Indian River Inlet, Delaware	American Society of Civil Engineers	Scour monitoring system (SM) using two three-dimensional profiling sonars to observe bathymetry.
2010	A Ghosh et al., 2010	Stability assessment and suggestion for control measures of a potential landslide slope on nh 94, Uttarakhand Himalaya, India	Conference: 5th Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics	The vulnerability assessment of the slope is being monitored through instrumentation. The study involved geological and geotechnical investigations, slope stability analysis, and monitoring of movements.
2013	Vinoth & Ajay Kumar, 2014	Applying real-time seismic monitoring technology for slope stability assessment—An Indian opencast coal mine perspective	International Journal of Mining Science and Technology	Seismic monitoring technique to investigate the stress changes within the rock mass along the slope due to underground mine development operation and their impact on the stability of the high wall slope
2013	M. Palomba et al., 2013	Chenani-Nashri Tunnel, the longest road tunnel in India:	World Tunnel Congress	3D Monitoring System, numerical analysis in understanding the real rock mass behaviour

		A challenging case for design optimisation during construction		
2013	Kanungo et al., 2013	Finite element modelling approach to assess the stability of debris and rock slopes: a case study from the Indian Himalayas	Natural hazards	The slopes were modelled as a continuum using a 2D finite element plain strain approach.
2014	Pitchumani & Madhav, 2014	A Field Monitoring Study on Pre-compression of Soft Deposit for Ballastless Railway Tracks for Chennai Metro Rail	Indian Geotech	Plate settlement markers were installed at the original ground level, and settlements were continuously monitored under a surcharge load.
2014	Gandhi, 2016	Observations on Pile Design and Construction Practices in India	Indian Geotech	Full-scale field tests and monitoring with instrumentation are emphasised to achieve an optimum pile design.
2014	Kainthola et al., 2015	Stability investigation of road cut slope in the basaltic rock mass, Mahabaleshwar, India	Geoscience Frontiers	Used numerical models to accomplish a holistic stability examination
2014	Giorgio Höfer-Öllinger et al., 2014	Underground Crude Oil Strategic Storage Projects in India.	World Tunnel Congress	Geological and/or geotechnical investigations carried out during the construction of unlined underground caverns through Geotechnical Instrumentation (optical targets and borehole extensometers) and Monitoring
2014	Gaurav Sahu et al., 2014	Performance Monitoring of Bridges Through Instrumentation	9th International Symposium on Advanced Science and Technology in Experimental Mechanics	Monitoring of deflection profiles, sinking of piers, temperature gradients, strain, tilt, and shrinkage.
2016	Mahanta et al., 2016	Stability analysis of potential failure zones along NH-305, India	Natural hazards	Hazard zonation studies using bivariate statistical analysis.
2017	Pal & Saha, 2018	Identifying dam-induced wetland changes using an inundation frequency approach: The case of the Atreyee River basin of Indo-Bangladesh	Ecohydrology & Hydrobiology	Concentrates on wetland delineation by Landsat satellite image-based water presence frequency approach.
2018	Yhokha et al., 2018	Application of Persistent Scatterer Interferometry	J . Earth Syst. Sci.	Persistent Scatterer Interferometry For monitoring slope movement.

		(PSI) in monitoring slope movements in Nainital, Uttarakhand Lesser Himalaya, Indi		
2018	Tiwari et al., 2018	Analysis of Tunnel Support Requirements Using Deterministic and Probabilistic Approaches in Average Quality Rock Mass	American Society of Civil Engineers	A new computational approach, based on the geological strength index (GSI) and the use of deterministic and probabilistic methods, is described for the reinforcement design of a tunnel in an average-quality rock mass.
2019	Samanta et al., 2019	Slope stability assessment and design of remedial measures for Tungnath Temple at Uttarakhand, India: a case study	Natural hazards	Slope stability analyses were conducted using the limit equilibrium method (LEM).
2019	Abhirup Dikshit & Neelima Satyam, 2019	Monitoring of Unstable Slopes with Low-Cost Sensor Network in Chibo, Kalimpong, Darjeeling Himalayas, India	Geotechnical Engineering in the XXI Century	MEMS-based tilting sensors. The system would help in developing an early warning system.
2020	Congress & Puppala, 2020	Evaluation of UAV–CRP Data for Monitoring Transportation Infrastructure Constructed over Expansive Soils	Indian Geotech J	The study highlights the significance of utilizing UAV–CRP technology in the health monitoring of pavement infrastructure built over problematic soils, providing a safe, inexpensive, and comprehensive approach. The results demonstrate a strong correlation between UAV–CRP-interpreted performance indicators and traditional survey methods, showcasing its potential as an effective tool for assessing pavement conditions and addressing geotechnical issues.
2020	Abraham, Satyam, Pradhan, et al., 2020	IoT-Based Geotechnical Monitoring of Unstable Slopes for Landslide Early Warning in the Darjeeling Himalaya	Sensors	The significance of this study lies in its contribution towards the improvement of landslide early warning systems (LEWS) in landslide-prone areas, specifically the Indian Himalayas. By monitoring slopes using sensor networks and analyzing the relationship between tilt rate, water content, and rainfall, the study highlights the importance of

				considering long-term rainfall conditions for developing effective rainfall thresholds, ultimately reducing the number of false alarms and enhancing the efficiency of LEWS in the region.
2020	Abraham, Satyam, Bulzinetti, et al., 2020	Using Field-Based Monitoring to Enhance the Performance of Rainfall Thresholds for Landslide Warning	Water	The significance of this study lies in the development of an integrated approach for Landslide Early Warning Systems (LEWS) that combines rainfall thresholds and field monitoring data. By incorporating real-time field measurements using tilt sensors, the approach reduces false alarm rates and improves the efficiency of the system, resulting in a higher accuracy of landslide predictions (92%) compared to solely relying on rainfall thresholds (84%).
2021	Pooja et al., 2021	Correspondence of PSInSAR monitoring and Settle3 modelling at Cochin International Airport, SW Indi	Applied Geomatics	Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR), using Sentinel-1A images,
2021	Falae et al., 2021	Geo-integrated assessment of the landslide zone around Gadora along NH 58 of the Garhwal Himalayas, India	Near-surface geophysics	The study was significant as it addressed the urgent need to mitigate the damage caused by the active Gadora village landslide zone and provided crucial information about the subsurface layering and drainage patterns to enable stability analysis of the slope.
2021	Mali et al., 2021	Determining the Geotechnical Slope Failure Factors via Ensemble and Individual Machine Learning Techniques: A Case Study in Mandi, India	Frontiers in earth science	ML techniques (Random Forest (RF), AdaBoost (AB), Bagging, Stacking, and Voting) and individual ML techniques (Bayesian network (BN), decision tree (DT), multilayer perceptron (MLP), and support vector machine (SVM))
2021	Dr Vinay K U M A R Pandey, 2021	Infrastructure projects and geotechnical challenges in the Himalayas, India	International Research Journal of Modernization in Engineering	New Austrian Tunneling Method (NATM), Drill and blast method, Tunnel Boring Machine

			Technology and Science	
2022	Dutta et al., 2022	Satellite hyperspectral imaging technology as a potential rapid pollution assessment tool for urban landfill sites: a case study of Ghazipur and Okhla landfill sites in Delhi, India	Environmental Science and Pollution Research	Hyperspectral imaging technology
2022	Mali et al., 2022	Identifying Geotechnical Characteristics for Landslide Hazard Indication: A Case Study in Mandi, Himachal Pradesh, India	Arabian Journal of Geosciences	Multivariate correlation analysis
2022	Gholinia et al., 2022	Validation of borehole extensometers result in geotechnical monitoring.	Environmental Earth Science	Rod and magnetic extensometers. .
2022	Ahmed et al., 2022	3D Monitoring in Tunnels, Ground-Support Interaction and its Implications with Emphasis on Tunnel T-74R of USBRL Project, India	Indian Geotech J	3D monitoring data
2022	Kozyrev et al., 2022	The Impact of Surface Water Seepage on Seismicity and rock bursting in Mines	Sustainability	The significance of study lies in identifying the relationship between snowmelt conditions and increased geodynamic events, particularly seismic activity, at mining sites. Understanding these conditions can contribute to improving geodynamic and environmental safety measures in mining regions, ensuring their sustainable development.
2023	Ramakrishna & Rao, 2023	Geotechnical Investigation and monitoring of underground excavation of tunnel-2 in Srisailam left bank canal tunnel project (AMRP),	Geosciences research	The underground excavation was mapped by face mapping and geological logging.

		Nalgonda District, Telangana, India		
2023	Thakur et al., 2023	Geological and geotechnical investigations of the Sataun landslide along the Active Sirmauri Tal Fault, Sataun, Northwestern Himalaya, India	Landslides	The investigation of the landslide was carried out using geological, geomorphological, geotechnical, and kinematic analysis. pre-landslide topography was used to analyse the slope stability using FEM (finite element modelling) technique.

11.7 Key Challenges and Practices

Field monitoring in geomechanics presents several key challenges that must be addressed to ensure accurate and reliable data collection and interpretation. Instrumentation and sensor placement are critical challenges in field monitoring. Selecting the appropriate monitoring parameters and instruments for a specific geotechnical application is essential. Factors such as the type of geotechnical system, the desired resolution of measurements, and the environmental conditions must be considered when choosing the right sensors. Also, proper installation techniques ensure reliable data collection and minimise measurement errors. Managing and processing large volumes of monitoring data pose challenges in data storage, organisation, and processing. Efficient data management systems and techniques, such as data archiving, metadata documentation, and quality control procedures, are necessary to handle the significant amounts of data generated by field monitoring campaigns. Advanced data processing and analysis techniques, including statistical analysis, data visualisation, and numerical modelling, are employed to extract meaningful information from the collected data. These techniques help identify trends, patterns, and anomalies in geo-mechanical behaviour, facilitating data-driven decision-making. Interpreting and analysing monitoring data requires expertise in geomechanics and knowledge of the specific geotechnical system under investigation. Challenges may arise due to data uncertainties, complex geo-mechanical processes, and the need to differentiate between natural variations and potential signs of instability or failure. It is essential to integrate field monitoring data with geological, geotechnical, and other relevant information to understand the subsurface conditions and their influence on the behaviour of geotechnical systems. Addressing the challenges of field monitoring involves implementing best practices. Standardised procedures for instrument installation and calibration ensure consistent and accurate measurements. Effective data management strategies, including data backup, quality control, and metadata documentation, are crucial for maintaining data integrity and accessibility. Continuous education and training of personnel involved in field monitoring are essential to stay updated with the latest advancements, methodologies, and technologies in the field. Collaborative efforts between researchers, practitioners, and industry stakeholders foster knowledge exchange and drive innovation in field monitoring practices.

By addressing these challenges and implementing best practices, field monitoring in geomechanics can achieve more reliable and insightful results, leading to better understanding, assessment, and management of geotechnical systems. Advancements in instrumentation, data processing techniques, and interdisciplinary collaborations will continue to drive the field forward, ensuring the safety and sustainability of geotechnical infrastructure in the face of dynamic geo-mechanical behaviour.

11.8 Way Forward

As we look to the future of field monitoring in geomechanics, the Field Monitoring Time Capsule (FMTC) serves as a valuable resource to guide the way forward. It captures the advancements and challenges faced in the field and provides insights into the practices and methodologies that can shape the future of field monitoring. Field monitoring holds immense potential for further advancements and improvements; embracing emerging technologies and technological advancements, such as wireless sensors, IoT connectivity, and artificial intelligence, can revolutionise data collection, analysis, and real-time monitoring capabilities. Automation and remote monitoring solutions, including unmanned aerial vehicles and satellite imagery, offer opportunities for more efficient and cost-effective monitoring practices. Integrating data from multiple sources and disciplines and enhanced data analysis techniques, such as machine learning algorithms and data-driven modelling, can provide deeper insights into geo-mechanical behaviour. Establishing standardised protocols, best practices, and guidelines for instrumentation installation, data quality control, and reporting will enhance the reliability and consistency of monitoring results. Long-term monitoring campaigns, supported by sustainable funding and maintenance strategies, will capture temporal variations and ensure the longevity of monitoring systems. Continuous research, innovation, and collaboration among academia, industry, and government agencies will drive the field forward, promoting knowledge exchange and pushing the boundaries of field monitoring in geomechanics. By adopting these strategies, field monitoring can continue to evolve, ensuring the safety, sustainability, and efficiency of geotechnical systems in the future. Education and training programs should be invested to build a skilled workforce capable of implementing and managing field monitoring campaigns. Finally, ongoing research and innovation should be encouraged in field monitoring techniques.

Some potential areas that can be explored:

Instrumentation Improvement: Creating more precise and effective monitoring instruments is made possible by ongoing improvements in sensor technology and data-gathering systems. Researchers can concentrate on creating cutting-edge sensors and data collection methods that can accurately and consistently measure a wider range of geotechnical characteristics. This entails investigating wireless sensor networks and remote monitoring systems and incorporating cutting-edge technology like artificial intelligence (AI) and the Internet of Things (IoT).

Integration of Structural and Geotechnical Monitoring: Structural and geotechnical monitoring is sometimes viewed as distinct disciplines. To acquire a complete understanding of the behaviour of geotechnical structures, it is becoming increasingly clear that these two components must be integrated. Future research can focus on developing methodologies and techniques to combine geotechnical and structural monitoring data to assess the interaction between the ground and structures more effectively.

Monitoring Long-Term Performance: For geotechnical constructions to be safe and reliable, it is essential to comprehend their long-term behaviour and performance. Future studies can concentrate on long-term monitoring programs to evaluate the effectiveness of geotechnical constructions over protracted periods. This entails looking into things like the effects of ageing, the effects of the environment, and the impact of cyclic stress on the behaviour of soil and rock masses.

Data Analysis and Interpretation: There is a need for better data analysis, and interpretation approaches as the amount of monitoring data being collected keeps growing. To glean relevant insights from huge datasets, researchers can investigate the use of statistical modelling, data mining, and machine learning. Making informed judgments on geotechnical design, building, and maintenance can be aided by this in terms of seeing trends, forecasting behaviour, and making sense of data.

Development of Monitoring Guidelines and Standards: Developing standardised guidelines and best practices for field monitoring in geotechnical engineering can contribute to consistent and reliable data collection and analysis. Future research can focus on establishing industry-wide monitoring protocols, instrumentation calibration procedures, and quality control measures. This will ensure that monitoring data obtained from different projects can be compared and utilised effectively.

Case Studies and Knowledge Sharing: Case studies and research findings connected to field monitoring must be continuously documented and disseminated for knowledge to be shared and learned. To share useful insights and lessons learned, researchers should concentrate on publishing more case studies, covering both successful and difficult monitoring experiences. This will contribute to better field monitoring comprehension and use in geotechnical engineering projects.

11.9 Acknowledgement

I would like to express my heartfelt gratitude to Sahiya Rahim and Falak of NIT Srinagar, who have contributed to the writing of the Time Capsule for Field Monitoring in Geomechanics. Their support, have been instrumental in bringing this project to fruition.

11.10 Disclosure Statement

No potential conflict of interest was reported by the author(s)

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12 TC 301 Preservation of Historic Sites

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12.1 Abstract

Indian heritage structures are famous for excellent architecture and structural form. From last few decades these structures are affected due to seismic events, deterioration, pollution and negligence by authorities. Heritage sites represent the cultural values of our past generation and conservation of these heritage sites becomes important. This paper presents a state-of-an-art of heritage in India, the conservation policies, scientifically evaluating the risk to the heritage sites, and contribution towards the heritage conservation in India. The further need for the conservation of heritage is also discussed.

Keywords: Heritage sites, Conservation policies, Seismic hazard, Seismic site characterization, Condition assessment, Heritage impact assessment

12.2 Introduction

Indian architecture and structures symbolize the rich history of India predicting diverse culture, the rule of empires, invasion, colonization and modern India. The temples, mosque, churches, monastery and many representing the diversity are well spread across the country. The structures representing this diverse culture are heritage and the conservation and preservation of these heritage structures is of important value. In India there are total 40 UNESCO world heritage sites and nearly 3,684 monuments of national importance designated by Archaeological Survey of India. Moreover, many structures are in the custody of religious endowments, archaeology departments under state governments, and many heritage structures do not come under any formal system due to lack of infrastructure and funds (Menon 2014). There are several unprotected monuments and heritage structures are brought to public notice and protected mainly due to the intervention of Non-Governmental Organisations (NGOs), such as Indian National Trust for Art and Cultural Heritage (INTACH). Conservation of heritage site includes preservation of shape and form, structural and material integrity, and increasing the existing safety from the risk associated with the natural hazards, manmade activities and infrastructure and real estate development near the heritage sites.

In natural events, seismic events are the main governing factor which increases the risk to the historical structures. Heritage sites across the globe are majorly affected by the seismic events as they are built in the past based on empirical knowledge of structural behaviour; such a process mainly took care of static loads, but they are often vulnerable to dynamic loads such as earthquakes because of their massive mass, poor connections between structural elements (walls and roofs) and structural distress due to deteriorated material properties (NPC 2014). More than 25% of the cultural heritage was destroyed during Nepal 2015 M_w 7.8 earthquake (Chaulagain et al. 2015). The L'Aquila 2009 M_w 6.3 earthquake in Central Italy destroyed more than 50% of cultural heritage buildings (Chiarabba et al. 2009). Some of the heritage sites are in good condition, yet too many sites are vulnerable to earthquake. It is noted that the state of general disrepair adds to the seismic vulnerability of heritage architecture in developing countries. Besides, the repair after actual damage or destruction from earthquakes, even when timely undertaken, may lead to alteration of the valuable originality of heritage structures, owing to the unavailability of material or skill from the time of the original constructions (Karkee et al. 2005). Moreover, at least 39% of the UNESCO sites all over the globe are subjected to any one of 4 major hazard criteria and are at the brink of failure or deterioration (Pavlova et al. 2017). For past couple of decades Nepal have faced severe losses in terms of economic and heritage destruction due to frequent seismic events (Chaulagain et al. 2016). In India, several heritage structures were either destroyed or extensively damaged during 2001 Bhuj earthquake, 1819 Allah Bund earthquake, 1956 Anjaar earthquake, 2011 Sikkim earthquake, and many major earthquakes (Gupta et al. 2003, Menon 2014, Menon 2017). India has seismicity varying from low to high (IS 1893: 1, 2016) and the ancient structures which are massive and have deteriorated are vulnerable to seismic event. Therefore, there is a need for the conservation of the heritage sites to safeguard them from these seismic events. National Policy for Conservation of the Ancient Monuments, Archaeological Sites and Remains (NPC-AMASR, ASI 2014) protected by the Archaeological Survey of India (ASI), requires monuments and their structural components such as materials and construction techniques to be evaluated to ascertain their behaviour, and to undertake necessary minimum retrofitting measures to safeguard the monuments, thereby mitigating possible damages to structures and facilities during and after disasters.

Generally, the preliminary study in the context of conservation of heritage site includes economical and social impact survey, site exploration, geotechnical investigation, material and structural stability assessment, and environmental impact assessment. Due to large-scale infrastructure and real estate developments in the major cities worldwide, the heritage structures are facing real challenges. Heritage Impact Assessment (HIA) is generally carried out before planning any infrastructure in vicinity of the existing heritage sites (Paul et al. 2020). In HIA, the geotechnical and structural inspection is carried out. In geotechnical inspection, the subsoil characterization is necessary by performing invasive and non-invasive test. The heritage sites and structures are at risk due to seismic activities, nearby construction activity, and to weathering actions. Therefore, there is a need to safeguard these heritage sites by addressing the conservation of heritage. This paper provides a state-of-an-art on heritage conservation in India and discusses the way forward for the conservation of heritage.

12.3 Contribution for conservation of Heritage in India

In India, major work related to the conservation of heritage sites include restoration of heritage site in Delhi (Aranha et al. 2019a; Joseline et al. 2019), structural behavior of Gopurams of temples in south India (Ronald et al. 2018; Sharma et al. 2019), seismic site characterization of Kedarnath temple, Uttarakhand (Bhowmik et al. 2019), Timber load masonry building in Himaliyan belt, India (Dhandapany and Menon 2019), seismic inputs for Gol Gumbaz, Vijayapura (Patil et al. 2016; Patil et al. 2018), seismic inputs for Kancheepuram temple, Tamil Nadu (Ornthammarath et al. 2008, Corigliano et al. 2012), structural assessment of dome of Presidential building, Delhi (Aranha et al. 2019b), structural behavior of historical monuments in earthquake (Mathews et al. 2003; Methews and Menon 2008; Santhakumar et al. 2010; Menon 2014), seismic behavior of tall masonry minar, Qutb Minar, Delhi (Chandran et al. 2006), seismic behavior of stone pillar halls and Gopurams at Ekamabaranathar temple, Kanchipuram, Tamil Nadu (Ronald et al. 2008; Ronald et al. 2018), seismic behaviour of Sri Kalahasti temple, Andhra Pradesh (Varatharajan et al. 2012), post-earthquake reconnaissance surveys and strengthening of Buddhist monasteries in Sikkim (Menon et al. 2012; Pradhan et al. 2012; Menon and Murty 2013; Rai et al. 2016; Tripathi and Rai 2019), heritage impact assessments for heritage structure in Kerela and for Agra metro (Paul et al. 2020; Paul et al. 2023), impact assessment for 150 years old government building in Chennai (Nair et al. 2022), and evaluating the risk associated to the heritage sites in Gujarat and Karnataka based on the seismic zonation map of India, probabilistic seismic hazard study and liquefaction hazard study (Anand et al. 2022; Sandish and Chavda 2023). Further, retrofitting and rehabilitation of temples, church, mosque, and heritage structures (Natarajan et al. 2010; Chourasia et al. 2012; Sandbhor and Botre 2013; Nanda 2017; Kamal and Brar 2021; Ghosal and Ghosh 2021; Krishnachandran and Menon 2021; Santhanam and Ramadoss 2022c), assessment of strength characteristics and conservation of Alamparai fort and damage assessment of ancients forts in India (Narayanmugam et al. 2019; Bhowmik et al. 2020; Santhanam and Ramadoss 2022a; Santhanam and Ramadoss 2022b), investigating the microstructure characterization of mortars from 800 years old heritage structures in south India (Degloorkar and Pancharathi 2020), investigating the geotechnical aspects of heritage sites (Sharma et al. 2008; Dewanjee 2018; Ghosh et al. 2018; Massinas et al. 2018; Mehendale et al. 2019), characterization of mortar, stones, bricks, lime of old heritage structures (Manohar et al. 2020; Shivakumar and Selvaraj 2020; Shukla et al. 2022; Degloorkar and Pancharathi 2020; Malladi and Selvaraj 2023), providing scientific conservation approach and policies towards the conservation of heritage in India (Bose 2012; Shankar and Uma 2012; Malhotra 2013; Kumar et al. 2016; Roy and Kalidindi 2017; Kumar et al. 2018; Roy et al. 2019; Devi and Sharma 2019) and use of digital technologies and digitization of heritage sites (Dhapekar and Saha 2013; Kondam et al. 2018; Mansuri et al. 2019; Kumar et al. 2020; Udeaja et al. 2020; Mansuri and Patel 2022; Mansuri et al. 2022; Singh et al. 2023).

In order to highlight the contribution of Indian authors towards the conservation of heritage, using the database of SCOPUS (total 593 documents), the VOSviewer of the keywords in the literature on “heritage” restricted to India is presented in Fig. 12.1. Based on the network visualization of the keywords, major focus was on cultural heritage, restoration, repair, heritage buildings, tourism, sustainability, climate change and earthquakes. The VOSviewer of the authors for literature (total 593 documents) on “heritage” restricted to India is obtained and presented in Fig. 12.2. The figure highlights the contributing authors towards the heritage conservation in the country.

Similarly, to highlight the worldwide contribution towards the conservation of heritage, the VOSviewer of the network of countries based on SCOPUS database i.e., literature (total 23138 documents) with keyword “heritage” is plotted and shown in Fig. 12.3. Based on the figure it is noted that Italy, United States of America, China, Spain, United Kingdom, Portugal, Germany, Netherland, etc. have majorly contributed towards heritage conservation. It is noted that the heritage conservation is taken into priorities worldwide by performing seismic risk assessment, evaluation of site-specific vulnerability of the heritage site, evaluation of the structural risk of the heritage structure, and development of risk assessment map for the area having all cultural sites. Therefore, it is opined that there is a need to perform the seismic risk assessment for the conservation of heritage sites in our country.

12.4 Risk Evaluation for the Heritage sites

Conservation of historical structures faces many challenges, such as: (1) inadequate knowledge about the seismic demand on the monuments (especially in low to moderate seismic zones or regions of infrequent large earthquakes, such as India), (2) limited information about the history and construction techniques, material properties and detailed drawings of historical monuments, (3) lack of instrumented records of past earthquakes. In order to overcome these limitations, one should design more robust and efficient assessment methodologies, which include among other possibilities, detailed inspection of the monument, site-specific seismic hazard assessment, detailed site characterization and robust numerical modelling of the monuments for vulnerability assessment.

As per the seismic zoning map of India (IS 1893: 1, 2016), India is divided in four seismic zones i.e., Zone II, Zone III, Zone IV, and Zone V having seismicity varying from low to high. Therefore, the ancient structures which are massive and have deteriorated are vulnerable to future seismic event, nearby construction activity, and to weathering actions. The conservation of monuments of national importance requires not only the preservation of shape and appearance but also their structural and material integrity. Seismic events create hazard to these monuments. In this context, there is a need to carry out seismic hazard analysis, seismic site characterization, determining the structural distress, evaluating risk, and providing the mitigating measures for the conservation of heritage structures and sites.

In this regard, in order to evaluate the risk associated with the seismic events, Anand et al. (2022) evaluated the risk to the 207 heritage sites in Gujarat based on the seismic zonation map of India, probabilistic seismic hazard study and liquefaction hazard study for Gujarat. For assessing the combined risk to the 207 heritage sites in Gujarat, from seismicity and the liquefaction potential of sites, three risk factors are defined; first, ***seismic risk factor*** derived from the seismic zone map (IS 1893: 1, 2016); second, ***hazard risk factor*** derived from seismic hazard map from Vipin et al. (2013) and third, ***liquefaction risk factor*** hazard map based on SPT values from Vipin et al. (2013). With the assigned risk factors, the vulnerability of each heritage site is calculated. Based on the location of each heritage site and corresponding associated risk, the risk factors to all 207 heritage sites are evaluated. Then, three types of mean risk are generated by varying the percentage weightage in each risk factor. Out of the three mean risks obtained, the maximum value is taken into consideration to assign the absolute risk that provide the hazard level of that heritage site. Finally, the absolute hazard risk is evaluated for all the UNESCO and ASI sites, and a hazard risk map is prepared (Fig. 12.4) that designates the risk to each 207 sites in four levels: *severe*, *high*, *moderate* and *low*.

However, the study is based on the evaluated seismic hazard for Gujarat by Vipin et al. (2013) which do not account site specific hazard analysis. Moreover, the seismic hazard for Gujarat considering the origin as vulnerable site considering the latest ground motion prediction equation and seismic site classification shall be performed to have more accurate hazard evaluation for each heritage sites in Gujarat. Further the risk factor assigned is linear variation which can be further improved. The structural condition of the heritage structure can significantly alter assign risk to the site. For example, if the site is underground structure which is in stable condition (arrived based on structural condition assessment) and moderate vulnerable to the seismic events, may have less overall risk and such structure whose structural condition is not stable (arrived based on structural condition assessment) may have higher risk even when seismic risk factor is moderate. Therefore, the condition assessment of the heritage structure plays a significant role in evaluating the seismic risk factors for the heritage sites. This study can be attempted for the entire country to evaluate the risk associated with the heritage sites under UNESCO and ASI monuments considering the seismic zonation map of India, probabilistic seismic hazard study, liquefaction hazard study, seismic site characterization and accounting the typology and condition assessment of the heritage structures.

12.5 Concluding remarks

The heritage structures in India are well known for its unique architecture, complex carving and structural form representing the rich history of civilization. The preservation of such heritage structures and heritage sites is of need as they represent the cultural values. This paper presents a state-of-an-art of heritage sites in India, the conservation policies, scientifically evaluating the risk to the heritage sites, and contribution towards the heritage conservation in India. The heritage sites are vulnerable to seismic events and hence there is a need to evaluate the risk associated with the heritage sites by performing the site-specific seismic hazard analysis, seismic site characterization, local site effect i.e., the ground response analysis, condition assessment of the heritage structure and seismic analysis of the heritage structure to account the structural typology. The urbanization and rapid infrastructure growth leads to a threat to the heritage structure if construction activities are carried out nearby these heritage sites. Therefore, heritage impact assessment shall be carried out to check the effect of those proposed construction on the heritage sites. In future, as observed in the other countries, there will be situation where the restoration, rehabilitation and shifting the entire heritage site may arise. Therefore, a detail study on this aspect is of need. To highlight the contribution towards the heritage conservation in India, using the database of SCOPUS (total 593 documents), the VoSviewer of "keywords" and "authors" of literature restricted to India was developed. Based on the network visualization of the keywords, major focus was on cultural heritage, restoration, repair, heritage buildings, tourism, sustainability, climate change and earthquakes. Similarly, to highlight the worldwide contribution towards the heritage conservation, using the database of SCOPUS (total 23138 documents), the VOSviewer of the network of countries with keyword "heritage" was developed. Based on the network map it is noted that Italy, United States of America, China, Spain, United Kingdom, Portugal, Germany, Netherland, etc. have contributed majorly towards heritage conservation. Further it is stated that the heritage conservation is taken into priorities in western countries by performing seismic risk assessment, evaluation of site-specific vulnerability of the heritage site, evaluation of the structural risk of the heritage structure, and development of risk assessment map for the area having all cultural sites. Therefore, it is opined that there is a need to perform the seismic risk assessment for the conservation of heritage sites in our country, India.

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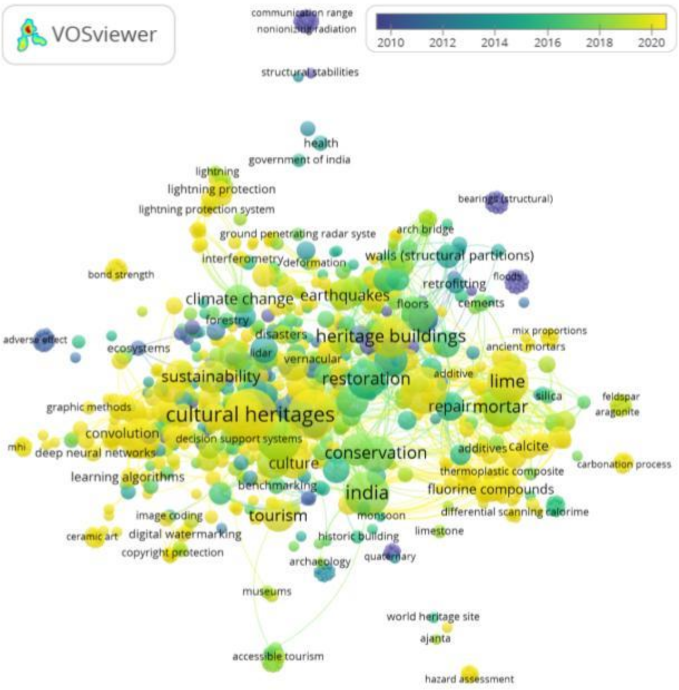

Figure 12.1 VOSviewer of the keywords for Indian literature (total 593 documents) on "heritage", accessed on 13 June 2023.

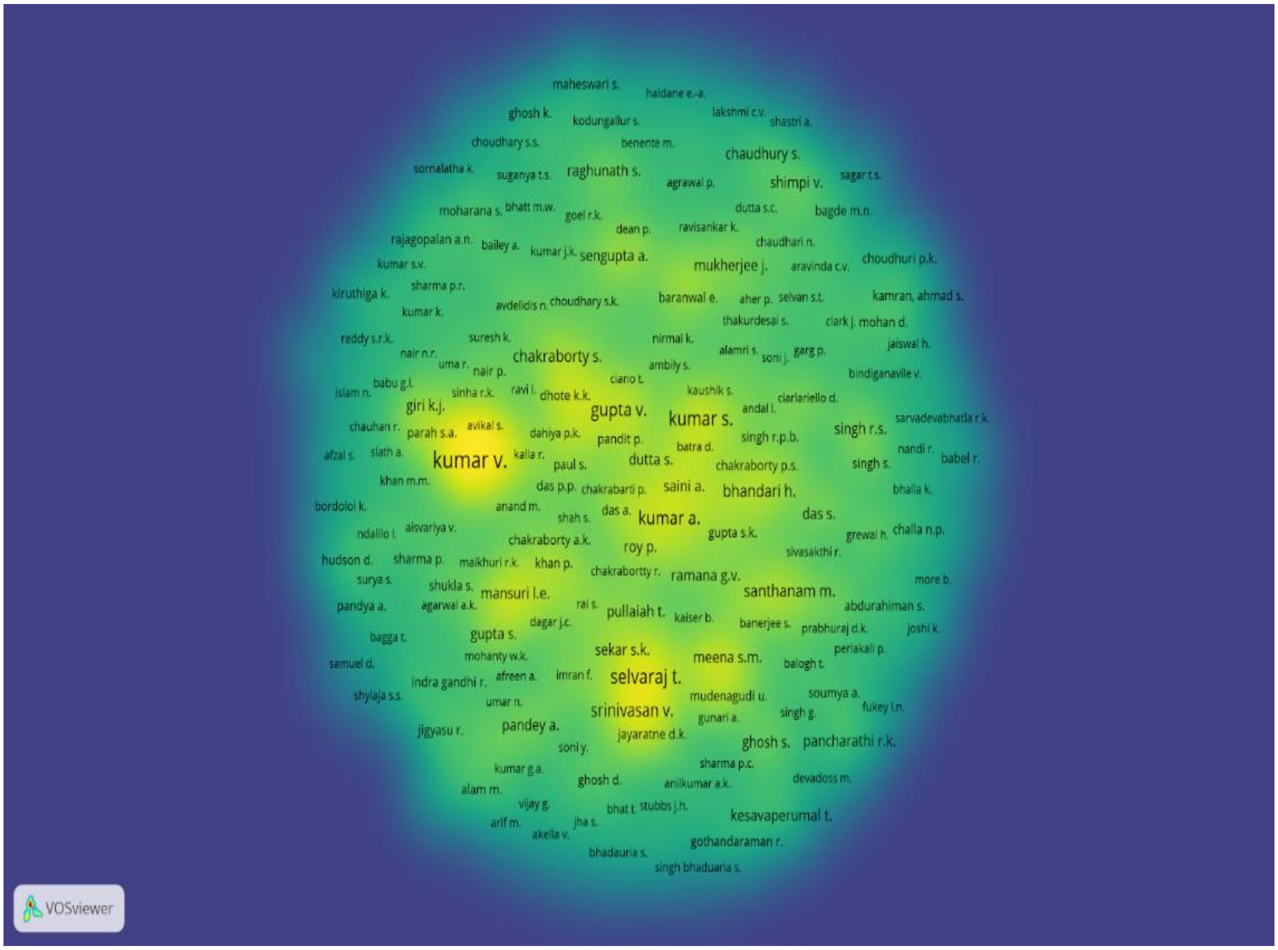

Figure 12.2 VOSviewer of the authors for Indian literature (total 593 documents) on "heritage", accessed on 13 June 2023.

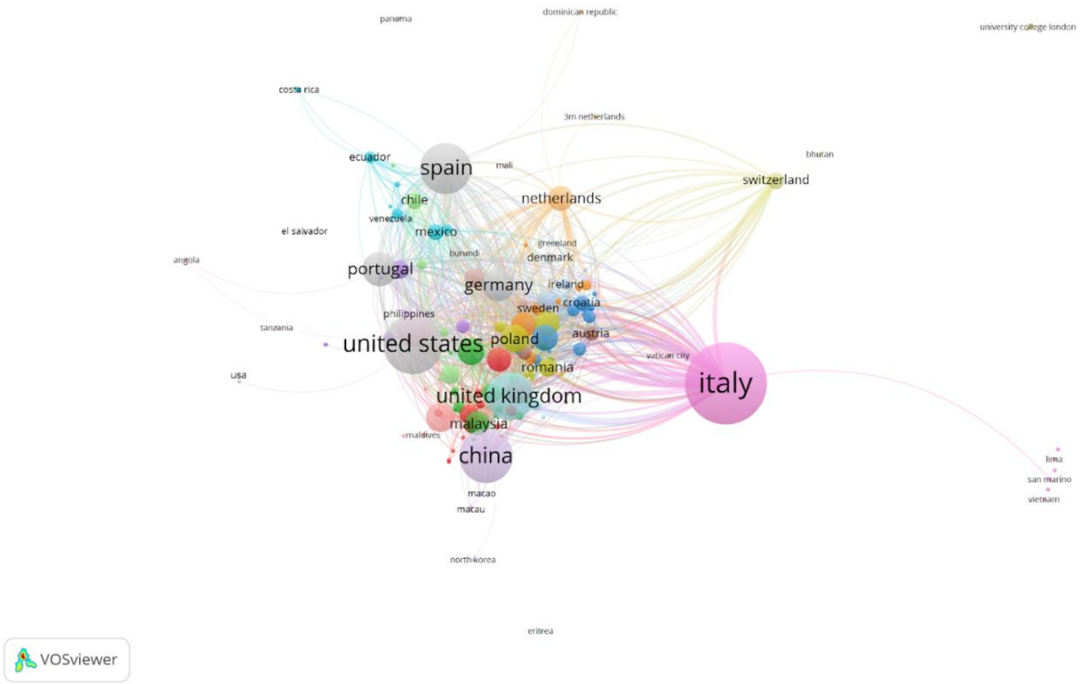

Figure 12.3 VOSviewer of the network of countries based on literature with keyword “heritage”, (total 23138 documents, accessed on 13 June 2023)

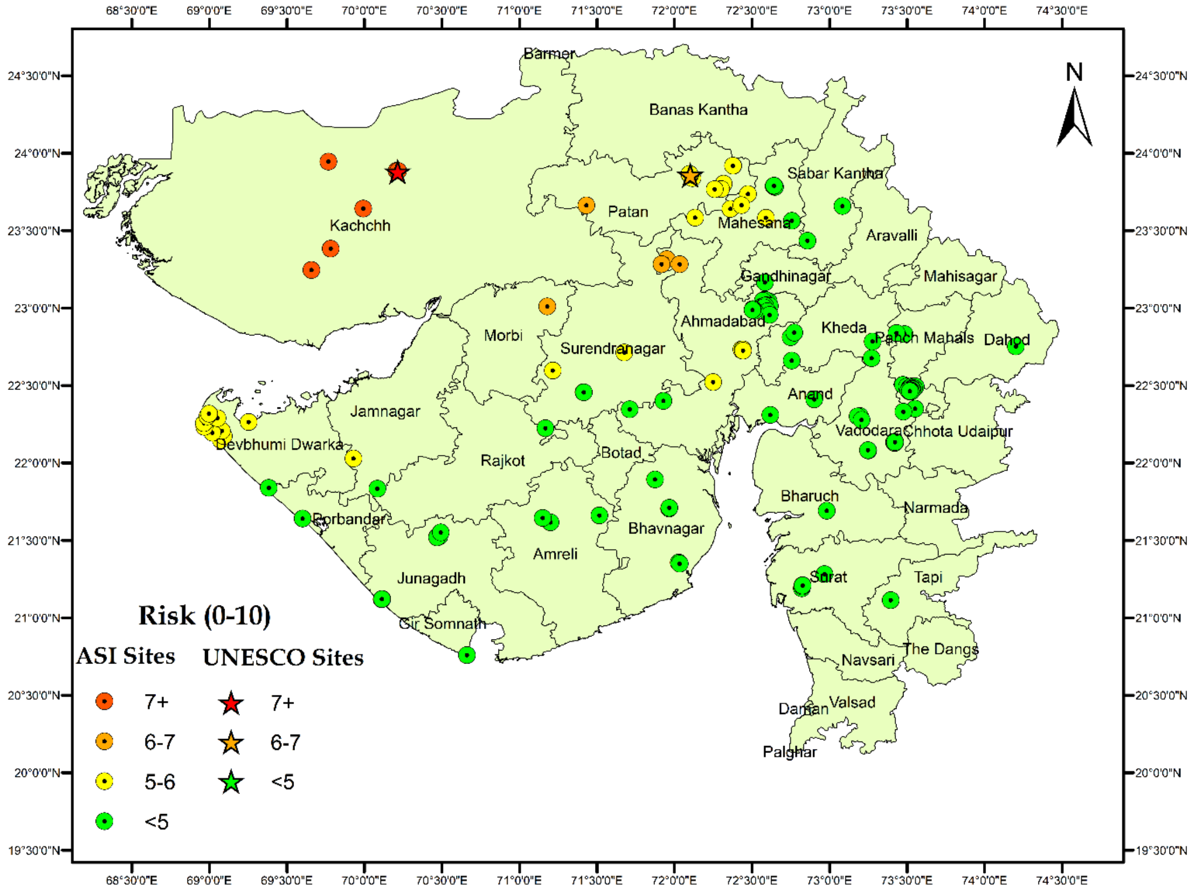

Figure 12.s4 Developed combined heritage hazard map of Gujarat considering seismic zone map as per IS 1893: 1, (2016), based on seismic hazard studies of Vipin et al. (2013) and liquefaction hazard studies by Vipin et al. (2013) (Anand et al. 2022)

13 TC 303 Coastal and River Disaster Mitigation and Rehabilitation

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13.1 Abstract

The time capsule encapsulates the evolution and milestones in the realm of coastal erosion and river embankment protection. This archival collection provides a comprehensive chronicle of historical directives, government notifications, committee formations, and significant policy changes spanning from 1981 to 2019 in India. The narrative encompasses directives, guidelines, notifications, committee reconstitution, and the establishment of key institutions and projects. Notable highlights include the evolution of coastal regulations, numerous amendments to notifications, the establishment of critical management entities, and the recommendations by expert committees, culminating in the issuance of a new notification in 2019 superseding the previous directive.This compilation consists of 34 research papers sourced from journals, focusing on diverse facets of field monitoring within the realm of geotechnical engineering. The time capsule serves as a reservoir of institutional and policy evolution, reflecting the ongoing efforts and advancements in preserving and managing coastal and riverine landscapes.

Keywords: Coastal erosion Protection, Coastal Regulation Zone (CRZ) Policies,s Groyne, Numerical modelling,Geo-textiles, Geo-tubes .

13.2 Introduction

In the global scenario, there is 71% of water and 29 % of surface area with land. In the land area there are numerous rivers; the longest river in the world is the Nile 6650Km and the longest in India river Ganga is of 2525Km. Due to climate change activities and disasters like floods, cyclones, Tsunamis, etc., the surface boundaries of land areas are affected. Coastal land also has adverse effects due to sea erosion. Each case of sea erosion is different from another, there are many reasons why coastal erosion happens. Also during high rainfall in the catchment area, due to lack of proper discharge flood-like situations are happening by disturbing the riverbanks, which disturbs the land surface.

To combat the flood, some methods like flood protection embankments and drainage congestion clearance through renovation and excavation of existing natural drains are to be maintained. Similarly to combat coastal erosion various techniques like seawalls & revetments, Groyne, Offshore breakwater, vegetation, Beach nourishment etc. are to be considered. Environment protection activities through the guidelines and methodologies are much helpful to combat flood & coastal erosion. Along with the adaption of science and technology therefore the protection works development of provision for sustainable livelihood is also a major tool for a better world. Data of rainfall, flood frequency, geotechnical parameters, Wave effects and designs for protection, cost analysis, population and habitat protections, ecological balances, environmental parameters, and livelihood supports can be exhibited for making the benefit cost-analysis of any project report.

Flood occurs due to rainfall, flash floods, storm surges, ice jams, Dams or levees breaking, and conjunction in the stream and drainage system. Flood protection embankments, also known as flood embankments or levees, are structures built to reduce the risk of flooding by controlling the flow of water. They are typically constructed along rivers, coastlines, or other bodies of water prone to flooding. Similarly, coastal erosion protection, the reason for coastal erosion, various methods of erosion protection, current practices on coastal erosion protection, and proposal practices have been included.

13.3 Flood Protection Embankments

The main purpose of flood protection embankments is to provide a barrier that prevents water from over-topping and inundating surrounding areas. They are typically made of compacted soil, reinforced with materials such as concrete, stones, or geotextiles to increase their strength and stability. The embankments are designed to withstand the hydraulic forces exerted by floodwaters and maintain their structural integrity.

13.3.1 Key features and functions of flood protection embankments:

Diversion of Water: Embankments can be built to redirect or channelize water away from populated areas or critical infrastructure, such as cities, towns, roads, or industrial sites. By creating a designated path for floodwaters, embankments help prevent widespread damage and protect valuable assets.

Height and Width: Embankments are constructed to a specific height and width based on the anticipated flood levels and hydraulic conditions. The height is designed to exceed the expected flood level, while the width provides stability and resists erosion caused by flowing water.

Slope Design: The slope of the embankment is carefully engineered to ensure stability and prevent erosion. The inner slope (facing the protected area) is typically gentler to reduce the risk of slumping or collapse, while the outer slope (facing the water) is steeper to withstand the forces of the floodwater.

Drainage Systems: Proper drainage is crucial for embankments to prevent seepage or saturation that can compromise their stability. Drainage pipes, weep holes, or other mechanisms are incorporated to allow excess water to flow out of the embankment, reducing the risk of internal erosion.

Monitoring and Maintenance: Regular inspection and maintenance of embankments are essential to identify any signs of deterioration or damage. Vegetation management, erosion control, and repair of any breaches or weak spots are part of ongoing efforts to ensure the embankments' effectiveness.

It's important to note that while flood protection embankments can be effective in reducing flood risks, they are not foolproof and may have limitations. Factors such as extreme weather events, changes in water levels, or inadequate maintenance can challenge their effectiveness. Therefore, comprehensive flood risk management strategies often involve a combination of embankments, floodplain zoning, early warning systems, and other measures to mitigate flood risks.

13.3.2 River erosion protection techniques

River erosion protection techniques aim to prevent or minimize the destructive effects of erosion caused by rivers. These techniques can vary depending on the specific situation, the characteristics of the river, and the level of erosion threat. Here are some commonly used river erosion protection techniques:

Riprap or Rock Armoring: This technique involves placing large rocks or stones along the banks of the river or on the riverbed to resist erosion. Riprap acts as a protective barrier, dissipating the energy of the flowing water and reducing the impact on the riverbanks.

Gabion Walls: Gabion are wire mesh baskets filled with stones or rocks. These baskets are stacked together to form a wall along the riverbanks. They provide stability, reduce erosion, and allow water to flow through, which helps in preventing scouring and undercutting of the riverbanks.

Retaining Walls: Retaining walls are vertical structures built parallel to the riverbanks to support and stabilize the soil. They can be constructed using various materials such as concrete, stone, or gabion. Retaining walls are effective in preventing bank erosion and providing stability to the riverbanks.

Vegetation and Bioengineering: Planting vegetation, such as grasses, shrubs, and trees, along the riverbanks helps in stabilizing the soil. The root systems of plants bind the soil together, reducing erosion and providing protection against river currents. Bioengineering techniques use a combination of plants, natural materials, and structural elements to enhance erosion control.

Terracing: Terracing involves constructing stepped or sloping platforms along the riverbanks. These platforms can be made of soil, rocks, or concrete and help to reduce the velocity of the water, preventing erosion. Terracing also provides flat areas for vegetation growth, further stabilizing the riverbanks.

River Training Structures: These structures are designed to redirect or control the flow of the river to minimize erosion. Examples include groynes (perpendicular structures extending into the river to trap sediment), spurs (angled structures extending from the bank to deflect water), and weirs (barriers across the river to regulate water flow).

Floodplain Zoning and Flood Control Measures: Proper land-use planning, zoning regulations, and flood control measures can help manage the risk of river erosion. By restricting development in high-risk areas and implementing flood control infrastructure, such as levees or flood walls, the impact of erosion during flood events can be reduced.

It's important to note that the selection of erosion protection techniques should be based on a thorough understanding of the local conditions, including the river's hydrology, sediment transport, and geological characteristics. In many cases, a combination of techniques may be required to effectively mitigate river erosion.

13.3.3 Past Challenges and Solutions in River Embankment for Flood Protection and Coastal Erosion Control

In the realm of river embankment projects aimed at flood protection and coastal erosion control, history is replete with challenges and innovative solutions that have evolved over time. This section delves into the difficulties encountered in different eras and the corresponding adaptive strategies applied to address them.

13.3.3.1 Ancient and Medieval Times

The Challenges were Limited engineering knowledge, Limited Construction Materials, rudimentary construction techniques. During this period basic levees and dikes were constructed with manual labor incorporating rudimentary materials. In ancient Egypt, the challenge was managing the annual Nile floods.

They built a system of dikes and canals to divert water, a remarkable feat considering the limited engineering knowledge of the time. In medieval Europe, the challenge was working with rudimentary materials. They used timber and earth embankments to protect against flooding, focusing on raising the ground level. In ancient India, communities settled along riverbanks often faced the devastating impacts of monsoon floods. The challenge was to protect settlements and farmlands from seasonal inundation. Simple embankments were constructed with mud and stone Utilizing indigenous knowledge and local materials to build rudimentary embankments. A system of embankments and canals, such as the Kallanai Dam (Grand Anicut) in Tamil Nadu were constructed during the Chola dynasty. These embankments diverted and managed floodwaters, providing flood protection and irrigation for agriculture. In 18th and 19th centuries the Challenges were mass urbanization, increased industrialization, need for larger-scale embankments. These challenges were addressed by mechanization and maintaining professional engineering standards.

13.3.3.2 In the mid-20th century

The challenges posed were predominantly centered around post-war rehabilitation, burgeoning population density, and escalating pollution levels. The resolution to these formidable issues materialized through advancements in construction materials, the fortification of embankment structures, and a heightened awareness of environmental implications throughout the construction processes. The Hoover Dam on the Colorado River is an iconic example, harnessing concrete technology to manage water resources and generate power. The construction of extensive dams and canal systems, aimed at flood control and irrigation, came to realization during this period. Notable projects included the Bhakra Dam initiative and the development of the Kosi River embankments in India. Sir Arthur Cotton, an engineer renowned for his contribution to river embankments, played a vital role in projects like the Dhavaleswaram project in Andhra Pradesh. The project aimed at incorporating modern engineering techniques to control flooding while considering ecological balance and the welfare of local communities.

13.3.3.3 Late 20th Century and Present day

Challenges are adapting to climate change, complying with stringent environmental regulations, manage water resources for urbanization, agriculture, and industry effectively and involving local communities in project decisions. Some of these challenges are addressed by utilizing advanced materials, employing predictive modeling, implementing eco-friendly designs, and engaging with the community. One notable example of modern river embankment project solutions is the Sabarmati Riverfront Development in Ahmedabad. This innovative urban riverfront design integrates flood control measures with environmental restoration, the creation of recreational spaces, and the promotion of sustainable urban development. This project represents a forward-looking approach to addressing the challenges faced in river embankment projects.

Another exemplary project in this regard is the Netherlands' Delta Works, a comprehensive system that comprises dams, locks, dikes, and storm surge barriers. This system effectively safeguards low-lying regions from inundation while also demonstrating a strong commitment to environmental preservation. Another noteworthy aspect is the incorporation of thorough environmental impact assessments and the embrace of sustainable practices within the Narmada Dam project and the embankments in the Sunderbans. River embankment projects in India have witnessed an evolving landscape of challenges and innovative solutions spanning different historical eras, reflecting the dynamic nature of engineering and environmental considerations.

> Throughout history, river embankment projects have evolved to address the unique challenges of each era. Advancements in engineering, materials, and environmental awareness have played pivotal roles in the solutions developed to protect against flooding and coastal erosion. These historical examples illustrate human adaptability and innovation in the face of ever-changing challenges.

13.4 Overview of the Time Capsule Document

This compilation consists of 34 research papers sourced from journals, focusing on diverse facets of field monitoring within the realm of geotechnical engineering. These selected publications have been meticulously curated to showcase the advancements, challenges, and innovative techniques in Riverbank embankment protection, soil erosion as well as Coastal erosion Protection as and related phenomena. The aim of this document, resembling a time capsule, is to furnish forthcoming researchers, engineers, and professionals with valuable insights into the landscape of field monitoring during the specified period.

13.5 Reason for Creating a Time Capsule Document

The primary aim of this Time Capsule document is to showcase and safeguard the collective knowledge and progress achieved in the realm of field monitoring in geomechanics. This comprehensive document serves as a synthesis of the current state-of-the-art practices. It provides a comprehensive overview of methodologies, case studies, challenges, and advancements related to coastal erosion protection and river embankment protection by collating a diverse array of scholarly papers. Moreover, this compilation endeavors to act as a wellspring of inspiration and education for future researchers and practitioners. By delving into the research papers featured in this Time Capsule, readers can acquire a holistic grasp of the field, spot emerging trends, and use the existing knowledge as a foundation to further enhance coastal erosion protection and river embankment protection.

13.6 Background

The importance of coastal erosion protection and river embankment protection lies in their role in assessing the behavior, efficacy, and stability of geotechnical systems. This involves a systematic observation, measurement, and analysis of variables such as vibrations, groundwater pressure, stress, and deformation. These protection efforts collect data in real-world settings and provide invaluable insights into how geotechnical systems respond to external forces, environmental fluctuations, and processes that evolve over time.

The rapid progress and growing significance of coastal erosion protection and river embankment protection have prompted the creation of a Time Capsule document. Significantly, the sector has witnessed notable advancements in instrumentation, data collection techniques, data processing, and their integration into design and decision-making processes. The purpose of the Time Capsule is to document and safeguard the knowledge generated by these advancements by consolidating research articles into a single document.

The Time Capsule paper pays tribute to the researchers, engineers, and industry professionals who have made substantial contributions to the field through their interdisciplinary work, expertise, and dedication. It underscores the significance of sharing and preserving their contributions to ensure that they continue to inspire and educate future generations.

13.7 Milestones

Year	Author	Paper	Journal	Significance
1992	Parua, Pranab Kumar	Stability of the banks of Bhagirathi Hooghly river system	Jadevpur University INFLIBNET Centre	Factors affecting stability and stability analysis
2010	M Di Prinzio, M Bittelli, A Castellarin, PR Pisa -	Application of GPR to the monitoring of river embankments	Journal of Applied …, 2010 - Elsevier	Ground Penetrating Radar (GPR) can assist decision making in a number of fields for detection of voids and discontinuities in hydraulic defense structures such as river embankments and levee systems. .
2010	D Adam, M Szabó, I Paulmichl -	"Innovative compaction technologies for rehabilitation of flood protection dikes	From Research to Design in European Practice, Bratislava, Slovak Republic, on June 2 – 4. 2010	Compaction technology, using vibrating rollers with polygonal drum, was applied for compaction optimization during the remedial works of the flood embankments at the river) along-with some case studies.
2011	MB Hossain, T Sakai, MZ Hossain -	River embankment and bank failure: a study on geotechnical characteristics and stability analysis	American Journal of Environmental Sciences 7 (2): 102-107,	Study on failure of bank, and the factors regarding stability and geotechnical characteristics with existing design methodology have been emphasized.
2020	K Oberhagemann, AMA Haque, A Thompson	A century of riverbank protection and river training in Bangladesh	[PDF] mdpi.com Water, 2020 - mdpi.com	This article provides an overview of the challenges faced when attempting to stabilize the riverbanks of the mighty rivers of Bangladesh through low cost protection adaption like sand bags.
2013	Y Yu, W Xiao, Y Wang, S Shang, H Wang	Evaluation of the carbon emission reduction effects of ecological	Journal of Water and …,climate change 2021 -	Like the study of the carbon emissions from structural and ecological revetments, and its

		river revetment construction		impact on China. It can also be studied for other areas also.
2013	YS Zhao, B Zhou 2013	Stability investigation of road cut slope in the basaltic rock mass, Mahabaleshwar, India	Advanced Materials Research, 2013 - Trans Tech Publ	It's crucial to recognize that constructing deep foundation pits adjacent to the Yangtze River embankment can pose significant risks to the stability of the embankment and the surrounding soil.
2013	JY Wei, BT Wang, JH Zhang, B Zhou	Application of High Pressure Jet Grouting Pile with Undrained Open Caisson Combined Construction Technology in the Protection of Yangtze River Levee	Applied Mechanics and Materials vols 368-370 Scientific.net	Levee constructions with Jet grouting pile combined with caisson
2014	Kalita, Hriday Mani	Optimal protection measures for controlling river bank erosion	Indian Institute of Technology Guwahati	Structural measures for controlling a river to minimize its devastating effect
2014	D Sarowski -, 2014	The concept of reconstruction and protection against filtration through backlinks embankment on the river Strochodzka in the region Radomyśl over the Vistula river	repo.pw.edu.pl	Flood protection embankment with best reconstruction solution.
2014	MF van Staveren, JPM van Tatenhove - Click or tap here to enter text.	Hydraulic engineering in the social-ecological delta: understanding the interplay between social, ecological, and technological systems in the	Ecology and Society, 2016 - JSTOR	River embankment protection strategy and flood management in the delta area .

		Dutch delta by means of …“delta trajectories.”		
2015	Sarma, Pranab Jyothi	Riverosion and its impact on dwellers of Brahmaputra dwellers of Brahmaputra valley in Morigaon district of Assam	North-Eastern Hill University	Problems on erosion, River bank shifting. Solutions to the issues through cropping pattern, occupational structures of resettled dwellers.
2016	L Busato, J Boaga, L Peruzzo, M Himi, S Cola	Combined geophysical surveys for the characterization of a reconstructed river embankment	Engineering Geology Volume 211, 23 August 2016, Pages 74-84 elsevie	Geophysical and geotechnical data helps for strengthening the embankments through various process like grouting injections etc..
2017	M Borys, E Zawisza, A Gruchot	River Embankments	books.google.com 2017	Embankment location, Geometric dimension, Stability,Settlement,Filtration calculation etc are covered in this book as guideline.
2019	G Basu, AN Roy, P Sanyal, K Mitra, L Mishra	Bioengineering of river earth embankment using natural fibre-based composite-structured geotextiles	Geotextiles and Geomembranes Volume 47, Issue 4, August 2019, Pages 493-501 ELSEVIER	Application of Jute-synthetic materials for river embankment protection.
2020	Vikas Kumar Das	Flume study on cohesive river bank erosion process and mechanisms	Jadavpur University	Cohesive River Bank Erosion Flume Study sediment removal processes
2022	Anju Mary Ealias	A Case Study on Earthern Embankment Protection Techniques	International Journal of Research in Engineering and Science (IJRES) September 2022	Combating Method applied water ingress to Paddy field by bond protecting system in Kuttnada, Kerla.
2022	Jun Yan et.al	Study on the Application of Sediment-Based	Materials	Sediment bases embankment protection

		Embankment Building and Ultra-High-Performance Concrete (UHPC) Preparation in the Resource Utilization of Yellow River Sediment	https://www.mdpi.com/1782166	
2023	Tuyen Phong Truong, Et.al	Hydrological Monitoring System Design and Implementation for River Embankment Protection	Proceedings of the 2023 12th International Conference on Software and Computer Applications	Dam monitoring technology can be used for river embankment systems like a sensor network using LoRa wireless communication technology .
2023	U Ji, H Woo	Technographical review of embankments for dams and levees in Joseon Dynasty (1392–1910), Korea	Water projects and technologies in Asia books.google.com	Embankment technological development in Korian History
2023	D Xu, D Zhu, Y Deng, Q Sun, J Ma…2023	Evaluation and empirical study of Happy River on the basis of AHP: A case study of Shaoxing City (Zhejiang, China)	Marine and Freshwater Research 2023 - CSIRO Publishing	Promotion for Ecological construction, water culture construction and waaater protection functions has been formulated.
2023	Indulekha K P	Studies On The Use Of Cocologs For River Bank Erosion Control And Restoration Of River Meanders	University of Kerala	Hard stabilization methods Groynes or spurs,Embankment or levees,Revetment works,Stream barbs or bend way weir and rock riprap etc.
Coastal Erosion Protection				
986	Thomas G. Dickert	Evaluating erosion susceptibility for	Coastal Zone Management Journal,	Methods of determining soil erosion susceptibility and land-

	& Robert B. Olshansky	land-use planning in coastal watersheds		use intensity measured by a land disturbance index
1998	Roger H. Charlier, Christian P. De Meyer	Coastal Erosion: Response and Management	books.google.com	Comprehensive plans for protecting existing economic activities help to ensure that defense measures are consistent with other coastal management objectives.
1998	Nobuo Mimura and Patrick D. Nunn	Trends of Beach Erosion and Shoreline Protection in Rural Fiji	Journal of Coastal Research	The challenges posed by sea-level rise and climate change require a reevaluation of coastal protection strategies. While seawalls have been a traditional solution, they often come with various design and material shortcomings. Here are suggestions to improve coastal protection and address the threats posed by predicted future accelerated sea-level rise and climate change:
2000	S Dunn, R Friedman, S Baish -	Coastal erosion: evaluating the risk	Environment: Science and Policy for sustainable development Taylor & Francis	Risk factors in Coastal erosion
2001	R Li, JK Liu, Y Felus	Spatial modeling and analysis for shoreline change detection and coastal erosion monitoring	Marine Geodesy, 2001 Taylor & Francis	A new method computes an instantaneous shoreline using a digital water level model, a coastal terrain model, and bathymetric data.
2003	CN Ehler	Indicators to measure governance performance in integrated coastal management	Ocean & Coastal Management,- Elsevier	processes involved in integrated coastal management , focusing on the … coastal area governance system can apply to the conduct of a single activity
2007	JU-CHIN HUANG et.al.	Economic Valuation of Beach Erosion Control	University press of Chicago Journal Press Marine Resource Economics	Economic benefit of erosion control. demonstrates feasible comparisons of beach erosion control programs that account for their multiple effects

2010	AV Hegde	Coastal erosion and mitigation methods–Global state of art	nopr.niscpr.res.in	The trend in modern coastal erosion mitigation and protection strategies is indeed shifting towards softer, more environmentally friendly, and innovative solutions.
2012	Matthew M. Linham et.al.	Adaptation technologies for coastal erosion and flooding: a review	Proceedings of the Institution of Civil Engineers - Maritime Engineering	(1) protect, (2) accommodate and (3) retreat – and considered from developed and developing country perspectives.
2014	NA Awang et.al.	Coastal Erosion at Tanjong Piai, Johor, Malaysia	Journal of Coastal Research	Model simulations, indicating positive and negative impacts of hydrodynamic changes around the study area, are not uncommon when implementing coastal protection measures.
2017	Ajaya Kumar Pradhan	Efficacy of river training measures for river bank protection and flood management a morphodynamic study of Toorsa river	KIITS University	Geomorphological modeling A combination of both hard and soft engineering solutions tailored to specific geographic and hydrological conditions often provides the most effective and sustainable approach to mitigate erosion and flooding along riverbanks.
2021	Peter Bacopoulos , Ralph R. Clark	Coastal erosion and structural damage due to four consecutive-year major hurricanes: Beach projects afford resilience and coastal protection	Ocean & Coastal Management, ELSEVIER	Adaptation of softer construction methods, e.g., beach nourishment, dune addition and stabilizing vegetation along with the rigid structural interventions.

13.8 Way Forward for India

India has a vast coastline along the Arabian Sea and the Bay of Bengal, which makes it vulnerable to coastal erosion. To combat this issue, India has implemented several coastal erosion protection techniques. Here are some commonly used methods:

Beach Nourishment: This technique involves replenishing eroded beaches with sediment, usually through dredging or importing sand. By restoring the beach profile, it helps absorb wave energy and prevents further erosion.

Shoreline Stabilization: Various measures are employed to stabilize the shoreline, including the construction of seawalls, revetments, and breakwaters. Seawalls are vertical structures built parallel to the coast to absorb wave energy, while revetments are sloping structures designed to dissipate wave energy. Breakwaters are offshore barriers that reduce the impact of waves before they reach the shore.

Dune Restoration: Sand dunes act as natural barriers against erosion. Restoring and nourishing dune systems is an effective way to protect the coast. This can involve planting vegetation on dunes to stabilize them and prevent sand from being blown away.

Groynes and Permeable Structures: Groynes are structures built perpendicular to the coast. They trap sediment and prevent its longshore movement, helping to build up beaches. Permeable structures, such as geotextile tubes or sand-filled bags, are sometimes used to dissipate wave energy while allowing water and sediment to pass through.

Mangrove Plantation: Mangroves are coastal vegetation that provide natural protection against erosion. They have extensive root systems that stabilize sediments and dissipate wave energy. India has implemented mangrove plantation programs along vulnerable coastlines to conserve these ecosystems and enhance coastal protection.

Offshore Reefs: Artificial or natural reefs can be constructed offshore to dissipate wave energy before it reaches the shore. These reefs help break waves, reducing their erosive force on the coastline.

Coastal Regulation Zone (CRZ) Policies: The Government of India has established Coastal Regulation Zone policies to regulate development activities along the coast. These policies restrict construction within a specified distance from the high tide line, protecting sensitive coastal ecosystems and minimizing coastal erosion risks.

It's worth noting that the effectiveness of these techniques can vary depending on local conditions, including the type of coastline, sediment availability, and wave patterns. A comprehensive approach that combines multiple techniques, taking into account local factors, is often the most effective strategy for coastal erosion protection in India.

Figure 3. Some common vegetation on the beach sand dune systems in India

Ipomoea pescaprae · *Spinifex littoreus* · *Sesuvium portulacastrum*

Chrysopogon zizanioides · *Cynodon dactylon* · *Launaea sarmentosa*

Saccharum sp · *Canavalia maritima* · *Cassia tora*

Image 1 Some common vegetation on the beach sand dune systems in India

13.9 Time Capsule in India on Coastal Regulation

Subordinate legislation enacted since 1981.

The timeline of coastal regulations in India reveals a series of initiatives and revisions aimed at managing and safeguarding the country's coastal areas. Here's a summary of the key developments:

1981: Directive by the Prime Minister of India to maintain beaches clean and free from development.

1987: Department of Environment issues beach guidelines.

1989–1990: Initial draft Coastal Regulation Zone (CRZ) notification released and revised in 1990.

19th February 1991: Final Coastal Zone Management Notification issued by the Government of India.

July 2009: Reconstitution of the M S Swaminathan Committee to address coastal issues and propose policy and legal frameworks.

2008: Draft Coastal Zone Management Notification introduced but later withdrawn due to various objections and suggestions.

July 2004: Constitution of the M S Swaminathan Committee to recommend the integration of diverse legislation concerning coastal areas.

1992–2011: Twenty-five amendments made to the 1991 basic notification, mostly related to individual cases.

2010–2014: Period marked by the establishment of various entities:

2010: Integrated Coastal Zone Management Project (ICZM) with World Bank Assistance.

2011: Formation of the Society for ICZM (SICOM).

2013: Establishment of the National Centre for Sustainable Coastal Management under SICOM.

2014: Formation of institutions in a consortium to create a Knowledge Source Hub.

March 2015–April 2016: The Ministry of Environment, Forest and Climate Change (MOEFCC) issued eight amendments based on the essence and logic of the SNC Report, of which only four followed the prescribed procedure.

June 2014: Dr. Shailesh Naik Committee (SNC) formed to review and suggest actions based on representations from various states regarding the provisions of the 2011 Notification.

January 2015: SNC Report recommended the issuance of a new notification.

January 2019: New Notification released, superseding the 2011 Notification, indicating a continuous evolution and revision in the coastal regulations and management practices in India.

13.10 Conclusion

Efforts for coastal erosion protection in the problematic area are to be identified , science behind erosion like actions of wave, wind and soil conditions are to be carefully studied. Habitat area, cultivation field, industry or property are to be protected from the river flood water, so it is essential to look into it. With the help of suitable planning, design and technology coastal erosion and river bank protection can be executed.Proper care in respect to geotechnical parameters are to be listed out and suitable methodology in each field of problems are to be adapted for protection. Similarly work on flood management system is also very much important as river embankment protection.For the economy sandy soils are used in many areas for river embankment protection as the required quantity can not be easily available for full river area. So it is essential to use the latest technology along with the local available materials to combat the disaster from protesting the problematic area.

13.11 Disclosure Statement

No potential conflict of interest was reported by the author(s)

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14 TC 306 Geo-Engineering Education

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14.1 Introduction

Geotechnical engineering, an indispensable branch of civil engineering, deals with the study of soil, rock, and their interaction with structures. It is the science that underpins the stability and performance of the built environment. As civilizations have grown, so too has the need for solid foundations upon which to construct their infrastructure. From the pyramids of Giza, the ancient Egypt to the towering skyscrapers of modern cities, the importance of understanding the ground upon which we build has never wavered. The collective knowledge, experiences, and innovations of generations of educators, researchers, and practitioners in the field of geotechnical engineering should be preserved. Geotechnical engineering education, much like the soils it studies, has demonstrated remarkable adaptability, addressed the requirements of an ever-evolving world by incorporating emerging technologies, educational methodologies, and inter-disciplinary linkages. The evolution of geotechnical engineering education is a testament to the resilience and dynamism of the discipline. The advent of computers and sophisticated software tools has reshaped the landscape of geotechnical engineering. No longer confined to manual calculations and simplified models, educators and students now harness the power of numerical simulations, three-dimensional modeling, and data analysis.

The transition from traditional lecture-based instruction to interactive and student- centric approaches has been accelerated by the pandemic. Problem-based learning, online resources, and virtual laboratories have become indispensable toolsin the modern geotechnical engineering classroom. The challenges and opportunities that lie ahead, including sustainable practices, geotechnical risk management, and global collaboration, are integral to Geotechnical engineering journey. This paper will provide not only a historical account but also a forward- looking perspective on the continuing evolution of geotechnical engineering education.

The primary purpose of this paper is to comprehensively examine the historical evolution of geotechnical engineering education and its adaptation to changing times. The paper primarily focuses on geotechnical engineering as a specialized field within civil engineering and its educational aspects, Historical Perspective- spanning from its early origins to contemporary practices, technological advancements in geotechnical education, Pedagogical Shifts, particularly highlighting innovative approaches that enhance student engagement and comprehension.

This paper seeks to:

- Document the key milestones and developments in geotechnical engineering education, highlighting its foundational principles and how they have evolved over time.
- Analyze the impact of technological advancements on geotechnical education, including the integration of computational tools and digital resources.

- Explore the shifts in pedagogical approaches and teaching methodologies within geotechnical engineering, such as problem-based learning and online education.

- Discuss the challenges and opportunities facing geotechnical engineering education in the present and future.

14.2 Origin of geotechnical engineering education

The origins of geotechnical engineering education can be traced back to ancient civilizations that recognized the importance of understanding soil and its properties for constructing stable and durable structures. While the formal education and organized study of geotechnical engineering as a distinct discipline developed much later, the seeds of this field were sown in antiquity. Here are some key points about the origins of geotechnical engineering education:

Geotechnical engineering has a rich history, marked by key milestones that have contributed to its development as a distinct discipline within civil engineering. Here are some key milestones in the evolution of geotechnical engineering: The foundations of geotechnical engineering can be traced back to ancient civilizations such as the Egyptians and Babylonians, who built impressive structures and developed rudimentary soil mechanics principles for constructing foundations and earthworks.

The Taj Mahal, built in the 17th century on the banks of the river Yamuna adopting special foundation techniques, and it's a testament to the engineers' skill that this grand structure still stands strong after three centuries.

In the realm of geotechnical engineering history, Coulomb (1776) introduced the first rational approach for calculating earth pressures on retaining walls. Poncelet (1840) extended this theory with a graphical method, while Culmann (1875) provided a geometric formulation. Rankine (1857) proposed a Classical Earth Pressure Theory, and Darcy (1856) established laws for water flow in permeable materials. Stokes (1856) contributed equations for the terminal velocity of solid particles in liquids. Engineers like Daniel Bernoulli and Leonhard Euler made significant contributions to soil mechanics theory. Their work laid the groundwork for understanding soil behavior under load.

Mohr's theory (1900) and Boussinesq's stress distribution theory (1885) significantly impacted geotechnical engineering. Atterberg (1911) developed tests for cohesive soil consistency, and Fellenius (1927) pioneered the Swedish Circle method, investigating the causes of embankment failures.

However, the most pivotal moment in soil mechanics and foundation engineering came in 1925 when Terzaghi laid down essential procedures for determining soil properties and strength characteristics. His work laid the foundation for understanding soil settlement due to the expulsion of pore water. Terzaghi's seminal work, "Erdbaumechanik" in 1925 (Theoretical Soil Mechanics), published in German, provided a comprehensive framework for soil mechanics and established the theoretical basis for modern geotechnical engineering. These advancements have shaped the current state of knowledge in soil mechanics and foundation design. In 1930, Karl Terzaghi, along with Arthur Casagrande, established the first soil mechanics laboratory at the Massachusetts Institute of Technology (MIT). This laboratory played a crucial role in advancing geotechnical engineering testing methods.

1. The systematic study of soil behavior and geotechnical engineering education has been significantly shaped by several pioneers and prominent figures in the field in addition to Karl Terzaghi. Arthur Casagrande was instrumental in developing the principles of soil mechanics and played a crucial role in standardizing soil testing methods. His work greatly influenced geotechnical education and practice. During this period,

spanning from 1856 to 1910, several noteworthy experimental findings from laboratory tests conducted on sand were documented in the available literature. Significant contributions were made by influential figures like Henri Philibert Gaspard Darcy (1803– 1858), whose work included a comprehensive study on the permeability of sand filters. Additionally, Joseph Valentin Boussinesq (1842–1929) made remarkable strides in the development of the theory pertaining to stress distribution beneath loaded bearing areas within a homogeneous medium, significantly advancing the understanding of these critical geotechnical principles.

Ralph B. Peck's (1940-1970) research and publications on soil engineering and foundation design have had a profound impact on geotechnical engineering education. His book "Foundation Engineering" is a seminal work in the field. Teruo Asaoka's contributions to geotechnical education and research, particularly in the area of unsaturated soils, have had a global influence. His work has advanced the understanding of soil behavior in various conditions. Harry Seed's (1950-1970) research in geotechnical earthquake engineering and seismic response of soil-structure systems has been highly influential in geotechnical education. His research on soil liquefaction significantly advanced the field. His contributions include pioneering work on the Standard Penetration Test (SPT) and liquefaction evaluation.

His work has improved the understanding of soil behavior during seismic events. John Atkinson's research and teaching in geotechnical engineering, particularly in the area of soil- structure interaction and numerical modeling, have advanced the field's education and practice. Bruce Bolt (1960s-1990s) made substantial contributions to seismology and earthquake engineering. His work on ground motion prediction and seismic hazard assessment has been essential for geotechnical engineers designing earthquake-resistant structures. George Housner (1960s-1990s)was a pioneer in earthquake engineering, particularly in the study of structural dynamics and earthquake-resistant design. His research on ground motion and structural response influenced seismic design principles. These pioneers made significant strides in earthquake geotechnical engineering and have left a lasting impact on geotechnical education.

John Burland's contributions to geotechnical engineering education, including his work on the teaching of soil mechanics, have been influential in shaping modern geotechnical education approaches. These pioneers and many others have collectively contributed to the systematic study of soil behavior and the development of geotechnical engineering education as it stands today.

In 1960’s the introduction of geosynthetic materials, such as geotextiles and geomembranes, revolutionized the field of geotechnical engineering by providing innovative solutions for soil reinforcement, erosion control, and environmental applications.

Following significant earthquakes, particularly the 1964 Alaskan earthquake, geotechnical earthquake engineering emerged as a specialized field, focusing on the study of soil behavior during seismic events.

During Late 20th Century, the development of powerful computers and numerical modeling software allowed for more sophisticated analysis and design in geotechnical engineering, enabling engineers to simulate complex geotechnical problems. Environmental concerns, such as soil contamination and waste disposal, led to the emergence of environmental geotechnics, which focuses on the interaction between soils and contaminants.

The 21st century challenge is using innovative materials, reducing waste, designing for durability and resilience, and considering the long-term effects of projects on the planet and its people Incorporating sustainability into geotechnical engineering practices is essential for addressing these challenges and ensuring that construction activities have a positive, lasting impact on society, the environment, and the economy. It involves. The recognition of geotechnical risks in infrastructure projects and the development of risk management strategies have become integral to modern geotechnical engineering practice.

Today, geotechnical engineering education is an integral part of civil engineering programs at universities worldwide, and it encompasses a wide range of topics, from soil mechanics and foundation engineering to geotechnical earthquake engineering and environmental geotechnics. The discipline continues to adapt to the changing needs of society and the challenges posed by complex infrastructure projects.

The Time Capsule paper on Geotechnical engineering education acknowledges the interdisciplinary contributions of researchers, engineers, and professionals in the field. It underscores the significance of preserving and sharing their work to inspire and educate future generations.

Year	Author	Paper	Journal	Significance
1980	Davis, E.H., Gunn, M.J., Mair, R.J., and Seneviratne, H.N.	The stability of shallow tunnels and underground openings in cohesive material.	Geotechnique 30, No. 4.	The paper investigates three distinct shapes of shallow underground excavations pertaining to tunneling, and it establishes upper and lower boundary stability solutions for potential collapse scenarios under undrained conditions
1984	Whitman, R.V.	Evaluating Calculated Risk in Geotechnical Engineering	Journal of Geotechnical Engineering	This paper addresses the need to demystify probability for engineers and provides examples of its practical use in decision-making processes, particularly in assessing slope stability, liquefaction analysis, embankment design, and risk evaluation for various geotechnical projects.
1988	Ambraseys, N. & Menu, J.	Earthquake induced ground displacements.	Earthquake Engineering and Structural Dynamics 16(7), p.p.985-1006.	This study derives graphs and formulas that enable the evaluation of permanent displacements in foundations and slopes based on the critical acceleration ratio by utilizing an extensive dataset of unscaled ground motions acquired at source distances less than half of the source dimensions
1991	W. F. Marcuson et.al.	Issues In Geotechnical Engineering Education	Journal of Professional Issues in Engineering Education and Practice	This paper provides a summary of the deliberations conducted during the 1990 National Forum on Education and Ongoing Advancements in Civil Engineering, with a focus on geotechnical engineering education.

2000	Muniram Budhu	Numerical and Visualization Techniques in Geotechnical Engineering Education	Proceedings - GeoDenver 2000 Educational Issues in Geotechnical Engineering	Aims to introduce visualization methods designed to facilitate students' comprehension of fundamental principles in geotechnical analysis.
2002	Petry, T. M., & Little, D. N.	Review of stabilization of clays and expansive soils in pavements and lightly loaded structures— history, practice, and future.	Journal of materials in civil engineering.	This paper reviews some of the key advances developed over the past 60 years in improving the understanding of the nature and methods of stabilizing expansive clay soils.
2003	Mašala, S., & Biggar, K.	Geotechnical Virtual Laboratory. I Permeability.	Computer Applications in Engineering Education	introduces the Geotechnical Virtual Laboratory, a computer-based instructional tool designed to enhance geotechnical engineering education by potentially replacing physical laboratory testing, focusing on the permeability module, its outcomes, evaluations, and user experience
2006	Budge, A. S.	Geotechnical opportunities for computer-aided education.	Joint International Conference on Computing and Decision Making in Civil and Building Engineering (pp. 2344-2350).	Describes the benefits of incorporating computer-aided tools in the classroom on the learning potential of engineering students.
2009	Griffiths D.V. and Huang J.	Influence of Spatial Variability on Slope Reliability Using 2-D Random Fields.	Journal of Geotechnical and geoenviromental engineering	This paper explores slope failure probability through the application of both conventional and advanced probabilistic analysis techniques. The advanced approach, known as the random finite-element method, integrates elastoplasticity within a finite-element model and combines it with random field theory in a Monte- Carlo framework.

2012	Vanapalli, S., & Lu, L.	A state-of-the art review of 1-D heave prediction methods for expansive soils.	International Journal of Geotechnical Engineering	This paper compiles and discusses various techniques found in the literature for estimating swelling pressure and the one-dimensional heave behavior of expansive soils. It also addresses the constraints of applying these techniques in geotechnical engineering practice.
2012	Guler, H., & Mert, N.	Evaluation of internship programs for educational improvements: a case study for civil engineering.	International Journal of Engineering Education, 28(3), 579.	This paper evaluates civil engineering internship programs for educational improvements by doing statistical analyses on comprehensive survey data gathered. Evaluates future carrier planning, multidisciplinary team working, learning theoretical and practical applications.
2013	Charles E. Pierce et.al	Environments for fostering effective critical thinking in geotechnical engineering education (Geo-EFFECTs)	European Journal of Engineering Education	This paper outlines the creation, application, and evaluation of instructional resources for teaching geotechnical engineering principles using the Environments for Fostering Effective Critical Thinking (EFFECTs) pedagogical framework, with an emphasis on enhancing core knowledge and nurturing critical thinking abilities in engineering students.
2014	Hashash, Y. M., Jammoul, M., Su, S. H., & Bhat, S. D.	Integrating Geotechnical Baseline Reports and Risk Allocation Frameworks in Geotechnical Engineering Education.	Geo-Congress 2014: Geo-characterization and Modeling for Sustainability (pp. 2290-2296).	This paper describes the advantages of combining the GBR (Geotechnical Baseline Report) and risk allocation approach in geotechnical engineering education. It also presents a framework for seamlessly integrating these approaches into current curricula.

2015	K Chatterjee, D Choudhury, HG Poulos	Seismic analysis of laterally loaded pile under influence of vertical loading using finite element method	Computers and Geotechnics, Elsevier	This paper presents an effective analytical method based on the finite element (FE) approach for assessing the bending moment and deflection of an individual pile subjected to the simultaneous impact of lateral and axial compressive forces in seismic conditions. The study considers scenarios involving both saturated and dry homogeneous soil as well as a common layered soil configuration.
2015	Basu, D., Misra, A., & Puppala, A. J.	Sustainability and geotechnical engineering: perspectives and review.	Canadian geotechnical journal, 52(1), 96-113.	This paper delves into the philosophies and interpretations of sustainability within the realm of geotechnical engineering. It provides an exhaustive examination of research and case studies in geotechnical engineering concerning sustainable development.
2015	López- Querol, S. Sánchez-Cambronero, S., Rivas, A., & Garmendia, M,	Improving civil engineering education: Transportation geotechnics taught through project-based learning methodologies	Journal of Professional Issues in Engineering Education and Practice	The paper describes the benefits of the project-based learning structure over conventional teaching approaches in Transportation Infrastructure course
2016	Xenia Wirth et.al.	Undergraduate Geotechnical Engineering Education of the 21st 1 Century	J. Prof. Issues Eng. Educ. Pract.	This paper proposes an undergraduate geotechnical curriculum which attempts to encompass not only the technical criteria but also the transferable skills needed for geo- engineers

2019	Fredlund, D. G.	Determination of unsaturated soil property functions for engineering practice	17th African Regional Conference on Soil Mechanics and Geotechnical Engineering	It covers estimation procedures for determining unsaturated soil property functions applicable to various engineering practices such as seepage, shear strength, and volume change.
2020	Howell, G. et al	Enriching the Geotechnical Engineering Classroom through Novel Multidisciplinary Examples.	Geo-Congress 2020. doi:10.1061/9780784482810.068	Discusses about novel examples and in-class activities that convey geotechnical engineering concepts to students in a multidisciplinary way
2020	Harteveld, C., Javvaji, N., Machado, T., Zastavker, Y. V., Bennett, V., & Abdoun, T.	Gaming4all: reflecting on diversity, equity, and inclusion for game-based engineering education.	IEEE Frontiers in Education Conference (FIE) (pp. 1-9). IEEE.	This paper describes about a gaming tool which amalgamates conventional classroom methods (such as lectures, lab work, field data, software models, and simulations) with virtual activities, students gain practical exposure to the Cone Penetration Testing (CPT) field technique.
2020	P. Kallioglou & S Vairamidou.	Student Centred Learning" Approach in the Development of Social Skills: Implementation in an Experimental Soil Mechanics Course	GEE 2020 - Geotechnical Engineering Education 2020 Athens, Greece International Conference © ISSMGE 2020	The paper discusses on Student Centered Learning approach as an efficient learning environment conducive to enhancing students' social skills, including but not limited to communication, initiative, responsibility, collaboration, critical thinking, adaptability, self-confidence, tolerance, and leadership.
2021	Philotheos Lokkas et.al.	Historical background and evolution of Soil Mechanics	WSEAS Transactions on Advances in Engineering Education	This paper delves into the historical evolution and advancements within Soil Engineering. Through extensive references to key technical literature and notable construction projects across eras, it serves as a valuable educational resource for instructing and enlightening students.

2021	Jiang, N. J et.al.	Geotechnical and geoenvironmental engineering education during the pandemic	Environmental Geotechnics	This paper discusses the global impact of COVID- 19 on geotechnical and geoenvironmental engineering education, outlining the challenges faced and solutions implemented based on faculty feedback from 14 countries/regions.
2023	Zia ur Rehman	Trends and challenges of technology-enhanced learning in geotechnical engineering education	Journal Sustainability (Switzerland)	This paper explores the integration of Technology-Enhanced Learning (TEL) with instructional design strategies in geotechnical engineering education while addressing challenges and proposing problem-based learning, experiential learning, collaborative learning, and critical thinking cultivation.
2023	Amir Tophel, Stefan Vogt & G. V. Ramana	Investigation of deformation behaviour of uniaxially loaded sand grains using a novel high-resolution imaging apparatus and ensemble machine learning models	International Journal of Geotechnical Engineering	Machine Learning (ML) models, including artificial neural networks (ANN) and long-short term memory neural networks (LSTM) were used, achieved a remarkable 1-2% error rate in predicting long-term grain strains, enhancing structural serviceability assessment for these materials.

14.3 Role of Tools and Technologies in Geotechnical engineering education

Technology plays a pivotal role in modern geotechnical engineering education. It has transformed how students learn, researchers conduct experiments, and practitioners analyze and design geotechnical structures. Here are some key aspects of the role of technology in geotechnical engineering education: These technologies have transformed geotechnical education by making it more interactive, data-driven, and adaptable to real-world challenges. They empower students to explore geotechnical concepts in depth, develop practical skills, and prepare for careers in geotechnical engineering with a strong foundation in both theory and practice.

14.3.1 Software

Simulation and Analysis: Advanced geotechnical software allows students to simulate complex geotechnical scenarios, perform numerical analyses, and visualize the behavior of soil and structures. The software like PLAXIS, GEO-SLOPE, SEEP/W, FLAC, OpenSees, RS3 , TALREN enhances their understanding of theoretical concepts and helps them develop problem-solving skills. Geospatial Technologies helps in analyzing spatial data related to soil properties, geological features, and site characterization. Software tools like AutoCAD Civil 3D, GeoStudio suite, ArcGIS, Surfer, RockWorks, Leapfrog Geo, Grapher enable to visualize data from laboratory experiments and field investigations. They can create graphs, charts, and 3D models to better interpret and present their findings Software like MATLAB, Python, R, Excel, Dakota, STABL, ANSYS are helpful to conduct parametric studies, exploring how different input parameters affect the outcomes of geotechnical analyses. This promotes experimentation and critical thinking.

14.3.2 Laboratory Equipment

Digital Sensors: Modern geotechnical laboratories are equipped with digital sensors and data acquisition systems. Precise measurements can be made during soil and rock testing experiments, enhancing the accuracy of their results. • Automation: Automated laboratory equipment, such as triaxial testing machines and consolidation devices, reduces the manual workload and allows students to focus on data interpretation and analysis.

14.3.3 Field Instrumentation

Real-Time Monitoring: Field instrumentation provides an opportunity to conduct real- time monitoring of geotechnical parameters in the field, such as groundwater levels, settlement, and slope stability. This data can be used for research projects and to validate theoretical concepts learned in class which also It bridges the gap between theory and practice. Field instrumentation is valuable for environmental geotechnics, enabling to study the impact of soil and groundwater conditions on environmental projects such as waste containment and remediation.

14.4 Resources in Geotechnical Engineering Education

14.4.1 Digital Learning Platforms:

Online learning management systems (e.g., Moodle, Canvas) facilitate the delivery of geotechnical engineering courses. These platforms provide access to course materials, lecture recordings, quizzes, and collaborative tools.

14.4.2 Open Educational Resources (OER):

Many universities and organizations provide free and open-access geotechnical educational materials, including textbooks, lecture notes, and video tutorials.

- **Remote Access:** Some universities offer remote access to laboratory equipment, enabling students to run experiments and collect data even if they are not physically present in the lab. This flexibility promotes accessibility and inclusivity. Advanced laboratory equipment often includes safety features that protect students and researchers during experiments, creating a safer learning environment. Field instrumentation often involves collaboration with professionals from other disciplines, providing students with exposure to interdisciplinary approaches to problem-solving.

14.4.3 Virtual Reality (VR) and Augmented Reality (AR):

Immersive Learning: VR and AR technologies offer immersive learning experiences. Students can visualize complex geological formations, construction processes, and geotechnical structures in 3D, enhancing their spatial understanding and problem- solving skills.

14.4.4 Online Collaboration and Communication Tools:

Webinars and Video Conferencing: These tools facilitate remote lectures, guest lectures by experts, and virtual meetings for research collaborations, enhancing networking opportunities for students and researchers.

14.4.5 Simulations and Virtual Labs:

Virtual Experiments: Simulations and virtual labs provide students with a risk-free environment to conduct geotechnical experiments and explore different scenarios,helping them develop problem-solving skills.

14.4.6 Mobile Apps and Field Tools:

Mobile Apps: There are numerous geotechnical apps for smartphones and tablets that assist in field data collection, soil classification, and slope stability analysis, making fieldwork more efficient and data-driven.

In summary, technology has not only expanded the tools available to educators and students in geotechnical engineering but has also made learning more interactive, accessible, and adaptable to real- world challenges. It empowers students to explore the intricacies of soil mechanics, foundation design, and geotechnical analysis in a dynamic and data-driven environment. Advances in software, laboratory equipment, and field instrumentation have had a profound impact on teaching and learning in geotechnical engineering. These advancements have transformed the educational experience by providing students with new tools, methods, and opportunities for hands-on learning. Several specific technologies have revolutionized geotechnical education by enhancing the way students learn, researchers conduct experiments, and educators teach.

14.5 Curriculum and Pedagogy

14.5.1 Changes in the geotechnical engineering curriculum

Changes in the geotechnical engineering curriculum have been influenced by evolving industry needs, technological advancements, and innovative pedagogical approaches. These changes have enriched modern pedagogical approaches in geotechnical engineering education:

14.5.1.1 Integration of Emerging Technologies:

The curriculum now includes topics related to the use of emerging technologies, such as advanced geotechnical software, geospatial tools (GIS), and data analysis techniques. Students learn to apply these technologies to geotechnical problem-solving.

14.5.1.2 Environmental Considerations:

Given the growing emphasis on sustainability and environmental protection, geotechnical engineering programs often incorporate courses on environmental geotechnics. Students learn about topics like soil and groundwater contamination, waste containment, and remediation strategies.

14.5.1.3 Geotechnical Risk Assessment:

There is a greater focus on geotechnical risk assessment, especially in the context of natural disasters and climate change. Courses on geotechnical earthquake engineering and probabilistic analysis help students understand and manage risks associated with geotechnical projects.

14.5.1.4 Interdisciplinary Education:

Geotechnical engineering is increasingly viewed within the context of larger civil and environmental engineering projects.

Interdisciplinary coursework encourages students to collaborate with other engineering disciplines and consider broader project implications.

14.5.2 Modern Pedagogical Approaches:

Modern pedagogical approaches emphasize active learning, problem-solving, and the practical application of geotechnical principles ensuring the preparedness for future challenges.

The integration of practical and real-world experiences into the geotechnical engineering curriculum is crucial for preparing students to be effective practitioners in the field. This integration enhances their understanding of theoretical concepts, develops problem-solving skills, and fosters a deeper appreciation for the challenges faced by geotechnical engineers. Here are ways in which practical and real-world experiences are incorporated into the curriculum:

14.5.2.1 Problem-Based Learning (PBL):

PBL is an active learning approach that challenges students to solve real-world geotechnical problems. In this approach, the students work in teams, identify issues, and propose solutions. PBL fosters critical thinking, problem- solving skills, and collaboration.

14.5.2.2 Simulation and Modeling:

The use of geotechnical software for simulations and modeling allows students to explore complex scenarios. They can analyze the behavior of soil and structures under various conditions, gaining practical insights into geotechnical engineering principles.

14.5.2.3 Online Education:

Online geotechnical engineering courses and programs have become more prevalent, offering flexibility to students who may be working professionals or have other commitments. These courses often incorporate video lectures, interactive quizzes, and discussion forums.

14.5.2.4 Flipped Classroom:

In a flipped classroom model, students review course materials independently before class. Class time is then used for interactive discussions, problem- solving exercises, and group projects. This approach encourages active engagement and application of knowledge.

14.5.2.5 Project-Based Learning (PBL):

PBL involves students in hands-on, project-based activities related to geotechnical engineering. Students are allowed to work on any problem statement like design foundations, analyze slopes, or conduct site investigations. PBL reinforces theoretical concepts through practical application.

14.5.2.6 Blended Learning:

Blended learning combines traditional in-person classes with online resources and activities. It offers the benefits of both in-person interaction and the flexibility of online learning.

14.5.2.7 Virtual Labs:

Virtual geotechnical laboratories enable students to conduct experiments and explore geotechnical equipment and procedures in a digital environment. This is particularly useful for remote learning or when physical labs are unavailable.

14.5.2.8 Gamification:

Gamification elements, such as educational games and quizzes, are used to make learning more engaging and enjoyable. These tools can be integrated into online courses to motivate and assess student progress. gamification can be used as a supplement to traditional teaching methods to align with the learning objectives. It can make learning more engaging and enjoyable while reinforcing key geotechnical engineering concepts.

Virtual Field Trips can be developed using 360-degree photos and videos of geotechnical engineering sites. Students can explore these sites online, answer questions, and complete challenges related to the specific geotechnical challenges of each location.

Developing board games and card games is another interesting way where students must navigate challenges related to soil types, foundation design, and construction. Card game based on soil classification systems like the Indian Soil Classification System or the AASHTO classification help the students match soil properties to the appropriate soil type, learn to classify soils effectively.

A geotechnical-themed escape room concept allows students use their knowledge to solve puzzles and escape within a time limit. Each puzzle or challenge can be related to a geotechnical concept.

Competitions in geotechnical engineering that involve tasks like constructing the tallest sandcastle, designing a model retaining wall, or building a bridge using limited resources provide engaging and practical ways for students to grasp essential concepts in the field.

Encouraging the students to craft concise narratives or comics that showcase challenges and solutions within the realm of geotechnical engineering. This approach can effectively immerse them in real-world applications while maintaining engagement.

Geotechnical Engineering Podcasts where students produce their own geotechnical engineering podcasts or video tutorials to explain complex topics in a simplified and entertaining manner is an effective way to create an effective learning environment.

14.5.2.9 Fieldwork and Site Visits:

Field trips to construction sites, geotechnical investigation sites, and geological formations offer students exposure to real-world conditions. They can observe soil and rock properties in their natural settings, learn about site-specific challenges, and appreciate the importance of site characterization.

14.5.2.10 Internships and Co-op Programs:

Offering internships or cooperative education (co- op) opportunities with engineering firms, construction companies, or government agencies allow students to work on actual geotechnical projects, apply their classroom knowledge, and gain practical skills. Collaborations with industry partners, such as engineering consulting firms and geotechnical laboratories, provide students with access to real-world data, projects, and expertise. Guest lectures and workshops by industry professionals enrich the curriculum.

14.5.2.11 Capstone Design Projects:

Capstone projects often involve solving real-world geotechnical engineering problems. Students work on design and analysis projects related to foundations, retaining walls, slope stability, or environmental geotechnics. They collaborate with industry professionals to develop solutions.

14.5.2.12 Geotechnical Competitions:

Participation in geotechnical engineering competitions, encourage creativity and teamwork.

In summary, the geotechnical engineering curriculum has evolved to include emerging technologies and interdisciplinary perspectives. Practical laboratory experiments form an integral part of the curriculum. Students have the opportunity to perform soil tests, conduct geotechnical experiments, and analyze real soil and rock samples. These hands-on experiences help students understand the physical behavior of soils and rocks. Courses or projects related to environmental geotechnics involve real- world issues such as soil contamination, groundwater remediation, and waste disposal. Students learn about regulatory compliance and sustainable solutions. Students are often required to prepare geotechnical reports as part of their coursework. These reports simulate the documentation and communication processes involved in real-world engineering projects. Undergraduate and graduate research projects offer students the chance to explore cutting-edge geotechnical research questions. They work closely with faculty mentors and gain experience in experimental design, data analysis, and scientific communication

14.6 Challenges in Geotechnical engineering education

1. Resistance to change from traditional teaching methods.

2. Limited access to specialized software licenses.
3. emphasizes interdisciplinary collaboration. Students work on projects that integrate geotechnical, structural, and environmental aspects, mirroring real-world engineering practices
4. Balancing work and Teaching for working professionals
5. Lack of physical lab access for online students.
6. Keeping the curriculum updated with evolving industry demands.
7. Attracting and retaining diverse talent in the field of geotechnical engineering.
8. addressing language barriers.
9. Balancing traditional teaching methods with modern pedagogical approaches.

Solutions:

1. Faculty training and support in using the software effectively. Demonstrations and student projects showcasing the benefits of software-driven analysis helped overcome initial resistance.
2. Negotiated software licenses that allowed students to access these tools on their personal computers, ensuring flexibility and accessibility.
3. Program introduced joint projects and courses involving students and faculty from multiple engineering disciplines
4. Scheduling and the use of recorded lectures and discussions accommodate the busy schedules of working students.
5. Virtual geotechnical labs that provide a hands-on experience through simulations and remote access to instruments and experiments.
6. The program maintains close ties with industry partners and advisory boards to ensure the curriculum aligns with industry needs. Regular curriculum reviews and updates are conducted.
7. Have established scholarships and support networks for underrepresented groups, organized outreach events
8. Language support services and facilitate a diverse and inclusive learning environment
9. Traditional lectures with active learning, practical assignments, and collaborative projects. They use geotechnical software and simulation tools to enhance student engagement and problem-solving skills.
10. stablished partnerships with international universities, facilitating student exchanges and collaborative research on global geotechnical challenges

Several geotechnical education programs have successfully adapted to changing times by embracing innovative approaches and addressing various challenges. Here are a few examples and insights into the challenges they faced and how they overcame them:

Geotechnical education programs in India have adapted to changing times by embracing modern pedagogical approaches, integrating technology, and addressing specific challenges.

- **Online Courses:** Several IITs offer geotechnical engineering courses online through platforms like NPTEL (National Programme on Technology Enhanced Learning). These courses are open to learners from across India and provide flexible access to quality education. state-of-the-art geotechnical engineering laboratories equipped with advanced testing equipment and digital data acquisition systems are established.

- **Industry Engagement:** By fostering strong ties with industry partners, Institutes have created opportunities for internships, projects, and job placements for its students, bridging the gap between academia and industry.

- Many geotechnical programs offer faculty development programs and workshops to train educators in modern teaching methods, software tools, and emerging trends in the field

The transformation of geotechnical engineering education has significantly influenced students' learning experiences and their readiness for the field. These changes encompass various facets. Firstly, innovative educational methods like problem-based learning and simulations have empowered students to grasp geotechnical concepts more effectively. Secondly, the incorporation of practical elements, including laboratory experiments and fieldwork, has nurtured their hands-on skills, vital for geotechnical engineers. Thirdly, these evolving approaches have nurtured students' problem-solving abilities, fostering critical thinking and innovative solutions. Furthermore, exposure to relevant technology and industry practices readies graduates for their careers. Interdisciplinary collaboration and a global outlook contribute to a well-rounded geotechnical education. Ultimately, these adaptations in education better prepare students for the complexities of the geotechnical engineering profession

Role of Professional societies:

Professional societies play a vital role in geotechnical engineering education by providing resources, support, and a platform for networking and knowledge sharing among educators, researchers, and students. These societies contribute to the advancement of geotechnical engineering education in several ways. Professional societies often develop and provide educational resources, including textbooks, reference materials, and online courses, to support geotechnical engineering programs. These resources help educators design curriculum and enhance teaching materials. Societies organize conferences, seminars, and workshops where educators can present their research findings, share teaching methodologies, and learn about the latest developments in the field. These events offer opportunities for professional development. Membership in these societies allows educators to connect with peers from around the world. This networking can lead to collaborative research projects, the exchange of teaching strategies, and exposure to diverse perspectives in geotechnical engineering. Many societies offer programs and scholarships to support undergraduate and graduate students pursuing degrees in geotechnical engineering. These initiatives help attract and retain talent in the field. The International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) is a prominent global organization in this field. Under ISSMGE, there are numerous national and regional geotechnical societies and technical committees that cater to various aspects of geotechnical engineering.

British Geotechnical Association (BGA), International Geosynthetics Society (IGS), Canadian Geotechnical Society (CGS), Australian Geomechanics Society (AGS): Indian Geotechnical Society (IGS), Japanese Geotechnical Society (JGS), Geotechnical Society of Malaysia (GSM), Brazilian Society for Soil Mechanics and Geotechnical Engineering (ABMS), Hong Kong Geotechnical Society (HKGS), Geotechnical Society of Singapore (GeoSS), South African Institution of Civil Engineering (SAICE), Mexican Society of Geotechnical Engineering (SOMEG), these societies, along with many others worldwide, contribute significantly to geotechnical engineering education, research, and practice by facilitating knowledge exchange, collaboration, and professional growth within the field.

14.7 Future direction in Geotechnical engineering Education

Future directions for geotechnical education should align with emerging trends and address evolving needs in the field. To prepare students for the challenges of the future, there is a need to bring reforms in geotechnical education.

Integration of Digital Twin Technology:

Incorporate digital twin technology into geotechnical education to teach students how to create and use virtual replicas of geotechnical structures and systems for monitoring and analysis.

Data Science and Analytics Emphasis:

Data science and analytics courses to equip students with skills in data analysis, machine learning, and artificial intelligence, which are increasingly important for geotechnical research and practice.

Sustainability and Environmental Geotechnics:

Coursework and research opportunities in sustainability and environmental geotechnics to address the growing emphasis on eco-friendly and resilient infrastructure projects.

Geotechnical Engineering in a Changing Climate:

Courses that focus on the impact of climate change on geotechnical engineering, including addressing issues related to sea-level rise, extreme weather events, and adaptation strategies need to be introduced.

Advanced Geotechnical Software Training:

Enhance training in advanced geotechnical software tools and emphasize their application in solving real-world problems, ensuring that students are proficient in digital tools used in industry.

Geospatial Technology Integration:

Integrate geospatial technology, including Geographic Information Systems (GIS) and remote sensing, into geotechnical education to enhance site characterization and geospatial data analysis skills.

Virtual Reality (VR) and Augmented Reality (AR):

Virtual reality (VR) and augmented reality (AR) applications offer students immersive learning opportunities in geotechnical engineering, enabling them to virtually engage in activities like site inspections and hazard assessments, thus enhancing their understanding of real-world scenarios.8.

Interdisciplinary Education

This interdisciplinary approach equips geotechnical engineering students to adeptly collaborate across fields to tackle complex infrastructure and environmental challenges. engineering, geology, environmental science, and architecture to prepare students for multidisciplinary projects.

Global Perspective:

Promoting global awareness and international collaboration by encouraging students to engage in international internships, research projects, and cultural exchange programs.

Soft Skills Development:

Offering courses that focus on soft skills, such as effective communication, teamwork, project management and leadership, to prepare students for leadership roles in the industry.

Continuing Education and Professional Development:

Establishing pathways for lifelong learning, including certificate programs and online courses, to support the ongoing professional development of geotechnical engineers throughout their careers.

Research Integration:

Encouraging undergraduate and graduate students to engage in research projects, fostering critical thinking and innovation in geotechnical engineering.

Industry Institute Partnerships:

Strengthening industry partnerships to provide students with opportunities for practical experience, internships, and exposure to real-world geotechnical projects.

Geotechnical Risk Assessment:

The curriculum to include advanced topics in geotechnical risk assessment, probabilistic methods, and resilience engineering to address uncertainties in geotechnical projects.

Providing training on disaster resilience and preparedness in the context of geotechnical engineering

Assessment of Learning Outcomes:

Implement rigorous assessment methods to evaluate students' practical skills, problem-solving abilities, and critical thinking, in addition to theoretical knowledge

Geotechnical education should adapt to these future directions to produce graduates who are well-equipped to address the evolving challenges and complexities of the geotechnical engineering field, contribute to sustainable infrastructure development, and meet the needs of the global community.

14.8 Summary

This paper provides a comprehensive exploration of the historical evolution, curriculum development, technological advancements, and pedagogical innovations within geotechnical engineering education. It underscores the transformative impact of technology on teaching methods and the curriculum, with a particular emphasis on practical experiences and hands-on learning. While acknowledging challenges such as staying current with technological advancements and resource limitations, the paper offers solutions such as faculty development and industry partnerships. Looking ahead, it outlines future directions for geotechnical education, advocating for the integration of digital technologies, interdisciplinary collaboration, sustainability considerations, and expanded international experiences, all geared towards better preparing students for the dynamic landscape of geotechnical engineering.

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15 TC 308 Energy Geotechnics

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15.1 Abstract

In this time capsule of Energy geotechnics TC 308, only the major themes of the energy geotechnics has been covered as it is difficult to cover the entire spectrum. Although many of the aspects of this research area has been explored by different researchers, but as a special area of research has been recognized after ISSMGE organized the first international conference on Energy Geotechnics (TCEGT), 2016. In the present time capsule some areas has been focused keeping in mind its importance in Indian context. The areas covered are geothermal systems, underground space for natural gas and liquid storage, carbon storage in geological formations and skill development. In these areas key challenges are discussed and way forward has been suggested.

Keywords: Time capsule, Energy geotechnics, TC308, Geothermal systems, Underground storage, Carbon storage

15.2 Introduction

Energy geotechnics is the area related with earth materials and its application in mining, petroleum extraction, coastal engineering and offshore constructions. This encapsulates the knowledge of geology, geophysics, hydrology and thermal effect of engineering properties of earth materials. In these the geotechnical engineering principles are coupled with thermal, hydrological, chemical and mechanical principles. These advance principles are helpful in understanding the processes involving collection and storage of energy; and interaction of engineering structures built for the same with the surrounding geomaterials.

15.3 Milestones in TC308 (Energy Geotechnics)

The principles of energy geotechnics are used for different energy related engineering processes but it was recognized as a separate entity through the first international conference on Energy Geotechnics (TCEGT 2016) held at the University of Kiel, Kiel, Germany. This was organized by international society of Soil mechanics and geotechnical engineering (ISSMGE) under the Technical Committee 308. In continuation of this in the conference Geo-Chicago 2016, sustainability, energy and the environment held at Chicago from August 4 to 18, 2016 highlighted some important areas of energy geotechnics. As a part of conference proceedings, the 2nd geotechnical special publications (GSP). Geotechnics of sustainable energy gives idea about the new innovations in storing and extracting energy from geomedia and geostructures e.g. shallow and deep geomedia, shallow and deep pile foundations and landfills.

The international symposium on Energy geotechnics 2018(SEG-18) was held on 25th to 28th September2018 at the Swiss Federal Institute of Technology in Lausanne. The symposium was organized under the auspices of the TC-308(Energy Geotechnics) of ISSMGE. In this symposium wide range research areas are covered under energy geotechnics. The proceedings papers covered themes in energy geostructures, energy geostorage, thermo-hydro-chemo-mechanical behavior of geomaterials, hydraulic stimulation, induced seismicity, CO2 geological storage, nuclear waste disposal, tower and offshore foundations.

The forthcoming symposium is the 3rd international symposium on energy geotechnics SEG23 will be held on 3rd to 5th October 2023 in Delft, Netherland under the auspices of ISSMGE Technical Committee 308 on Energy geotechnics(in cooperation with Delft University of Technology and Eindoven university of Technology). The various theme of energy geotechnics will be covered such as geothermal energy, energy geostructures, energy storage, offshore geotechnics, carbon sequestration, radioactive waste disposal and induced seismicity.

15.4 Key Challenges and Practices in TC-308

Around the world including India, there are challenges in mitigating climate change and environmental issues at the same time securing the energy supply for ever increasing demand. Energy geotechnics have great potential in streamlining the traditional energy recovery as well as helps in conceptualizing and developing new energy sources and the relevant technologies. In this regard, India is doing well in developing these new technologies but it can do better when compared to other developed countries like USA. Area wise key challenges and practices in different aspects of energy geotechnics TC 308 are discussed.

Geothermal systems:

In general there are two geothermal energy systems: deep geothermal energy systems and shallow geothermal energy systems. In deep geothermal systems the main source of energy is found from hot dry rock and the reservoir should be designed for efficient energy production and it is done by hydraulically fracturing the geomaterial formation, thereby increasing hydraulic conductivity and more surface area for heat transfer. In comparison to this shallow geothermal energy system is used for homes and commercial buildings. In this case È thermal capacitance È of the ground, transfer the heat from the structure to the structure in winter. This heat energy is transferred through thermally active pipes buried in ground beneath. This shallow system can have high efficiency upto 600% but long term efficiency of these systems significantly influenced by the balance between cooling and heating heads. When the load is not balanced, ground temperature gradually increases or decreases thereby affecting the efficiency. In case of deep geothermal system, early depletion of energy can affect the long-term performance of this energy reservoir.

Underground space for natural gas storage:

The underground facilities like depleted reservoirs of oil and natural gas fields and natural salt cavern formation are used for storage of liquid and gaseous hydrocarbons. The suitability of these storage space is decided by the physical characteristics like porosity, permeability and gas retention capability; and operational economic like site preparation and maintenance cost, and deliverability rate etc. India has started storing strategic oil reserves from year 2008 in underground rock cavern upto 10 days requirement of the nation. The government of India has created strategic crude oil storage at Vishakhapatnam in Andhra Pradesh, Mangalore and Pour in Karnataka. Liquid petroleum gas is also stored at Vishakhapatnam for commercial use. In these types of storage structures, the mail challenges for the geotechnical engineer are the response of the rock caverns to the large pore fluid pressure cycles, thermal fluctuations due to gas compression and expansion, effect due to moisture change and mineral solubility in the liquid.

Carbon storage in geological formations:

A large amount of finance is devoted to the development of technology for efficient capture of CO2 from coal and hydrocarbon-based power plants, kilns and other such sources; but more research focus on storage of the same is needed. One of the CO2 storage options from geotechnical point of view can be deep saline aquifer, deep ocean sediments to create CO2 hydrate and replace CH4 with CO2 in the methane hydrate bearing sediments. Many of these technologies are in pilot program stages and many loop holes are yet to cover.

Education and Practical Skill development:

It is now understood that the energy geotechnics field needs well-established scientific principles and advanced engineering concepts to analyze and solve the complex processes coming under its purview. Most of present-day geotechnical engineers are not sufficiently updated of the knowledges and skill as required to work in this complex field. In India, we focus on traditional geotechnical engineering knowledge but not on some of these complex theories e.g., thermos-hydro-chemo-mechanical properties of geomaterials etc. So, changes are needed in renewing the geotechnical engineering curriculum, updating field professional knowledge and make management aware of the contribution the geotechnical engineer can make and thereby increasing their employability.

15.5 Way forward in Energy Geotechnic TC 308

Based on the research output in field in the field of energy geotechnics following forward has been suggested.

Geothermal systems:

For the deep geothermal system, early depletion of energy production can be taken care of by optimal design and sustainable operation of geothermal systems. For the shallow geothermal systems to operate efficiently, proper design of the system is required. For a comprehensive and efficient design of the system, the thermal properties of soil and backfill material is considered and sufficient focus should be there.

Underground natural gas storage:

In these storage facilities robust monitoring instrumentation with automation option for lesser human interference should be there for continuous assessment of integrity of the facility and long term performance. Dedicated research on these underground storage systems should be done by varying the scale of the project and ground depth of the same, for more of commercial use keeping the safety features in mind.

Carbon storage in geological formations:

Although well proven technologies are available to inject CO2 into the ground but for real field application many complexities are there, such as identification and characterization of suitable geoformations, long term stability of sealing agent and robust monitoring system.

Education and practical skill development:

To close the gap between energy industry requirement and geotechnical engineer’s expertise in the same field the given initiative should be initiated:

- Update the geotechnical engineering curriculum to include the basic scientific principles used to define the engineering behaviour of the geomaterials subjected to hydro-chemo-thermo-mechanical loading.

- In the curriculum, case histories of geostructures used for energy geotechnics requirements should be included.

- Geotechnical students should be encouraged to do energy relevant inter-disciplinary projects with student of other disciplines.

15.6 References

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