

Navigating 21st Century Geotechnical Challenges in Highway Engineering

Nisha Meena

Research Scholar

Kalinga University, Raipur (C.G.)

nishameena199695@gmail.com

1 Abstract

In the contemporary landscape, Transportation Authorities and Highway Engineers worldwide grapple with challenges distinct from those faced by their counterparts in the nineteenth and twentieth centuries. These challenges

not only the creation of novel highways and bridges but also the refurbishment of existing roads and bridges deteriorated due to aging or increased vehicular loading. The escalating frequencies of deterioration in existing roads and the looming threat of imminent bridge failures have compelled numerous Highway Authorities to conduct comprehensive evaluations of current infrastructure. Consequently, there is a prioritization of retrofitting efforts to align with present specifications and anticipate future conditions.

The contemporary challenges at hand encompass a diverse range of issues, including, but not limited to: a) Navigating construction over inadequate foundation materials, such as organic soils, aged landfills, expansive and collapsing soils, compounded by the non-availability of alternative routes; b) Negotiating right-of-way restrictions, particularly in urban environments and in close proximity to existing structures; c) Addressing environmental concerns that were previously deemed less critical, now necessitating compliance with increasingly stringent environmental and safety regulations; d) Incorporating certain problematic native on-site materials, such as shale, in backfills and embankments; e) Managing higher vehicle loading and coping with an increase in the size and number of vehicles; and f) Meeting the heightened expectations of road users for enhanced driving conditions, improved safety features, and superior riding quality.

Effectively surmounting these challenges requires the application of innovative ideas and the integration of modern technology throughout the planning, design, and construction phases of highway development. This paper delineates some of the contemporary challenges based on historical context and introduces a myriad of tools to address these challenges. Through the adoption of improved and expedited analytical methods, the incorporation of novel construction materials (e.g., low-density fill materials, geo-synthetics, geofabric, geogrids), the utilization of innovative procedures (e.g., soil stabilization, reinforced earth, soil nailing), and the implementation of robust planning, execution, and quality control measures, these challenges can be overcome efficiently and cost-effectively.

Furthermore, this paper identifies existing geotechnical practices that, while once effective, may now be considered inadequate for modern-day highway design and construction. Despite the evolution of engineering practices, certain methods have persisted without updates for decades. In conclusion, the paper not only recognizes areas where current geotechnical practices may fall short but also provides recommendations for revising these practices. The ultimate goal is to present updated and comprehensive geotechnical guidelines for the safe and sound design and construction of highways from a geotechnical perspective.

Keywords – Geotechnical Challenges, Highway Engineering, Emerging Technology

2 Introduction

Over the course of history, Transportation Authorities and Engineers have traversed a remarkable journey, progressing from the inception of the first Depressed Motorway in Detroit, Michigan, USA, to the renowned Autobahn in Germany and the proliferation of Super Highways worldwide. Figure 1 illustrates the Davison Highway in Detroit, Michigan, a pioneering example of the first depressed highway constructed in the United States.



Fig. 1 - Davison Highway in Detroit, Michigan

Meanwhile, Figure 2 showcases a complex seven-level urban highway interchange in California, USA. The Twentieth Century witnessed substantial advancements in the design and construction of roads and bridges across the globe, with the United States alone witnessing the creation of millions of miles of roads, highways, embankments, bridges, culverts, and viaducts in the post-World War II era.



Fig. 2 Seven-Level Super Highway Interchange, California, USA

However, as time has marched forward, many of these infrastructures have aged and are now deemed unsafe, despite persistent maintenance and upgrading endeavors. This is primarily due to the evolution of design parameters, an expanded knowledge base, and heightened user expectations. The advent of automobiles in the early Twentieth Century significantly enhanced mobility, with the construction of US Highways playing a pivotal role in shaping the socio-

economic landscape of America during the Progressive Era. This transformative influence extended globally, with European, Asian, African, Australian, and New Zealand countries substantially developing their transportation systems throughout the Twentieth Century.

As we stand on the threshold of the Twenty-First Century, significant progress continues to unfold in the Transportation Industry. However, challenges persist, ranging from minor to catastrophic failures of roads and bridges worldwide, often attributed to natural disasters, extreme weather conditions, and human error. Many of these failures trace back to the inadequacy of the ground supporting these structures. In the contemporary era, Transportation Authorities, structural engineers, and geotechnical experts worldwide face the formidable task of averting similar failures. This entails retrofitting existing structures and implementing innovative designs for new ones.

Thankfully, the landscape is not devoid of solutions. Advances in engineered materials and cutting-edge technology are not only available but also continuously evolving throughout the transportation industry. These advancements serve as crucial allies in overcoming the challenges posed by aging infrastructure and unforeseen external factors. The collaborative efforts of professionals in the field aim to harness these technological strides to fortify existing structures and pave the way for the development of resilient, state-of-the-art transportation systems that meet the demands of the present and future.

3 Review of Literature

In Khandker, Anagnostou, and Deo's (2013) research on geotechnical challenges in highway engineering, it was identified that past experiences have significantly influenced the advancements in the field. The study emphasized the importance of incorporating new technologies, such as electronic data collection, to overcome challenges in interpreting and trusting the gathered information. Tomography, a technique generating a three-dimensional electronic picture of subsurface conditions, was highlighted as a valuable tool, complementing traditional methods of site investigation.

Wardani, Chu, and Lo's (2011) findings from the 5th International Conference on Geotechnical and Highway Engineering provided a comprehensive overview of the practical applications, challenges, and opportunities in the field. The research emphasized the need for a collaborative

and multidisciplinary approach to address the evolving landscape of geotechnical and highway engineering.

Amadi and Higham (2017) explored latent geotechnical pathogens contributing to cost overruns in highway projects. The study revealed various factors, including inadequate attention to site characterization, leading to financial challenges in geotechnical aspects of highway development.

Hazarika et al. (2017) investigated the geotechnical damage resulting from the 2016 Kumamoto Earthquake. The findings underscored the importance of understanding and addressing the impact of seismic events on geotechnical infrastructure. The study also outlined future challenges, emphasizing the need for resilient designs and construction techniques.

Ganse and Fischer's (2021) research on geotechnical considerations for tunnels under highways provided insights into factors influencing tunnel construction beneath highways. The study highlighted the importance of advanced technologies and methodologies in ensuring the stability and safety of such structures.

Maduka et al. (2017) conducted a geotechnical assessment of road failure and slope monitoring along the Nsukka-Adoru-Idah highway. The findings revealed specific challenges related to soil conditions in Southeastern Nigeria, emphasizing the importance of tailored solutions for different geographical regions.

Breedeveld's (2013) exploration of the future position of geotechnical engineering discussed the evolving role of the field. The research emphasized the transition from traditional methods to new-age techniques, including tensor techniques for unsaturated soils, providing more confidence in final designs.

Zhussupbekov and Omarov's (2016) research on modern advances in geotechnical testing investigations of pile foundations showcased the significance of technological advancements in improving the reliability of foundation assessments.

Sandven and Solberg's (2014) geophysical and geotechnical investigations in a quick-clay area highlighted the challenges associated with highway development in regions with specific geological characteristics. The findings underscored the importance of thorough investigations to mitigate potential risks, such as landslides.

Overall, the collective research findings emphasized the importance of embracing new technologies, incorporating multidisciplinary approaches, and addressing specific challenges in different geographical contexts to advance the field of geotechnical and highway engineering.

4 LESSONS FROM THE PAST EXPERIENCE

Drawing insights from past experiences, it has been a prevailing assumption that foundation failures exclusively stem from soft and unsuitable soils. However, the reality is more nuanced, with a myriad of factors contributing to the failures of roads and bridges. Examining recent cases of failures in highways and bridges across different regions highlights the diverse reasons behind these incidents.

4.1 Earthquake Damage

One significant category of failures arises from seismic events, particularly earthquakes. Historically, a lack of knowledge and understanding led to the design of many earlier bridges and roads without accounting for the potential damage caused by ground movement and liquefaction triggered by seismic activities. For instance, in several instances, it was observed that the maximum damage during earthquakes is intricately linked to peak particle velocity, contrary to the erstwhile belief that it was solely determined by peak particle acceleration. This shift in understanding underscores the importance of evolving insights and incorporating updated knowledge into the design and construction of infrastructure to mitigate the impact of seismic events.



Fig. 3 - Stretch of Badrinath highway caves in, sinks by 3ft in 24hrs

3 feet within a span of 24 hours. This alarming incident indicates a substantial deterioration in the stability and integrity of the highway, posing immediate challenges to vehicular movement and overall road safety. Urgent attention and remedial measures are imperative to address the compromised condition of the highway and ensure the swift restoration of this crucial transportation route.

4.2 Storms And Floods

The insufficient focus on implementing effective flood protection and drainage systems in earlier design practices has proven to be a significant factor contributing to numerous pavement failures in the aftermath of major storm events. The oversight in addressing these crucial aspects has resulted in the vulnerability of pavements to the damaging effects of storms and floods, highlighting the imperative need for enhanced flood protection measures and improved drainage systems in contemporary design approaches.



Fig. 4 - **Flood** damage on NH6 in Meghalaya, India, June 2022

The National Highway 6 (NH6) in Meghalaya, India, faced severe flood damage in June 2022, as captured in a photo by the East Jaintia Hills Police. The image portrays the aftermath of flooding, illustrating the challenges posed to transportation infrastructure by the inundation of water. The incident underscores the vulnerability of critical road networks to natural disasters like floods, emphasizing the importance of strategic planning and resilient design in mitigating the impact of such events on vital transportation corridors.

4.3 Landslide Damage

Landslides and rock slides can be activated by various factors, including seismic events and saturation of slopes due to storm events. This susceptibility is exacerbated when coupled with weakened shear zones along bedding planes parallel to the slope. The intricate interplay of these elements underscores the complex nature of slope instability, emphasizing the importance of comprehensive risk assessments and mitigation strategies to address these geotechnical challenges effectively.



Fig. 5 - The Shimla-Kinnaur road damaged due to a landslide

The Shimla-Kinnaur road suffered extensive damage as a result of a landslide, leading to disruptions in the transportation infrastructure. The landslide, characterized by the movement of earth and debris, inflicted substantial harm to the road, necessitating prompt attention and rehabilitation efforts to restore the thoroughfare to its functional state. The aftermath of the landslide posed challenges in terms of both vehicular mobility and road safety, highlighting the critical need for comprehensive geotechnical assessments and mitigation measures to address such natural events effectively.

4.4 Sinkholes

Insufficient geological and geotechnical characterization of a project site can give rise to issues such as sinkholes, particularly in regions characterized by Karst topography. The absence of a thorough understanding of the site's geological features increases the risk of sinkhole formation,

underscoring the necessity for comprehensive assessments in areas prone to such geological phenomena.



Fig. 6 - Noida-Greater Noida Expressway collapse

A significant sinkhole emerged on the Noida-Greater Noida Expressway following the collapse of a 15-foot-long and two-foot-wide section of the crucial route near Sector 96 in Uttar Pradesh's Greater Noida. The incident occurred on Friday, leading to extensive traffic congestion on both sides of the expressway. In response, officials swiftly arrived at the scene, initiating immediate repair work to address the issue. Police officials reported that by Saturday, the movement of vehicles had returned to normalcy.

5 Geotechnical Challenges: Navigating the Complex Terrain

Delving into the realm of geotechnical challenges, the following provides a comprehensive checklist for evaluating potential geological and geotechnical hazards that could impact transportation projects:

5.1 Problematic Soils:

The presence of organic soils, uncontrolled fill, natural collapsible soils, expansive soils, acid sulfate soils, and corrosive soils along the road alignment can pose significant challenges to serviceability and durability. Examples include aeolian deposits of silts and fine sands in arid regions like Loess, wind-deposited beach sands, and volcanic ash. Some collapsing soils result from weathering and internal leaching, collapsing under a critical load upon wetting. Special

investigations are imperative to identify these problematic soils, and tailored design and construction methods are required to mitigate related issues.

5.2 Problematic Rocks:

Shale, weathered limestone, and very hard granite present challenges for road and bridge design and construction. Ongoing research explores the utilization of shale in roadbeds and embankments, while design methods for foundations on weathered soft rock, such as limestone, are under development. Modern heavy rock-cutting equipment is available to handle challenging rock conditions.

5.3 Coarse Alluvium with Boulders and Cobbles:

Excavation, drilling, and piling in materials with boulders and cobbles pose difficulties. Specialized equipment and techniques are essential to overcome challenges associated with these formations.

5.4 Poor Sub-grade Drainage:

The importance of sub-grade drainage cannot be overstated. Inadequate sub-grade drainage, especially over clay sub-grade or shallow rock, can lead to pavement damage and surface deterioration. The use of open-graded sub-base and drainage fabric draining to roadside ditches helps minimize the adverse effects of stagnant water below the pavement.

5.5 Possibility of Sinkholes:

Areas prone to sinkholes extend beyond Karst topography to include abandoned mine areas and locations where underground streams wash out fines. Proper geotechnical investigation can detect such conditions, allowing for mitigation using available ground improvement techniques.

5.6 Soil Slope Instability:

The potential for slope failure or landslides should be thoroughly investigated for road projects. Local geological maps, landslide record searches, site reconnaissance by experienced geologists, and geotechnical investigations can significantly reduce the risk of unexpected slope failure. Various stabilization methods, including retaining walls, sheet piles, metal nets, short piles, soil nailing, and rock bolts, are available.

5.7 Rock Slope Instability or Rock Fall:

Deep cuts in weathered rock with steep slopes may appear stable initially but could prove otherwise. Periodic monitoring and the use of metal mesh and geo-grid can enhance road user safety.

5.8 Earthquake Epicenter and Active Faulting Zone:

Before selecting a site for a bridge or aligning a highway project, a record search of seismic activities in the project area is essential. Structures should be designed to withstand anticipated earthquake forces, considering soil behavior under dynamic loading and liquefaction potential. A well-designed geotechnical investigation program can detect liquefaction potential early on, allowing for modifications or route changes to prevent catastrophic failures.

5.9 Unstable Pavement Subgrade:

Cohesive soils at high water content can be challenging to compact and remain unstable. Lime-stabilization, cement-stabilization, or fly-ash stabilization techniques can improve such soils.

5.10 Bridge Foundation Problems:

Common issues for bridge foundations include soft soils, heavy loads, and accessibility of foundation locations. Deep scour potential for piers in flowing streams is often overlooked. Protecting bridge piers in navigable rivers and considering the danger of floating ice is crucial. The potential for differential settlement between approach embankments and slabs relative to the bridge deck should be addressed using transition slabs, and various methods such as reinforced earth are employed for abutments and wing walls.

5.11 Erosion on Embankment Slopes or Stream Banks:

Slope surface protection is vital to avoid recurring repair costs. Stream bank protection (river training) is essential in bridge design, particularly in flat delta regions with meandering rivers. Technologies such as gabions, select graded boulders and cobbles, geo-grid, rock mat, concrete apron, and others can be utilized for erosion control.

5.12 Earth Retaining Structure:

Modern earth retaining structures, from gravity walls to sheet piles, reinforced earth, slurry walls, cofferdams, and soil nailing, present considerable challenges to geotechnical engineers. Stability considerations, including overturning, sliding, and bearing, require careful attention.

5.13 Inferior Grade Aggregate in Pavement:

When suitable aggregate for pavement is not readily available, and importing proves cost-prohibitive, engineers may need to permit the use of inferior grade aggregate. In such cases, extensive testing is crucial to evaluate the actual properties of the aggregate and incorporate them into the pavement design.

5.14 Freeze-Thaw Effects:

Regions with several freeze-thaw cycles, such as Michigan, face significant pavement deterioration. Ongoing research explores solutions, with the current effective approach involving the use of open-graded aggregate to the frost depth, connected with side ditches to facilitate sub-base drainage.

5.15 Natural Springs & Artesian Water:

Natural springs weakening surrounding soils by slowly washing fines and artesian pressure created by impermeable layers confining water below the natural water table pose challenges. Special techniques are needed to address water-related issues in these cases.

5.16 Culverts beneath High Fills:

Special design methods are crucial for culverts beneath high fills, as failure can lead to costly repairs. Thorough consideration of these geotechnical challenges is essential for the successful planning and execution of transportation projects, ensuring their resilience against a range of natural and man-made hazards.

6 Emerging Technology in Highway Engineering

The realization of a successful highway engineering project necessitates the seamless integration of both conventional technologies and innovative emerging techniques. Consider the following key aspects in this endeavor:

6.1 Subsoil Investigation:

In the realm of highway engineering projects, the process of subsoil investigation has evolved into a global standard. Diverse drilling and sampling techniques are employed to gain a comprehensive understanding of the underlying soil conditions. The utilization of in-situ testing methods, such as the Standard Penetration Test, Vane Shear Test, Cone Penetrometer Test, Pressuremeter Test, and Dilatometer Test, has become pivotal. These tests provide a nuanced assessment of soil strength and compressibility parameters, offering heightened reliability and accuracy. The integration of these techniques ensures a robust foundation for subsequent engineering decisions, fostering the success of the project.

6.2 Geologic and Geotechnical Site Characterization:

Enhancing the characterization of geological and geotechnical features is crucial for informed decision-making in highway engineering. Geophysical Exploration Techniques play a pivotal role in this endeavor, offering a more comprehensive understanding of the subsurface. Techniques such as Seismic Refraction Survey, Cross-Hole Seismic Survey, Ground Penetrating Radar, and Infra-red Survey contribute valuable insights. These methods collectively enhance the site characterization process, providing engineers with a detailed picture of the geological and geotechnical conditions. This knowledge forms the basis for robust design and construction strategies.

6.3 Tomography in Earth Imaging:

Tomography, a technique involving imaging by sections through the use of penetrating waves, emerges as a powerful tool for large-scale earth imaging. In the context of highway engineering, Seismic Tomography stands out as a notable application. The Tomograph Image of the 410 km Tonga Island arc, as depicted in Figure 19, exemplifies the utility of this technique in capturing intricate details of the earth's subsurface. By offering a sectional view, tomography aids in understanding the complex geological features that influence highway construction, paving the way for more informed planning and execution.

6.4 Slope Stability Analysis:

The advent of computer software has revolutionized slope stability analysis in highway engineering projects. This technology facilitates faster and more reliable assessments, allowing

engineers to perform detailed comparisons. The ability to swiftly analyze slope stability is instrumental in decision-making processes related to design and construction. The utilization of available software streamlines these analyses, ensuring that potential issues related to slope stability are identified and addressed efficiently.

6.5 Geo-Hydrologic Modeling:

In the contemporary landscape of highway engineering, the modeling of geo-hydrologic processes has undergone a transformation with the advent of advanced computer software. These state-of-the-art tools have not only simplified the modeling process but have also enhanced its dependability. Geo-hydrologic modeling, critical for understanding subsurface water flow and interaction, is now more accessible. This increased accessibility allows for more dependable assessments, contributing to the development of resilient and sustainable highway infrastructure.

6.6 Soil Structure Interactions:

Predicting the interactions between soil and structures has become more precise and sophisticated through the use of advanced computer software. Engineers can now simulate and analyze how structures interact with the underlying soil, providing valuable insights into the behavior of the infrastructure. This predictive capability ensures that the design and construction processes are optimized for the specific soil conditions, ultimately leading to safer and more durable highway structures.

6.7 New Tunneling Methods:

The landscape of tunneling methods in highway engineering is witnessing significant advancements from around the world. Innovations such as Earth Balance Tunneling, Micro-Tunneling, and the New Austrian Tunneling Method introduce novel approaches to tunnel construction. These methods, incorporating rock bolting and reinforced shotcrete, redefine the efficiency and safety standards in tunneling. As tunnels play a vital role in highway infrastructure, these emerging methods present promising solutions for more sustainable and secure transportation networks.

6.8 Soil-Nail Retaining Walls:

In the pursuit of effective slope stabilization and retention structures, soil-nail retaining walls have emerged as a subject of testing in specific states. The apparent success observed in these tests highlights the potential of this innovative approach. Soil-nail retaining walls offer a dynamic solution to the challenges of stabilizing slopes, providing an alternative that combines effectiveness with cost-efficiency. As these walls undergo testing, they hold promise for broader implementation in highway engineering projects.

6.9 Seismic analyses

Seismic analyses have become more accessible and advanced with the aid of computer software. AnalysisNET, an exemplary software for GeoSonics 3000 Series Seismograph, stands out as a comprehensive tool for engineers involved in seismic assessments. This technological advancement streamlines the seismic analysis process, providing engineers with valuable insights for designing infrastructure that can withstand seismic events.

6.10 The design and construction of Soil Reinforcement,

The design and construction of Soil Reinforcement, particularly in the form of Reinforced Earth, have become more reliable and field-verified. This evolution is marked by advancements in materials, construction techniques, and a deeper understanding of soil-structure interaction. The result is a more robust and resilient approach to soil reinforcement in highway engineering.

6.11 Modern ground improvement techniques

Modern ground improvement techniques have emerged as crucial tools in minimizing the settlement potential of structures and pavements. Techniques such as Preconsolidation with sand drains or wick drains, Vibroflotation, Blasting, Stone Columns, Dynamic Compaction, Compaction Grouting, and Deep Soil Mixing offer diverse solutions to address varying ground conditions. These techniques play a pivotal role in ensuring the stability and longevity of highway infrastructure.

6.12 Total Stress Tensor

The field of soil mechanics for unsaturated soil is experiencing a momentum shift with the utilization of the total stress tensor and Kroneker delta. These advanced concepts contribute to a

more nuanced understanding of the mechanical behavior of unsaturated soil. As engineers delve into the intricacies of total stress tensor and Kroneker delta, the field of unsaturated soil mechanics gains depth and precision, enhancing the overall understanding of soil behavior in highway engineering applications.

7 Innovative Materials

In the realm of geotechnical applications, the utilization of innovative materials has become pivotal in enhancing the efficiency and sustainability of various projects. Here are some noteworthy materials that have revolutionized geotechnical engineering:

7.1 Geo-Textiles and Geo-Membranes:

Geo-textiles, crafted from petroleum-based materials such as polyester, polyethylene, polypropylene, or fiberglass, serve multifaceted purposes. These fabrics, available in non-woven, woven, or knitted forms, play a crucial role in drainage, filtration, separation, and soil reinforcement. Geo-membranes, a variant of geo-fabrics, find extensive application in landfill covers, contributing to environmental protection and containment.

7.2 Geo-Grids and Geo-Cells:

High modulus polymer materials, specifically designed through tensile drawing, manifest as Geo-Grids and Geo-Cells. These materials excel in soil and rock reinforcement, offering robust solutions for enhancing the structural integrity of geotechnical projects. Their application extends to stabilizing slopes, reinforcing retaining walls, and supporting various earth structures.

7.3 Wick Drains (Prefabricated Vertical Drains):

Wick Drains, also known as Prefabricated Vertical Drains (PVD), play a pivotal role in accelerating the pre-consolidation of thick, soft strata to mitigate settlement issues. This innovative solution proves instrumental in reducing settlement timeframes, particularly in areas with challenging soil conditions.

7.4 Geo Foam:

Geo-foam, an ultra-lightweight material, presents a breakthrough in high-volume fill and soil stabilization projects. Weighing over 100 times less than traditional soil, Expanded Polystyrene (EPS) Geo-foam has demonstrated success in various applications, including roads, bridges,

levees, and buildings. The material offers advantages such as high load-bearing capacities, resistance to decomposition, recyclability, and durability. Figure 22 showcases a practical application of Geo-foam near Montrose, Colorado, on US 50.

While Geo-foam has proven advantageous in simplifying construction and reducing costs for public works projects, challenges related to long-term structural stability and environmental concerns persist. Figure 23 illustrates a typical road construction scenario over soft soil, highlighting both the benefits and considerations associated with Geo-foam applications.

7.5 Metallic Soil Reinforcing Strips:

Metallic Strip Reinforcement, employed in conjunction with reinforced concrete skin, serves as a fundamental component in the construction of reinforced earth retaining walls. Additionally, fiberglass strips are available as an alternative for soil reinforcement, contributing to the versatility of materials in geotechnical engineering.

These innovative materials underscore the dynamic evolution in geotechnical practices, offering tailored solutions to address specific challenges and elevate the overall performance and sustainability of infrastructure projects.

Navigating the future landscape of geotechnical engineering presents seasoned professionals with a unique set of challenges, demanding a paradigm shift in methodologies and embracing technological advancements. One paramount challenge lies in overcoming any apprehension towards the integration of electronic data collected onsite through state-of-the-art instruments and commercial computerized systems. The crux of this challenge lies in discerning when to trust and how to interpret electronic outputs while acknowledging the inherent limitations of the system.

The advent of tomography introduces a transformative element, generating three-dimensional electronic representations of subsurface conditions. This approach, complementing or potentially supplanting traditional site investigation methods, signals a departure from conventional practices in subsurface exploration.

A pivotal challenge for future geotechnical engineers involves the seamless transition from established methods to contemporary techniques. The amalgamation of traditional and modern

approaches, with a particular emphasis on tensor techniques for unsaturated soils, promises to instill greater confidence in the final designs and construction of upcoming projects.

The influx of computer-based design techniques has witnessed a significant surge in the past two decades. The challenge lies in comprehending the capabilities and limitations of these programs, necessitating a comprehensive understanding of their workings, input requirements, and expected outputs. Rigorous validation of input and acknowledgment of limitations are imperative to ensure the accuracy and safety of the design outcomes.

The evolving landscape also sees a paradigm shift from conventional Factor of Safety approaches to the incorporation of acceptable deformation methodologies. The embrace of probabilistic approaches in geotechnical design and analysis acknowledges the inherent uncertainty and variability in natural processes. Internationally, Load and Resistance Factor Design (LRFD) techniques for geotechnical components are gaining prominence and are poised for widespread adoption in the near future.

Economic constraints have prompted public agencies to reduce in-house staffing, leading to increased outsourcing of various project components. The challenge here is to uphold the quality and integrity of outsourced work, necessitating stringent quality control measures for in-house staff. A well-structured in-house training program becomes imperative to ensure competence in geotechnical aspects.

In an era marked by shortened project timelines, effective communication emerges as a critical challenge. Ensuring clear and concise communication within specific organizational units and across all stakeholders involved in a project becomes paramount for success.

The inevitability of politics in public service requires geotechnical engineers to navigate and understand the political landscape. Working within these political frameworks becomes essential to produce and maintain high-quality transportation products for the public.

Despite advancements in techniques, equipment, and design methodologies, the challenge for geotechnical engineers lies in embracing continuous research and development. The opportunity exists to deliver the most accurate and detailed geotechnical designs ever by leveraging available technologies and remaining committed to creative solutions that address the evolving professional challenges of today and tomorrow.

8 Conclusion

In conclusion, the performance of transportation infrastructures is continually monitored, with failures meticulously recorded and investigated. Extracting valuable lessons from these experiences is paramount, as compiling and sharing these insights enables researchers and innovators worldwide to focus their efforts on real-life challenges. This collaborative approach is instrumental in fostering the development of new materials and design techniques for road and bridge engineers.

Recognizing the uniqueness of each highway project is essential for transportation authorities, planners, and designers. A bespoke, multi-disciplinary team, encompassing geologists, hydrologists, and geotechnical engineers, should be engaged from the project's early planning stages. This holistic approach ensures a comprehensive understanding of the project's intricacies and facilitates the implementation of effective solutions.

In the United States, several State Transportation authorities, including CalTran, MassDot, and MDOT, have taken proactive measures. They have not only updated their Roads and Bridges specifications but have also initiated or enhanced their Geotechnical Engineering Departments to play a pivotal role in all aspects of highway planning, design, and implementation. Caltrans Earth, a comprehensive source for planning, programming, operations, maintenance, and asset information, utilizes high-resolution imagery and terrain in a web-based, 3-D virtual globe, focusing on California's transportation landscape.

Collaborations between universities and transportation authorities are flourishing, with a shared commitment to conducting cutting-edge research and field applications. These initiatives aim to push the boundaries of technology in various sectors, testing both new and recycled materials for diverse applications in geotechnical and transportation industries. The wealth of innovations and research findings is readily accessible through electronic platforms, including research papers, symposiums, and publications, serving as invaluable resources for engineers navigating the challenges of the Twenty-First Century.

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