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General Report of TC 307 – Sustainability in Geotechnical Engineering Rapport général du TC 307 -Développement durable en géotechnique

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General Report of TC 307 – Sustainability in Geotechnical Engineering

Rapport général du TC 307 - Développement durable en géotechnique

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ABSTRACT: The emergence of sustainable geotechnics has ushered in a paradigm shift across the civil engineering discipline. In this general report, a brief overview of the role of geotechnical engineering in sustainable development is presented in the context of the papers allocated to the sustainability session of the 19th ICSMGE. A review of these papers is provided in the report. Most of the papers deal with monitoring and mitigation of geohazards. These apart, the pertinent topics covered in the allocated papers include use of recycled and alternate geomaterials, sustainable foundations, innovative ground improvement techniques, waste management, and tools/frameworks for assessment of sustainability and resilience. Some of the topics related to sustainable geotechnics not covered by the allocated papers are also mentioned.

RÉSUMÉ: L'émergence d'une géotechnique durable a accompagné un changement de paradigme dans la discipline du génie civil. Dans ce rapport général, un bref aperçu du rôle de l'ingénierie géotechnique dans le développement durable est présenté à travers les documents alloués à la session sur la durabilité du XIX^e congrès de l'ICSMGE. Une synthèse de ces documents est fournie dans le rapport. La plupart des documents traite de la surveillance et de la réduction des risques naturels. Les sujets couverts dans les documents présentés comprennent l'utilisation de géomatériaux recyclés et alternatifs, les fondations durables, les techniques novatrices d'amélioration de sol, la gestion des déchets nucléaires et l'impact socioéconomique des activités du génie civil. Certains des sujets liés à la géotechnique durable non couverts par les documents présentés sont également mentionnés.

KEYWORDS: sustainable geotechnics, geosustainability, geohazard, resilience, reuse.

1 INTRODUCTION

In September 2015, the 194 member countries of the United Nations General Assembly formally adopted the 2030 Agenda for Sustainable Development to embrace a set of 17 Sustainable Development Goals (SDGs) to be implemented in every member nation by year 2030. Besides addressing the pressing issues such as eradication of poverty and hunger, gender equality, and access to clean water and sanitation, the doctrine stressed the importance of resilient infrastructure and sustainable communities. Sustainable development involves a holistic consideration of economic growth, social development and environmental protection. Consistent with the spirit of sustainable development, in recent years, researchers and practitioners have focused their attention toward achieving sustainability and resilience in the built environment.

2 SUSTAINABILITY AND GEOTECHNICS

Anthropocentric development forms the core of civil engineering industry. Geotechnical construction and activities constitute important interfaces through which the human society and the ecosystem interplay. Comprehending this interrelationship is crucial to understanding sustainability in the context of civil engineering. For example, construction of a dam/reservoir affects the community living in the downstream areas by influencing the frequency of flooding in the area; levees and reinforced slopes alter the hydrological response of a basin; and contaminant transport of minerals from mining sites into groundwater impacts public health. Mitigation of geohazards such as earthquakes and hurricanes also forms an important element of geotechnical practice. Thus, geotechnical

engineering can be leveraged to attain the goal of sustainable development of cities and communities.

A vast majority of civil infrastructure invariably involves geotechnical engineering as one of the components. As Pantelidou et al. (2012) noted, the scope of sustainability is highest at the initial stages of a project and decreases as the project moves from planning to the implementation stage. Geotechnical engineering, being positioned at the incipient stages of a project, provides ample opportunities for sustainable development. Incorporating sustainable geotechnical alternatives and practices at the initial stages can contribute toward the sustainability of the project at subsequent stages (Abreu et al. 2008; Basu et al. 2014) (Figure 1).

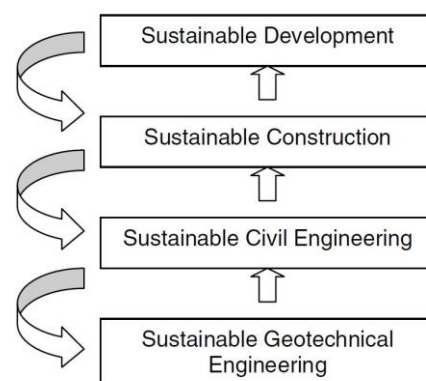


Figure 1. Geotechnical engineering in the construction chain (Abreu et al. 2008).

According to a report by the US National Academy of Sciences entitled “Geological and geotechnical engineering in the new millennium: opportunities for research and technological innovation”, there are seven categories where geotechnical engineering can contribute to improve the sustainability of the societal system (Long et al. 2009). These include (i) waste management; (ii) infrastructure development and rehabilitation; (iii) construction efficiency and innovation; (iv) national security; (v) resource discovery and recovery; (vi) mitigation of natural hazards; and (vii) frontier exploration and development. Pantelidou et al. (2012) advocated seven sustainability objectives for geotechnical engineering: (i) energy efficiency and carbon reduction; (ii) materials and waste reduction; (iii) maintaining natural water cycle and enhancing natural watershed; (iv) climate change adaptation and resilience; (v) effective land use and management; (vi) economic viability and whole life cost; and (vii) positive contribution to society. Abreu et al. (2008) identified four key areas of research into sustainability in geotechnical engineering: (i) energy: reducing energy consumption and use of renewable energy and alternate technology; (ii) materials: reusing and recycling of materials; (iii) pollution: producing less toxicity; water, noise and spatial pollution; and (iv) waste: management of waste production, reducing and recycling waste. According to Basu et al. (2013), sustainability linked studies can be broadly grouped into the following areas: (1) use of recycled and alternate materials in geotechnical construction; (2) innovative and energy-efficient ground improvement techniques, and bioslope engineering; (3) use of geosynthetics for soil reinforcement, (4) sustainable foundations, retrofitting and reuse of foundations, geothermal pile foundations; (5) efficient use of underground space – public transit, energy storage; (6) mining and energy geotechnics; (7) environmental protection, waste management, and preservation of geodiversity; (8) socioeconomic impact of geoactivities; (9) geohazard monitoring and mitigation; (10) incorporating geotechnics in practice; and (11) development of sustainability assessment tools in geotechnical engineering.

3 RESILIENCE IN GEOTECHNICS

In addition to sustainability, it is also imperative to consider the resilience of an infrastructure against natural and human-induced hazards. Any considerations of sustainability without accounting for resilience would render the goal of sustainable development infeasible. Bruneau et al. (2003) proposed four parameters (four Rs) to measure infrastructure resilience: (i) robustness, or the capacity to tolerate a certain level of stress without loss of function; (ii) redundancy, determined by the extent to which a component is substitutable in the event of failure; (iii) resourcefulness, or the ability to address disruptions; and (iv) rapidity, with which the losses are contained. According to Bocchini et al. (2013), holistic consideration of both sustainability and resilience is indicative of the quality of an infrastructure. They emphasize that sustainability and resilience are two complementary attributes; while sustainability deals with the steady impacts on environment, economy and society over the service life of an infrastructure, resilience primarily addresses the sudden impact due to unexpected failure.

4 THEMES COVERED IN SUSTAINABILITY SESSION

ISSMGE advanced the cause of sustainable geotechnics with the formation of the technical committee “Sustainability in Geotechnical Engineering” (TC 307) in 2012. The 18th ICSMGE in 2013 provided further impetus by devoting a technical session to the sustainability theme, which was documented in the general report by Basu et al. (2013). Continuing with the tradition, this general report provides a review of 14 papers related to sustainability and resilience in

geotechnical engineering, which have been accepted for publication in the proceedings of the 19th ICSMGE. The topics covered by these papers can be grouped into six broad areas, as described next.

4.1 Geohazard Monitoring and Mitigation

Sigtryggisdóttir and Snæbjörnsson conceived a framework for analyzing multiple geohazards, and designated parameters for monitoring the hazards. The methodology, based on interrelation matrices, was devised for dams and reservoirs in particular and could be applied to any infrastructure. Some of the geohazards highlighted by the authors include climatic processes such as precipitation, temperature and wind, surface erosion and scouring, crustal movements, earthquakes, reservoir flooding, and fault movement in the dam/reservoir foundation. Parameters deployed for monitoring these hazards include reservoir elevation, groundwater level, leakage/turbidity, pore pressure measurements, meteorological data, and seismicity of the region. The researchers demonstrated how multi-source monitoring of the aforementioned parameters can be linked to multiple geohazards (Figure 2). A natural hazard such as an earthquake could induce failure in a dam/reservoir which could trigger another geohazard (reservoir induced hazard). Therefore, the assessment of multi-hazards is crucial for dam/reservoir safety. A monitoring protocol such as the one outlined here would help in assessing the safety of an infrastructure besides enhancing its sustainability.

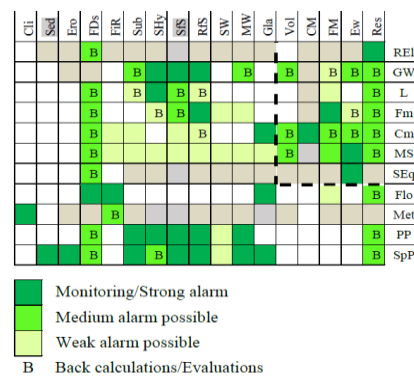


Figure 2. Interrelations between the multi-hazard processes and the monitoring parameters (Sigtryggisdóttir and Snæbjörnsson).

The impact of climate change on landslides in Central Taiwan was analyzed by Shou and Lin. They attributed the increase in extreme rainfall occurrences in Taiwan to the climate change phenomena. These bouts of concentrated and heavy rainfalls reduce the soil strength and trigger large-scale landslides along the mountainous highways. In this study, the temporal variation of rainfall in Taiwan was obtained using a limit equilibrium analyses software, Slide 6.0 (Rocscience 2015), to estimate the landslide prone areas. The profile of a large-scale landslide analyzed by the researchers is shown in Figure 3. An attempt to understand the deep-seated landslide mechanism was made by collecting LiDAR and boreholes data. Landslide interpretation was done with the help of satellite images used to build digital elevation model (DEM), and slope data was extracted from the DEM. A landslide-rainfall index was developed by overlapping the data available in the Geographical Information System (GIS). Susceptibility analysis was conducted using logistic regression method. Landslide hazards in the Central Taiwan region were also ranked to assist in mitigating the risks from these geohazards.

Hashemi and Heron directed their research toward pipeline sustainability by studying soil-structure interaction between the outer pipeline material and the surrounding soil. Variations in fluid and soil temperatures subject the oil and gas pipelines to

substantial cyclic axial displacements, thereby creating shear friction at the pipe-soil interface. Because of this abrasive interaction, the pipeline coating eventually wears off and deteriorates after a large number of cycles. Hashemi and Heron developed a new device to physically model this cyclic and large deformation shearing behavior. The soil used in the research was a grade A coarse sand with sub-angular and sub-rounded particles ($D_{50} = 1.66 \text{ mm}$) which interacted with a smooth steel plate of roughness R_t less than $1 \mu\text{m}$. They noticed an increase in friction ratio after 200 cycles and encountered particle breakage at higher displacements. Hashemi and Heron also demonstrated the interface roughness and particle crushing visually through digital image correlation technique (Figure 4).

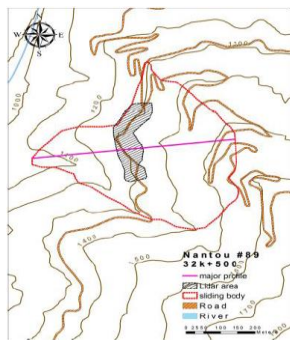


Figure 3. Profile of a large-scale landslide (Shou and Lin).

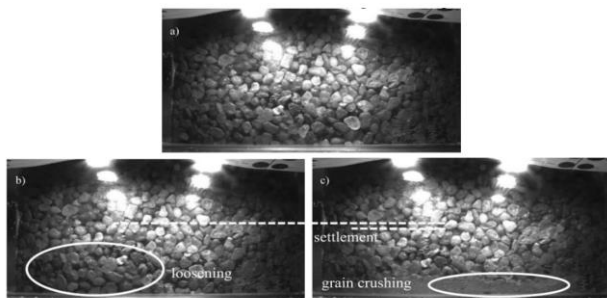


Figure 4. Image analysis through digital image correlation technique depicting particle crushing and settlement (Hashemi and Heron).

Tavares et al. created an integrated numerical water flow model of Quitite and Papagaio basins located in Rio de Janeiro, Brazil. The mountainous basins are vulnerable to extreme rainfall events which trigger landslides and cause flooding, thereby affecting the community living in the valley. The runoff drains into the downstream rivers along with transported sediments eroded from the slopes. The proposed model analyzed and seamlessly integrated the hydrological phenomena prevailing in the region during rainfall occurrences over a period of 3 years. The model used a software package, Mike SHE (by Danish Hydraulic Institute 2013) coupled with Mike 11 program, to calculate runoff into the rivers and evaluated the erosive potential of surface flow. A digital topographical map of the basins was generated using LiDAR (Light Detection and Ranging) to specify sections and coordinates for Mike SHE software. The module created using Mike SHE was linked to the river flow module developed through Mike 11 program in order to construct a topographical surface linked with Quitite and Papagaio rivers. The surface flow velocity was computed, based on flow rate, to assess the erosion pattern and identify high risk zones within the catchment (Figure 5). The model could be applied to study the hydrological response of a region during excessive precipitation and to develop a resilience framework to address the risks. It may be noted that the study does not simulate the water flow through soil medium because of lack of information.

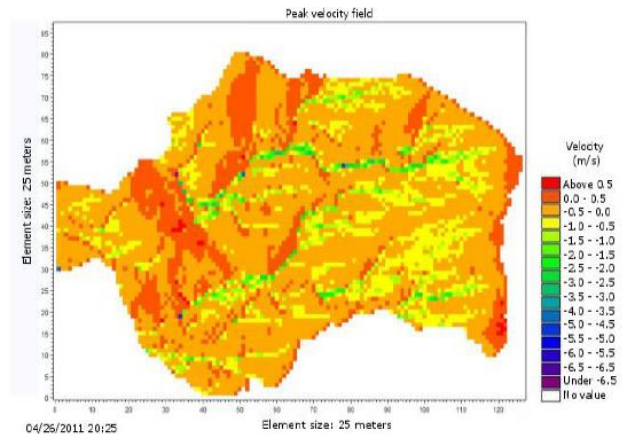


Figure 5. Topographical surface linked with Papagaio and Quitite rivers illustrating the risk-prone areas (Tavares et al.).

Basu et al. conducted a one-dimensional (1-D) ground response analysis (GRA) using DEEPSOIL to assess the liquefaction susceptibility of subsurface profile in the city of Agartala in India. The seismic response from the Sikkim Earthquake in 2011 was utilized by the authors to scale and generate four different values of PBRA. These seismic responses were used to understand the influence of varying peak ground accelerations on the liquefaction susceptibility of a soil profile. The variation of factor of safety (FoS) against liquefaction was assessed using the cyclic stress approach. The generation of excess pore water pressure (PWP) with time was computed. The variation of FoS with depth (Figure 6) followed the same trend as the variation of shear wave velocity with depth. Additionally, the excess PWP generation was observed to be high for the upper layer (which has lower FoS), while the lower layer (medium to dense sand) showed less excess PWP generation. Hence, the variation of FoS and excess PWP generation with depth showed a similar trend.

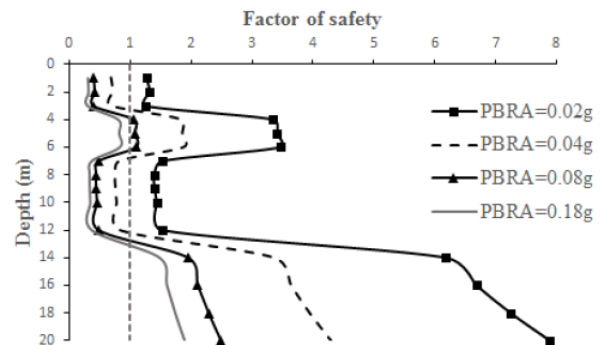


Figure 6. Variation of factor of safety with depth (Basu et al.).

Beesley et al. used a physics-based numerical model, Combined Hydrology and Stability Model (CHASM), which couples the dynamic sub-surface hydrological mechanisms in soils with limit equilibrium slope stability analysis to simulate the effect of urbanization on the factor of safety of a slope (Figure 7). Various climatic conditions like rainfall and resulting infiltration were considered in the study. The effect of variation of slope geometry, effective cohesion and effective angle of internal friction on the stability of slope for varying values of permeability of soil was considered. Urbanization was simulated in the form of removal of vegetation, cutting within the slope, and loading from additional structures. An elaborate series of simulations were performed to develop a parametric study. It was observed that cuts within the slope had the most detrimental effect on slope stability. The use of such a simplistic approach to determine the effect of urbanization on slope

stability is interesting. Future attempts could be made to validate the model using in-situ data, especially corroborating the effects of removal of vegetation cover and desaturation of soil on the mechanical and hydraulic properties of soil.

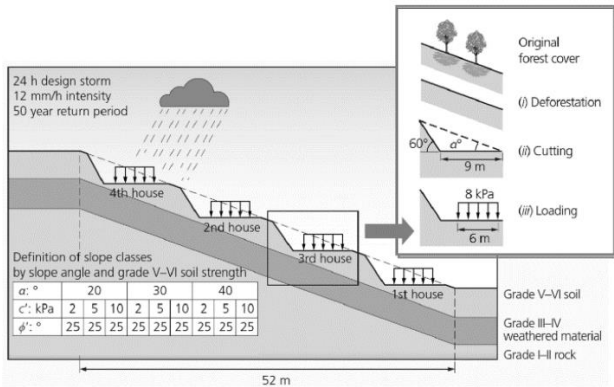


Figure 7. Representation of a typical progression of slope urbanization using the CHASM model (adapted from Holcombe et al. 2016) (Beesley et al.).

4.2 Use of Recycled and Alternate Materials

The reuse of plastic waste for foundation reinforcement was pursued by Dave and Thaker as a sustainable alternative to unreinforced and conventional geogrid reinforced soil. They conducted plate load tests on unreinforced soil and compared the load-settlement behavior with that of conventional geogrid (C-geogrid) reinforced soil and plastic (P-geogrid) reinforced soil. As part of the experimental set up, a test pit of dimensions 2.1 m × 1.05 m × 0.9 m was constructed and filled with uniformly graded river sand (USCS classification: SP, relative density: 70%, angle of internal friction: 36°). The reinforced soil was compacted with four layers of C-geogrid and P-geogrid reinforcements (Figure 8). A mild steel plate of dimensions 205 mm × 185 mm × 25 mm served as the bearing plate. A steel reaction truss was used to transfer the load, and settlement of the plate was recorded by two linear potentiometers with an accuracy of 0.02 mm. The experimental results indicated that the ultimate bearing capacity increased by 22% for C-geogrid and by 15% for P-geogrid. However, the use of P-geogrid derived from PET bottles cut costs by 60% as compared with conventional geogrids.



Figure 8. Soil reinforced with conventional geogrid (C) and PET derived geogrid (P) (Dave and Thaker).

Detterborn et al. suggested that materials used in transportation infrastructure such as concrete could be recycled and reused as earthwork material. This could considerably reduce both the depletion rate of natural aggregates and the impact of construction and demolished (C&D) waste on the environment. Results from their study indicates that crushed concrete aggregates (CCA) has comparable modulus values with natural aggregates. The strength of CCA increase with time

because of rehydration of cement bonds. Furthermore, concrete uptakes the atmospheric carbon dioxide by the process of carbonation throughout its life and, therefore, reduces greenhouse gases. This uptake rate is even greater for crushed concrete when compared with a concrete structure. Detterborn et al. mentioned that, in practice, sustainable design of CCA for earthwork depends on factors like the availability of C&D waste, emissions caused by haulage, and impact of crushing of concrete on the environment. Therefore, prior to any sustainable design with CCA, it is important to assess all the factors that influence the environment and economy.

4.3 Sustainable Foundations

Tarragó et al. proposed a novel re-usable shallow foundation system for light loads, which consists of a concrete block with four steel tubes penetrating the ground at different spatial orientations (Figure 9). The precast concrete block has a square cross-section (260 mm × 260 mm) with the height ranging between 280 mm and 300 mm. The steel tubes project from the concrete block and embed into the soil at an angle of 40° with different orientations. The resulting three-dimensional (3D) skeleton creates interlocking with the ground. The depth of penetration varies between 70 cm and 90 cm. The steel tubes have a thickness of 2.9 mm and an outside diameter of 42.9 mm. The elastic limit of the tubes is 500 MPa and these tubes undergo plastic deformations over a bending moment of 175 kN-m. Tarragó et al. conducted two load tests (compression and tensile) and observed a significant improvement in the bearing capacity compared to that of an equivalent conventional shallow foundation system (Figures 10 and 11). In addition to physical modeling, a Mohr-Coulomb elasto-plastic constitutive model based three-dimensional (3-D) finite element analysis was developed and its performance in predicting the foundation response was compared with the actual field response of the foundation. They utilized field results and the 3-D analysis to obtain the limiting load for the foundation system. The authors concluded that re-use of the foundation system was not advisable if the applied load exceeded 50 kN. The system offers re-usability option only if the tubes do not experience plastic yielding resulting in local rotations.

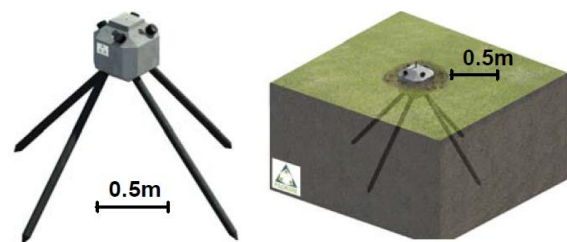


Figure 9. Shallow foundation system for light loads (Tarragó et al.).

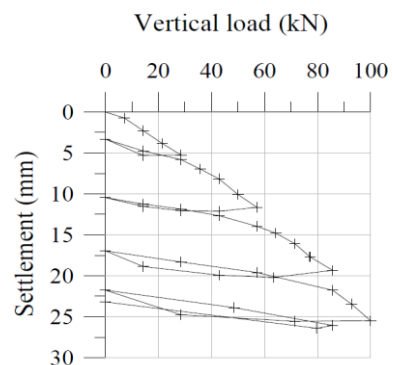


Figure 10. Compression load test results of a shallow foundation system (Tarragó et al.).

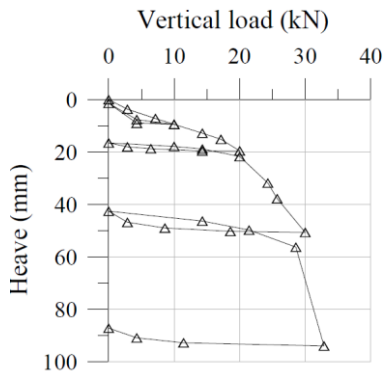


Figure 11. Tension load test results of a shallow foundation system (Tarragó et al.).

Katzenbach and Leppla endeavored to optimize the foundation system design for a high-rise building in Frankfurt, Germany based on considerations of stability and sustainability. As part of this research, an adequate site investigation program was undertaken to determine the soil profile underneath the structure. For the optimization of the foundation elements, two pile load tests were conducted at the construction site and the results were used to calibrate the finite element method (FEM) based model using back calculations (Figure 12). The calibrated FEM model was then used to analyze and quantify the complex soil-structure-interaction between the high-rise building and adjoining structures (Figure 13). The final design was then carried out keeping the deformations of the surrounding structures within permissible limits. The authors contended that, for a sustainable design, it is essential to implement the newest developments in design and construction methods rather than solely adhering to the standards and regulations. They also advocated the use of independent peer review and observational method for quality assurance of such projects.

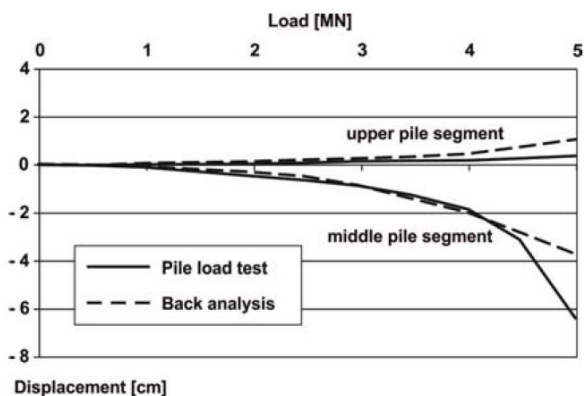


Figure 12. Measurement and back-analysis of one phase of a pile load test (Katzenbach and Leppla).

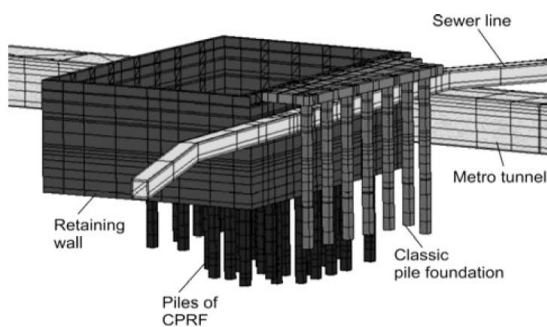


Figure 13. Numerical model of south-west of the project area, Panorama building, view direction south-west (Katzenbach and Leppla).

4.4 Waste Management and Environmental Protection

The final disposal of spent nuclear fuel in a safe manner is an urgent and contentious topic these days. Sinnathamby et al. reviewed the nuclear waste management and disposal strategies that are currently in practice or being considered for adoption in the near future. They reported that spent nuclear fuel (SF) accounts for 95% of radioactivity even though its volume amounts to only 3% of the waste produced. It could take several centuries for the radioactivity to diminish within safe limits. They categorized nuclear waste management as either (a) direct disposal or (b) reprocessed. According to the authors, currently, the most well developed SF disposal method is based on using geological repositories by encapsulating the nuclear waste in metal canisters and storing these canisters in stable geological formations several hundred meters below the ground surface. These repositories have multiple barriers that prevent the SF from leaking or spilling. The authors compiled information on different nuclear waste disposal strategies around the world (Figure 14). Finland and Sweden favor the direct disposal method and have together started constructing a geological repository at a depth of around 400-700 m in crystalline bedrock. France has applied for license to build a proposed 500 m deep geological repository in a natural clay layer. Germany has decided to terminate the operation of its plants by 2022 because of protests, and is actively searching for disposal options. The UK is still gathering support for geological repositories by building understanding and awareness in communities since the idea was voted out. Switzerland is actively testing on samples that were horizontally embedded in crystalline bedrock and enclosed with bentonite buffer. Belgium is studying possible geological repository in a 90 m thick Boom Clay reference formation at about 200 m beneath the ground level at the Mol-Dessel nuclear site. In the US, the proposed deep geological repository project at Nevada's Yucca Mountain was abandoned in 2010. Proposals for geological repositories in Canada seem to point to a location at the Bruce nuclear site in Tiverton, Ontario where the repository will be located in clay-rich limestone formation. The proposed repository concept for China is a shaft-tunnel model, located in the saturated zones of granite formation at a depth of around 500 m below the ground level. Japan is in the preliminary stages of site selection for an underground facility.

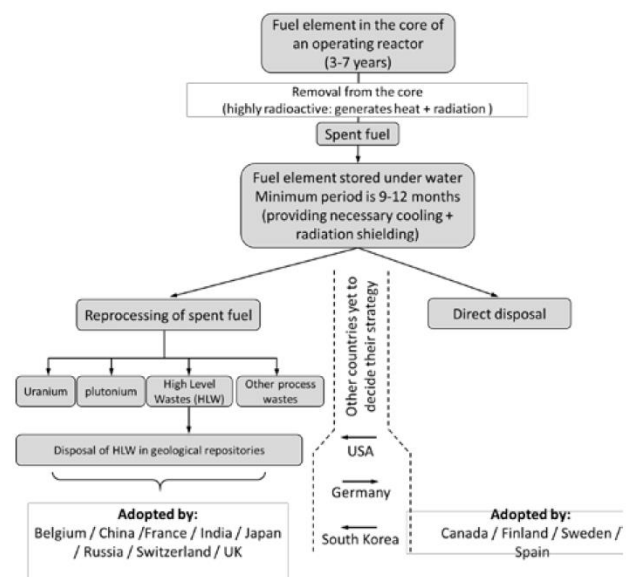


Figure 14. Nuclear waste management strategies around the world (Sinnathamby et al.).

The engineering properties of bentonite in highly alkaline environment were investigated by Watanabe to assess the long-term safety and sustainability of compacted bentonite barriers in radioactive waste disposal facilities. The alkaline condition results from leaching of the cementitious materials, which chemically alters the bentonite composition. The experimental specimens were compacted to a diameter of 20 mm and height of 40 mm by applying a static load. The montmorillonite content of the bentonite, as estimated by methylene blue absorption, was 84%. Watanabe probed the shear, permeability and swelling behaviors of the specimens immersed in alkaline solutions of NaOH and Ca(OH)₂. It was observed that the shear strength and residual stress decreased as the bentonite materials dissolved; however, the shear strength increased upon bonding with the precipitate. This was confirmed by SEM-EDS analysis (Figure 15). The swelling pressure and hydraulic conductivity of the specimens remained fairly constant.

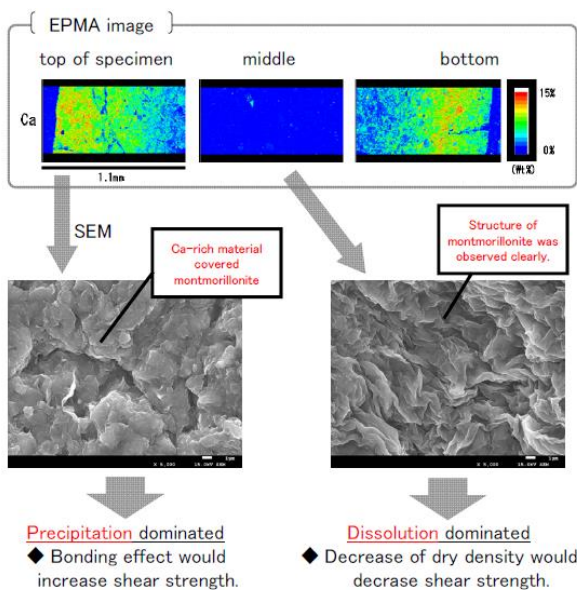


Figure 15. Mechanism of changes in engineering properties by alteration of bentonite (Watanabe).

4.5 Innovative Ground Improvement Techniques

Nawagamuwa and Prasad explored the use of fly ash as a ground improvement technique for road applications in Sri Lanka. The necessity stemmed from unavailability of soils with good California Bearing Ratio (CBR) value (greater than 30) for use in roads and pavements in the rural area. The soils sourced from borrow pits satisfied other criteria but could not achieve the required CBR value for implementation in road projects. A good CBR value increases the service life of roads subjected to surface water and traffic. Use of fly ash, a waste product of thermal power generation, could also enhance the sustainability of pavements. Rejected soil collected from a road construction site in the Southern Province of Sri Lanka was mixed with different amounts of fly ash by weight (2%, 5%, 10%, 15%, 20% and 30%). Several laboratory tests such as sieve analysis, Atterberg limits, and standard proctor compaction were conducted on the specimens. It was found that the liquid limit values with different proportions of fly ash were below the specification requirement (< 45%). However, it was observed that there was a sudden rise in liquid limit at 5% fly ash content because of soil variability. Plasticity Index (PI) values increased for fly ash contents up to 2%, and then decreased with increase in fly ash content. The trend of maximum dry density had an incremental behavior up to 10% fly ash content (Figure 16) and CBR was observed to be more than 40 (Figure 17). These

results highlight that the CBR value increases by 6.5 times upon addition of 10% fly ash (by weight).

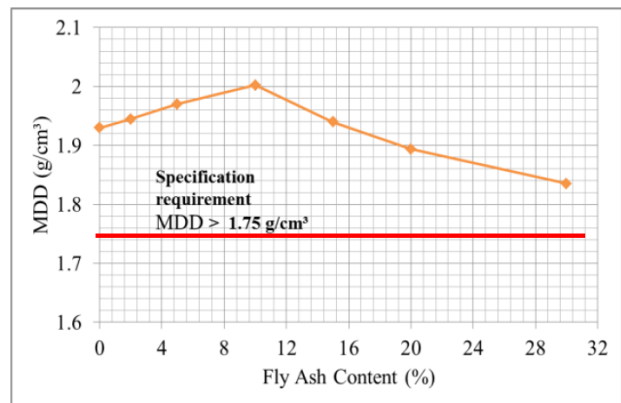


Figure 16. Maximum dry density (MDD) with different fly ash contents (Nawagamuwa and Prasad).

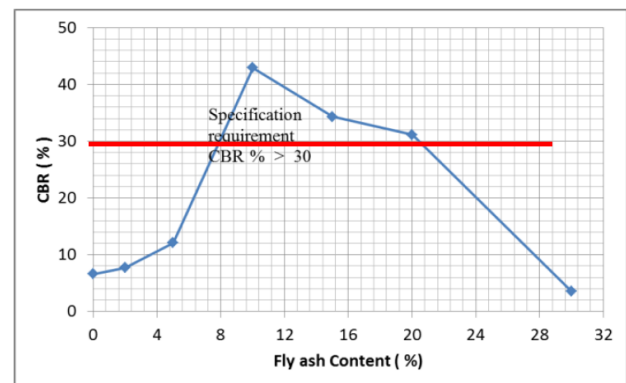


Figure 17. CBR with different fly ash contents (Nawagamuwa and Prasad).

4.6 Sustainability and Resilience Assessment Tools

Lee and Basu proposed an integrated framework for assessing the sustainability and resilience of a transportation network against geo-hazards. They state that an integrated framework for assessing both sustainability and resilience should consider human intervention as well as interaction of the infrastructure system with environmental, social and economic systems, in addition to considering the technical integrity of the engineered system. The proposed framework was implemented for a road network consisting of seven different sections of road embankments and connecting the cities of London and Toronto in Ontario, Canada. Resilience of the transportation network was analyzed against a flood event with 100 mm/hr of rainfall intensity, 6 hours of rainfall duration, and 100-year return period. The integrated assessment approach is based on the “Driver-Pressure-State-Impact-Response” (DPSIR) framework, which considers the feedback amongst the five components. The causes and motives behind transportation of humans and goods constitute the driving forces. Five possible scenarios were considered to buffer the impact of the floods (Table 1). Normalized factor of safety (FoS), settlement, network entropy and leisure time were the performance functions that helped quantify resilience (Figures 18-21). Sustainability was assessed based on cost, environmental impact and human health impact (Figures 22 and 23). Scenario 4 that combines mitigation (berm construction) with rehabilitation (retrofitting) was found to be the most sustainable and resilient option out of the five scenarios.

Table 1. Response scenarios

Response scenario	Mitigation	Rehabilitation
1	No action	Retrofitting
2	No action	Reconstruction
3	Berm construction	No action
4	Berm construction	Retrofitting
5	Berm construction	Reconstruction

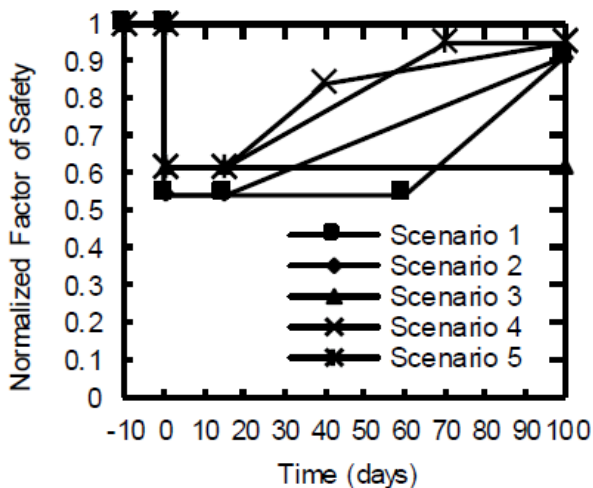


Figure 18. Normalized Factor of Safety of road embankments (Lee and Basu).

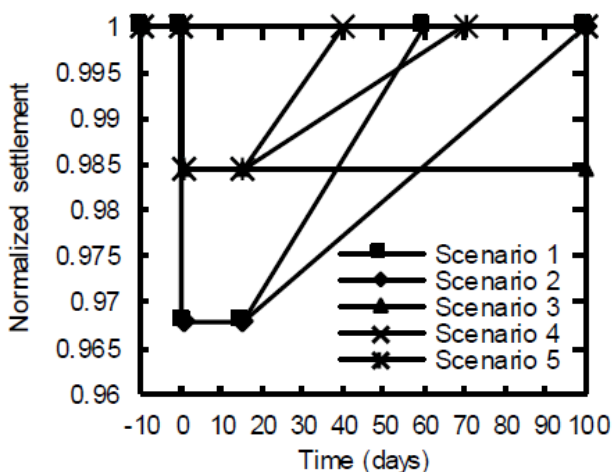


Figure 19. Normalized settlement of road embankments (Lee and Basu).

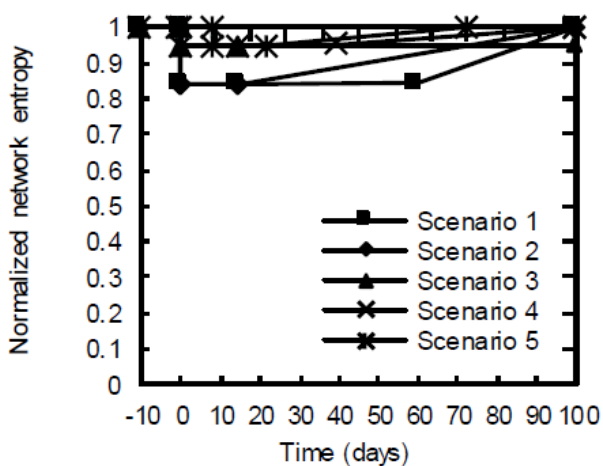


Figure 20. Normalized network entropy of transportation network (Lee and Basu).

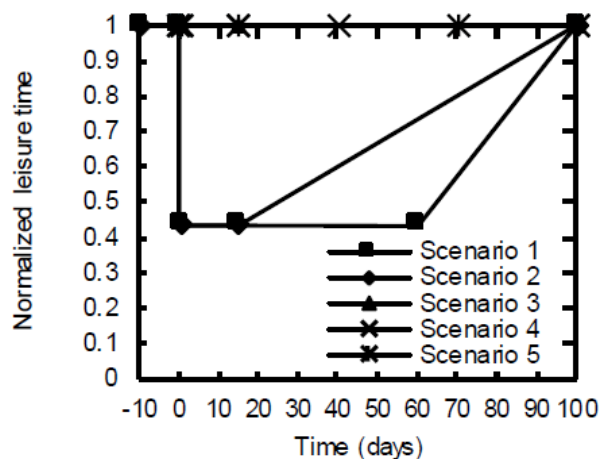


Figure 21. Normalized leisure time of road users (Lee and Basu).

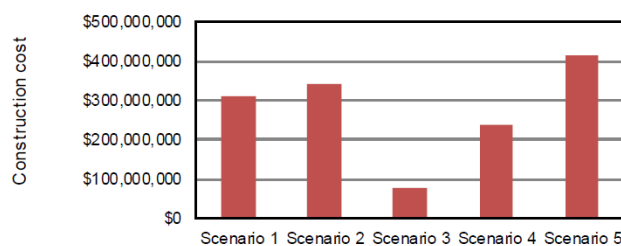


Figure 22. Construction costs for road embankments (Lee and Basu).

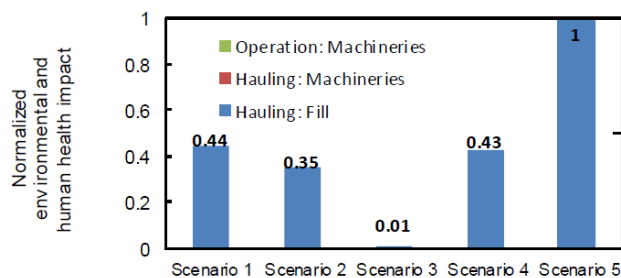


Figure 23. Normalized environmental and human health impacts (Lee and Basu).

5 IMPORTANT THEMES NOT COVERED

Sustainability being a wide concept, it is imperative that all possible topics related to sustainable geotechnics cannot be covered within the technical session dedicated to the sustainability theme in the 19th ICSMGE. Some of the important areas of sustainable geotechnics such as mining and energy geotechnics, socioeconomic impacts of geo-activities, and geotechnics in practice have not been covered.

6 SUMMARY

Sustainable geotechnics has emerged as an important sub-discipline focusing on the role of geotechnical engineering in balancing environment, economy, and social equity. Geotechnical engineering, being positioned at the incipient stages of a project, provides ample opportunities for sustainable development. However, any considerations of sustainability without accounting for resilience would render the goal of sustainable development infructuous. This general report provided an overview of 14 papers related to sustainability and resilience in geotechnical engineering, which have been accepted for publication in the proceedings of the 19th

ICSMGE. The topics covered by these papers can be grouped into six broad areas: geohazard monitoring and mitigation, use of recycled and alternate materials, sustainable foundations, waste management and environmental protection, innovative ground improvement techniques, and tools/frameworks for assessment of sustainability and resilience. However, the papers do not cover some important topics such as the socioeconomic impact of geoactivities, and geoeconomics in practice.

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