NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING

Sustainability Aspects of Geotechnical Earthquake Engineering in New Zealand

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ABSTRACT

Geotechnical engineering is a resource intensive sector of civil engineering that has a substantial effect on sustainability aspects of many transport, building, water and power projects. Improving sustainability of the geotechnical design solutions is extremely important to achieve sustainable development. Sustainability in geotechnical engineering gained particular importance in New Zealand due to the unacceptably high material and socio-economic losses that resulted from the 2010-2011 Canterbury Earthquake Sequence and 2016 Kaikoura Earthquake. The main drivers behind sustainable geotechnical design in New Zealand are discussed. Aspects of geotechnical engineering that may improve civil and geotechnical design in terms of sustainability outcomes are considered. Several design examples utilising innovative design methodologies and resulting in positive sustainability outcomes are described.

1 INTRODUCTION

The terms resilience and sustainability have been used extensively in recent years. When designing infrastructure with extreme events in mind, resilience relates to reducing the effect of natural hazards on infrastructure through more extensive design optioneering, robust design methodologies, and more effective recovery strategies. However, a resilient design does not necessarily result in the best outcome in terms of sustainability. Sustainability as a concept was developed in the late 1980s and includes resilience as an aspect. Sustainability deals with the long-term impact on the environment, economy, and society over the design life of infrastructure. The American Society of Civil Engineers defines it as “a set of environmental, economic, and social conditions – the Triple Bottom Line – in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality or the availability of natural, economic, and social resources.”

In 2015, the United Nations adopted 17 Sustainable Development Goals (SDGs) as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity. The SDGs that most closely relate to civil and geotechnical engineering include Clean Water and Sanitation; Decent Work and Economic Growth; Industry, Innovation, and Infrastructure; Sustainable Cities and Communities; Responsible Consumption and Production; and Climate Action. In response to the New Zealand government’s commitment to UN Sustainability Goal 13 - *Take urgent action to combat climate change and* *its impacts*, the New Zealand Ministry of Business, Innovation & Employment is developing *Building for Climate Change Programme* designed to reduce emissions from buildings during construction and operation.

Geotechnical engineering should contribute to the improvement of sustainable infrastructure development and rehabilitation; simply providing good geotechnical engineering design based on compliance with regulatory requirements or resilience principles is no longer enough. It is important to consider sustainability during all stages of the design process to ensure that the best outcomes are achieved. The Triple Bottom Line principle can be used to develop a sustainable geotechnical design framework.

2 ROLE OF GEOTECHNICAL ENGINEERING

Geotechnical Engineering contributes to many industry sectors, including Transport, Water, Buildings, Environment, and Research, as most infrastructure systems require reliable geotechnical solutions to support sustainable infrastructure development. The consideration of sustainability in geotechnical engineering is critical as many fields of infrastructure engineering as well as government and commercial clients already have sustainability methodologies and policies that geotechnical designers need to embrace. Geotechnical engineering can improve sustainable infrastructure development, construction efficiency, and innovation, as well as mitigate natural hazards because of its early position in the planning, design, and construction cycle (Figure 1).

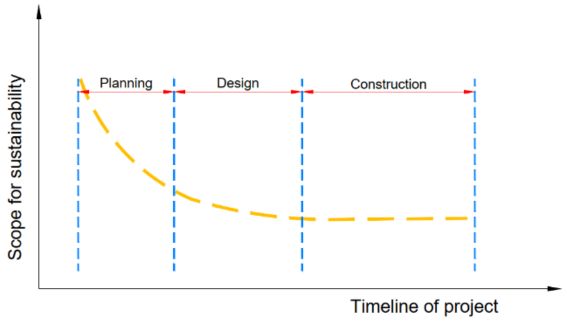

Figure 1. Indicative scope for sustainability as a function of project timeline

3 THE COST OF SEISMIC FAILURE

Materials production requires a large amount of energy use and is a significant source of greenhouse gas emissions, producing approximately 25% of all anthropogenic CO2 emissions. It also produces large volumes of waste both in production and at end-of-life disposal. Therefore, more efficient use of materials could play a key role in achieving multiple environmental and economic benefits. When damaged structures require demolition and rebuild before the end of their design life, the use of materials becomes more extensive. The production of materials uses additional natural resources, produces more carbon emissions, so isn’t sustainable.

We’ve seen that inadequate performance of geotechnical systems in earthquakes results in substantial damage to New Zealand’s road, rail, and harbour transportation network and a large number of buildings. Many seismic failures of infrastructure occurred due to poor performance of soils, slopes, and foundation systems. These events highlighted the need to develop a sustainable and resilient geotechnical design framework. The excessive losses that resulted from the unsatisfactory seismic performance of some buildings and structures in the recent earthquakes have created discomfort in the New Zealand geotechnical and structural communities. While the structures that failed were designed in accordance with the commonly accepted design principles and standards, they had to be demolished due to extensive unrepairable seismic damage, including damage to the foundation systems.

For example, the BNZ Harbour Quay Building located on the Wellington waterfront and founded on liquefiable reclamation fills was damaged beyond repair due to failure of the foundation system and superstructure, necessitating the demolition of the building (Figure 2, left). Meanwhile, the foundation system and superstructure of the AMI Stadium in Christchurch were damaged beyond repair due to poor performance of ground improvement (stone columns) in the Kaikoura Earthquake sequence (Figure 2, right). Subsurface distress included bulging, softening and contamination of the stone columns and loosening of the densified ground between them that resulted in an unacceptable risk of future seismic performance of the stadium structures. Multiple buildings and structures in Christchurch and Wellington had to be demolished due to damage caused by liquefaction during the 2010 – 2011 Canterbury Earthquake Sequence and the 2016 Kaikoura Earthquake because of the cost to repair. In Christchurch, a large portion of the CBD has been demolished, resulting in an economic loss of approximately $NZ40 billion – around 20% of the New Zealand Gross Domestic Product.

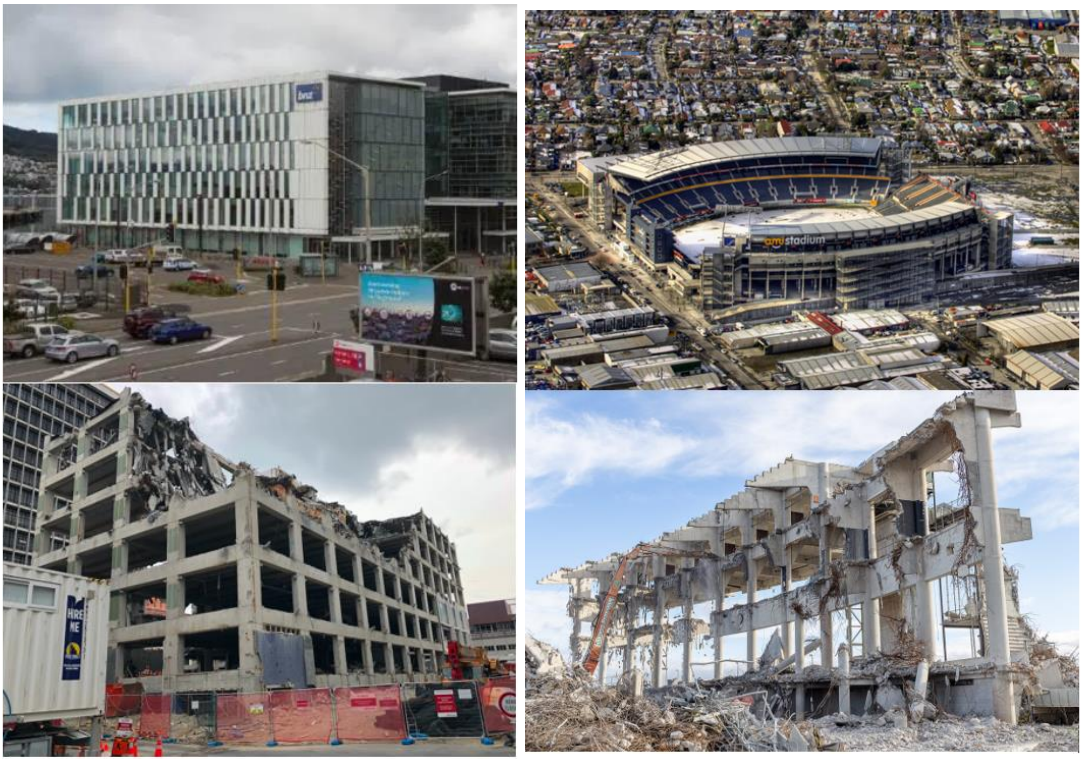

Figure 2. BNZ Harbour Quays Building, Wellington (left) and AMI Stadium, Christchurch (right) before and during demolition.

4 ACHIEVING SUSTAINABLE DEVELOPMENT GOALS

Current structural and geotechnical design methodologies predominantly focus on the life safety objective with little consideration given to sustainability issues such as post-earthquake functionality, damage reparability, and social impact. We've seen that in earthquakes exceeding the design event, many buildings and structures designed in accordance with the current design philosophies have been damaged beyond repair and required demolition. This has adverse effects on the functionality of our cities and a negative impact on the natural and social environment. Therefore, the geotechnical and structural design methodologies need to be revised to achieve sustainable development goals (SDGs). The geotechnical engineering community can provide strong support to the design philosophy transition process and achieving sustainability goals by concentrating on better understanding of natural hazards, refinement of seismic hazard for New Zealand and for specific project sites, improvement of geotechnical design standards, development and use of new environmentally friendly materials and engineering systems, understanding of environmental impact of geotechnical design solutions, use of design optimisation tools, consideration of low damage design principles, consideration of resilience aspects within sustainability design framework, consideration of whole-of-life costs, and development of a commonly accepted sustainability rating system for geotechnical projects.

5 NATURAL HAZARD ASSESSMENT FOR SUSTAINABLE DESIGN

According to the World Health Organisation, natural hazards cause 90,000 deaths and affect some 160 million people per year worldwide. Added to these effects on people are socioeconomic repercussions such as the direct loss of infrastructure, buildings, agricultural land, and indirect losses in the production of goods and services (interruptions of business and public services such as transport, health and education), as well as intangible losses such as environmental harm. Therefore, a good understanding of natural hazards at a project site, including site seismicity, is critical for sustainable development and low damage design.

New Zealand's high seismicity and complex geology present technical challenges in delivering sustainable geotechnical design for roads, bridges, buildings, ports and marine structures. Many sites in New Zealand are exposed to multiple natural hazards. For example, the Wellington CBD and especially Wellington waterfront are exposed to seismic shaking, fault rupture, liquefaction of reclamation fill (also prone to lateral spreading), coastal erosion, tsunami, and sea-level rise associated with global warming. A geological model of the Wellington CBD (Kaizer et al., 2019) is shown in Figure 3. All known site hazards should be considered in the geotechnical design process to avoid premature failure of foundation systems and geotechnical structures. A better understanding of seismic hazards is required to refine seismic demands in the geotechnical design process.

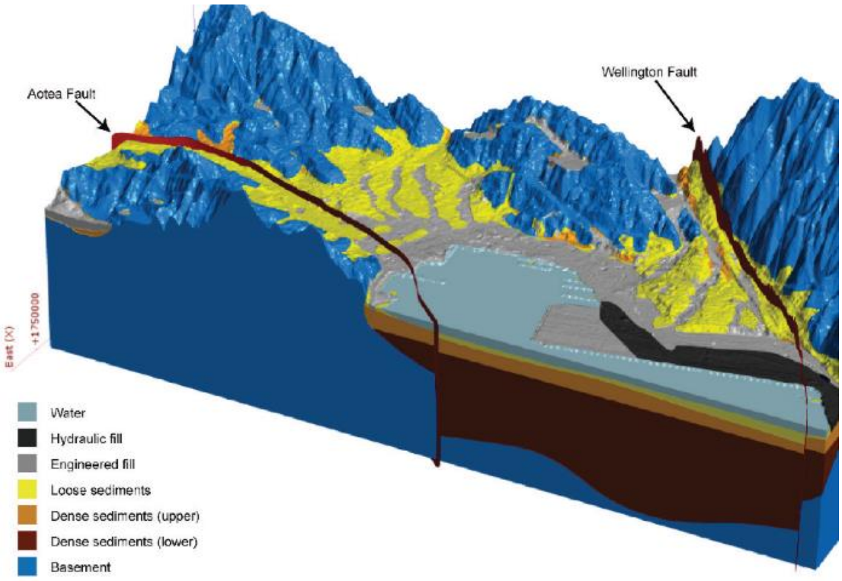

Figure 3. Geological model of Wellington CBD showing faults, loose sediments and liquefiable reclamation fills (after Kaizer et al., 2019)

The Ministry for Business, Innovation and Employment (MBIE) currently has a project underway to update the NZ Seismic Hazard Model. The updated model will refine the seismic design loads, reduce the risks of inadequate geotechnical and structural design, seismic damage to structures, and result in better sustainability outcomes.

6 ROLE OF GEOTECHNICAL DESIGN STANDARDS IN SUSTAINABLE DESIGN

Poor understanding of seismic risks and lack of advanced geotechnical design standards result in unreliable geotechnical design and extensive seismic damage, requiring demolition and rebuild of buildings and structures which has an adverse effect on economy, functionality of our cities, and negative impact on natural and social environment. For example, a substantial part of Christchurch was damaged due to liquefaction and lateral ground movement that were not properly considered in the design process. This was partly because New Zealand lacked a well-developed system of geotechnical standards and guidelines until 2017.

International experience has shown that buildings founded on liquefiable sites can perform well, where well-engineered, robust ground improvement is carried out. The experience in Christchurch was more varied, noting that the ground shaking, in some areas, was more intense than that was allowed for in the design. The Canterbury Earthquake Royal Commission, established to report on the causes of buildings failure, recommended that consideration be given to the preparation of national geotechnical earthquake engineering guidelines to improve uniformity in the design approach and outcomes. MBIE and the New Zealand Geotechnical Society (NZGS) put substantial effort into the preparation of the Earthquake Geotechnical Engineering Standards (Modules), which specify seismic hazards as well as geotechnical design methods and requirements. The original revision of the Modules was published in a few years after the 2010-2011 Canterbury Earthquake Sequence, and the updated Modules were published in December 2021.

Waka Kotahi NZ Transport Agency recently updated its Bridge Manual, introducing Section 6 – Geotechnical Design, and funded the development of design guidelines for bridges and structures founded on liquefiable ground. These documents specify detailed methodologies for the assessment of seismic hazards and geotechnical earthquake engineering design. The use of the Modules, Waka Kotahi design guidelines and Bridge Manual by geotechnical practitioners has resulted in a higher level of reliability of geotechnical design solutions.

The ground’s response affects the response of the structure, and the motion of the structure affects the ground’s response. Therefore, the new MBIE and Waka Kotahi design guidelines require consideration of soil structure interaction (SSI) and design optimisation. SSI is a crucial part of geotechnical earthquakes engineering that enables the designers to develop more reliable designs, assess and control likely structural damage within the performance-based design framework, and, in many cases, reduce quantities of used materials. WSP engineers were involved in the development and update of the MBIE and Waka Kotahi documents.

7 EFFECT OF NEW MATERIALS AND SYSTEMS ON SUSTAINABILITY

Different building materials, structural and geotechnical systems and ground improvement techniques have varying environmental impacts during manufacturing, construction and maintenance. The adoption of geotechnical design solutions such as using recycled or new environmentally friendly materials has a substantial effect on sustainability outcomes. For example, the type retaining structure used affects global warming potential and cumulative energy demand. Comparisons of geosynthetic-reinforced soil (GRS) retaining walls with reinforced concrete gravity and cantilever walls indicates that GRS walls are more environmentally friendly (Figure 4). The use of more environmentally friendly alternatives such as glass fibre polymer (GFRP) reinforcing and soil nail bars in lieu of steel bars is becoming more common. A large portion of new geosynthetic materials, GRS and GFRP systems have been introduced to New Zealand in recent years. A detailed review, assessment, and certification process for geosynthetics and GRS and GFRP systems developed by Waka Kotahi and supported by WSP ensures that only high-quality reliable materials and systems are used on NZ highway projects, resulting in low risk of seismic damage and better sustainability outcomes.

Remediating or strengthening structures founded on liquefiable ground or those damaged due to liquefaction has been a complex process, and in many cases, resulted in the decision to demolish such structures. Most of the currently available ground improvement solutions are highly invasive, costly, time-consuming, messy, and require tenant relocation or have negative impact on business operations. The use of new resin material proposed by Mainmark Contractors now enables geotechnical engineers to improve ground under the existing structures with only minimal effect on business operations of building occupants. With this technology, liquefaction mitigation primarily occurs from the densification of the soil by an aggressively expanding polyurethane resin product injected into the ground (Figure 5). Innovative resin injection ground improvement has been used to mitigate soil liquefaction potential for many buildings and structures in New Zealand and avoid their demolition and rebuild. Recent involvement from WSP with resin injection includes the mitigation of liquefaction for Wellington Water's Hut Valley Wastewater Treatment Plant and Waterloo Water Treatment Plant. On many slope stabilisation projects WSP have used GFRP soil nails and anchors.

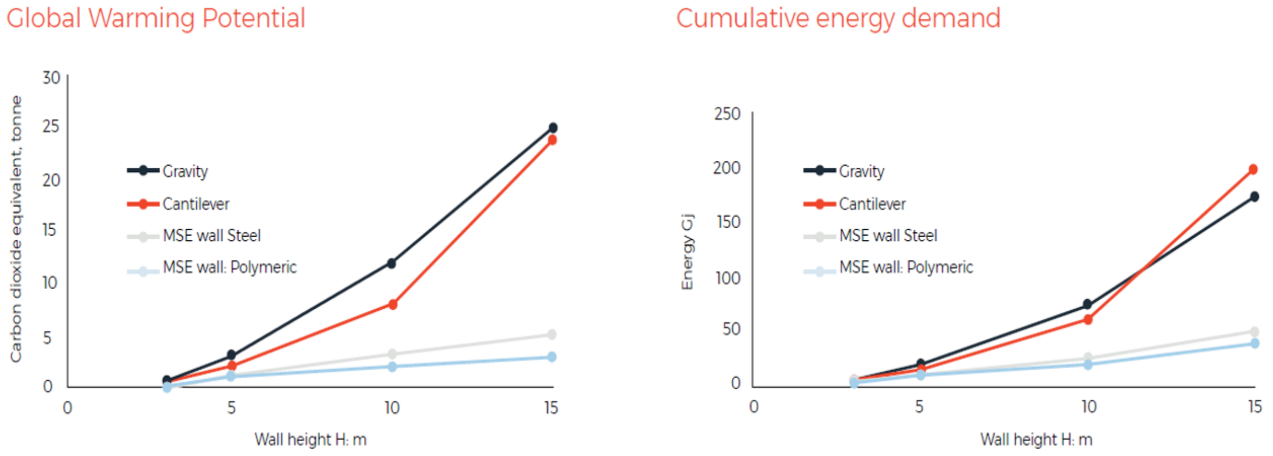

Figure 4. Effect of retaining wall type on environment

Figure 5. Mainmark's resin injection process (left) and hand-exhumed resin veins (right), after Traylen et al (2017)

8 DESIGN OPTIMISATION AND SUSTAINABILITY

In recent years, sustainability and optimisation have become inseparable concepts. The main goal of optimisation is to improve a system or design solution in terms of environmental sustainability, social sustainability, economic sustainability and energy resource sustainability. Because the materials used in construction projects are responsible for a significant part of the environmental footprint, better material selection and efficient use of those materials may result in better sustainability outcomes. Efficient use of materials, as well as the use of innovative design methodologies, is also part of Leadership in Energy and Environmental Design (LEED) rating framework developed under the umbrella of the U.S. Green Building Council (USGBC). In many cases, design optimisation requires complex numerical modelling of soil-structure interaction effects, including non-linear time-history analysis.

9 RESILIENCE, LOW DAMAGE DESIGN AND SUSTAINABILITY

In terms of infrastructure performance, resilience can be defined as the ability of a system to be able to withstand and continue to function after a disturbing event, such as a storm or earthquake, or rapid recovery from disruptions. Resilient infrastructure systems should also be able to cope with extreme events, minimise environmental impacts and economic losses and ensure public safety. After NZ 2010-2016 earthquakes, developing a low damage design philosophy for buildings and structures has become important for the NZ engineering community. A low damage design approach enables buildings and structures to function and be reparable following an earthquake event, as it minimises the adverse effects on businesses and communities. Stannard (2020) suggested that the seismic performance of buildings and structures can be substantially improved if better resilience and sustainability outcomes need to be achieved (Figure 6). The brown line in Figure 10 shows approximately the performance expectations currently in NZ Standard NZS 1170.5. The blue line indicates better seismic performance criteria that reflects low damage design approach and an overall better sustainability outcome. This design philosophy is also applicable to geotechnical design and will improve seismic performance of structural foundation systems and geotechnical structures, resulting in better sustainability outcomes.

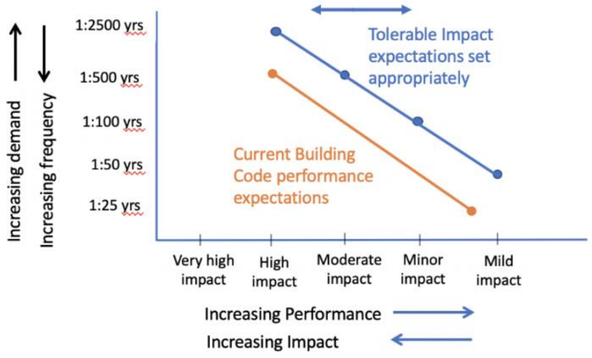

Figure 6. Seismic design performance objective matrix (after Stannard, 2020)

10 GEOTECHNICAL DESIGN FRAMEWORK

For decades, geotechnical design has been based on adopting low-cost design solutions that are easy to implement, compliance with regulatory requirements, and later, geotechnical design standards and resilience requirements. However, little consideration was given to low damage design methodologies and sustainability goals. The sustainability Triple Bottom Line should form the core of the current and future geotechnical design philosophies and combine all aspects of natural hazard assessment framework, advanced design methods, design optimisation, SSI, environmental impact assessment, and resilience to achieve sustainability goals (Figure 7, left). Several sustainability assessment tools for geotechnical design have been proposed. One of the tools is a simple sustainability rating for geotechnical systems and projects, where sustainability is assessed at all life-cycle stages of a geotechnical system (Raza, 2020), see Figure 7 (right).

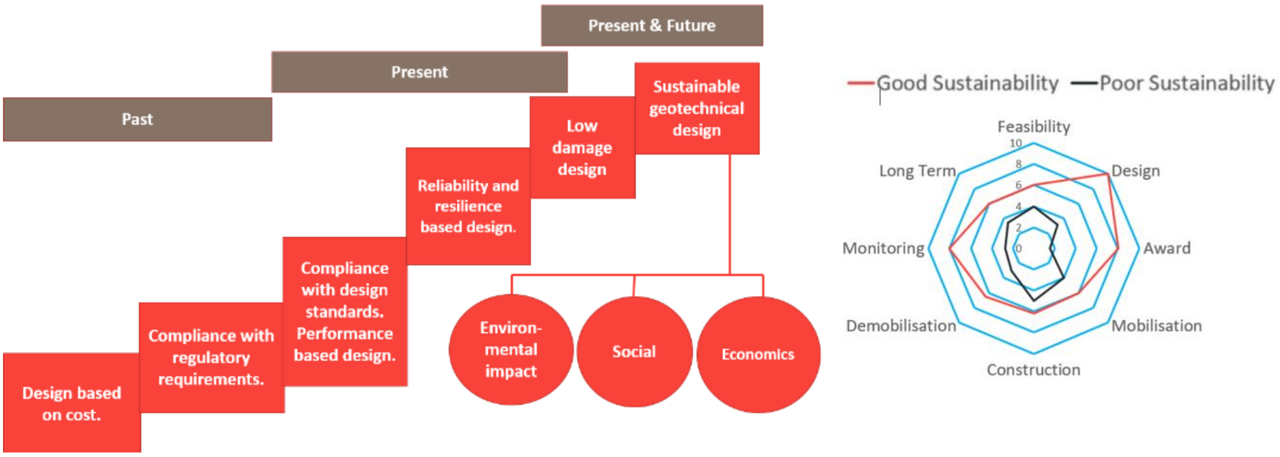

Figure 7. Historical evolution of geotechnical design framework (left) and sustainability rating system for geotechnical systems and projects (right)

11 CONCLUSIONS

Sustainability is a concept that focuses on managing natural and anthropogenic resources to improve the quality of human life while living within the carrying capacity of the supporting ecosystem. It’s an important concept for engineers to understand and apply in their practice because engineered systems dominate current human societies and have had severely detrimental effects on the natural environment.

The design and construction of structural foundation systems, ground improvement, retaining walls, slopes, dams, and various geotechnical structures involve the use of building materials from different sources, machinery, earthworks, demolition of existing structures, use of green fields, which can all impact environment in many ways. Geotechnical engineering is a major part of the economy. Therefore, it is essential that past and existing conventional design and construction practices are gradually replaced with sustainable all life-cycle methodologies.

While there is currently no commonly accepted sustainability design framework in geotechnical engineering, recent developments in geotechnics enable designers to address sustainability aspects by improving geotechnical design standards, adopting low damage design principles, using natural hazard studies, new materials and systems with lower environmental impact, innovative design solutions, design optimisation, SSI, and resilience design philosophies.

Further work is required to develop a universal internationally recognised sustainability framework and rating system for geotechnical engineering that would cover all stages of the design, construction, monitoring, and whole-life environmental impact and costs.

12 REFERENCES

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