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HOW TO INTEGRATE SUSTAINABILITY INTO GEOTECHNICAL PRACTICE

L. Villoria & D. Sandilands
Aurecon, Tauranga.

ABSTRACT

There is an overwhelming consensus among scientists that human-induced global warming has already caused profound alterations to natural and human ecosystems. According to the Intergovernmental Panel on Climate Change, if the current trend in carbon emissions continues, global temperature is likely to rise between 3.7 and 4.8 degrees Celsius above pre-industrial levels by the end of the century (IPCC, 2018), which would bring devastating consequences to our natural and built environment. According to national statistics, 20% of New Zealand's carbon dioxide emissions come from manufacturing and construction. In this context, the government has set ambitious environmental targets to incentivise behaviour change of clients and end users to pursue more sustainable practices. Geotechnical engineering offers great potential for enhancing the sustainability of infrastructure due to early involvement in the design and construction process and ability to influence design outcomes. However currently, socio-environmental aspects are typically prioritised low or not even considered, within geotechnical assessments. The lack of understanding of sustainability concepts and the need for a flexible assessment methodology directly applicable to geotechnical engineering are key challenges that practitioners face when trying to integrate sustainability into their projects. The paper reviews the economic, social and environmental aspects of sustainability and some of the assessment tools most relevant to geotechnical engineering. Several case studies are then presented to demonstrate the implementation of sustainable practices into geotechnical engineering practice. Lastly, a 'sustainability checklist' has been created for use by the practitioner during the early stages of development projects.

1 INTRODUCTION

Over the last decades, the importance of sustainable development has been increasingly recognised by governments, businesses and individuals across the globe. Although there is no one single definition that encapsulates the concept of sustainable development, the most notable is that quoted by Brundtland in the United Nations report 'Our Common Future' (Brundtland, 1987):

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

More than three decades have passed since publication of Brundtland's report and still today, sustainability is often regarded as a complex, intangible idea, involving intricate economic, social and environmental factors – on this at least there is consensus – which everyone seems to embrace but hardly anyone can put into practice. Fortunately, at the same time, global initiatives such as the creation of the Sustainable Development Goals (United Nations, 2015) have driven many strategies and action plans which are now implemented and proven successful in many countries around the world.

In the New Zealand context, through the implementation of the Climate Change Response (zero carbon) Amendment Act, the Government has committed to reduce all net greenhouse emissions (except biogenic methane) to zero by 2050. According to current statistics, New Zealand's greenhouse gas emissions are about 44 per cent carbon dioxide, of which 20 per cent come from manufacturing and construction (MfE, 2019). The environmental impact of construction is large compared to other aspects like vehicle emissions and household energy consumption (Chau et al. 2008), so sustainable changes in construction would have a significant beneficial impact. Also, the Code of Ethical Conduct of Engineering New Zealand (2016) states that engineers 'must have regard to reasonably foreseeable effects on the environment from those activities and have regard to the need for sustainable management of the environment; the environment being ecosystems and their constituent parts, including people and communities and all natural resources and physical (man-made) resources'.

In this scenario, civil and geotechnical engineering play a crucial role in creating the infrastructure needed for New Zealand's zero carbon future while promoting social equity and supporting the national economy. Cut to waste earthworks is not as cheap as it used to be (particularly if contaminated) and financiers like banks and investment companies are beginning to require sustainability measures on their projects. Future projects will probably comprise a higher proportion of brownfield sites, with a focus on densification of cities, and less of the greenfield developments of the past.

Improving current geotechnical practices would help reduce adverse impacts at the early stages of a construction project, when some of the greatest gains can be made (Jefferis, 2008). However, there is a widespread lack of awareness and uncertainty on how to integrate sustainability into geotechnical practice, compounded by the need for a well-established sustainability assessment tool applicable to all areas of geotechnical engineering. Section 3.1 of this paper presents various existing methodologies that have been developed and tested overseas and can be adapted in New Zealand.

The aim of this paper is to identify the key obstacles that are preventing sustainability to be embedded into geotechnical projects, and to encourage practitioners to define and implement sustainable strategies that could lead to a paradigm shift in the attitude of the geotechnical industry.

2 SUSTAINABILITY IN GEOTECHNICAL ENGINEERING

2.1 Principles

Sustainable development in the context of our built environment can be considered an interaction between the four E's: equity, environment, engineering and economy (Figure 1, Basu & Puppala 2015). The challenge is managing the trade-offs and conflicts between the four E's and realising that a sustainable engineering solution today might be different tomorrow, as priorities evolve. Monitoring and alteration of solutions over time is necessary.

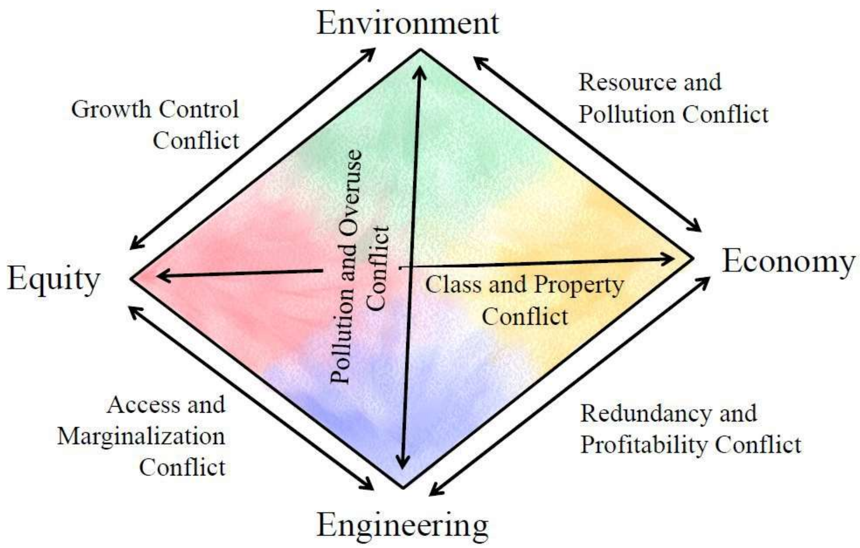


Figure 1: The four E's of engineering sustainability

The core principles to sustainable projects, (Kibert, 2008; Weaver, 2002; IPENZ, 2004), all of which geotechnical engineering can impact on, include:

Figure 2: Principles of engineering sustainability, colour coded into the four E's

Overall, the current development of the geotechnical engineering industry follows the inertia of traditional practices in global consumption, production and decision-making, which disregard the principles of engineering sustainability and are the direct cause of the accelerated deterioration of our natural and socio-economic environment. There are emerging alternatives, such as 'circular economy', that are already driving a global change towards a more sustainable way of living, where the longer the resources and materials are in use (through reuse, recycling), and the lesser the impact they have on the environment, the more valuable they become.

2.2 Main barriers to sustainable design and practice in geotechnical engineering

At present, the main obstacles that are preventing the adoption of more sustainable practices in geotechnical engineering are lack of awareness and incentive, and cost. Furthermore, the complexity and fragmentation in the current construction chain makes it difficult to assess the effect of different choices and procedures in a holistic way (Holt et al, 2009). **Error! Reference source not found.**~~Table 1~~ presents some of the current barriers to sustainable geotechnical construction and the approaches that can be taken to overcome each of them. In order for sustainable construction practices to become the norm, a combined effort between the public, the government and all construction professionals is required.

Table 1: Summary of the main barriers to sustainable geotechnical construction

Type of barrier	Description	Solution approach
Financial	Cost of undertaking sustainability studies to ensure design and construction sustainability principles are implemented effectively. Risk of higher design and construction costs of sustainable projects compared to conventional projects.	Embedment of new design methods and new materials specifications in the geotechnical industry to eliminate extra time and cost associated with new skills and materials. Consideration of multi-attribute cost assessments over simpler single action cost-benefit approached.
	Often, the developer investing in sustainable practices during design and construction is not the direct beneficiary of the long-term investment return.	Market and governmental incentives, increased users demand for sustainable developments.
Technical	Problems with identifying the impacts of certain geotechnical activities on the overall sustainability of a project.	Early engagement of geotechnical practitioners (and all other disciplines) when developing sustainable construction strategies for a project.
	Introduction of new skills and technologies, which might increase construction risks.	Governmental incentives combined with suitable training.
	Preclusion due to regulation.	Government investment into periodic review of regulation and openness/incentivisation to accept new solutions and material types.
	Lead managers and designers that drive a project are usually not geotechnical professionals, somewhat reducing the effectiveness of geotechnical initiatives.	Geotechnical engineering has the privilege of typically being required early in the project life cycle e.g. preliminary ground investigations to assess project feasibility and support resource consent. Geotechnical sustainability ideas and advice can therefore be broached to project leads early in the project.
	Risk aversion, professionals are less likely to design/specify new solutions and materials that they are not experienced with and do not have a proven track record.	Progression of education and research, to improve confidence. Adoption of sustainability practices by the geotechnical profession will develop a proven track record.
Lack of awareness	Geotechnical professionals not being aware or are uncertain about new technologies, processes and materials. Prevalence of conventional thinking.	Increase research, training resources and knowledge transfer within the geotechnical industry. Both government and private companies need to promote sustainability and empower employees to implement it.

3 REVIEW OF EXISTING SUSTAINABILITY ASSESSMENT TOOLS

The vast majority of the sustainability research in geotechnical engineering has been focused on reducing the environmental impact of specific materials and construction processes. However, very few attempts have been made to develop assessment methods aimed at improving sustainability in geotechnical projects in a holistic way (Jefferis, 2008). This section reviews some of the existing sustainability assessment tools and rating systems and it provides an overview of various methodologies developed specifically to support sustainability decision making in geotechnical engineering projects.

One of the challenges of assessing sustainability is that it involves both physical (i.e. air pollution) and non-physical (i.e. health and wellbeing) aspects and therefore different approaches and ways of measurement are required to address them all. There are several tools which can be used to inform sustainable decisions in the built environment, these can be broadly categorised as follows:

- Environmental tools, such as Life Cycle Assessment or Environmental Impact Assessment;
- Economic tools, such as Cost-Benefit Analysis;
- Social value measurement tools, such as Cost-Effectiveness Analysis;
- Rating-based tools, such as BREEAM, LEED, Gren Star or CEEQUAL.

Environmental tools are used to identify the impacts of the different construction processes on the natural environment and can be used at the early stages of a project to select the most environmentally sustainable design. The authors find life-cycle analysis (LCA) to be most appropriate to geotechnical projects as it uses quantitative mechanisms to evaluate carbon emissions associated with different construction and operation processes throughout the life of a project. Environmental impact assessment (EIA) can also be used but is more appropriate for qualitative-based analysis.

Cost-benefit analysis (CBA) is a decision-making tool built to identify the optimal alternative by simply comparing its monetary costs and benefits. This tool is widely used within the construction sector. The cost-effectiveness analysis (CEA), on the other hand, is a methodology similar to CBA that measures the effect of an activity from a societal point of view, rather than considering only the monetary value. This is particularly useful when comparing multiple project methodologies - for example, when choosing materials to be locally sourced or imported, as it allows the relative social benefit of each approach to be assessed.

Although the tools mentioned above can be used in isolation to assess certain aspects of a geotechnical project, it is evident that a multicriteria analysis (MCA) that combines environmental, economic and social tools is the most appropriate to inform sustainability decision making. MCA can be used to assess conflicting criteria, such as cost and environmental impact, by adding weights or scores to defined objectives or categories, based on their relative importance for each project. An example of how this can be applied to geotechnical projects is presented in Section 3.1.

As of today, a well-established system that equally addresses the four E's of sustainability has not yet been developed within the construction industry. Nevertheless, there are several rating tools available aimed at assessing sustainability (or parts of it) of construction projects, most of them in the form of internationally recognised certification schemes. Broadly speaking, the most common rating tools can be classified as follows:

- Rating tools used to assess the environmental performance of buildings: BREEAM, LEED or Green Star are examples of rating and certification systems where a certification level is achieved based on building's performance under each of a number of environmental categories;
- Rating tools focused on environmental performance of civil infrastructure: CEEQUAL and Infrastructure Sustainability (IS) rating tool are used for roads, railways, airports and other civil infrastructure and are also focused on achieving the highest certification level based on environmental performance during design and construction stages.

As anticipated, none of the existing rating-based tools provide a holistic sustainable approach (incorporating the four E's) and all of them are too award focused, which reduces the incentive to exceed the minimum standards on any particular category or subcategory.

3.1 Existing sustainability assessment methodologies for geotechnical engineering

Misra & Basu (2011) developed a MCA framework combining LCA, EIA and CBA to calculate a sustainability index for pile foundations. In a hypothetical case study, they assessed the suitability of driven piles and drilled shafts from a sustainability perspective and found that driven concrete piles were a slightly more sustainable option. The proposed methodology is as follows:

1. An LCA is done to quantify the resource consumption and CO_2 emissions associated with each alternative from planning to disposal stages;
2. An EIA is carried out to quantify the impact on climate change and biodiversity;
3. Generation of a socio-economic indicator through CBA, in this case by comparing cost benefit against community disturbance caused by noise and vibrations.

4. Weights are applied to resource consumption, environmental and socio-economic categories based on their relative importance for the project. All category scores are added and the final score for each alternative is compared.

Jefferson et al. (2007) developed a set of environmental geotechnics indicators (EGIs) specifically tailored to assess the sustainability of geotechnical projects, which can be considered as an enhanced version of Jimenez (2004) sustainable geotechnical evaluation model (SGEM). For each pre-defined indicator, points are allocated (on a score from 1 to 5) based on predominantly qualitative sustainability measurements, as appropriate. The scores from each stage (from feasibility to long-term monitoring) are then added to provide an overall sustainability score. The EGIs were applied to a case study site in the UK where land contamination remediation measures were required. The study assessed soil washing which enabled 100% of previously unusable land to be redeveloped for mixed residential and commercial use. Between 20 and 30% of the materials delivered were from sustainable sources and >50% of the materials and workforce were sourced locally.

Another tool specifically developed for geotechnical engineering is GeoSPeAR, an indicator system developed by Holt et al. (2009) by modifying the Sustainable Project Appraisal Routine (SPeAR©), previously developed by Arup (2007). GeoSPeAR uses a colour coded diagram to assess a project's performance on four main areas: social equity, economic viability, environmental protection and efficient use of natural resources. The performance of each indicator is assessed against a scale of best and worst cases (based on current legislation and best industry practices) and the average performance of each sector is then transferred into the diagram in the form of shaded segments. The closer the shaded segment is to the centre of the diagram, the more sustainable the project is with respect to those particular criteria.

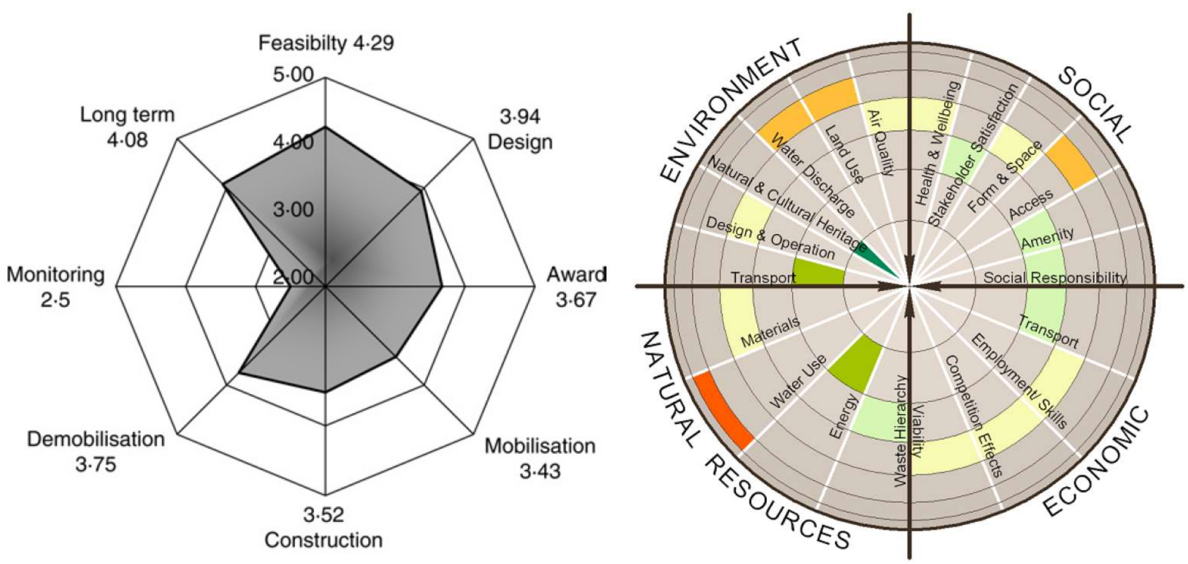


Figure 3: EGI's rose diagram for a case study site (left) and GeoSPeAR (right) typical diagram

Error! Reference source not found.~~Table 2~~ identifies the main strengths and weaknesses of each of the methodologies described in this section. All can be adopted within New Zealand geotechnical practice.

Table 2: Overview of some of the existing sustainability assessment methodologies for geotechnical engineering

Sustainability system	Strengths	Weaknesses
Jefferson's EGIs Methodology	- Indicators are not segregated into economic, social and environmental categories, which offers an opportunity for a more holistic approach. - Flexible, allows for adaptation of indicators to suit every project's requirements and can be applied for every stage. - Results are presented in a visual, understandable way.	- Predominantly a qualitative analysis. - Despite its potential to provide a holistic analysis, pre-defined indicators are heavily environmentally focused, lacking consideration of socio-economic aspects. - No weighting system is applied, which means that it is by default 'easier' to rate higher on those stages with a lesser number of indicators.
GeoSPeAR	- Flexible, allows for adaptation of indicator to suit every project's requirements and can be applied for every stage. - Results are presented in a powerfully visual way which helps to quickly identify areas of improvement.	- Predominantly a qualitative analysis. - Some of the best and worst cases used to evaluate performance are based on UK policies and best practices. Requires adaptation to NZ context.
Misra & Basu's Sustainability Index	- Good combination of qualitative and quantitative analysis. Provides a clear methodology adaptable to most geotechnical projects.	- Allocation of weighting to the different categories has a big impact on the final score and it is completely subject to the practitioner's judgement. Most suited to early stages of a project (i.e. planning, design).

4 SUSTAINABILITY OPPORTUNITIES

Implementation of sustainable practices in geotechnical engineering don't need to be onerous for the practitioner. Simply being aware of a project's potential impact on the environment, and fundamental decision making is a good start. For example, designing a foundation that minimises the volume of reinforced concrete which is not necessarily always defaulting to a shallow foundation. In some cases, a pile foundation can have less volume than a shallow pad foundation and can be constructed with the same plant (excavator with an auger attachment rather than a bucket). For remote project sites like a cellphone tower on a hill, the saving on reinforced concrete is supplemented further by saving on concrete truck movements.

There are also simple approaches to improve sustainability through design philosophy. For example, the NZ Building Code (via NZS1170.5) currently requires new buildings to avoid collapse, prevent loss of life and allow evacuation following an Ultimate Limit State (ULS) earthquake (typically with a 1/500 or 1/1000 year recurrence period and probability of occurrence of 5-10% over a 50 year building life). This implies that the code minimum building design can meet this requirement but may need to be demolished following the earthquake. Is this design philosophy sustainable when an intermediate earthquake smaller than the ULS could also cause irreparable damage to a building? Liquefaction induced ground damage is often calculated to be triggered at lower than ULS earthquake shaking levels with a binary response (i.e. it either occurs or doesn't, rather than structural load which may be considered to increase linearly with the level of earthquake shaking). If significant liquefaction is calculated to be triggered at approximately a 1/150 to 1/250 year recurrence period earthquake (not uncommon) for a new building designed to the code minimum requirement, the probability of that building requiring demolition following an earthquake may be approximately 20-30% over its 50 year design life (due to liquefaction induced damage). This is a considerably higher risk than intended by the code but is still currently allowed and often acceptable to a developer who assumes that their insurer will provide cover. Such an approach isn't resilient and fails the sustainability principles of equity within and between generations. A sustainable approach to this situation would be to mitigate the liquefaction risk and engineer the building for a lower probability of demolition/repair post earthquake.

Other scenarios may be more complex to assess for sustainability. Timber poles may be an attractive ground improvement solution beneath a building at first glance from a sustainability perspective, because timber is a renewable resource. Conversely, the design life of the timber poles would be shorter than an alternative, such as stone columns, so it is unclear which option is more sustainable.

Studies are available to help guide us, such as:

- Research by Egan et al. (2010) found dynamic compaction and stone column ground improvements to have a smaller environmental impact than traditional deep foundations (Continuous Flight Auger and driven cast in-situ piles), particularly if recycled materials and aggregates were used to form the stone columns. The embodied carbon dioxide savings were found to be up to 90%, in addition to time and cost savings provided by the stone columns as compared with the traditional piles. Jefferson et al. (2010) also assessed the sustainability of stone columns.
- Spaulding et al. (2008) undertook three case sustainability studies of ground improvement:
    - Dynamic compaction vs undercut of uncontrolled fill and replacement with engineered fill imported from a nearby borrow pit (22km from the jobsite).
    - Controlled Modulus Columns vs driven piles.
    - Soil-bentonite wall vs a cement-bentonite wall.
    - In all three cases the ground improvement options (dynamic compaction, Controlled Modulus Columns and soil-bentonite wall) were found to be more cost effective and also significantly reduced the carbon footprint of the projects.
- Chau et al. (2011) assessed the embodied energy and gas emissions of four types of retaining walls. Propped steel sheet piles and minipile walls were found to have less embodied energy and gas emissions than cantilever steel tubular wall and secant concrete pile wall systems. The difference in CO_2 emission for a propped sheet pile or minipile retaining wall and a secant pile wall of 100m length, was found to be approximately equivalent to an average 2.0L family car being driven for 5.5 million kilometres (or roughly 550 cars being driven for a year in NZ).
- Soga et al. (2011) calculated the embodied energy for several retaining wall options for; a hypothetical motorway widening, a basement of an actual high rise building in London, and embankments and cuttings on an actual highway widening project in London. The results indicated that the highest concentration of embodied energy was within the construction materials, over the installation energy and transport energy. A recycled steel wall generally has less embodied energy than the equivalent concrete wall system, which is in turn more efficient than the equivalent virgin steel system. The study found that minimising materials usage has the most impact for reducing embodied energy for retaining walls.
- The life-cycle environmental impact of a reinforced concrete retaining wall was compared to a bioengineered slope by Storesund et al. (2008), finding; the bioengineered slope had about half of the environmental impact of the concrete wall, however the concrete wall had lower whole of life costs as it didn't require as much maintenance.
- On the positive impacts of retrofitting and reuse of foundations (Misra and Basu, 2011).
- Earthquake resilient foundation systems (Kupec et al. 2019, Mahoney et al. 2015 among others).
- On sustainable landslide management (Flentje et al. 2018).
- Ali et al. (2011) showed though laboratory testing that recycled glass could be blended with recycled aggregate by up to 30% by mass and provide satisfactory performance as a pavement subbase.
- A review of sustainability papers from the 19th ISSMGE conference by Anand et al. (2018), covering topic including use of recycled and alternate geomaterials, sustainable foundations, innovative ground improvement techniques, waste management, and tools for assessment of sustainability and resilience.

- The authors of this paper consider that ground improvement is generally more sustainable than traditional deep foundation solutions. Because in comparison, ground improvement typically has a lower carbon footprint, is less likely to inhibit future foundations and often generates less or no spoil (particularly advantageous for contaminated sites).

Key sustainability aspects that can be considered for a geotechnical project are presented below in Figure 4, along with a proposed checklist for geotechnical engineers at the back of this paper.

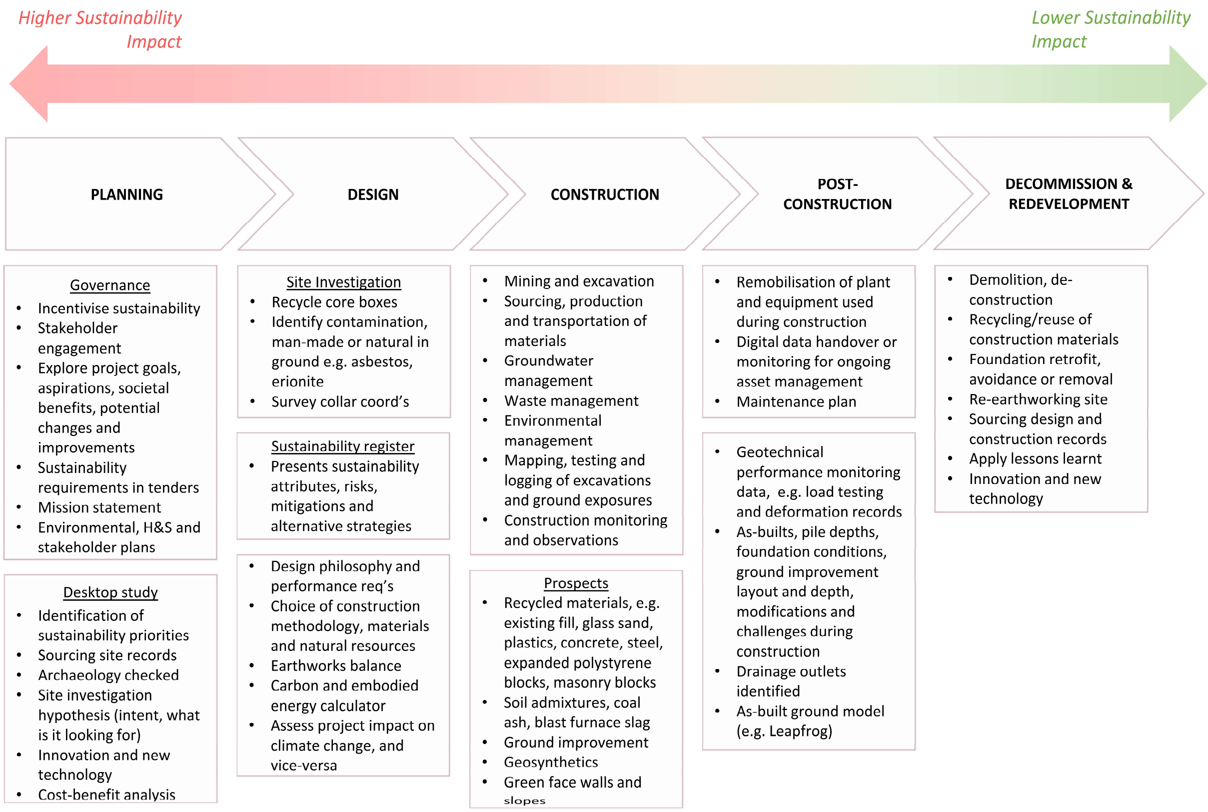


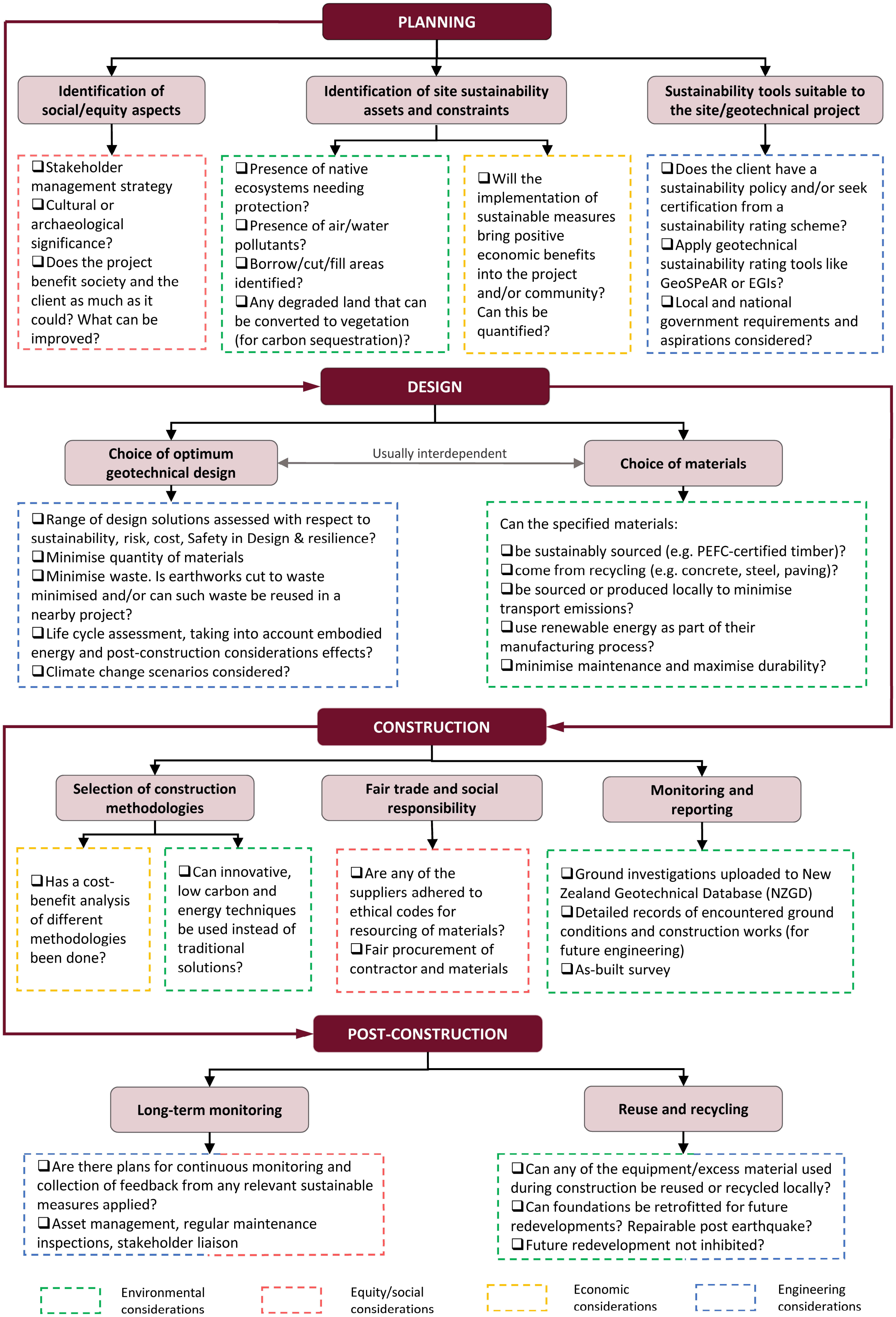
Figure 4: Key sustainability components and ideas for geotechnical projects

5 CONCLUSIONS

We all have a part to play in contributing to a sustainable world. Geotechnical engineers have the benefit of early project involvement across all industry markets and can make a difference to our current practices, for the better. Hoping that others may take action for us is not a strategy. Look for opportunities to embed sustainability principles, big or small, and consider balance across the four E's of sustainable development.

To succeed, it will be vital to raise awareness and overcome barriers to sustainability. Research and knowledge transfer must be expanded, and we need to work collaboratively with government and other disciplines in the industry.

There are many powerful tools available that can be used in our daily decision-making processes to help us find the most sustainable solution for every project. Simply by being aware of the impacts of our projects on the natural and socio-economic environment in the long-term and trying to go beyond the established minimum industry requirements can have a huge effect and pave the way towards a more responsible future for the geotechnical engineering practice.


PLANNING
Identification of social/equity aspects
Identification of site sustainability assets and constraints
Sustainability tools suitable to the site/geotechnical project
❑Stakeholder management strategy
❑Cultural or archaeological significance?
❑Does the project benefit society and the client as much as it could? What can be improved?
❑Presence of native ecosystems needing protection?
❑Presence of air/water pollutants?
❑Borrow/cut/fill areas identified?
❑Any degraded land that can be converted to vegetation (for carbon sequestration)?
❑Will the implementation of sustainable measures bring positive economic benefits into the project and/or community? Can this be quantified?
❑Does the client have a sustainability policy and/or seek certification from a sustainability rating scheme?
❑Apply geotechnical sustainability rating tools like GeoSPeAR or EGIs?
❑Local and national government requirements and aspirations considered?
DESIGN
Choice of optimum geotechnical design
Usually interdependent
Choice of materials
❑Range of design solutions assessed with respect to sustainability, risk, cost, Safety in Design & resilience?
❑Minimise quantity of materials
❑Minimise waste. Is earthworks cut to waste minimised and/or can such waste be reused in a nearby project?
❑Life cycle assessment, taking into account embodied energy and post-construction considerations effects?
❑Climate change scenarios considered?
Can the specified materials:
❑be sustainably sourced (e.g. PEFC-certified timber)?
❑come from recycling (e.g. concrete, steel, paving)?
❑be sourced or produced locally to minimise transport emissions?
❑use renewable energy as part of their manufacturing process?
❑minimise maintenance and maximise durability?
CONSTRUCTION
Selection of construction methodologies
Fair trade and social responsibility
Monitoring and reporting
❑Has a cost-benefit analysis of different methodologies been done?
❑Can innovative, low carbon and energy techniques be used instead of traditional solutions?
❑Are any of the suppliers adhered to ethical codes for resourcing of materials?
❑Fair procurement of contractor and materials
❑Ground investigations uploaded to New Zealand Geotechnical Database (NZGD)
❑Detailed records of encountered ground conditions and construction works (for future engineering)
❑As-built survey
POST-CONSTRUCTION
Long-term monitoring
Reuse and recycling
❑Are there plans for continuous monitoring and collection of feedback from any relevant sustainable measures applied?
❑Asset management, regular maintenance inspections, stakeholder liaison
❑Can any of the equipment/excess material used during construction be reused or recycled locally?
❑Can foundations be retrofitted for future redevelopments? Repairable post earthquake?
❑Future redevelopment not inhibited?
Environmental considerations
Equity/social considerations
Economic considerations
Engineering considerations

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