Global challenges, geosynthetic solutions, counting carbon and climate change impacts

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ABSTRACT: The earth is experiencing unprecedented change driven by increasing population, industrialization and urbanization. This is leading to rapid climate change and scarcity of resources. There is growing agreement globally of the need to deliver sustainable development to improve the lives of millions of people in low and middle income countries through provision of clean water, sanitation, energy and transport solutions. The response of the international community to this challenge is via the United Nations programme (published in January 2016), which establishes 17 Sustainable Development Goals (SDG) including the response of nations to climate change. This paper provides a summary of the keynote lecture aspects that address: Drivers for sustainable development, the United Nations SDG, climate change projections, global action on climate change, and the sustainability case for using geosynthetics and how it can be quantified. A more detailed discussion of these topics is provided by Dixon et al. (2017). This paper then focusses on the importance and approaches for assessing impacts of climate change on the performance of geosynthetic systems. An example of a landfill capping system is used to demonstrate how modeling of changing weather patterns can be used to assess long-term stability and hence inform design decisions. The geosynthetics community is challenged to be proactive and play a leading role in helping engineers deliver a better future for populations world-wide.

Keywords: Geosynthetics, global challenges, sustainability goals, climate change, carbon emissions, modelling, soil/geosynthetic systems

1 INTRODUCTION

This paper introduces the key themes of the keynote lecture presented at the 11th International Conference on Geosynthetics, Korea, September 2018, on the role that geosynthetics can play in meeting the global challenges facing society. The lecture addresses the global challenges, United Nations sustainability goals, approaches for counting carbon and the role that geosynthetics can play in both mitigating and adapting to the impacts of climate change. Elements of the lecture were first presented in a keynote at the 3rd Pan American Conference on Geosynthetics in Miami Beach, USA, in April 2016, and a full written version of this Miami lecture is available in Dixon et al. (2017). As a published record exists for the core themes of the lecture, this paper focusses on presenting a new study on the impacts of changing climate on the design of exemplar geosynthetic systems.

The keynote lecture, this supporting paper and Dixon et al. (2017) aim to stimulate thinking and discussion on the global challenges that society face and how geosynthetics can help contribute to sustainable global development, including response to a changing climate. The aim is not to focus on solutions using specific geosynthetic materials or design approaches as there are numerous sources of excellent advice on such measures in published papers, standards and industry reports. However, there are strong moral and business cases to consider the high level drivers of global change and to question how as individuals and collectively as a geosynthetics industry, these challenges can be met.

The global challenge of sustainable development is the key driver for change and this is being championed through the United Nations Global Sustainable Development Goals (United Nations, 2015a). These encompass economic development, social development and environmental protection for future generations. As the key driver for much of the legislation and changes in behaviour world-wide, climate change forecasts and the international response are highlighted, including mitigation opportunities and adaptation solutions. Approaches used for calculating embodied carbon for solutions incorporating geosynthetics are summarized as is their use in delivering evidence for the 'sustainability' case for using geosynthetics. As a specific example, the paper considers how a changing climate could impact on the long-term stability of geosynthetic solutions, using a case study of a landfill cap subject to current and forecast climates. The modelling approach is detailed and exemplar results are presented. The keynote lecture and paper challenge the conference delegates to help make a difference to the world in which we live.

2 DRIVERS FOR SUSTAINABLE DEVELOPMENT

Sustainable global development is of critical importance to deliver an improved standard of living for the many billions of people that currently live in poverty in low and middle income countries. There is an urgent need to provide infrastructure that establishes critical life lines for these people (e.g. safe places to live, clean water, food, mobility and energy). It is widely acknowledged that the current model of global development is unsustainable. If low and middle income countries attempt to replicate the approach and forms of infrastructure that have developed in high income countries in the last 200 years, this will lead to exhaustion of natural resources and generation of greenhouse gas (GHG) levels (i.e. of which CO_2 is the most prevalent and, along with methane, the most important) that will cause irreversible climate change and adverse impacts to populations across the globe. Therefore, in simple terms the global aim is to deliver the three pillars of sustainability: Social, environmental, and economic. The keynote and this paper primarily consider environmental sustainability. Civil engineers are at the forefront of efforts to achieve sustainable development; they can transform communities and deliver transformative infrastructure and hence improvements to the quality of life of communities. Readers are asked to consider whether the geosynthetics community has a specific role to play in delivering sustainable development?

3 UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS

The scale of the challenge facing the global population at the present time is staggering. For example, out of a total population of 7.4 Billion people, 1 in 10 lack access to safe water, women and children spend 125 million hours each day collecting water, 1 in 3 people lack access to a toilet and every 90 seconds a child dies from a water related disease. In addition, communities are increasingly vulnerable to natural disasters from global changes in climate, urbanization and land use (World Health Organization and UNICEF Joint Monitoring Programme, 2015). In attempts to solve these problems, 50% of world resources are being used to create infrastructure and it has been estimated that $57 trillion investment is needed in infrastructure before 2030 (World Health Organization and UNICEF Joint Monitoring Programme, 2015). The international community is responding to this unprecedented scale of need via the United Nations Programme - *Transforming our world: The 2030 Agenda for Sustainable Development* (United Nations, 2015a). This programme, which came into effect in January 2016, establishes 17 *Sustainable Development Goals* to guide decisions taken by nations and organizations over the next 15 years (United Nations, 2015a). These high level national decisions will focus the scale and priorities for funding, with each country facing specific range and combination of challenges. The 17 development goals are depicted in Figure 1.

Many of the development goals are linked to the availability and operation of appropriate infrastructure, and there are particular opportunities for those involved in making, promoting, designing and constructing with geosynthetics to play a role in achieving the five goals below:

- *Goal 6 - Clean water and sanitation:* Ensure available and sustainable management of water and sanitation for all. Collection, storage, treatment and delivery of clean water, and storage, treatment, minimization and safe disposal of human waste.
- *Goal 9 - Industry, innovation and infrastructure:* Facilitate sustainable and resilient infrastructure development through enhanced technological, technical and financial support, with affordability being critical.
- *Goal 12 - Responsible consumption and production:* Deliver sustainable management and efficient use of natural resources including via increased prevention, reduction, recycling and reuse of waste.

- *Goal 13 - Climate action:* Take urgent action to combat climate change and its impacts, including strengthening resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.
- *Goal 17 – Partnerships for the goals:* Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development, including transfer of appropriate technology, capacity building and trade.

Figure 1. United Nation sustainability goals launched in January 2016 (United Nations, 2016a)

4 CLIMATE CHANGE PROJECTIONS

Climate change is of central concern for nations as it impacts on many of the development goals. Those working to deliver sustainable solutions must do so in the context of climate change projections as these provide both drivers and a framework within which future infrastructure should be designed, constructed and operated. Failure to deliver infrastructure that mitigates climate change and/or delivers adaptation solutions, will condemn millions of people to a poorer quality of life. Those using climate change information have questioned and sought to interpret the science behind headlines reported in the media and this has established both the rigor and usefulness of information currently available. For example, Dijkstra et al. (2014) have investigated the impacts of projected climate change on performance of geotechnical structures, such as cutting and embankments, which support critical transport infrastructure. It is important that designers understand the context of their solutions and uses that can be made of climate change information.

There is now almost unanimous agreement world-wide by scientists and governments that our climate is changing and that the most probable cause is human activity. The most recent Intergovernmental Panel on Climate Change (IPCC) report in 2014, the 5th in the series, presents unequivocal evidence that the climate system is warming (IPPC 2014). Using published peer reviewed sources, IPPC (2014) present detailed assessments of impacts world-wide, for a range of sectors, which can be attributed to climate change. As an example, projected temperature and precipitation changes taken from IPPC (2014) are shown in Figure 2 for both temperature and precipitation. Measured changes in the period 1986 to 2005 are on the left and the projected changes 2081 to 2100 are shown on the right. All areas are projected to get warmer by a number of degrees, but precipitation is more mixed with some areas getting wetter and some dryer. Of importance is that these are average changes and variation of extremes (e.g. precipitation) is expected to be larger.

However, despite the clarity and consistency of the climate change projections there is still uncertainty due to a number of factors. Firstly, the level of future global GHG emissions is unknown so the projections use a family of four emission scenarios, the likelihood of each being dependent on the success or otherwise of climate change agreements and hence of plans to deliver the sustainable development goals. Although the relative likelihood of emissions scenarios is unknown, climate change is almost independent of emissions scenario in the next few decades (IPPC, 2014) and, therefore, change will still occur even if GHG emissions are drastically cut in the near future, which is highly unlikely. A second important source of uncertainty in projections is due to the natural variability of weather. This natural variability is incorporated in projections by running models with the same emissions scenario but different initial conditions multiple times. Thirdly, is modelling uncertainty that is due to our current incomplete understanding of climate processes and inability to model them perfectly. This is incorporated in projections by aggregating the outputs from many models (e.g. produced by national bodies from around the world responsible for climate change projections and research organizations) and doing multiple runs. This detailed consideration of uncertainty informs the projections published by IPPC and also those produced by other bodies.

Despite this uncertainty, a consistent message provided by the numerous modelled climate change projections is that variability and occurrence of extreme events will increase, with standard deviation of precipitation and temperature events forecast to change two times that of mean values (IPPC, 2014). Those who doubt the validity of climate change projections should recognize that the IPCC (2014) conclusions are based on the scientific method: Systematic observation, measurement and experiment, and the formulation, testing and modification of hypotheses (Dixon et al. 2017).

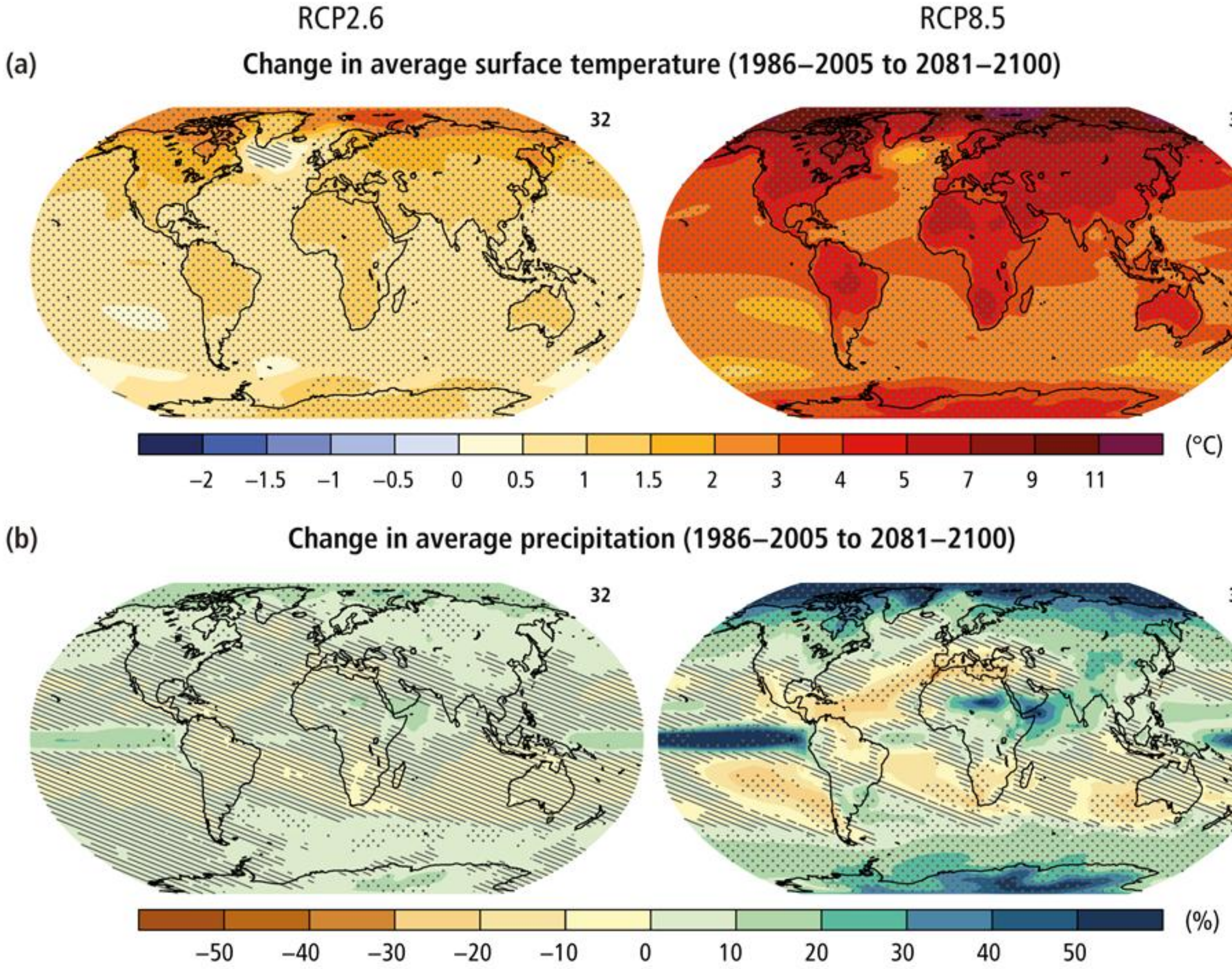


Figure 2. Changes in temperature (a) and precipitation (b) for the periods 1986-2005 to 2081-2100 (IPPC 2014, Figure SPM.7)

5 GLOBAL ACTION ON CLIMATE CHANGE

The 2015 United Nations Framework Convention on Climate Change held in Paris, December 2015 (United Nations 2015b), delivered the most comprehensive global climate change agreement to date. Signatory counties agreed to deal with greenhouse gas emissions mitigation, adaptation and finance starting in the year 2020. The agreement set a goal of limiting global warming to less than 2°C and was reached by an unprecedented 196 parties. Enough countries had ratified the agreement for it to enter into force on 4th November 2016. Although one of the world’s highest greenhouse gas emitters (GHG), the current USA administration has stated that it will pull out of the agreement. This has added to growing uncertainty around the likely effectiveness of the treaty given that at is core is a requirement for nations to develop, disseminate and adopt practices that deliver sustainable development. A significant aspect of the agreement is that it was made possible because 186 countries published action plans prior to the Paris convention. Each plan sets out the way in which the country intends to reduce their GHG emissions.

Two categories of action are needed to tackle climate change and its effects: **Mitigation** to reduce greenhouse gas emissions that cause climate change and **adaptation** to address its impacts. Mitigation by Governments is at the heart of contributions to reduce GHG emissions. Mitigation objectives are at the national economic level and include all industrial sectors. Adaptation will be achieved through implementing policies and measures to adapt to climate change impacts and to build resilience and reduce vulnerability. Geosynthetics can make a contribution to mitigation by reducing carbon emissions from constructing and operating infrastructure, and they can also make a significant contribution to adaptation, specifically in resilience of communities and infrastructure to extreme climate disasters such as flooding, landslides and drought.

As a case study, Republic of Korea has experienced an increased precipitation in the order of 20% since 1970s and a doubling in intensity of events as reported in the National Climate Change Adaptation Plan of Korea 2012 (Soojeong 2012), leading to increased cost of extreme weather events such as highway and bridge damage by intense rainfall events. The Republic of Korea's climate change action plan (United Nations, 2015c) reports that Korea plans to reduce its greenhouse gas emissions by 37% from the business-as-usual level by 2030 across all economic sectors, including energy, industrial processes and product use, agriculture and waste. This includes providing a legislative framework and national plans for addressing climate change. As examples, in the building sector, the Korean government is seeking to manage energy efficiency from the design to operation stages and in the transport sector infrastructure is being expanded for environment-friendly public transport. Changes in standards and codes, and infrastructure development all provide opportunities for geosynthetics to be part of the solutions used.

While the scale of the challenge is somewhat daunting, examples exist of how high level global agreements are resulting in local and industry specific change. Responding to GHG emission targets established via the EU, the UK construction industry has developed a strategy articulated in the report Construction 2025 (United Kingdom Government, 2013), which identifies low carbon and sustainable construction as a strategic priority of the industry, with an ambition to reduce GHG emission by 50% by 2025. There is an expectation that GHG emission will be a key criteria used to select construction solutions and all major projects have to have GHG evaluation as part of their environmental assessment.

6 GEOSYNTHETIC SOLUTIONS: COUNTING CARBON

Measurement of the sustainability credentials of a product, process or solution is now common practice across a wide range of industries, including construction. Approaches are available that use social, environmental and economic aspects of sustainability. However, international agreements (e.g. see Section 5) have set targets defined using GHG emissions and therefore this is an obvious measure to use as governments seek to fulfil the Paris climate change agreement targets. Industries, including construction, will be expected to deliver reductions in GHG emission. Therefore, the pragmatic approach is to concentrate on GHG emissions when championing geosynthetics as a sustainable solution.

Carbon footprint is a measure of total GHG emissions caused directly and indirectly by a person, organization, event or product. It is measured in tonnes of carbon dioxide equivalent (tCO_2e). A carbon footprint can cover emissions over the whole life of a product, service or solution (i.e. including a construction solution) and embodied carbon (EC) is an indicator of cumulative carbon emissions used in the solution adopted. Comparison of calculated carbon footprints for alternative solutions can be used to inform selection of the most 'sustainable' option. A site-by site approach can consider project specifics such as: available materials on site and nearby; supply logistics; site layout; method of construction etc. Life Cycle Assessment (LCA) is a tool for measuring the environmental impact of products or systems over their lifetime. It can consider extraction of raw materials, through production, use, recycling and disposal of waste. LCA is often used to compare the impact of two competing products or systems, with the analysis process informed by ISO14040 (2006a) and ISO14044 (2006b) or other approved tools. LCA boundaries are clearly defined boundary conditions and are required to describe which parts of the material production, manufacture and deployment are taken into account in calculating the carbon footprint. Typically used LCA boundaries are shown in Figure 3 mapped against the stage of product manufacture and application. There is need for a geosynthetics industry standard approach for LCA endorsed by geosynthetic manufacturers and suppliers, recognized and trusted by construction organizations and clients (Dixon et al. 2017). Figure 4 details a framework for CO_2 assessment of a construction solution incorporating geosynthetics that was used by Dixon et al. (2016). The framework comprises five stages of analysis, however, depending on the LCA boundaries, Stages 4 and 5 may be omitted.

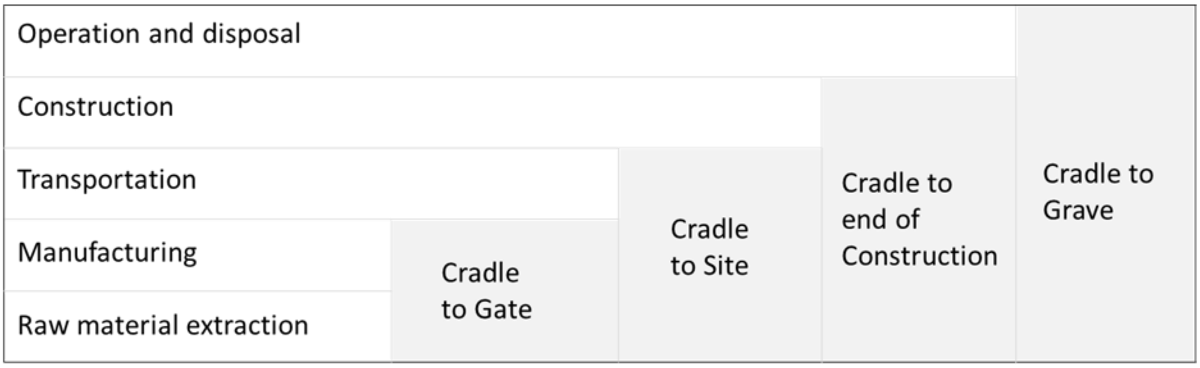


Figure 3. Life Cycle Analysis boundaries for typical stages of product manufacture and application (after Dixon et al. 2016)

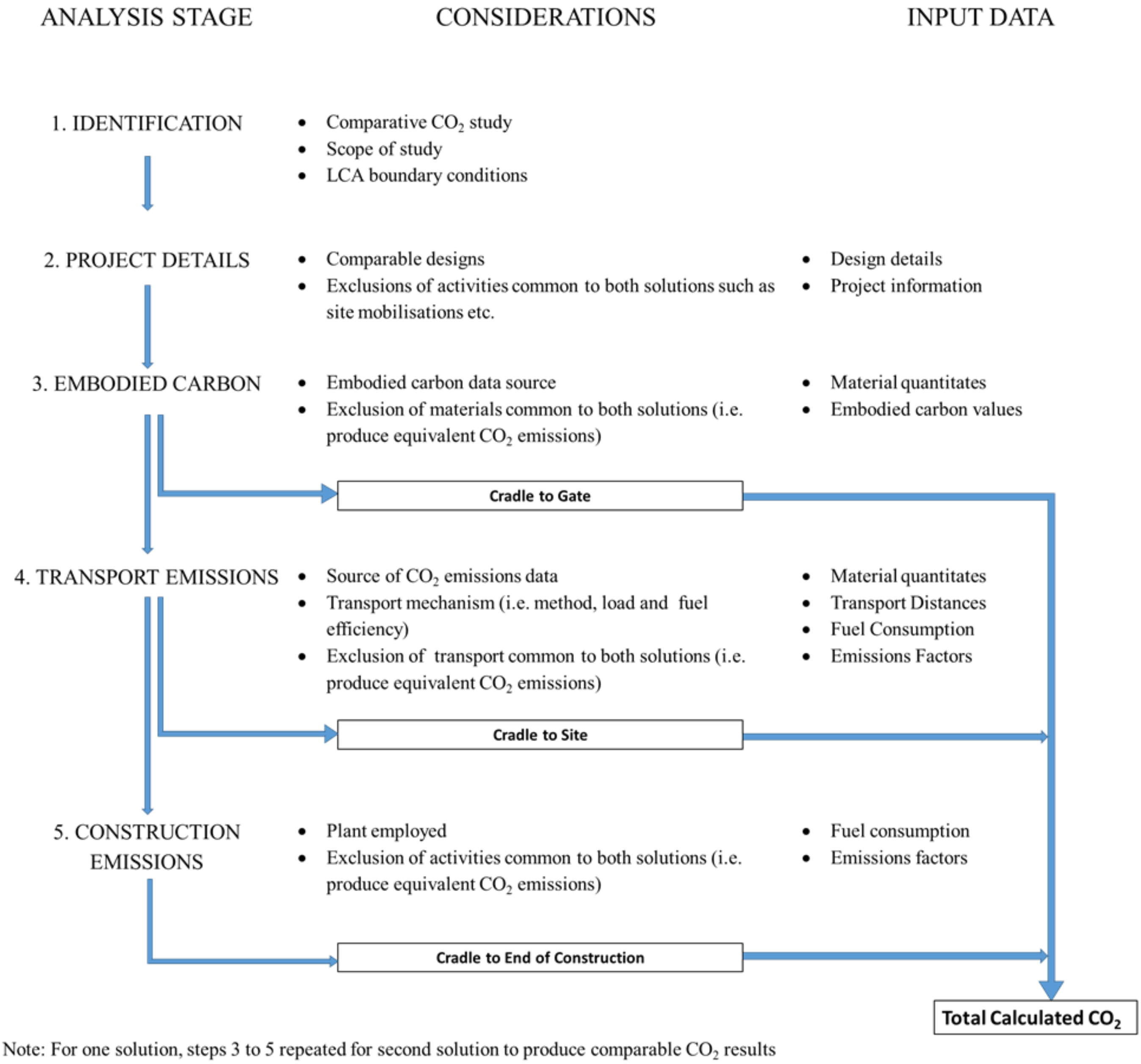


Figure 4. Five stage framework for a CO2 assessment of a construction solutions (after Dixon et al. 2017)

The rigor of any LCA is based on the validity of material EC values employed and hence accurate embodied carbon data is required for geosynthetic materials. To date, the majority of studies reported in the literature for geosynthetics have used EC values from two published databases; the Inventory of Carbon & Energy (ICE) database (Hammond and Jones, 2011) and the European life cycle analysis database called

'EcoInvent v3.3' (e.g. EcoInvent Centre, 2016). However, neither includes geosynthetic product specific values with only generic plastic materials reported. This lack of geosynthetic product specific information has allowed advocates of 'competitor' solutions to question the rigor and accuracy of studies that show geosynthetic solutions to be more sustainable. However, published studies such as by Raja et al. (2015) add to information produced by manufacturers to now provide EC values for specific geosynthetic product ranges (e.g. non-woven geotextiles and geogrids). Those conducting LCA of geosynthetic solutions are encouraged to take particular care in the selection and use of representative EC values.

LCA calculations for embodied carbon of construction solutions that incorporate geosynthetics are now well established and there is growing literature demonstrating use of the approach and reporting examples of assessments (Table 1, after Dixon et al. 2017). All studies published to date conclude that solutions incorporating geosynthetics are consistently more sustainable based on calculating embodied carbon and also measured using a range of other environmental indicators. Savings in EC are often realized because geosynthetics allow use of site derived often 'marginal' soils, thus reducing the amount of imported fill material; this minimizes the transport related carbon emissions. A number of the studies have also concluded that geosynthetic based solutions also delivered significant cost savings. Established methods can be used to undertake site specific LCA calculations that inform decisions on selection of construction approaches contributing to sustainable practices. The need for sustainable construction solutions is a major opportunity for the geosynthetics industry, particularly given the cost savings that can also result.

Table 1 LCA published case studies for geosynthetic solutions (after Dixon et al. 2017)

Author/Type of study	**Solutions compared**	**LCA boundaries**	**Source of material EC**	**Sustainability measure**	**Key findings**
WRAP (2010)/ Projects	• Environmental bund – gabion wall vs. reinforced soil • Road embankment – Imported stone vs. reinforced soil • Four retaining wall examples – Concrete/sheetpile and block walls vs. reinforced soil	Cradle-Gate	ICE	CO_2	Significant CO_2 (85 to 31%) and cost savings are related to reduced import and export of fill materials
Stucki *et al.* (2011)/ Functional units	• Pavement – Gravel vs. geotextile filter • Pavement – Fill/lime treatment vs. geogrid reinforcement • Landfill cap – Gravel vs. geocomposite drain • Retaining wall – Concrete vs. geogrid reinforced soil	Cradle-Grave (excluding maintenance and operation)	EcoInvent	CO_2 + 7 other indicators	Geosynthetic solutions have lower CO_2, plus lower environmental impact factors using a range of other measures. Savings are related to reduced import and export of fill materials. Uncertainty is considered.
Heerten (2012)/ Projects	• Slope protection – Concrete vs. reinforced soil • Pavement – Lime treatment vs. geogrid reinforcement	Cradle-End of construction	FFR	CO_2, CH_4 & CED	GHG reductions using the geosynthetic solutions, with associated cost savings identified.
Raja *et al.* (2014)/ Projects	• Landfill cap - Clay vs. geomembrane & geotextile	Cradle-End of construction	ICE	CO_2	Geosynthetic solution generated a third CO_2 compared to the compacted clay barrier but the relative difference is sensitive to the distance to the clay fill source.
Damians et al. (2017)/ Projects	• Retaining walls – Concrete (gravity and cantilevered vs. MSE walls (polymeric and steel)	Cradle-End of construction	EcoInvent	CO_2 + range of mid and end point indicators	MSE walls consistently produced lower environmental impacts across the range of mid-point, end point and single end point indicators.
Dixon et al. (2016)/ Func-	• Protection – Sand vs. geo-	Cradle-Site	Material specific	CO_2	Significant CO_2 savings on all three solutions dues to reduced import

tional units	textile • Working platform – Gravel vs. geogrid reinforced reduced layer thickness • Landfill cap – Clay vs. geomembrane & geotextile	Cradle-End of construction Cradle-End of construction	(Raja *et al.* (2015)		and export of fill, but the relative difference is sensitive to the distance to the fill source.
Bizjak & Lenart (2018)/ Project	• Bridge system – Geosynthetic reinforced earth vs. reinforced concrete	Cradle-Grave	EcoInvent	CO_2 + range of other measures	Geosynthetic reinforced bridge system has much lower environmental impact than equivalent bridge using conventional reinforced concrete.

7 IMPACTS OF CLIMATE CHANGE ON PERFORMANCE OF GEOSYNTHTIC SYSTEMS

7.1 *Need for adaptation*

Climate projections indicate not only changes in average temperature and precipitation values but also in the magnitude and frequency of extremes such as intensive storm events. Significant changes are indicated within the typical design life of constructed infrastructure. For example, in the UK the design life for road and rail infrastructure is 120 years. This means that designers of drainage systems, earthworks, retaining structures, pavements etc must consider the implications of climate change to ensure acceptable performance. This *future proofing* designs means providing additional capacity or functionality. In addition to new-build, it is also appropriate to apply updated requirements to designs for maintenance, renewal and improvement works when these are implemented within the normal cycle for such activities. The aim of adaptation strategies is to adopt a precautionary approach in future proofing designs, so that the asset/activity will perform satisfactorily throughout its life in the event of climatic change.

7.2 *Examples of climate change impacts*

As an example, Highways England in the UK have updated the Design Manual for Roads and Bridges (DMRB) guidance (Highways England 2015) to ensure that all new drainage assets are provided on a consistent basis, using updated critical design storm guidance, to assure serviceability and minimize the risk of failure. The guidance provides clear, unambiguous assessment and design guidance to ensure consistency of design approach for new and improved assets, providing robust design parameters to accommodate climate change parameters. The aim is to improve highway network resilience in the event of extreme events. In simple terms, design storm events used to size drainage system components (e.g. pipes and storage chambers) are increased by 20% from recent historical events to account for the anticipated greater intensity of storm events in the future. However, while this simple approach can be used to account for the intensity of events, it cannot account for the impact of a changing climate on the long-term performance of relatively low hydraulic conductivity (i.e. fine grained) soil structures (e.g. earthwork slopes), the performance of which are controlled by seasonal wetting and drying (Dijkstra and Dixon 2010, Glendinning et al. 2014). In these fine grained soil systems, it is the magnitude of the effective stress change over multiple dry summer and wet winter cycles, modified by vegetation cover, that can control stability. Changes in the magnitude of these effective stress cycles resulting from a changing climate are of concern to the owners and operators of infrastructure (Glendinning et al. 2014).

To demonstrate how climate change can influence the performance of soil/geosynthetic systems, below is an example assessment of a landfill cover system subject to both current and future climates. The problem investigated is for a landfill cover system comprising a high plasticity clay veneer soil layer 1.5 metres thick overlying a geomembrane. Two design cases considered: i) without a drainage geocomposite above the geomembrane so that positive pore water pressures can occur during wetting periods; and ii) with a drainage geocomposite above the geomembrane so that no positive pore water pressures can occur along the interface (Figure 5). The slope has a horizontal length of 30 metres, a height of 10 metres, a slope of 18.4° and a grass cover. A relatively high strength and stiffness fine grained soil blinding layer is located beneath the geomembrane and hence it does not significantly influence behaviour of the cover system. Waste below the soil blinding layer is also assumed to be stable allowing the model to be fixed both horizontally and vertically along the lower edge of the soil/geomembrane interface and below the soil blinding layer (i.e. the only mechanism being investigated is strain softening at the cover soil/upper geosynthetic interface).

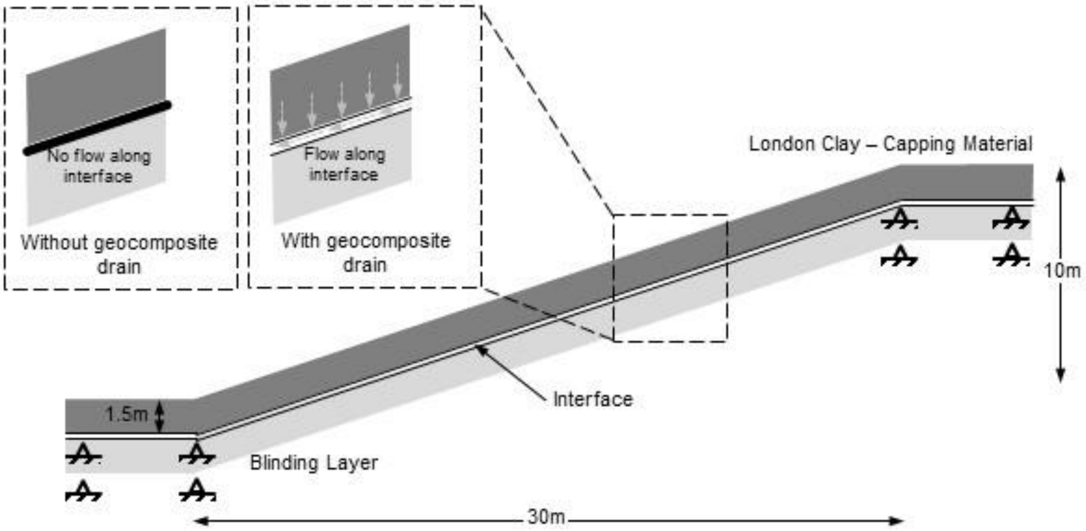


Figure 5. Landfill cover system model details for the two cases assessed for flow along the soil/geomembrane interface: i) No drainage layer – no flow; and drainage layer – flow

7.3 *Numerical modelling framework*

A two-phase flow numerical model framework capable of modelling saturated and unsaturated soil behaviour has been used to model a high plasticity clay landfill capping layer overlying a geomembrane with and without a geocomposite drain, with both cases subjected to repeated annual cycles of wetting and drying under both current climatic conditions and simplistic projected trends of climate change.

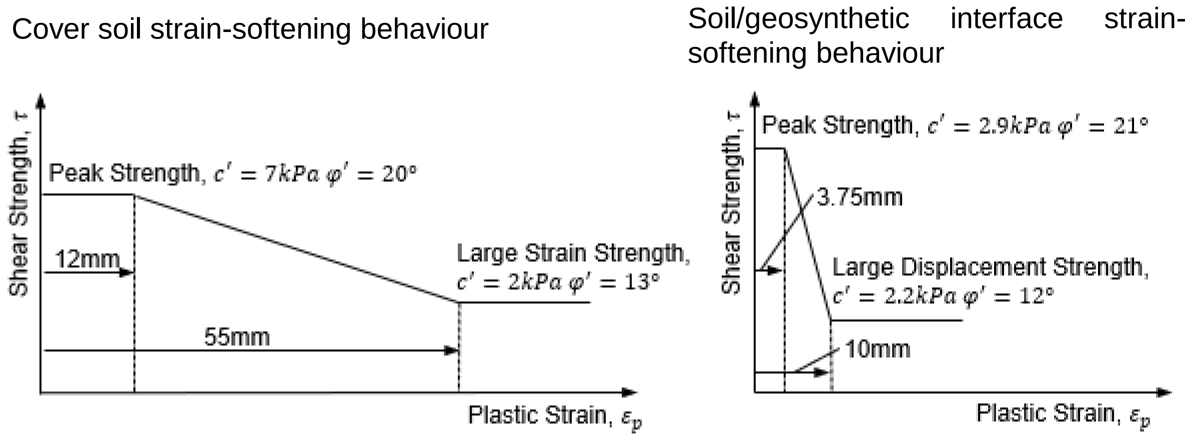
The numerical modelling approach has used FLAC – Two-Phase Flow (FLAC-TP) (Itasca, 2011). The code allows saturated behaviour to be modelled if the soil is fully saturated during wet winter conditions and unsaturated behaviour if the soil becomes desaturated in dry summer conditions. Unsaturated soil behaviour is modelled using Bishop’s generalized effective stress and a van Genuchten (1980) style soil water retention curve and relative hydraulic conductivity function to couple mechanical and hydrogeological behaviour. This approach has been developed and used by researchers to investigate the long-term performance of UK road/rail cuttings and embankments under projected climate change (e.g. Glendinning et al. 2014; Glendinning et al. 2015).

A key focus of this study is the strength deterioration of the soil/geosynthetic interface under repeated seasonal stress cycles driven by wetting and drying of the landfill cover soil. Therefore, a single soil/geosynthetic interface has been modelled using strain-softening interface elements. Note that in the ‘without drain’ case this interface is between the cover soil and a textured geomembrane and in the ‘with drain’ case this interface is between the soil and a geocomposite drainage layer (e.g. a lightweight non-woven protection geotextile above a core). For simplicity and to aid comparison of the two cases, the properties of these two interfaces have been taken as the same. In addition, the high plasticity clay landfill capping material is also modelled as a strain-softening material with the properties taken as those for London Clay, which is commonly used in landfill construction in the south east of the UK. A Mohr-Coulomb strain-softening constitutive model with material softening considering local plastic displacements normalized against element thickness has been adopted to model this soil cover layer. Surface boundary seasonal wetting and drying cyclic weather conditions have been used to subject the cover system to multiple years of both current conditions experienced in the UK based on weather records for the past 30 years, and under projected climate change conditions with wetter winters and drier summers representative of the overall trend of UK Climate Change Projections (UKCP09, Murphy et al. 2009).

7.4 *Material Properties*

As noted above, the high plasticity cover soil and the soil/geosynthetic interfaces (i.e. for both the soil/textured geomembrane and soil/drainage geocomposite as discussed above) have been modelled as strain-softening materials. Plastic displacement criteria have been normalized to the element thickness for the soil and element length for the geomembrane. The strength and plastic displacement criteria are summarized in Figure 6 and Table 2. Plastic displacement criteria and strength parameters for the cover soil (i.e. London Clay) have been obtained from modelling an undrained triaxial test using a single element axisymmetric numerical model and validated against stress-strain curves presented by Potts, et al. (1997).

Plastic displacement criteria and strength parameters for a fine grained soil/textured geomembrane interface have been taken from experimental large direct shear test data for such interfaces presented by Sia (2007). Plastic displacement criteria have been taken considering normal stresses on the geosynthetic in the range of 10 to 50kPa, based on the thickness of the soil capping layer being modelled. Also presented in Table 2 are stiffness parameters used for modelling of the soil and soil/geosynthetic interfaces. The saturated hydraulic conductivity, used to determine the relative hydraulic conductivity when unsaturated, of the cover soil (i.e. compacted fill) has been taken as 1x10^{-9}m/s (i.e. which is relatively low but not unusual) and the soil water characteristic curve are summarized in Table 2 after Briggs, et al. (2013).


Cover soil strain-softening behaviour

Soil/geosynthetic interface strain-softening behaviour

Figure 6. Material properties used for the cover soil (London Clay fill) and soil/geosynthetic interfaces

Table 2. Summary of soil and soil/geosynthetic interface material properties

High plasticity clay fill strain-softening properties	
Peak plastic local displacement (mm)	12
Large strain plastic local displacement (mm)	55
Peak cohesion (kPa)	7$^{\wedge}$
Large strain cohesion (kPa)	2$^{\wedge}$
Peak friction angle (º)	20$^{\wedge}$
Large strain friction angle (º)	13$^{\wedge}$
Clay fill stiffness properties	
Bulk modulus, K (kPa)	3333
Shear modulus, G (kPa)	1538
Poisson's ratio, ν	0.2$^{\wedge}$
Other	
Bulk density, γ (kN/m^3)	18.8$^{\wedge}$
Soil/geosynthetic interface strain-softening properties	
Peak plastic displacement (mm)	3.75
Large displacement (mm)	10
Peak adhesion (kPa)	2.9*
Large displacement adhesion (kPa)	2.2*
Peak friction angle (º)	21*
Large strain friction angle (º)	12*
Soil/geosynthetic interface stiffness properties	
Shear stiffness (kPa)	5230
Soil water retention properties	
van Genuchten, n	1.18†
van Genuchten, m	0.153†
van Genuchten, α (kPa)	125†
$^{\wedge}$ (Potts, *et al.*, 1997); * (Sia, 2007); † (Briggs, *et al.*, 2013)	

7.5 *Weather boundary conditions*

To drive seasonal wetting and drying weather cycles, flux boundary conditions have been applied to the surface of the capping soil material to replicate summer drying (7 months) and winter wetting (5 months). The boundary conditions used allow wetting and drying to be modelled without the inclusion of extreme wet events as this allows strength deterioration of the soil/geosynthetic interface to be investigated under steady conditions. Use of steady conditions facilitates investigation of changes in long-term weather patterns impacting on rates of stability deterioration for the soil/geosynthetic cover system, without extreme short-term wet events shocking the system and triggering collapse. As noted above, two climatic scenarios have been considered. For the current climate scenario, cycles of 70kPa at the mid-slope surface have been imposed, such that at the end of summer the pore water pressure suction is 70kPa and at the end of winter the pore water pressure is 0kPa. If at the end of summer or winter the pore water pressures did not reach the prescribed condition, the flux boundary condition is adjusted for the next seasonal cycle so that each cycle starts with the prescribed boundary conditions. For the scenario considering climate change, the analyses are run under current climate conditions for 20 years and then the pore water pressure cycles are increased to 90kPa suctions at the end of the summer and the time spent at near hydrostatic (i.e. 0kPa) conditions at the end of winter is also increased. These changed boundary conditions are representative of the headline trend of UKCP09 (Murphy et al. 2009) of wetter winters and drier summers by the 2050s.

7.6 *Assessing interface strength deterioration and times to failure*

Assessment of soil/geosynthetic interface strength deterioration that can result from down-slope displacements on this strain softening surface has used the average strength along the sloped portion of the interface, calculated every 5 seasonal weather cycles. This has then been used to allow comparison of strength deterioration of the two design cases (i.e. with and without a drain) and under current and future climatic conditions. Figure 7 shows outputs from the numerical model for the case where a geocomposite drain is located above the geomembrane (i.e. pore water pressures are kept at zero at the base of the soil cover layer) under current and future climates. Figure 7a and b show the seasonal cycles of pore water pressure on the slope surface at mid-height for the current and future climates respectively, which drive behaviour of the veneer slope system. Figure 7c shows a more detailed view of the pore water pressure for cycles (i.e. years) 90 to 95. Figure 7d plots the mid-slope vertical and horizontal displacements and shows that down-slope displacements occur in response to the cycles of weather, and with smaller vertical displacements but slightly larger horizontal displacements given under the changed climate. The time to failure, as denoted by acceleration of the slope horizontal displacements shown in Figure 7e, is greater than 100 cycles (i.e. years) for both climate conditions when a drain is provided above the geomembrane and with the slope failing marginally quicker under the changed climate.

Figure 8 shows comparable plots to those shown in Figure 7 but for the case without a drain between the soil cover layer and the geomembrane. Of note is the significantly reduced time to failure for the current steady climate, which is around 65 years, compared to 120 years for the design cases incorporating a drain (Figure 8e). This is of course as expected and justifies current design practice of including a drainage layer beneath fine grained cover soils to ensure veneer stability. The results for climate change conditions indicate that the increased cycles of pore water pressure that result from dryer summers and wetter winters (Figures 8b and c) reduces the time to failure from 65 to 45 years, which is a significant reduction in design life of the capping system.

Cycles of pore water pressure generated by seasonal weather drive a progressive failure mechanism at the soil/geosynthetic interface. This results from increments of strain at the interface cumulatively mobilizing post peak strengths due to strain softening behaviour of the interfaces modelled, which is typical for a range of planar geosynthetics interacting with soil. Figure 9 shows deterioration in soil/geosynthetic interface strength with weather cycles under current and future climates as denoted by reductions in mobilized friction angles. In all cases investigated, the average mobilized friction angle reduces from the peak by 40 years. For the design case without a drain the reduction in mobilized friction angle to residual conditions is rapid even under the current climate. Inclusion of a drain prolongs the design life by a factor greater than 2 as discussed above but mobilization of residual friction angles eventually occurs, leading to failure of the cover soil by large uncontrolled slippage at the interface. Figure 9 also confirms the conclusion that in both design cases, climate change reduces the time to failure of the capping system.

7.7 *Climate change implications for design*

The examples presented to illustrate the importance of considering climate change in design of geosynthetic systems are of course specific and conclusions cannot easily be extrapolated to other design cases and conditions. However, the examples demonstrate the two extremes of complexity that can be applied: Adding 20% to current design storm events in order to ‘future proof’ drainage systems, or undertaking state-of-the-art modelling of weather/vegetation/soil/geosynthetic interactions to investigate long-term deterioration mechanisms developing over tens of year. There are of course a range of available approaches between these two extremes. The aim of this section of the paper is to raise awareness of the importance of considering climate change in design of geosynthetic systems. In many cases it will not have a significant effect but as demonstrated in the landfill capping example, changing weather can lead to increased rates of degradation in some soil/geosynthetic systems. A conclusion from the study presented is that including drainage routinely in such designs can prolong design life and help adapt to a changing climate.

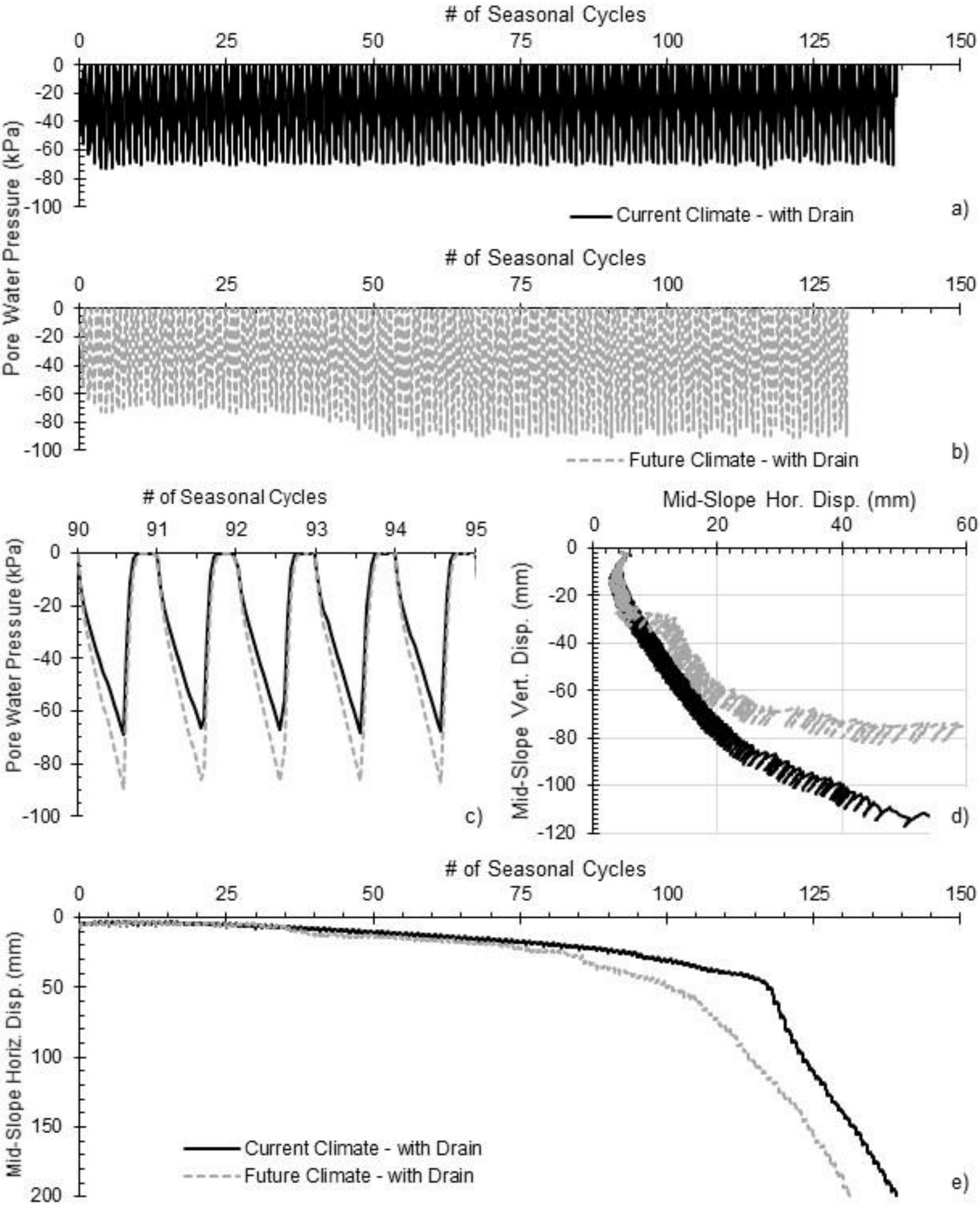


Figure 7. Results of analysis of soil/geomembrane interface with a drain under current and future climates: a), b) and c) are seasonal cycles of pore water pressure on the slope surface at mid-height; d) vertical and horizontal mid-slope displacements; and e) mid-slope horizontal displacements

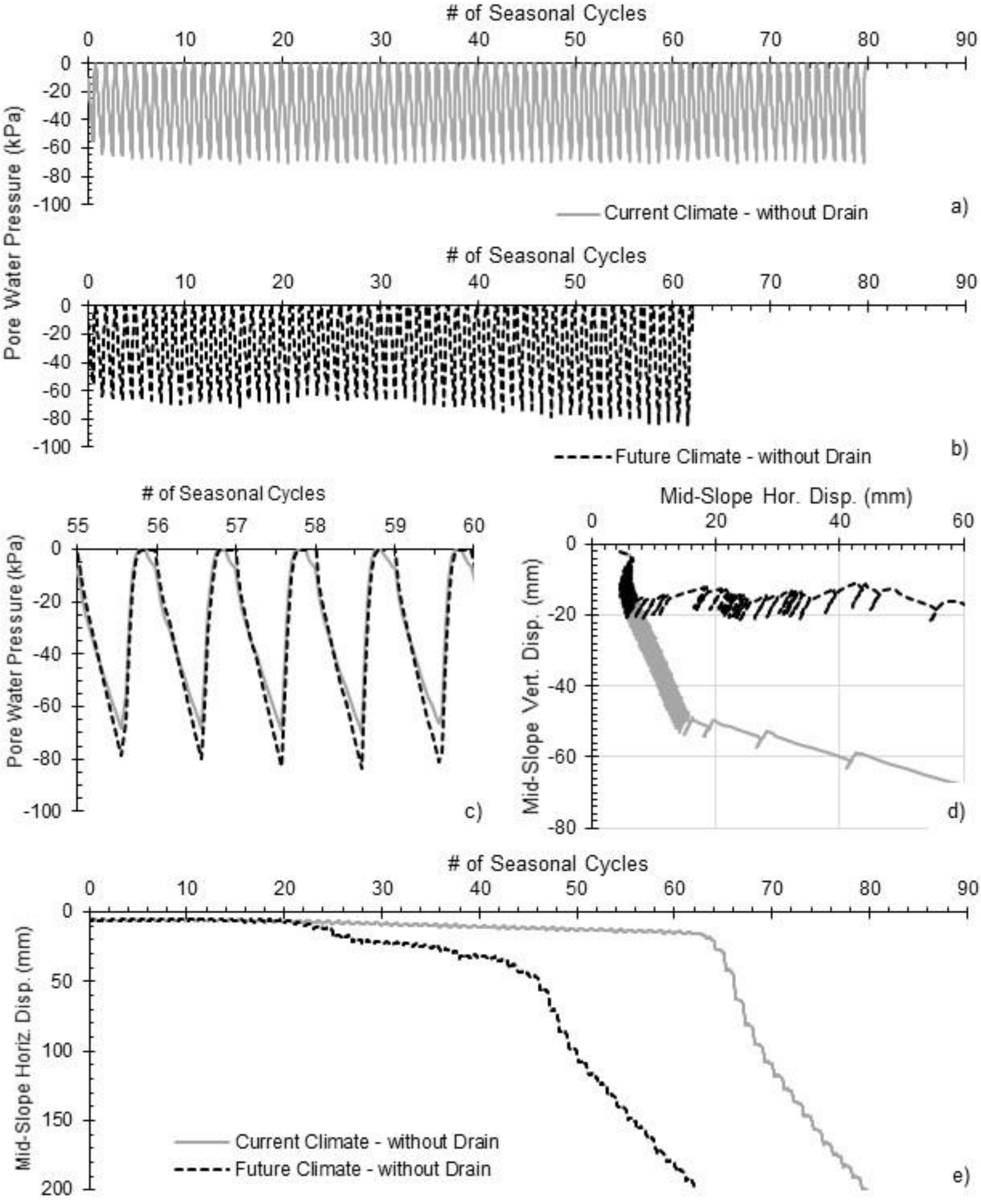


Figure 8. Results of analysis of soil/geomembrane interface without a drain under current and future climates: a), b) and c) are seasonal cycles of pore water pressure on the slope surface at mid-height; d) vertical and horizontal mid-slope displacements; and e) mid-slope horizontal

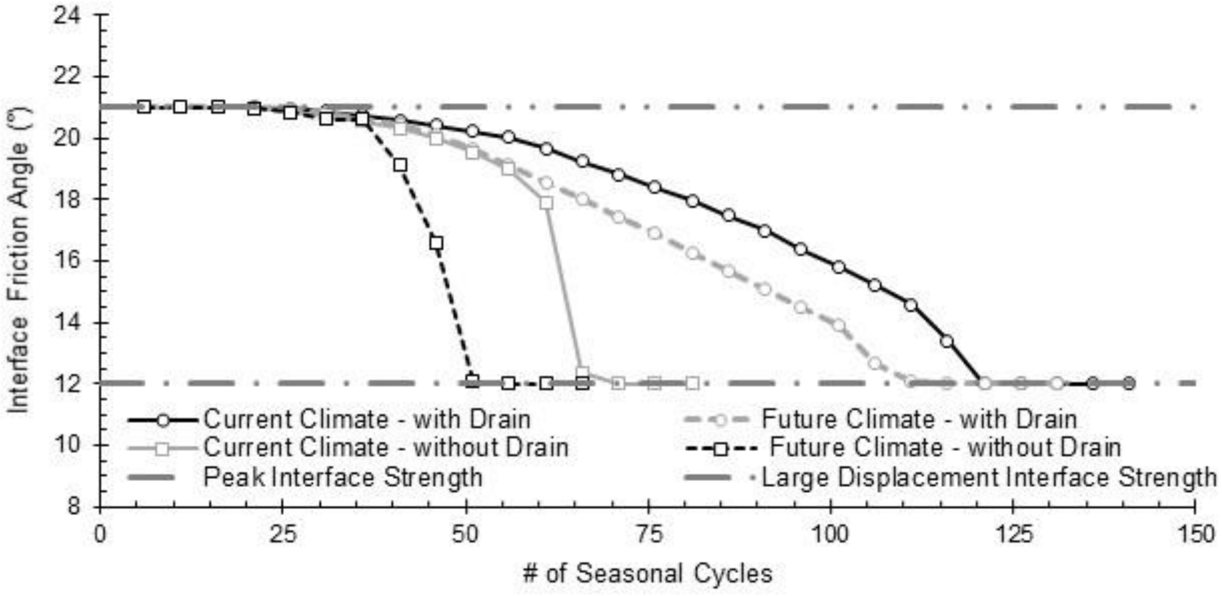


Figure 9. Soil/geosynthetic interface strength deterioration as denoted by mobilized friction angle under current and future climates

8 ACHIEVING SUSTAINABILITY AND RESPONDING TO CLIMATE CHANGE

The breadth and scale of global challenges are so large that it is tempting to conclude that the geosynthetics industry is unlikely to be able to make a difference. However, the doctrine of marginal gains (i.e. making multiple small changes that cumulatively have a large impact) is relevant for the ambition of reducing GHG using geosynthetic solutions. Given the scale of global infrastructure construction planned over the next 20 years, even small reductions on each project will add up to a very significant contribution to meeting national and global targets. This will help slow climate change and contribute to improving the lives of millions of people around the world.

As important, geosynthetic solutions can play a significant role to help people and nations adapt to global change, including delivering improved resilience to extremes of weather. However, as demonstrated in the example for a landfill cap, climate change can have serious detrimental impacts on the long-term performance of soil/geosynthetic systems. Climate change should be considered routinely for geosynthetics designs, although as demonstrated this may not be a simple task for some applications.

United Nations' Sustainable Development Goals challenge nations, organizations and citizens to make a difference to the lives of millions, including: providing access to clean water and sanitation; building and operating resilient infrastructure; and sustainable use of resources. Tackling the impacts of climate change underpins many of the development goals. Equal focus is needed to mitigate future GHG emissions and to develop adaptation solutions to meet impacts of climate change that is already occurring and is locked into the future, irrespective of reductions in GHG that will result from the Paris agreement. The challenge for the geosynthetics community is to be proactive and play a leading role in helping engineers deliver a better future for populations world-wide.

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