TECHNICAL NOTE

Comparative life cycle assessment of geosynthetics versus conventional construction materials

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Photo: www.eagm.eu

Introduction

Geosynthetic materials are used in many different applications in the civil and underground engineering. In most cases, the use of geosynthetic material replaces the use of other materials. The authors quantify the environmental performance of commonly applied construction materials (such as concrete, cement, lime or gravel) versus geosynthetics [1]. To this end a set of comparative life cycle assessment studies have been carried out concentrating on various application cases, namely filtration, foundation stabilised road, landfill construction and slope retention. The complete study is available at www.eagm.eu.

The environmental performance of geosynthetics is compared to the performance of conventional construction materials used for the same application. The specifications of the four construction systems were established by the members of the Association for Geosynthetic Manufacturers (EAGM), which represents the European market for geosynthetic materials, and these specifications represent best current practice.

The study adheres to the ISO 14040 and 14044 standards [2, 3]. A critical review is performed by a panel of three independent experts. The study refers to the year 2009. Foreground data about geosynthetic materials was gathered by questionnaire in 2009 with a few carried out in 2008. Data available about further material inputs and about the use of machinery are somewhat older. All data refers to European conditions.

The alternative construction designs in each case are defined such that they can be considered technically equivalent or at least comparable. The geosynthetics used in the four cases represent a mix of different brands suited for the respective application. The conventional systems represent the most common type of construction.

The environmental performance is assessed by eight impact category indicators. These are cumulative energy demand (CED) [4], climate change (Global Warming Potential, GWP100) [5], photochemical ozone formation [6, 7], particulate formation [8], acidification [6, 7], eutrophication (effects of nitrate and phosphate accumulation on aquatic systems) [6, 7], land competition [6, 7], and water use (indicator developed by the authors).

To evaluate the uncertainty of the data used, Monte Carlo analyses are performed. The results of the Monte Carlo analyses show the effects of the independent uncertainties of the two alternatives compared. The lifetime and the technical specification (layer thicknesses, etcetera) of the different

Table 1: Overview of the objects of investigation

Description	Alternatives	Case
Filter layer	Gravel based filter	1A
	Geosynthetics based filter	1B
Road foundation	Conventional road (no stabilisation needed)	2A
	Geosynthetics based foundation	2B
	Cement/lime based foundation	2C
Landfill construction	Gravel based drainage layer	3A
	Geosynthetics based drainage layer	3B
Slope retention	Reinforced concrete wall	4A
	Geosynthetics reinforced wall	4B

constructions are not included in the uncertainty assessments.

However, uncertainty due to variability in gravel density and in matching the thickness of the layers (95 % interval of +/- 7 %, or about +/- 3.5 cm for a 50 cm gravel layer) or of transport services required (95 % interval of about + 100 %/- 50 %) is taken into account.

Sensitivity analyses are carried out to further explore the reliability of the results. Four alternatives for road foundations are analysed in case 2. This includes 2 alternative road foundations using reinforcement with geosynthetics and two alternatives for the stabilisation of the road using cement or quick lime only.

Object of investigation

The functional units of the four cases are distinctly different, which is why the results of the four cases must not be compared across cases.

Filter layer: The function of the first case is the provision of a filter layer. Geosynthetic materials can serve as separator or filter layer between the well compacted foundation and the subgrade. This is essential to make sure the foundation keeps its bearing capacity. The geosynthetic prevents the foundation aggregates from sinking into the subgrade, while also avoiding the pumping of fines from the subgrade into the foundation.

The functional unit is thus defined as the construction and disposal of a filter with an area of 1m^2, with a hydraulic conductivity (k-value) of 0.1mm/s or more and a life-time of 30 years.

Foundation stabilisation: In the second case, the design concerns the improvement of weak soils. The designs look at three situations – a conventional road, where no stabilisation is needed (case 2A), is compared to a geosynthetic reinforced road (case 2B) and to a cement/quicklime stabilised road (case 2C).

The function of the second case is the provision of a road class III – a route with up to 3M passes per year (equivalent 10t axle). The functional unit is thus defined as the construction, and disposal of a road class III with a length of 1m, a width of 12m and a life-time of 30 years.

Landfill construction: The third case compares the use of a geosynthetic drainage system (case 3B) with a gravel drainage system (case 3A) in a cap of a waste landfill site. A geosynthetic on top of the drainage gravel is often used to prevent movement of fines from the top soil into the drainage, and a second geosynthetic is used below

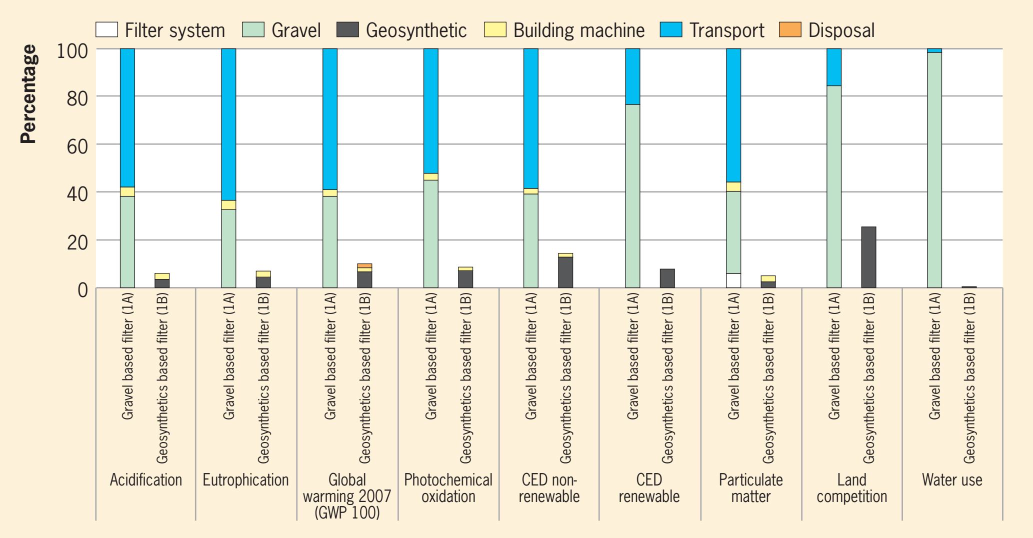

Fig. 1: Environmental impacts of the life cycle of 1m^2 filter for the cases 1A and 1B. For each indicator, the case with higher environmental impacts is scaled to 100%.

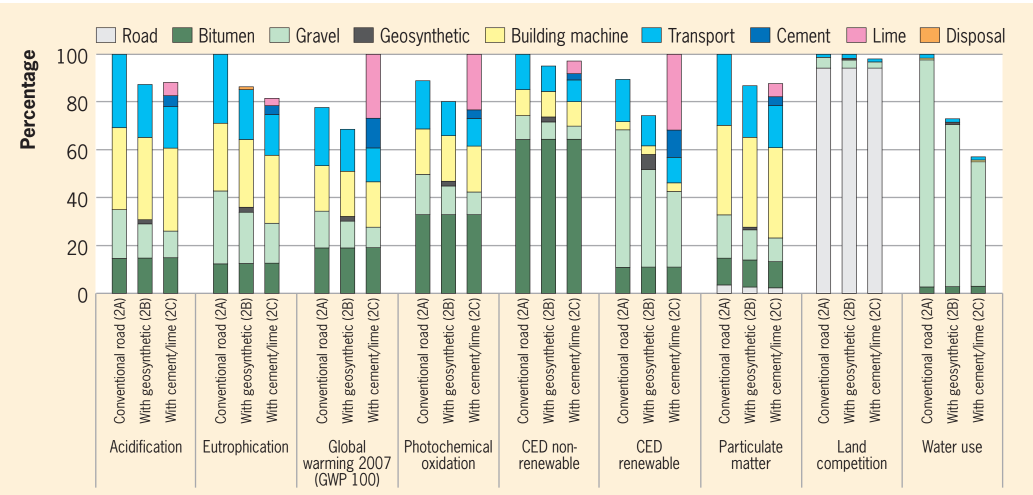

Fig. 2: Environmental impacts of the life cycle of 1m of road with a stabilised foundation, cases 2A, 2B and 2C. For each indicator, the case with higher environmental impacts is scaled to 100%.

the drainage as a protection layer to ensure that the sealing element is not damaged by the drainage. Hence, in practice both solutions use geosynthetics – on top of and below of the drainage layer. All the other layers in a landfill site change neither in thickness nor in material requirements.

The function of third case is to provide a drainage layer in a landfill cap of a hazardous/non-hazardous waste landfill site. The purpose of this drainage layer is to discharge infiltrating rainwater from the surface. The functional unit is defined as the construction and disposal of 1m^2 surface area drainage layer with a hydraulic conductivity (k-value) of 1 mm/s or more and an equal life time of 100 years.

Slope retention: It may be necessary in some cases, especially in the construction of road infrastructure, to build-up very steep slopes for embankments or cuttings. For such slopes, supporting structures are necessary and the retaining walls for these applications need to meet defined tensile and shear strengths. Retaining walls reinforced with concrete (case 4A) are compared to soil slopes reinforced with geosynthetics (case 4B).

The function of the fourth case is to provide a slope retention with a very steep and stable wall. The functional unit is defined as the construction and disposal of 1m slope retention with a 3m high wall, referring to a standard cross-section. Thus, the functional unit is independent of the length of the wall.

For all cases, data about geosynthetic material production has been gathered from numerous European manufacturers. The company specific life-cycle inventories (LCI) have been used to establish average life-cycle of geosynthetic material. Average LCIs have been established for each case on the basis of equally weighted averages of the environmental performance of the products manufactured by the participating member companies.

The technical specifications of the four cases, for example, how much gravel and diesel is required, has been verified with European norms [9-12] and civil engineering experts. The materials and processes needed to erect the constructions are modelled with generic background inventory data. The primary source of background inventory data used in this study is the ecoinvent data v2.2 [13], which contains inventory data of many basic materials and »

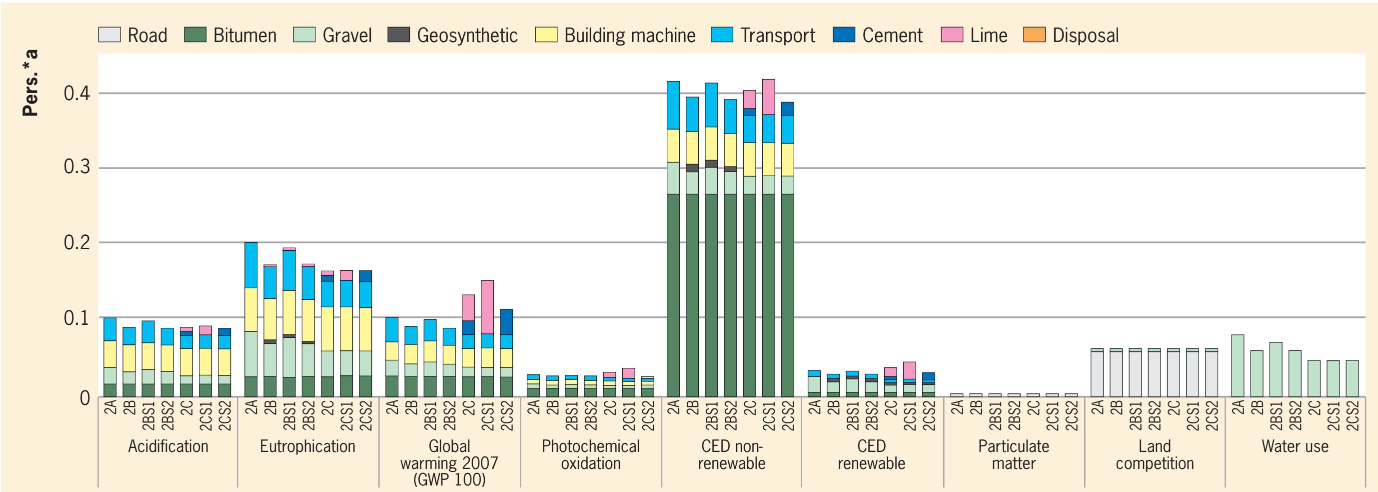

Figure 3: Sensitivity analyses: environmental impacts of the life cycle of 1m road class III, cases 2A, 2B and 2C. Case 2BS1: construction of a class III road reinforced with geosynthetics with soil replacement; case 2BS2: construction of road reinforced with geosynthetics without separation geosynthetic; case 2CS1: construction of road reinforced with quicklime stabiliser; case 2CS2: construction of road reinforced with a cement stabiliser. For each indicator, the results are normalised with the annual world impacts per capita. Eg, dividing the result of 730kgCO_2-eq. (case 2A) with the world average greenhouse gas emissions of 7,100kg CO_2-eq./(Pers. * year) results in a normalised result of 0.1 Pers.*year.

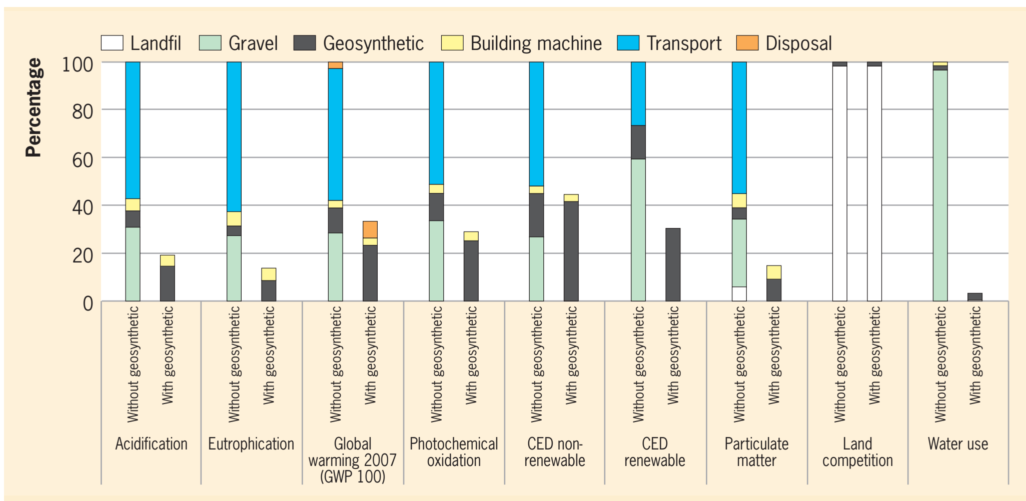

Fig. 4: Environmental impacts of the life cycle of 1m² mineral drainage layer (case 3A) and a geosynthetic drainage layer (case 3B). For each indicator, the case with higher environmental impacts is scaled to 100%.

« services. Others sources include statistical publications [14-16] and published LCA studies [17-24].

Life-cycle impact assessment

In figures 1 to 5, the environmental impacts of the full life cycle of the four cases are shown. For each indicator, the environmental impacts of the alternative with higher environmental impacts are scaled to 100%. The total impacts are divided into the sections infrastructure (road, landfill, slope retention), raw materials (bitumen, gravel, geosynthetic layer, cement, quicklime, concrete, reinforcing steel, wooden board), construction equipment (construction requirements), transport (of raw materials to the construction site) and disposal (includes transports from the construction site to the disposal site and impacts of the disposal of the different materials).

A filter using a geosynthetic layer (case 1B) causes lower impact compared to a conventional gravel based filter layer (case 1A) with regard to all impact category indicators investigated. For all indicators the filter with geosynthetics causes less than 25% of the impact of a conventional gravel based filter. The non-renewable cumulative energy demand of the construction of 1 square meter filter with a life time of 30 years is 131MJ-eq in case 1A and 19 MJ-eq in case 1B. The cumulative greenhouse gas emissions amount to 7.8kgCO_2-eq/m² in case 1A and 0.81kgCO_2-eq/m² in case 1B.

A conventional road (case 2A) causes higher impact compared to a road reinforced with geosynthetics (case 2B) with regard to all impact category indicators (see Figure 2). The higher impact of case 2A is caused by the emissions and the resource consumption related to the production and transportation of the additional amount of gravel required. With regard to global warming, the road construction with a cement/lime stabilised foundation (case 2C) causes higher impact compared to cases 2A and 2B mainly because of the geogenic CO_2 emissions from the calcination process in the clinker and quick lime production. With regard to land use, the impacts of all three alternatives are more or less equal, with a maximal deviation in case 2C, using only 2.2% less land than case 2A. Case 2C causes lower eutrophying and particulate matter emissions and requires less water compared to cases 2A and 2B,

The non-renewable cumulative energy demand of the construction and disposal of 1m stabilised road with a width of 12m and a life-time of 30 years is 25,200MJ-eq in case 2A, 23,900MJ-eq in case 2B and 24,400MJ-eq in case 2C. The cumulative greenhouse gas emissions amount to 0.73tCO_2-eq/m² in case 2A, to 0.6tCO_2-eq/m² in case 2B and to 0.95tCO_2-eq/m² in case 2C. Correspondingly, the cumulative greenhouse gas emissions of 1km stabilised road are 730tCO_2-eq in case 2A, 650tCO_2-eq in case 2B and 950tCO2-eq in case 2C.

The uncertainty assessment confirms that case 2B causes lower environmental impact than case 2A with regard to all indicators. For the comparison of case 2B and case 2C, the uncertainty analysis shows lower impact for the categories CED renewable, photochemical oxidation and global warming potential for case 2B. Regarding the indicator land competition the case 2B causes higher environmental impacts than case 2C. With regard to all other indicators, the uncertainty analysis reveals no clear ranking between cases 2B and 2C.

Figure 3 shows the sensitivity analyses for a road reinforced with geosynthetics and soil replacement (case 2BS1) and without separation

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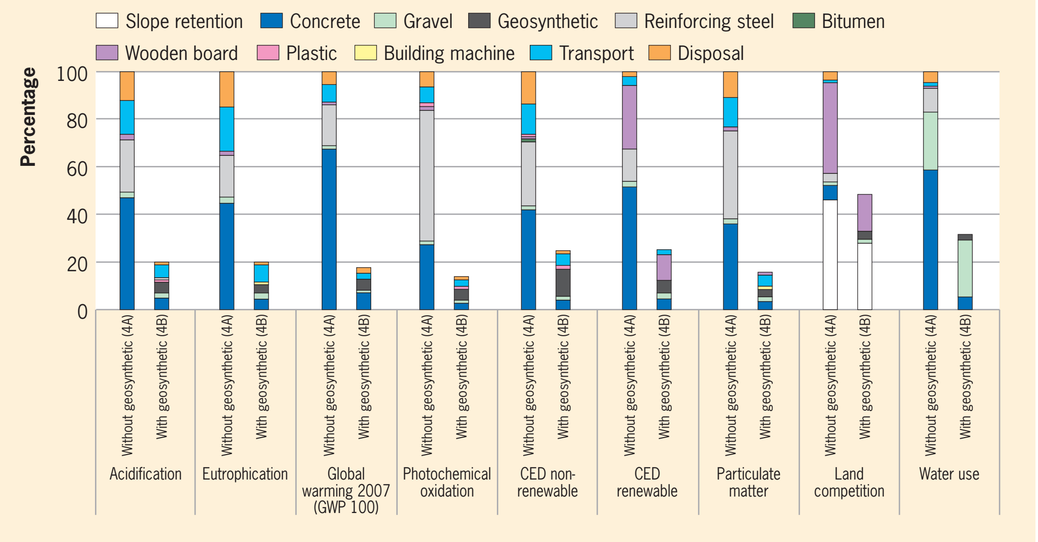
Fig. 5: Environmental impacts of the life cycle of 1m slope retention, cases 4A and 4B. For each indicator, the case with higher environmental impacts is scaled to 100%.



geosynthetic (case 2BS2), and for road construction with stabilised foundation using quicklime only (case 2CS1) and using cement only (case 2CS2). Using quicklime as stabiliser causes the highest environmental impact with regard to global warming, photochemical oxidation, CED non-renewable, and CED renewable. Choosing a cement stabiliser leads to higher environmental impact for global warming, CED renewable and water use compared to case 2B.

A geosynthetic drainage layer (case 3B) causes lower environmental impact compared to a gravel based drainage layer (case 3A) in all impact categories considered, except land competition which is about the same in both cases (see Figure 4). The non-renewable cumulative energy demand of the construction and disposal of $1m^2$ drainage layer is 194MJ-eq in case 3A and 86MJ-eq in case 3B. The cumulative greenhouse gas emissions amount to $10.9kgCO_2$-eq/m^2 in case 3A and $3.6kgCO_2$-eq/m^2 in case 3B. Correspondingly, the cumulative greenhouse gas emissions of the drainage layer of a landfill with an area of $30{,}000m^2$ are $330tCO_2$-eq in case 3A and $110tCO_2$-eq in case 3B respectively.

The Monte Carlo Simulation reveals a probability of more than 99% that the geosynthetic drainage layer has lower environmental impact than the mineral drainage layer for all indicators investigated except land competition. Regarding land competition, the probability that geosynthetic drainage layer has lower environmental impact than the mineral drainage layer is 62%.

A geosynthetic reinforced wall (case 4B) causes lower environmental impact compared to a reinforced concrete wall (case 4A) in all impact categories considered (see Figure 5). The non-renewable cumulative energy demand of the construction and disposal of 1m slope retention with a height of 3m is 12,700MJ-eq in case »

4A and 3,100MJ-eq in case 4B. The cumulative greenhouse gas emissions amount to 1.3tCO_2-eq/m in case 4A and 0.2tCO_2-eq/m in case 4B. Correspondingly, the cumulative greenhouse gas emissions of 300m slope retention are 400tCO_2-eq in case 4A and 70tCO_2-eq in case 4B respectively. The Monte Carlo simulation shows a probability of 100% that the environmental impact of the conventional slope retention is higher compared to the environmental impact of the geosynthetic slope retention with regard to all indicators.

A sensitivity analysis regarding transportation of the materials with a Euro5 lorry instead of an average fleet lorry shows lower environmental impacts regarding those indicators and cases where the transportation of the materials has an important share in the result. This applies for the conventional separator layer in case 1, the geosynthetic stabilised layer in case 2B (see Figure 3), the conventional drainage layer in case 3A and in both types of slope retention. The sequence of the environmental impacts that were compared in this situation did not change in any of the four cases.

Conclusions

A filter layer with geosynthetics causes lower environmental impact compared to a conventional alternative (gravel). The difference is considerable for all indicators (more than 85%) and reliable. The difference in the environmental impact arises mainly because the applied geosynthetic substitutes gravel, which causes considerably higher impact when extracted and transported to the place of use.

At least a layer of 80mm of gravel must be replaced by geosynthetics used as a filter in order to cause the same or lower environmental impacts regarding all indicators.

The use of geosynthetics in road construction in order to reinforce the road foundation (case 2B) causes lower environmental impact than a conventional road construction (case 2A). Comparing road construction using geosynthetics (case 2B) and the road construction with cement/lime stabilised foundation (case 2C), a trade-off between the cases 2B and 2C can be observed. On the one hand, the use of a cement/lime stabiliser causes higher climate change impact mainly because of the geogenic carbon dioxide emissions from the production process of cement and quicklime.

On the other hand, the use of a geosynthetic stabiliser shows higher results for the environmental indicators eutrophication, water use and particulate matter because of the emissions and the resource consumption related to the production and transportation of the additional amount of gravel required. The use of quick lime only (case 2CS1) causes higher environmental impacts than the use of cement (case 2CS2) for the stabilisation of the road foundation.

At least a layer of 250mm of gravel in a conventional road must be replaced by geosynthetics in a road foundation in order to cause the same or lower environmental impact regarding all indicators.

The uncertainty analysis shows that results are reliable for all indicators when comparing case 2A and 2B and that the results are stable for the indicators photochemical oxidation, global warming, land competition and CED renewable when comparing the case 2B and 2C. Regarding the other indicators the difference between the cases 2B and 2C is considerably less reliable.

The main driving forces for the difference between the geosynthetic drainage layer in a landfill site and the conventional gravel drainage layer is the extraction and transportation of gravel used in the conventional case. For all indicators except land competition, the impacts of the conventional drainage layer are more than twice as high as compared to the impact from the geosynthetic drainage layer. The Monte Carlo simulations show that differences can be considered reliable and significant with regard to all indicators except land competition. Regarding the latter, the two alternatives can be considered as equivalent.

Compared to the conventional slope retention, the geosynthetic reinforced wall substitutes the use of concrete and reinforcing steel, which results in a lower environmental impact of between 52% and 87%. The uncertainty analysis shows that it is reliable that the use of geosynthetics causes lower environmental impact compared to a conventional slope retention.

The main part of the environmental impact from the manufacture and disposal of geosynthetic layers are caused by the raw materials (plastic feedstock) and electricity consumption. However, the proportion of the total environmental impact in each of the four cases is small, except in case 4 where geosynthetics can have an important contribution to some indicators. The variation in environmental impact of geosynthetics manufacture does not affect the overall results as shown with the Monte Carlo simulations. Hence the results are valid for the products of any particular manufacturer.

Geosynthetic layers and geogrids can contribute to civil engineering constructions with significantly lower climate change impacts in all cases considered. The use of geosynthetic layers may also lead to lower environmental impacts such as acidification, eutrophication, and to lower cumulative energy demands, except for the case of foundation stabilisation (case 2), where these environmental impacts are higher compared to conventional solutions.

It is recommended to establish key parameter models for each of the four cases, which allow for an individual assessment of any alternatives construction design. This is particularly true for case 4, where actual situations may ask for highly specific technical solutions. In such key parameter models, the main determining factors such as amount of gravel, cement, concrete or geosynthetics required by the design, can be entered to calculate the environmental impacts of the construction alternatives at issue.

DIARY

Forthcoming geotechnical events and noticeboard.
Send new entries to GE, email: claire.symes@emap.com

CETA Technology Showcase
2-4 October. Newbury Race Course
Construction Equipment Technology Alliance members will be showcasing the latest equipment including ground stabilising and piling plant and systems including materials to tackle subsidence and low ground bearing pressure.
Contact: www.cetauk.org

Hot Deserts
4 October, 10.30am. The Geological Society, Burlington House, London
During the last half century, much of the world's most intense development and civil engineering construction has taken place in the geologically hostile conditions found in the hot desert regions. At this conference the working party which prepared the recently published *Hot Deserts: Engineering, Geology and Geomorphology* will present selected sections stressing the latest knowledge, concepts and techniques that are key to successful engineering in hot desert regions.

The programme is structured around the three themes of the book: a specialist review of the geological and geomorphological background; an expert update on the modern techniques for terrain and ground investigation; and a

Hot topic: Hot Deserts takes place on 4 October

DIARY

The Glossop Lecture takes place on 21 November at the Royal Geographic Society

practical consideration of the many challenges to soils, materials and civil engineering in hot desert conditions.
Contact: Steve Whalley, event co-ordinator, tel: 020 7432 0980 or email: steve.whalley@geolsoc.org.uk

BTS Young Members: Numerical modelling
4 October, 6.30pm. ICE, London
This meeting of the British Tunnelling Society Young Members' group will look at the growing use of numerical modelling.
Contact: BTS Secretary, tel: 020 7665 2229 or email: bts@ice.org.uk

The Design and Performance of OHL Transmission Tower Foundations
9 October, 6.45pm. Teacher Building, St Enoch Square, Glasgow
Dave Richards from Southampton University and Michael Purkis of Donaldson Associates will discuss issues related to foundation design for OHL transmission towers.
Contact: Ross Turnbull, tel: 0141 354 5625 or email: ross.turnbull@urs.com

Cone Penetration Testing
19 October, all day. Nottingham
This free course is an update on Cone Penetration Testing theory and application including its advantages and limitations. The course includes information about how and when to make use of the wider range of other geotechnical and geo-environmental cones, vehicle types and a demonstration of a test on a truck.

The event will also run on 23 November in Exeter and on 14 December at Wallingford.
Contact: Steve Poulter email: s.poulter@fes.co.uk

Managing Geotechnical Risk
26 October, 1pm. Main Building, Cardiff University
This free seminar is an opportunity to listen to experts from the built environment on their views of risk. This has been stimulated by the emerging issues of the low-carbon economy, investment in infrastructure, building information modelling, reduction in construction costs, energy investment and whole-life value.

Construction has been identified as a key driver for economic growth. However, this can only be achieved if everyone engaged in the process understands the issues that their fellow professionals recognise and the importance those issues have in decision making.

The aim of this meeting, therefore, is to start a process of developing a broader view of construction risk through an inclusive engagement of built environment professionals so that risks can be placed in context and effectively mitigated to reduce the overall economic, environmental and social cost of construction.
Contact: cewalesevents@cewales.org.uk

2012 Touring Lecture: Energy Geotechnology
5 November, 5.30pm. University of Birmingham
6 November, 6pm. University of Cardiff
7 November, 6pm. Imperial College, London
The role of geotechnical engineers in the energy challenge will be discussed by J Carlos Santamarina. According to Santamarina, there will be a pronounced increase in energy demand in the next decades associated to economical development and population growth worldwide. Geotechnology is at the centre of the energy challenge, from production, transportation, consumption and conservation, to waste management and carbon sequestration.

Geotechnology's central role extends to all energy resources, including fossil fuels, nuclear energy and renewable sources. Classical geotechnical concepts gain critical relevance and are revisited in the context of energy geo-engineering, including: filters (fines migration and clogging); heterogeneity (spatial variability); diagenesis and ko (reactive fluid transport and state of stress); unsaturated soils (mixed fluid conditions); hydraulic fracture (fluid-driven discontinuities); frozen ground (phase transformation); and repetitive loading (ratcheting and terminal density).
Contact: BGA coordinator, tel: 020 7665 2229 or email: bga@britishgeotech.org.uk

Christchurch Earthquake Recovery
8 November, 5.30pm. Cardiff School of Engineering, Cardiff
Paul Eastwood of Opus International will talk about his experience as a civil engineer in Christchuch, New Zealand, following the 2011 earthquake.
Contact: Book online at www.ice.org.uk

Wind on the Bog – Design and Experience of Floating Wind Farm Roads on Soft Ground
14 November, 5.45pm. University of Bath
Thousands of kilometres of "floating" road are constructed across the world each year as a method of facilitating vehicle access over boggy ground. In the UK it has developed as the preferred method for providing durable access for windfarms, oil and gas pipelines and other civil engineering applications. This talk will discuss a commercial approach to "floating" wind farm access road design and construction. Best practice specification requirements will be outlined as well as how design requirements should be interpreted.
Contact: Joanne Mallard, tel: 01752 766230 or email: joanne.mallard@ice.org.uk

EPBM and Slurry Tunnelling Principles – Safe operational protocols for full-face TBMs
15 November, 6pm. ICE, London
The British Tunnelling Society presents a meeting to discuss operational protocols for earth pressure balance and slurry tunnel boring machines.
Contact: BTS Secretary, tel: 020 7665 2229 or email: bts@ice.org.uk

Glossop Lecture
21 November. The Royal Geographic Society, London
GWP Partners chief engineering geologist Ruth Allington will deliver the 2012 Glossop Lecture.
Contact: www.geolsoc.org.uk

Fleming Award
5 December, 6pm. ICE, London
Finalists in this year's Fleming Awards, organised by Cementation Skanska, will present their projects to the judging panel and the winners will be announced at the end of the evening.
Contact: Cementation Skanska, tel: 01923 423522 or email: cementation.marketing@skanska.co.uk

Geotechnical Instrumentation for Field Measurements
7-9 April 2013. Cocoa Beach, Florida, US
This CPD course will offer practical presentations by engineers, with lectures and displays of instruments by manufacturers.
Contact: John Dunnicliff, tel: 01626 832919, email john@dunnicliff.eclipse.co.uk

Upcoming Ground Engineering conferences

Basements
3 October. London
www.gebasements.co.uk

Tunnelling
20 November. London
www.ncetunnelling.co.uk

Slopes
28 November. London
www.slopeengineering.co.uk