# General Report of TC 307
# Sustainability in Geotechnical Engineering

## Rapport général du TC 307
## Durabilité en géotechnique

Basu D.
*University of Waterloo, Canada*

Puppala A.J., Chittoori B.
*University of Texas at Arlington, U.S.A.*

ABSTRACT: Sustainable geotechnics is an emerging sub-discipline within geotechnical engineering that covers a wide range of topics related to the sustainable development of civil infrastructure and society. In this general report, a brief overview of this new sub-discipline is provided with an aim to connect the broader scope of sustainability to geotechnical engineering research and practice. In addition, the papers allocated to the sustainability session (TC 307) of 18th ICSMGE are reviewed in the context of the big picture. Most of the papers deal with material recycling, reuse, and use of alternate materials in geotechnical engineering constructions. These apart, the topics covered in the allocated papers include use of geosynthetics, sustainable foundation engineering, subsurface remediation and site redevelopment, and sustainability assessment. Some of the important topics related to sustainable geotechnics not covered by the allocated papers are also mentioned.

RÉSUMÉ: La géotechnique soutenable est une nouvelle sous-discipline de la géotechnique qui couvre un large éventail de sujets liés au développement durable des infrastructures et de la société. On présente dans ce rapport général un bref aperçu de cette nouvelle sous-discipline avec l'objectif de relier le champ plus large du développement durable avec la recherche et la pratique en géotechnique. En outre, les articles de la session dédiée à la géotechnique soutenable (TC 307) de la 18e ICSMGE sont examinés dans un contexte plus large. La plupart des articles traitent de recyclage de matériaux, de réutilisation, et de l'utilisation de matériaux alternatifs dans les constructions géotechniques. En plus de cela, les sujets abordés dans les articles incluent l'utilisation des géosynthétiques, les travaux de fondation durable, la décontamination et le réaménagement de sites et l'évaluation de la durabilité. Certains sujets importants liés à la géotechnique soutenable non couverts par les articles considérés sont également mentionnés.

KEYWORDS: sustainable geotechnics, geosustainability, geohazard, resilience, life cycle assessment, recycling, reuse, remediation.

## 1 INTRODUCTION

Sustainability is a multi-scale, multi-disciplinary and multi-dimensional paradigm that aims at ensuring the well being of the world for the current and future generations. With its origin in the environmentalism of the nineteenth and early twentieth century, sustainability has come a long way since its inception in the later half of the twentieth century and is now widely recognized as a principle that advocates a balanced development maintaining harmony between the three Es — environment, economy and equity (Edwards 2005). The environmental aspect has mostly been the driver of sustainability movement because of global concerns regarding the rise in atmospheric carbon dioxide and temperature, rapid depletion of natural resources, and other similar environmental and ecological hazards. The construction industry accounts for about 40% of the global energy consumption, depletes large amounts of sand, gravel and stone reserves every year, contributes to desertification, deforestation and soil erosion, and causes land, water and air pollution (Dixit et al. 2010, Kibert 2008, Puppala et al. 2012, Saride et al. 2010). Therefore, green practices within the civil engineering industry can reduce the impact of construction on the environment. Geotechnical design and construction, being placed early in a typical civil engineering project, can significantly contribute to sustainable development by adopting environment-friendly, cost-effective and socially-acceptable choices and setting a precedent for the remainder of the project. The role of geotechnical engineering in sustainable development is being increasingly recognized, as evidenced by the formation of the ISSMGE technical committee "Sustainability in Geotechnical Engineering" (TC307) in 2012. In fact, the 18$^{th}$ ICSMGE has set a precedent by devoting a technical paper discussion session to the sustainability theme.

The purpose of this general report is (i) to provide a perspective on the new area of sustainable geotechnics, and (ii) to review the papers allocated to the sustainability session of the 18$^{th}$ ICSMGE in the context of the big picture.

## 2 SUSTAINABILITY AND GEOTECHNOLOGY

Engineered systems serve human societies by developing cost-effective products and, in the process, draw resources from natural systems and generate emissions and wastes that nature has to absorb. Thus, engineered systems are inextricably connected to the social, environmental, and economic systems. Because humankind is heavily dependent on engineered systems, sustainability of the physical world cannot be achieved without contributions from the engineered systems. This has been summed up by Basu et al. as the four Es of sustainability — engineering design, economy, environment and equity, as described in Figure 1.

Geo-structures and geo-operations often form important interfaces between the built and natural environments, and interact with and affect a wide variety of externalities. For example, dams and levees buffer the fluctuations in hydrologic cycles and affect water movement across regional and political boundaries; extraction of petroleum resources from the subsurface affects the natural environment and global economy; and landfill systems prevent contaminants from reaching groundwater across regional scales. Further, geotechnical engineering has a very important role in mitigating and containing disasters, and failure to do so is often catastrophic to the society. Breach of a levee system during a hurricane or tsunami, breakdown of underground water pipeline network during an earthquake, landslides triggered by rainfall or earthquake, disruptions and distress in an underground transit system due to terror attack are examples of disasters related to geotechnical systems. Thus, geotechnical engineering has a wide gamut and a global reach, and can influence the sustainable development of infrastructure and civil societies in a significant way. According to Long et al. (2009), there are seven categories where geotechnical engineering can contribute to improve the sustainability of the societal system. These include (i) waste management, (ii) infrastructure development and rehabilitation, (iii) construction efficiency and innovation, (iv) national security, (v) resource discovery and recovery, (vi) mitigation of natural hazards, and (vii) frontier exploration and development. A similar set of sustainability objectives for geotechnical engineering was also identified by Pantelidou et al. (2012): (i) energy efficiency and carbon reduction, (ii) materials and waste reduction, (iii) maintaining natural water cycle and enhancing natural watershed, (iv) climate change adaptation and resilience, (v) effective land use and management, (vi) economic viability and whole life cost, and (vii) positive contribution to society.

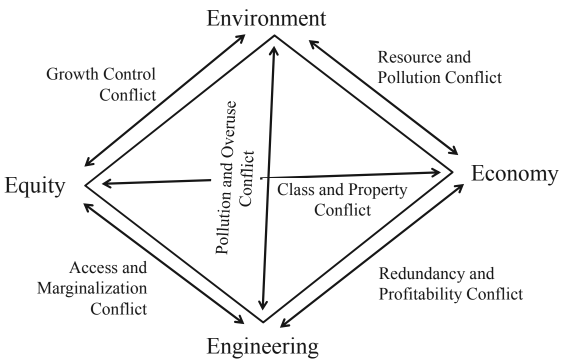


Figure 1. The four Es of sustainability in engineering projects (Figure 1 of Basu et al.).

On a project level, Basu et al. outlined the necessary steps to achieve sustainability objectives as (i) involving all the stakeholders at the planning stage of the project so that a consensus is reached on the sustainability goals of the project (such as reduction in pollution, use of environment friendly alternative materials, etc.), (ii) reliable and resilient design and construction that involves minimal financial burden and inconvenience to all the stakeholders, (iii) minimal use of resources and energy in planning, design, construction and maintenance of geotechnical facilities, (iv) use of materials and methods that cause minimal negative impact on the ecology and environment, and (v) as much reuse of existing geotechnical facilities as possible to minimize waste. In addition, emphasis should be put on proper site characterization so that geologic uncertainties can be minimized, on instrumentation so that proper functioning of a geotechnical facility can be ensured and required retrofitting can be performed, and on adaptive management strategies so that the resilience of the geotechnical facility can be enhanced and the vulnerability of the community linked with the facility can be reduced.

According to Basu et al. and Vaníček et al., sustainability related studies can be grouped into the following areas: (1) the use of alternate, environment friendly materials in geotechnical constructions, and reuse of waste materials, (2) innovative and energy efficient ground improvement techniques, (3) bio-slope engineering, (4) efficient use of geosynthetics, (5) sustainable foundation engineering that includes retrofitting and reuse of foundations, and foundations for energy extraction, (6) use of underground space for beneficial purposes including storage of energy, (7) mining of shallow and deep geothermal energy, (8) preservation of geodiversity, (9) environmental protection including protection of greenfields, (10) geohazard mitigation including mitigation of the effects of global climate change and multi-hazards, and (11) incorporation of geoethics in practice. Basu et al. emphasized the need for reliability- and resilience-based design as a part of sustainable geotechnical engineering. Additionally, Basu et al. summarized the different sustainability assessment tools available in geotechnical engineering and categorized them into (1) single criterion based metrics (e.g., carbon footprint), (2) multiple criteria-based tools (e.g., GeoSPEAR and life cycle assessment), and (3) point-based rating systems (e.g., I-LAST and GreenLites).

Based on the above discussion, it is evident that sustainable geotechnics is an emerging sub-discipline of geotechnical engineering that covers a wide area ranging from reliability- and resilience-based design and environment-friendly construction practices to energy geotechnics and geohazard mitigation. It also includes the development of sustainability assessment tools applicable to geotechnical engineering practice.

## 3 THEMES COVERED IN SUSTAINABILITY SESSION

There are 28 papers allocated to the sustainability session with authors from 20 countries representing all the ISSMGE regions. These papers cover a wide range of topics that can be broadly grouped into five areas.

### *3.1 Use of recycled and alternate materials*

According to Vaníček et al., a variety of waste products are generated in the society that can be utilized in geotechnical constructions. These waste products can be categorized into industrial wastes (e.g., ash and slag), construction and demolition wastes (e.g., used bricks, concrete, and asphalt), mining wastes (mine tailings), and other wastes (e.g., tires, plastics, glass, and dredged material). Basu et al. provided an overview of the different waste utilization methods in geotechnical constructions and discussed about chemical soil treatment. Waste utilization and use of alternative material is one of the most widely researched areas in geotechnical engineering and it is not surprising that, out of the 28 papers allocated to this session, 20 papers contribute to this topic.

The papers on industrial waste recycling deal with a variety of geotechnical applications. Baykal investigated the use of silt-sized fly ash in manufacturing artificial, sand-sized pellets for use in construction projects (Figure 2). He reviewed the cold bonding pelletization technique, and studied the index and mechanical properties of the fly-ash pellets. The manufactured pellets behave like calcareous sands found in the nature.

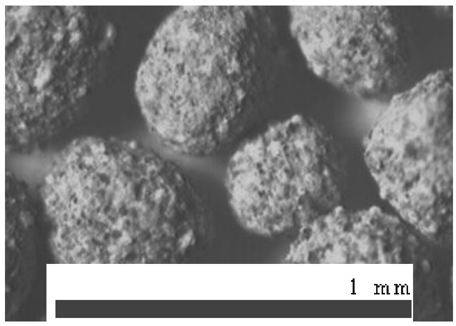


Figure 2. Manufactured fly ash pellets (Figure 7 of Baykal).

In another example of recycling of fly ash, Vukićević et al. investigated the reusability of a class-F fly ash (KFA) from a Serbian thermal power plant as a stabilizer in low plasticity silt and in high plasticity expansive clay. Several geotechnical engineering properties including grain size distribution, Atterberg limits, unconfined compression strength, moisture-density relationship, swell potential, and California bearing ratio (CBR) were determined for the control and treated soils. Based on the study, the authors concluded that the particular fly ash in question can be used as a stabilizer, and advocated a case-by-case approach with proper investigations for making decisions regarding the suitability of fly ash as a construction material.

Kikuchi and Mizutani proposed the use of granulated blast furnace slag (GBFS) as an alternative construction material for port structures because GBFS can reduce liquefaction potential and earth pressure when used as a backfill material for quay walls. The inherent ability of GBFS to solidify upon contact with seawater was explored and methods were proposed for its standardized application in the field. As GBFS solidification is a lengthy process and often the solidification is not uniform, Kikuchi and Mizutani proposed the use of powdered blast furnace slag (PBFS) in conjunction with prior homogeneous mixing treatment (PHMT) to accelerate the GBFS solidification process. In their experimental investigation, Kikuchi and Mizutani considered several issues, e.g., material separation after construction due to water flow, solidification of GBFS underground with flowing water, and the effect of the change in pore fluid chemistry due to a change from sea to fresh water on GBFS solidification, in determining the most appropriate mixture of GBFS and PBFS for accelerating the GBFS solidification. The authors found that PHMT treated GBFS-PBFS mixture is effective in reducing the amount of material separation in the GBFS-PBFS mixture and produced sufficient unconfined compression strength after about 2 months of curing in the seawater because of which it can be used to prevent liquefaction.

Nawagamuwa et al. investigated the properties of waste copper slag for use in vertical sand drains and sand piles as a substitute for sand. Geotechnical properties such as particle size distribution, hydraulic conductivity, shear strength, and stiffness were studied for the sand-sized waste copper slag particles mixed with poorly graded sand. It was observed that the particle size distribution, shear strength and hydraulic conductivity were not significantly affected due to the addition of the slag. However, the stiffness of the slag-sand mixture increased significantly. Based on the study, Nawagamuwa et al. concluded that waste copper slag can be safely and effectively used as a replacement for sand in vertical drains.

Vizcarra et al. (2013) investigated the applicability of municipal solid waste (MSW) incineration ash mixed with non-lateritic clay in pavement base layers. Chemical, physical, index, and mechanical tests were performed on the ash-soil mixture with 20% and 40% ash content, and the mechanistic-empirical design (Figure 3) for a typical pavement structure were carried out. The mechanical tests included modified Proctor test, resilient modulus test, and permanent deformation test. The addition of 20% fly ash to the non-lateritic clay soil improved the mechanical behavior and reduced the expansion of the clay. The fly ash mixed soil had a mechanical behavior compatible with the requirements for a low traffic volume.

Edil also focused on pavement geotechnics and provided an overview of different recycled waste products used in pavement construction. He discussed about the rapid characterization of industrial wastes like fly ash and bottom ash, and construction and demolition wastes (CDW) like recycled asphalt pavement and concrete aggregates with respect to their physical characteristics, geomechanical behavior, durability, material control, and environmental impact.

In another study related to pavements, Cameron et al. proposed the use of recycled concrete aggregates (RCA) blended with recycled clay masonry (RCM), obtained after demolition, in unbound granular pavements. The CDW were obtained from two local producers in South Australia, and conventional classification tests for soils and aggregates, Los Angeles abrasion test, Micro-Deval test, falling head permeability test, drying shrinkage test, undrained triaxial and repeated loading triaxial tests, and permanent strain rate modeling were performed. The test results were compared with the specifications from road authorities both within and outside Australia, and the RCA products were classified as Class 1 or base and the blended products as Class 2 or subbase materials.

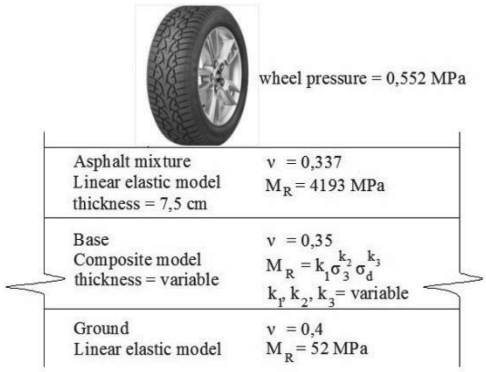


Figure 3. Pavement structure adopted in mechanistic-empirical analysis (Figure 1 of Vizcarra et al.).

Farias et al. also studied the feasibility of using CDW in paving of a shopping-center site in Recife, Pernambuco, Brazil. They performed a series of physical, chemical and mechanical tests with mixtures of different proportions of CDW obtained from the site and in situ excavated soil, and concluded that the recycled residues of civil construction (RRCC) alone and RRCC mixed with soil meet all the criteria of the local standard NBR 15.116:2004. Farias et al. (2013) also performed an economic analysis of different construction alternatives with the RRCC, which is described in section 3.5.

The study by Santos et al. also involves CDW. They presented a laboratory-scale experimental investigation on the performance of instrumented wrapped-faced retaining walls constructed using recycled construction and demolition wastes (RCDW) consisting of soil, bricks, and small particles of concrete. CDW is abundantly available in Brazil and approximately 70% by mass of municipal solid waste consist of CDW. CDW was found to have excellent mechanical and chemical properties for use as a back-fill material in geosynthetics reinforced walls. Consequently, two 3.6-m high, wrapped-faced retaining walls with facing batter angle of 13° were constructed at the University of Brasilia (UnB) Retaining Walls Test Facility. One retaining wall was constructed with geogrid and the other with geotextile with identical reinforcement lengths and spacings of 2.52 m and 0.6 m, respectively, using RCDW as the compacted backfill (Figure 4). The walls were instrumented along their central sections to measure strains, displacements, and earth pressures. The walls performed well during and after construction with the maximum horizontal displacement at the wall face being 150 mm. The only downside was the creation of uneven surfaces near the face due the presence of coarse particles. The use of a selected RCDW near the face for better aesthetic appeal was recommended.

Vaníček et al. presented an example of waste recycling in which a new construction material consisting of brick, fiber and concrete was used to reinforce dykes for flood protection and erosion control.

Winter discussed the use of lightweight tire bails (Figure 5) as a potential alternative for pavement foundation on soft soils. Tire bales comprise of 100 to 115 tires of light-goods vehicles and cars compressed into a lightweight block with a mass of about 800 kg and density of approximately 0.5 $Mg/m^3$. The bales measure approximately 1.3 m × 1.55 m × 0.8 m and are secured by five galvanized steel tie-wires running around the length and depth of the bale. The key advantage of tire bales is their modular nature which leads to potential savings in plant, labor, and time. These bales have been used in pavement constructions, slope protection, river bank erosion control, and lightweight embankment constructions. Winter described the different construction techniques and provided information regarding the measurement of properties, engineering properties and behavior associated with tire-bale use in construction, example applications, and end-of-service-life options.

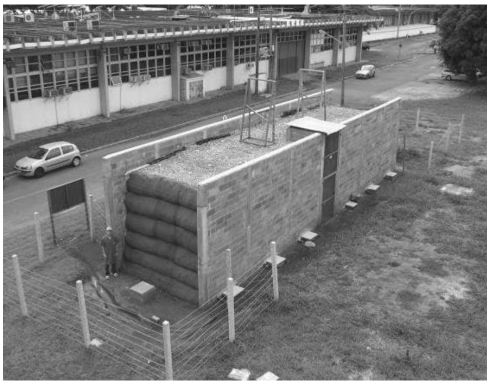

Figure 4. UnB retaining wall test facility (Figure 3 of Santos et al.).

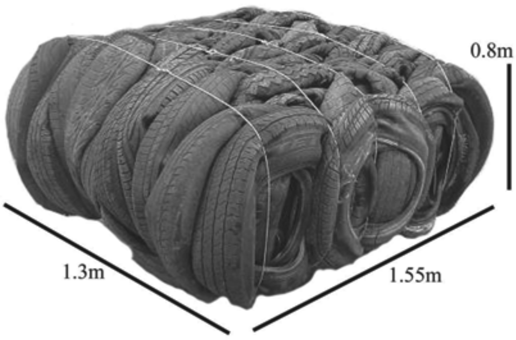


Figure 5. A typical tyre bale (Figure 1 of Winter).

Abdelhaleem et al. considered the use of recycled rubber and rubber-sand mixtures (RSM) as replacement soils in seismic areas due to the increased damping capacity of RSM. They performed site response analysis using the two-dimensional finite element method with equivalent-linear constitutive models for the geo-materials. Three earthquake ground motions of comparable magnitude and varying frequency content were applied to a deposit of sand with replacement soil and with different configurations of RSM. A parametric study was performed for investigating the effect of depth and thickness of the RSM layer and of the relative magnitudes of the natural period of the site and predominant period of earthquake on the sand-replacement soil-RSM system.

Kalumba and Chebet investigated the possibility of using discarded polyethylene shopping bags as soil reinforcement, and performed direct shear tests on Klipheuwel and Cape Flats sands mixed with perforated and non-perforated polyethylene strips of different lengths and of widths (Figure 6). Direct shear tests were performed with sand-polyethylene mixture and it was observed that there was an overall increase in the friction angle due to addition of the strips and that the increase in the friction angle depends on the length and width of the strips, perforations present in the strip, and percent weight of the strips (see, for example, Figure 7). Based on their results, Kalumba and Chebet suggested that the polyethylene strips can be used to increase the shear resistance of sandy soils.

Abdelrehman et al. performed a laboratory-scale study to investigate the efficacy of expanded polystyrene (EPS), a cellular polymeric material commonly used in the packaging industry, in reducing the heave in footings placed on expansive clay (Figure 8). They studied the compaction characteristics of EPS of different size and bead density mixed with silica sand. Subsequently, Abdelrehman et al. studied the response of circular footings of different diameters resting on a layer of sodium bentonite by replacing a part of the bentonite layer with the EPS-sand mixture. They performed a parametric study of the footing heave-settlement response as a function of different proportions of EPS-sand mixture, different replacement soil-layer thickness, footing size, and bead density. Abdelrehman et al. found that the swelling deformation of the footing decreases as the replacement-layer thickness increases.

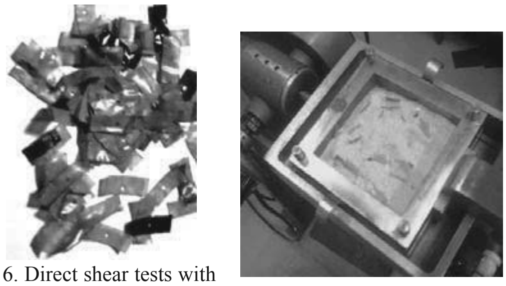

Figure 6. Direct shear tests with polyethylene chips from shopping bags (adapted from Figures 1b and 2b of Kalumba and Chebet).

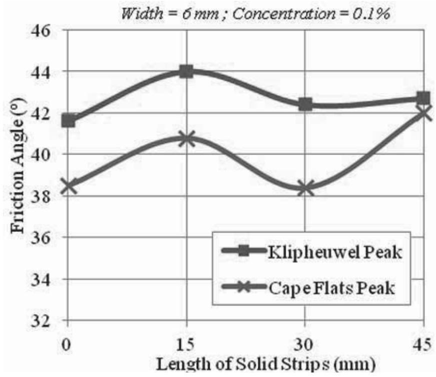


Figure 7. Friction angle of sand mixed with non-perforated polyethylene strips versus strip length (Figure 3a of Kalumba and Chebet).

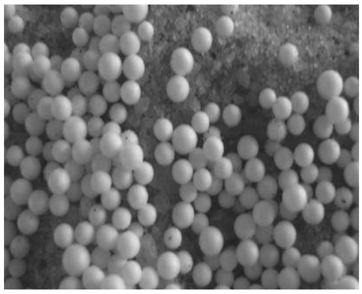

Figure 8. Expanded polystyrene (EPS) beads mixed with sand (Figure 1 of Abdelrehman et al.).

In another example of EPS recycling, Teymur et al. compared the performance of glass foam and EPS geo-foam as components of controlled low strength material (CLSM) often used as compacted backfill. They performed index tests, unconfined compression tests, and CBR tests, and found that glass mixtures have greater unit weight and strength than those of EPS foam mixtures. They concluded that glass foam CLSM can be used as pavement subbase, as fill for slopes and retaining structures, and to increase the strength and stiffness of soft clay deposits.

Drinking water sludge (DWS) discharged during water purification has potential use as a road infrastructure material (Watanabe and Komini). However, decomposition of the organic matter present in DWS decreases its shear strength because of which it is important to determine its durability for reuse. Watanabe and Komini collected DWS samples from Irabaki, Japan that contains aluminum and organic matters in the solid phase, and performed triaxial tests on the samples after subjecting them to aluminum leaching and biodegradation. They found that the shear strength of DWS decreases due to loss of organic matter and aluminum (Figure 9). Watanabe and Komini further quantified the effect of aluminum leaching and organic loss on the shear strength by modeling the leaching as a diffusion process and the organic loss as an exponential decay process. The study shows that DWS can be used in geotechnical applications.

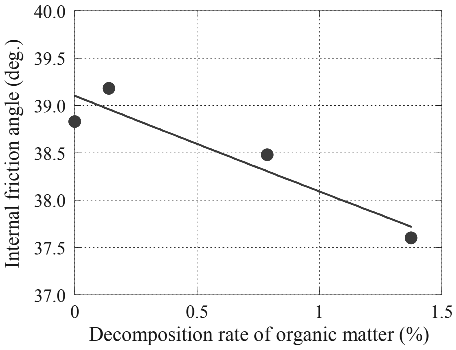


Figure 9. Friction angle of drinking water sludge as a function of decomposition rate of organic matter (Figure 7 of Watanabe and Komini).

Di Emidio et al. investigated the possibility of reusing dredged materials in landfill cover as a low-cost alternative. Enormous amounts of dredged material are generated from maintenance, construction, and remedial works related to water systems, and these materials are usually disposed of in landfills. Therefore, the reuse of dredged materials is important all over the world. For use in landfill cover, the dredged material must have low hydraulic conductivity and must retain the contaminants already present in it. In their study, Di Emidio et al. used dredged sediment obtained from Kluizendok in Ghent, Belgium and commercially processed kaolin Rotoclay® HB clay, and treated both with an anionic polymer Sodium CarboxyMethylCellulose (Na-CMC). Polymerization is particularly useful for dredged materials contaminated with metallic wastes. The authors investigated the mechanisms through which polymers can improve the efficiency of dredged sediments in waste containment impermeable barriers. Di Emidio et al. also conducted hydraulic conductivity and batch sorption tests to study the barrier performance and transport parameters of the treated dredged material and clay. The results showed that polymer treatment maintained low hydraulic conductivity of soil in electrolyte solutions and helped the material contain the spread of pollution. The results indicated that dredged sediments can be reused as alternative low-cost impermeable landfill cover.

Nakano and Sakai performed consolidation and triaxial tests on cement treated dredged soil samples collected from Nagoya Bay, Japan and modeled their elemental behavior using the SYS Cam-clay model. About 1.3 million $m^3$ of dredged soil is produced annually in Nagoya Bay, which has limited storage capacity because of which there is a pressing need for using the dredged soil as a geo-material. However, the clayey soil has low shear strength and high water content because of which cement is used as a stabilizer to improve its mechanical properties. The constitutive model of Nakano and Sakai reproduced the elemental test results reasonably well and the authors also performed finite element analysis using the software *GEOASIA* in order to capture the nonuniform deformation of triaxial test samples.

Air-foam treated lightweight soil, known as Super Geo-Material (SGM), is an example of an alternate material that is useful in harbor and airport constructions because of its light weight, safety features, and recyclability. Kataoka et al. mixed six different types of soils from Japan with seawater, blast furnace cement, and animal-protein hydrolyzed air-foam to prepare SGM specimens. They measured the unconfined compressive strength and small-strain shear modulus of the specimens, and studied their microstructure using a scanning electron microscope. Kataoka et al. observed that the strength and stiffness of the SGM samples increased with increase in the number of curing days, and attributed this increase to the growth and bonding of needle-like ettringite crystals within the SGM sample pores caused by the curing process.

Jefferis and Lam discussed the use of polymers as an alternative to bentonite in geotechnical construction fluids (slurries). Polymers have several advantages over bentonite in that polymer fluids require smaller preparation plants that can access congested urban areas, require shorter preparation time, and are environmentally less hazardous. In addition, constructions made with polymers have better performance than their bentonite counterparts. However, there are some limitations of polymers like reduction of fluid properties due to continued shear in recirculation systems and potential for loss of properties in saline soils. Therefore, Jefferis and Lam recommended that polymers should be used carefully with proper monitoring.

In order to investigate the reusability of in situ excavated soil with poor mechanical properties, Blanck et al. studied the effect of three non-traditional additives, an acid solution, an enzymatic solution, and a lignosulfonate, on the compaction characteristics and strength of silt. The test results showed that the acid solution did not improve the compaction characteristics and that adequate soil compaction can be achieved with low water content using the enzymatic solution and lignosulfonate. Blanck et al. concluded that enzymatic and lignosulfonate treatments would reduce water usage in constructions.

### 3.2 *Efficient use of geosynthetics*

The use of geosynthetics can reduce resource consumption and environmental impacts of geotechnical constructions, and can prevent soil erosion (Herteen 2012, Jones and Dixon 2011). Frischknecht et al. showed through life cycle assessment of pavement drainage systems that constructions using geosynthetics have less environmental impact.

Herteen et al. presented a general discussion on the use of geosynthetics, particularly geogrids, and pointed out that constructions with geosynthetics is more economical and environment friendly than traditional alternatives. According to Herteen et al., political reasons and population density and distribution often dictate the construction choices related to the national and international traffic routes within the European Union (EU), and geosynthetics can be used to advantage in many such constructions. The authors discussed about the use of geosynthetics in slope stabilization, reinforced earth walls, sound barrier walls, and embankments on soft clay, and pointed out the beneficial features of geosynthetics. They also discussed about the provisions given in Eurocode-7, German standards and British standards regarding constructions related to geosynthetics. Based on Herteen et al., it can be concluded that efficient, economic, aesthetically pleasing, and environment friendly constructions with minimal monitoring requirement are possible using geosynthetics.

### 3.3 *Sustainable foundation engineering*

Foundations form an integral part of geotechnical constructions, and sustainable design and construction of foundations are very important for overall sustainable development (Basu et al.). As part of sustainable foundation engineering, Basu et al. advocated the use of proper constitutive models and appropriate numerical analyses, adoption of reliability based design approach (e.g., LRFD), incorporation of spatial heterogeneity of soil in analysis and design, adoption of economical and environment friendly construction practices, reuse and retrofitting of existing foundations, and use of foundations in harvesting wind and geothermal energy.

Bourne-Webb et al. presented a case study of piled raft construction for a shopping center in Cambridge, UK as a cost-effective, time-saving and resource-efficient alternative to conventional pile foundations. Based on detailed site characterization that consisted of collection of data from adjacent sites, stress-path tests on bore hole samples, suction tests, and estimation of coefficient of earth pressure at rest, on monitoring of an instrumented basement of an adjacent hotel structure, and on linear and pseudo-nonlinear soil structure interaction analysis considering plate-on-spring approach, the piled raft foundation was designed with the piles used as settlement reducers. The design also ensured that there was minimal disturbance to the adjacent structures.

Reuse of foundations is often preferred over new foundations because reuse reduces waste disposal and environmental impact. Guilloux et al. presented three case studies of foundation reuse projects in Paris and Pantin. Figure 10 shows a cross section of one of the rehabilitation projects in Paris in which the existing pile foundations were strengthened by jet grouting and additional support was provided by newly installed micropiles. Guilloux et al. concluded that a site specific approach involving proper site characterization, condition assessment of existing foundations, delineation of existing and new foundation geometry, accurate estimation of changes in load, deformation and capacity during the construction process, consideration of different possible construction alternatives, proper choice of reinforcement technique, and proper monitoring is required for successful reuse of foundations. Vaníček et al. also advocated reuse of foundations particularly in the context of brownfield redevelopment.

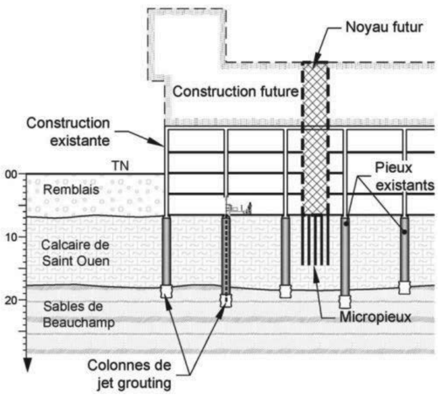


Figure 10. A cross section of foundation reuse project of Calberson warehouses, MacDonald Boulevard, Paris (Figure 1 of Guilloux et al.).

### 3.4 *Subsurface remediation and site redevelopment*

Redevelopment of contaminated sites including brownfield sites and landfills is an important part of sustainable geotechnics. According to Vaníček et al., brownfield redevelopment involves an initial reconnaissance study involving site characterization and economic feasibility study, followed by detailed site investigation, site remediation, and construction of new facilities at the site. Site remediation involves ground improvement by physical means (e.g., compaction and clay injection) and chemical treatment using encapsulation, permeable reactive barrier (Figure 11) and chemical stabilization. Vaníček et al. also provided an example of use of coal mine sites in Czech Republic where clayey overlays covering coal seams were excavated during mining activities and subsequently backfilled, and constructions were made on the mine sites using the mine-spoil heaps.

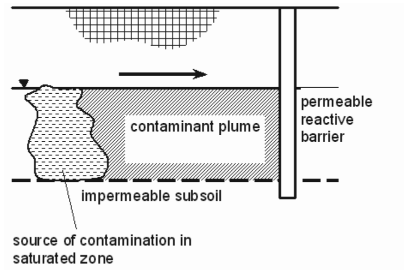


Figure 11. Site remediation by permeable reactive barrier (adapted from Figure 4 of Vaníček et al.).

McIntosh and Barthelmess provided a case study of reuse of a derelict (puticible waste) landfill site at Unanderra, NSW, Australia. Different geotechnical and geoenvironmental studies were conducted to assess the potential of the landfill site for construction. Environmental monitoring included testing of groundwater for contaminants and metals, and of gas monitoring wells for methane, hydrogen sulphate, and carbon dioxide. Monitoring for vibrations, noise and dust produced during site preparation was also conducted. The landfill density was increased by dynamic compaction, and environmentally neutral coal washery rejects locally present in the landfill site were used as cheap backfill material. A leachate control pond was constructed to receive the leachate during compaction and also to manage storm water on a long-term basis. Future civil and building services have been designed such that they do not penetrate the capping layer of the landfill. Driven steel piles bearing on underlying latite bedrock will be designed as building foundations. Flexible aprons will be provided between buildings and adjacent car parks, walkways and recreation areas, and raft slabs may be feasible for some lightweight, single-story buildings. The environmental design includes capping consisting of HDPE, GCL, geotextile fabric, 300 mm gravel gas drainage layer with a reinforcing geotextile, a gas drainage layer forming part of the cap, and leachate collection drains.

### 3.5 *Sustainability assessment*

The foregoing studies show that geotechnical engineering can contribute significantly to solutions of sustainability problems. Most studies are based on the common notions of sustainability like recycling, reuse, and use of alternate materials, technologies and resources. However, whether such new approaches are actually sustainable or not cannot be ascertained without proper assessment using, for example, whole life cost analysis and risk based performance analysis. Thus, a sustainability assessment framework is necessary for geotechnical projects to ascertain the relative merits of different options available for a project.

Frischknecht et al. performed a comparative life cycle assessment (LCA) of a pavement filtration system by comparing the performance of a gravel filter and a geosynthetics-based filter drain with the same hydraulic conductivity of 0.1 mm/s or more and with the same design life of 30 years. Life cycle inventory (LCI) of gravel and geosynthetics filter for a 1 $m^2$ functional unit was performed — Table 1 shows some key figures of LCI. Polypropylene granules was used as the basic material for the geosynthetics filter, and the LCI of geosynthetics manufacturing was performed using the ecoinvent data v2.2 based on the categories of raw materials, water, lubricating oil, electricity, thermal energy, fuel for forklifts and factory building. The environmental impact assessment (EIA) was performed considering eight impact indicators: cumulative energy demand, global warming potential, photochemical ozone formation, particulate formation, acidification, eutrophication, land competition, and water use. Based on the study, Frischknecht et al. found that the geosynthetics based filter layer causes lower environmental impact than the conventional gravel-based drain and that the environmental impact of geosynthetics manufacturing is mostly controlled by the impacts of raw-material production and electricity consumption during manufacturing.

Table 1. Selected key figures describing the constructions of one square meter of gravel and geosynthetics filter (Table 2 of Frischknecht et al.).

| Material/Process | Unit | Gravel filter | Geosynthetics filter |
|---|---|---|---|
| Gravel | $t/m^2$ | 0.69 | 0 |
| Geosynthetics layer | $m^2/m^2$ | 0 | 1 |
| Diesel used in building machines | $MJ/m^2$ | 2.04 | 1.04 |
| Transport, lorry | $tkm/m^2$ | 34.5 | 0.035 |
| Transport, freight, rail | $tkm/m^2$ | 0 | 0.07 |
| Particulates > 10 μm | $g/m^2$ | 4.8 | 0 |
| Particulates > 2.5 μm and < 10 μm | $g/m^2$ | 1.3 | 0 |

Holm et al. developed an assessment and decision making tool for sustainable management of contaminated sediments in the Baltic sea, which included an emerging technology of solidification/stabilization. They presented the results of three case studies based on the ports of Oxelösund (Sweden), Gävle (Sweden) and Hamburg (Germany). Different management scenarios were considered at each port, and LCA were performed to choose the best options. Recycling of sediments, disposal in river and sea, energy use, and environmental impact were considered in the LCA. Holm et al. further developed a multicriteria decision analysis (MCDA) to integrate the three Es of sustainability in their decision making tool following a structured and balanced way.

Basu et al. also developed a multicriteria based sustainability assessment framework and applied it to pile foundation projects. The framework considers a life-cycle view of the pile construction process, and combines resource consumption, environmental impact, and socio-economic benefits of a pile-foundation project over its entire life span to develop a sustainability index (Figure 12).

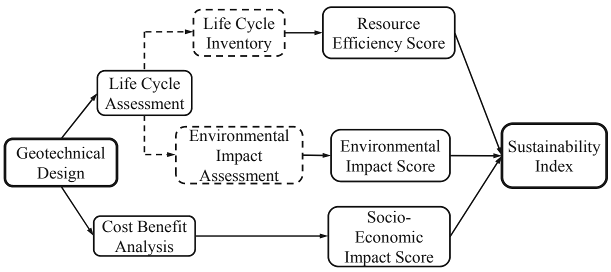


Figure 12. Multicriteria based sustainability assessment framework (Figure 3 of Basu et al.).

Edil provided an overview of the sustainability assessment tools used in pavement construction projects. He mentioned that LCA and life cycle cost analysis (LCCA) can be successfully used to assess the sustainability of pavement constructions. He further described a rating system for sustainable highway constructions known as Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways ($BE^2ST$-in-Highways$^{TM}$), which evaluates the sustainability of a highway project in terms of quantitative difference between a reference design and proposed alternative designs.

Farias et al. performed an economic analysis of different construction alternatives for their CDW paving project described in section 3.1. Although this is not a complete sustainability analysis, the environmental and social benefits are inherently present in the project. They considered two alternatives, first in which the CDW is completely disposed of in landfills and second in which the CDW and in situ soil mixture is used in paving the construction site. The high cost of disposal (Table 2) made the first option the most viable one with a direct cost savings of US$ 1.9 million, which does not even include the indirect cost-saving benefits from the reduced environmental impact that the project ensures.

Table 2. Costs for final disposition of wastes in licensed places (Table 6 of Farais et al.).

| Disposition place | Unit | Unitary cost (US$) |
|---|---|---|
| Inert landfill | $m^3$ | 47.30 |
| Processing plant | $m^3$ | 18.36 |

* Transportation cost not considered

In their study on the use of enzymatic solution and lignosulfonate as additives in silt (described in section 3.1), Blanck et al. performed LCA-EIA using 10 impact categories proposed in the NF P 01-010 standard. The analysis showed that the use of enzymatic solution reduces impacts in seven out of ten categories (Figure 13). The use of lignosulfate, however, did not produce sufficient environmental benefits.

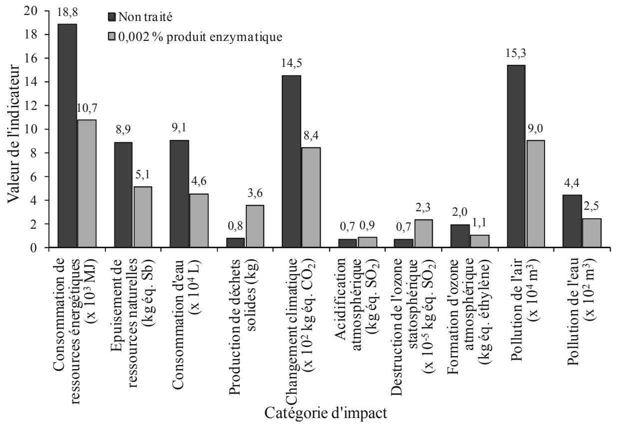


Figure 13. Results of environmental impact analysis for the use of enzymatic solution (Figure 3 of Blanck et al.).

## 4 IMPORTANT THEMES NOT COVERED

As sustainable geotechnics covers a wide range of topics, it is natural that the papers allocated to the sustainability session do not cover all the areas related to geosustainability. Some of the important topics not covered in details include sustainable site characterization, geohazard mitigation, reliability- and resilience-based analysis and design, geothermal energy foundations, geo-structures for wind and solar energy, sustainable ground improvement techniques, sustainable use of underground space, carbon sequestration, and ethical practices in geotechnical engineering. The other sessions and workshops of 18th ICSMGE cover some of these themes.

## 5 CONCLUSIONS

Sustainable geotechnics is a new sub-discipline focusing on geotechnical engineering practices that reduce the detrimental effects of geotechnical constructions and ensure the well being of the society and natural environment at all times. It not only includes environment-friendly practices that are cost effective and cause minimal financial burden to the present and future generations, but also promote reliability- and resilience-based design and adaptive management strategies so that social vulnerability is minimized and overall well being is upheld.

This general report provided an overview of this emerging area of geosustainability and reviewed the twenty eight papers allocated to the sustainability session of 18th ICSMGE. The authors of these papers represent 20 countries covering all the ISSMGE regions. Most of the papers emphasized the environmental aspect of sustainability, while some papers on sustainability assessment focused on the economic and social aspects. The topics covered by these papers can be broadly classified into five sub-themes: material recycling, reuse and use of alternate materials, efficient use of geosynthetics, sustainable foundation engineering, subsurface remediation and site redevelopment, and sustainability assessment. Although these papers deal with a variety of topics that contribute to the sustainable development of civil infrastructure and society, they do not cover all the important topics that are parts of sustainable geotechnics.

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