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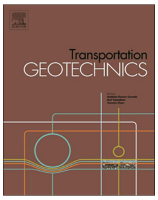

Engineering Advance

A review of sustainable approaches in transport infrastructure geotechnics [☆]

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ABSTRACT

Transportation geotechnics associated with constructing and maintaining properly functioning transportation infrastructure is a very resource intensive activity. Large amounts of materials and natural resources are required, consuming proportionately large amounts of energy and fuel. Thus, the implementation of the principles of sustainability is important to reduce energy consumption, carbon footprint, greenhouse gas emissions, and to increase material reuse/recycling, for example. This paper focusses on some issues and activities relevant to sustainable earthwork construction aimed at minimising the use of energy and the production of CO_2 while improving the in-situ ground to enable its use as a foundation without the consumption of large amounts of primary aggregate as additional foundation layers. The use of recycled materials is discussed, including steel slag and tyre bales, alongside a conceptual framework for evaluating the utility of applications for recycled materials in transportation infrastructure.

Contents

Introduction

Transport infrastructure consists of facilities such as roads, highways, bridges, airports, railways, waterways,

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canals and terminals, that place heavy demands on material resources, and is undergoing a market transformation in terms of the planning, design, construction, maintenance and exploitation of more sustainable structures. This infrastructure has an effect on the earth's resources and environment but also changes the land use pattern that has persisted for centuries and affects the societal values of a community [1]. Thus, geotechnical aspects and related activities are of primary importance from the earliest planning and design stages of an infrastructure project in achieving overall sustainable development in construction projects to: (1) meet basic human needs; (2) use resources effectively; and (3) preserve/restore the surrounding ecosystems [2]. This means that the main contribution of geotechnical engineers in achieving sustainability at a project level lies in efforts to utilise limited resources and explore ways of reducing processes that result in adverse impacts on sustainability. A few such areas are energy efficiency of the materials and methods used; potential reuse, recycling and re-engineering of materials and wastes; carbon footprint analyses; and the control of air, water and soil pollution [3]. A brief overview of geotechnical examples covering some of these areas are addressed in this paper. This includes sustainable ground improvement methods, earthworks constructed by minimising the use of energy and the production of CO_2, and the use of recycled alternative materials, foundation reuse, and rehabilitation and maintenance without the consumption of large amounts of primary natural geomaterials.

Ground improvement

Improving or modifying ground conditions to suit the engineering needs of construction projects has been practiced for decades. This practice often results in cost savings and other tangible benefits for both the project and the owner. Today, there are several ground improvement methods encompassing shallow, medium and deep soil treatments and involving drainage, reinforcement and soil improvement techniques available for geotechnical engineers to choose from, contingent to construction project needs. This practice has become such an important toolkit in the armoury of the geotechnical engineer that the *Proceedings of the Institution of Civil Engineers* in the UK now devotes an entire journal, *Ground Improvement*, to the subject (http://www.icevirtuallibrary.com/content/serial/grim); other related practices are more specifically targeted at transportation geotechnics [4–6]. The selection of a ground improvement method for a particular project is usually made in deference to the project cost and timelines. Nowadays, this decision is also made from the sustainability standpoint as well. Engineers can select two or three ground improvement alternatives for a given project and then perform a comprehensive analyses of the carbon footprint, life cycle cost and energy consumption of each of the methods and then determine the one that proves to be the most sustainable [7].

Sustainable earthworks

Reuse of natural geomaterials

Earthworks seek to reuse and incorporate as much as possible of the geomaterial already existing on the construction site as is practicable [8]. This will avoid the disposal of such materials and save on the consumption of natural resources, which include high quality and other quarried materials, as well as minimising the demand for land and transport. Although not explored in detail in this paper, issues surrounding the acceptability of natural earthworks materials form an important part of the earthworks planning and implementation process and their correct application can have a fundamental effect on achieving sustainable earthworks construction. Similarly, where natural earthworks materials (including glacially deposited materials) incorporate large particle sizes (soil–rock fill mixtures), account must be made of differences between the limited particle size ranges of the samples tested at the planning (ground investigation) and construction stages and the materials that are actually placed [9–11]. Failure to do so can lead to failure of the earthworks process and significant additional costs and energy consumption.

Nevertheless, the first step in determining whether a material can be used is to evaluate whether the excavated geomaterial meets the specification(s) for the specific application. However, if it does not meet the specifications, mechanical and chemical treatments may be considered to render the material suitable. Amongst chemical treatments, lime is commonly used in many countries to allow the reuse of very wet or soft fine soils in the construction of embankments, road foundation capping layers, and other applications [6,8,12–15]. An immediate improvement in the soil properties is expected and the treatment increases workability and assists compaction during earthworks. This technique has been common practice in Europe for several decades but the long term effects of lime treated soils have not been generally taken into account in design. Even mixing rather small amounts of lime with soils induces pozzolanic reactions that may continue over a period of years, resulting in a continuous increase of strength and stiffness [16,17]. The results presented in Flores et al. [16,17] show that for a silty soil treated with 3% quicklime only four days after construction (and thus four days of curing) the slope factor of safety increased from 1.5 for the untreated soil to 2.5 for the treated soil. This evolution continued with time and values of the factor of safety close to 4 and 10 were reached after 3 months and one year (in constant humidity and temperature conditions, 20 °C), respectively. Neglecting this long-term development resulting from pozzolanic reactions between lime, water, and the silica and alumina that exist in the clayey particles, has a direct impact on the costs of the earthworks, for example, as slope stability, erosion, bearing capacity will be underestimated. Although these reactions and their products are now well established, their influence on the evolution of the geomechanical properties of the treated soil has, until recently, been relatively unexplored. As a consequence, these effects are generally either not taken into account in design or the effects taken into account are at a much lower level that will be experienced in reality. However, Pan exploration of the causes of stabilized subgrade failures and showed that information on both the clay mineralogy and durability, or from long-term performance laboratory studies is needed to design an effective stabilization method for given subgrade conditions [18]. They noted that plasticity soils with varying amounts of Montmorillonite can be effectively stabilized with lime products. However, for soils with high plasticity, it may be necessary to increase the percentage of the chemical additive in order to obtain sustained performance over a longer time period. Similar observations may be made for cement treated soils. Overall, it is strongly recommended that laboratory mix design tests be performed to aid the selection of appropriate stabilizer types and the associated amount, despite the use of some predictive models based on data-mining techniques [19]. In addition, performance-based tests to determine durability are recommended [4,20,21]. From a sustainability point of view, the best stabilization treatments will be those that have the smallest carbon footprint and the use of byproducts such as ashes, quarry waste fines, quarry dust and slags, is often recommended along with lime or cement or other additives, which are responsible for alkali activation [22–25]. Ashes and fines typically contain large amounts of oxides including silicon dioxide and they contribute to pozzolanic activity in the soil treatments. As a result, strength and stiffness improvements will be recorded in these treated soils.

An example of the sustainable reuse of natural soil is the Integrated Pipeline (IPL) project, which involves a large diameter pipeline construction that is aimed at bringing additional water supplies to the Dallas/Fort Worth metroplex. A research study was undertaken to examine the potential chemical treatment of in-situ excavated soil material that can be reused as either bedding, or zone or backfill materials for supporting a large diameter pipeline. Based on the comprehensive laboratory and field implementation studies, the soils along the pipeline alignment are identified for potential reuse as backfill, bedding and zone materials after chemical amendment studies [7]. Cost and potential environmental benefits, as well as emissions reductions of using in-situ native treated material versus imported aggregate and select fill materials, are described in Fig. 1. It can be observed from the figure that the higher the overlap among the social, economic and the environmental impacts, the more sustainable a given project is going to be. Research works such as these would help agencies to develop sustainable ground improvement solutions for the infrastructure construction projects.

Qualitatively, the initial additional costs of lime or cement treatment of soils can be counterbalanced by other advantages related to the durability of the earthworks, which can be quantitatively demonstrated by a proper life-cycle and risk analysis [26].

Reuse of recycled aggregates

A conceptual framework for the understanding of recycled aggregate applications was developed [27] and was structured in terms of the environmental and economic utility (or value) of the application, and the utility relative to the original application. In the determination of utility, the factors considered included those related to production (energy consumption, financial cost, amount of pollution and waste generated) and those related to the market value of the product and the 'renewability' of the primary resource. Typically, three levels of applications are considered: low utility, intermediate utility and high utility. High utility and intermediate utility are examined in section "Recycled alternative materials, foundation reuse, rehabilitation and maintenance", since applications

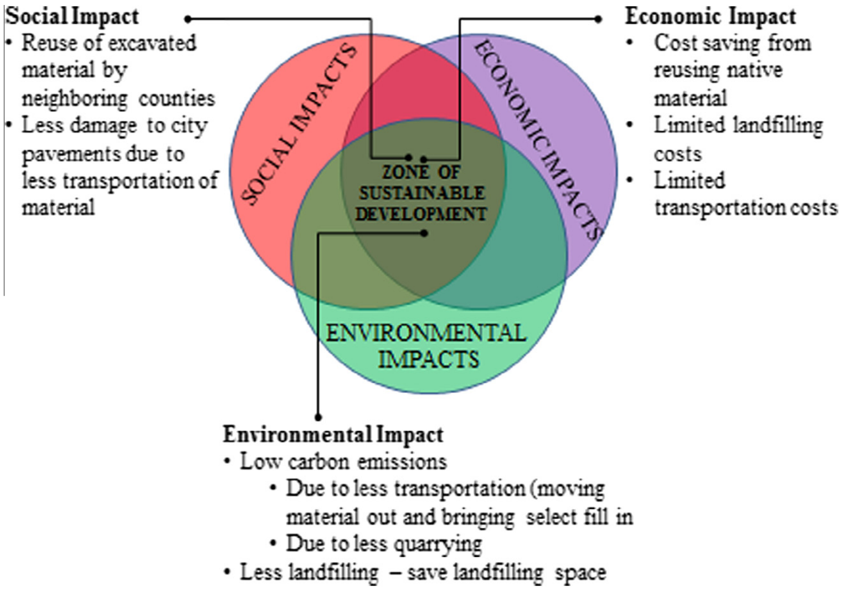

Fig. 1. Soil reuse effects on various sustainability factors (from [7]).

are more relevant in structural elements. The *low utility* applications for recycled aggregates are typically based upon their use as general fill. A study of the use of recycled aggregates in Scotland [28] found that around 87% of spent oil shale, 100% of colliery spoil and 28% of PFA (pulverised fuel ash or fly ash) were recycled to low utility applications, predominantly as general fill. This is despite the fact that each material has been shown to be suitable for higher utility applications [29–31].

CO_2 emissions in earthworks operations

Recently, new environmental concerns regarding earthwork construction have emerged. Such concerns range widely from the water economy through carbon dioxide emissions to waste control in the construction phases. These concerns go beyond the usually implemented environmental rules that relate to ecology and nature conservation or regard for the preservation and/or enhancement of the landscape and townscape.

Most of these construction concerns have been taken into consideration during the construction of and preparation for the London 2012 Olympic Games (presented here as an example), including [32]:

1. Carbon (to minimise the carbon emissions associated with the construction of the Olympic Park and venues).
2. Water (to optimise the opportunities for efficient water use, reuse and recycling).
3. Waste (to optimise the reduction of waste through design, and to maximise the reuse and recycling of material arising during demolition, remediation and construction).
4. Materials (to identify, source, and use environmentally and socially responsible materials).
5. Biodiversity and ecology (to protect and enhance the biodiversity and ecology of the Lower Lea Valley, and other venue locations).
6. Land, water, noise, air (to optimise positive, and minimise adverse, impacts on land, water, noise, and air quality).

Carbon emissions and air quality are of direct relevance to earthworks tasks. In fact, as noted within the Environmental Statement, the key emission to air is the generation of dust from demolition, earthworks and construction activities.

Emissions from vehicles associated with construction sites can significantly add to levels of local air pollution, so it is important that the best practical means of reducing vehicle emissions are adopted. As such, several mitigation measures can be taken in order to minimise air quality impacts.

Optimisation of earthwork tasks

Earthworks involve sequential tasks such as excavation, transportation, spreading and compaction that are strongly based on heavy mechanical equipment and repetitive processes, thus becoming as economically (and energy) demanding as they are time-consuming. Given the percentage balance of costs and duration of earthworks in infrastructure construction projects (30–50%), the optimal usage of every resource in these tasks is paramount. The characteristics of earthworks construction mean that, it can be viewed as a production line process based on resources (mechanical equipment) and a series of sequential, but interdependent, tasks; the process thus has the potential to be optimised [8,33–35]. With the use of soft computing techniques, such as evolutionary computation (i.e. genetic algorithm), it was possible to develop an integrated optimisation system which was applied to a case study [36]. The available data include the daily allocation of earthworks equipment throughout a road construction site (including information on available equipment), material volumes and types of excavation and compaction fronts, and the distances between fronts. By modelling and optimising a specific number of phases, results indicated that it would be possible to reduce execution times adopted in a conventional design for some of the construction phases by between 20% and 50% of their original duration, without increasing costs. In fact, if this system was to be applied to this construction project, a high impact could be achieved, with an estimated reduction of around 50–70% of both cost and duration, thus addressing some of the principles of sustainability.

Recycled alternative materials, foundation reuse, rehabilitation and maintenance

A major component of sustainability-related applications in transportation geotechnics has been focused on alternative construction materials by using environmentally friendly materials, concentrating on the use of recycled waste materials. For example, the waste from end-of-life asphalt and concrete pavements can be recycled into aggregate or pulverized and then stabilized into full or partial depth reclamation bases with cement or other additive as hydraulic binders [37,38]. The use of old pavements as stabilized bases not only reduces landfill costs, but also reduces the overall project carbon footprint as the requirement for conventional quarried natural aggregates is reduced. Additionally, the costs incurred in building transportation infrastructure can be in many cases substantially reduced when alternative recycled or secondary materials are used in construction works.

In a research study referred in [38,39], two types of recycled materials, namely reclaimed asphalt pavement and cement-stabilized quarry fines, were successfully used as pavement base materials for a highway extension project in Arlington, Texas, USA. Analysis of results obtained from field monitoring studies demonstrates that these secondary materials can be effective as a sustainable alternative to conventional pavement bases and hence this reuse application reduced the use of conventional and natural aggregates, but also reduced the overall costs of the infrastructure project.

Winter [29,30] also refers to *intermediate utility* applications for the use of spent oil shale and burnt colliery spoil in road foundation construction as capping layer and sub-base materials. Reclaimed asphalt pavement (RAP), can also be used for the construction of capping layer and subbase and experience indicates that they perform at least as well as, and often better than, the standard crushed rock control material [40]. In particular, construction of embankments containing bituminous materials such as RAP, RPM (recycled pavement material), or RAS (recycled asphalt shingle) is recommended to be undertaken during summer to induce thermal preloading and reduce long-term settlement.

High utility applications represent the peak of the range of environmental and economic utility that can be derived from recycled aggregates. Examples include the use of construction and demolition waste (such as crushed concrete) in a hydraulically stabilised cracked-and-seated roadbase construction [28,41,42] and other studies have demonstrated the effect of brick waste on the properties of recycled concrete aggregate [43].

The concept of relative utility was a key component of the conceptual framework [27]. Where aggregates are recycled from an existing use (as opposed to industrial wastes and by-products that have no original use) it is possible to make a judgement on the utility of the secondary compared to the primary application. Terms were thus adopted to provide a framework for such judgements, as follows:

- *Down-cycling*: recycling in which the secondary application has a lower utility than the primary (e.g. RAP recycled as general fill).
- *Level-cycling*: recycling in which the secondary application has the same or similar utility as the primary (e.g. RAP recycled in bituminous pavement layers).
- *Up-cycling*: recycling in which the secondary application has a higher utility than the primary (e.g. pavement foundation layer recycled in bituminous pavement layers).

In Scotland in the early part of this century [28] that the bulk of aggregate recycling was carried out as down-cycling and that up-cycling was comparatively rare and highly specialised. For example, crushed concrete and RAP were most often recycled as general fill. The most successful mix of recycling in a given waste stream was considered likely to be a mix of predominantly down-cycling and level-cycling. The recycling of certain types of plastic bottles as fleece clothing is a prime example of up-cycling, albeit unrelated to aggregates.

The framework was developed for recycled aggregates but is equally applicable to other categories of material. Indeed, the concept of relative utility, in particular, has gained common currency and is frequently used in arenas far beyond that for which it was originally and primarily intended. Utility is suitable for project level comparisons of recycled aggregate applications and also for strategic evaluations at a national level [28]; it is particularly helpful in articulating (and maximising) the value derived from the materials available. Relative utility, while more immediately accessible as a concept, is suitable for project level evaluations of recycled aggregate applications, but less so for strategic evaluations.

Other examples of sustainable use of recycled by-products have been presented [44] concerning a case study of Portuguese inert steel aggregate for construction – ISAC [45,46] and tyre bales [47]. The authors illustrate how typically the respective introductions of these two materials (ISAC and tyre bales) to the construction market follow the sequential stages of Fig. 2 [43]. It should be stressed that the ISAC can have a high utility use for high speed railways and has been studied in an EU research project (LIFE GAIN-Slag layers in railway foundations, LIFE12 ENV/ES/000638). Also, successful applications for tyre bales including as road foundations in both the USA (New York State) and the UK [48]. Other applications such as slope failure remediation, lightweight embankment fill, gravity retaining walls, drainage layers/paths, erosion control, landfill engineering, storm water management systems and rainwater soakaways, and environmental barriers have been described [49–51].

A more recent research topic that could have a great impact on the reuse of materials in the future by improving

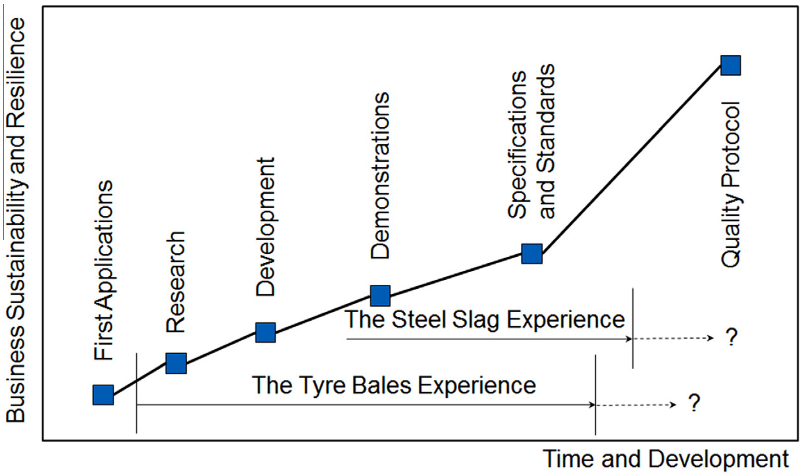

Fig. 2. The development of business based on the production and sale of a new product based on reused, recycled or recovered waste materials (from [44]).

their performance is the incorporation of nanotechnology in the formulation of materials [52]. In fact the reinforcement of soil using short and discrete synthetic and natural fibres has long been used to improve various properties of soils such as tensile strength and stiffness, shear strength, post-peak strength loss, ductility, etc. Due to their high aspect ratio combined with excellent mechanical strength and stiffness, nano fibres can be advantageously used for soil reinforcement in a wide range of geotechnical applications.

Besides that, the use of conductive nano fibres (e.g. carbon nano fibre) may impart electrical conductivity and piezoresistivity to the reinforced soils. These properties can be used to automatically sense deformation and damage as it occurs to these structures [53,54]. Furthermore, reinforced embankments exhibit numerous advantages over conventional fills, especially along steep or unstable slopes and in seismic areas, as well as in layer reinforcements [9]. For fills, usually the reinforcement does not cover the entire area, unless spreading of an embankment is a particular issue, or the construction involves slender earth structures [9,55,56].

It should also be noted that recycled materials can be significantly improved if they are mixed with other by-products that exhibit cementitious properties, such as self-cementing fly ash (or PFA) (ASTM, 2011, D7762 Standard Practice for Design of Stabilization of Soil and Soil-Like Materials with Self-Cementing Fly Ash) or waste incineration ash, which are responsible for alkali activation [24]; other combinations are with mine wastes [57].

The routine use of geosynthetics situated between individual compacted layers in reinforced road embankments and railroad tracks is very well established and demonstrated as a sustainable solution [58–61]. Moreover, other more innovative solutions are also available, including brick–fibre-concrete for example [62]. The principle of this system is simple, and utilises old bricks and concrete, which, after crushing and sorting into different fractions, create the base for the new material – concrete reinforced by short synthetic fibres.

It is well known that effective and timely maintenance can prolong the life of structures and thus minimise, and sometimes avoid, costly, and energy- and emissions-intensive, recycling and disposal operations. Consequently strategies should be configured so as to provide timely maintenance and preservation of the built environment. However, continuing maintenance and remediation are becoming major engineering constraints for infrastructure owners. Several trial remedial measures have been tested over the years, including stabilization technologies for embankment foundations and/or of the embankment. They can be categorised as follows:

- reducing disturbing forces (e.g. geogrids, piles, retaining walls, soil pinning, track support),
- increasing soil strength (e.g. stabilization, geomats), and
- controlling water (drainage), mechanical support to resist deformation (e.g. interception drainage, geogrids).

Hybrid solutions can involve installing a row of concrete piles at the mid-slope to transfer load from the sliding surface soil into the underlying stable ground [63].

Many of these technologies can also be applied to accommodate higher loads, geometry changes, and extreme environment conditions, like floods and earthquakes. Special attention should be paid to geometry changes (e.g. widening). In these cases it is necessary to estimate the influence of the new structure on the existing one, which is often difficult to assess, especially for water sensitive materials. For old and new road and rail embankments the main responsibility for the infrastructure owner is how to know when maintenance works should be carried out in order to provide the maximum benefit at the minimum cost and asset management systems can be an invaluable tool for the effective resolution of this problem.

Nevertheless, whatever the problem is, the principles of sustainability should always be applied, ensuring that design and construction options are compared and evaluated in terms of energy efficiency, carbon emissions, costs and societal benefits for the full design life of the structure.

Summary and conclusions

Geotechnical planning, design, construction and rehabilitation in the early phases of an infrastructure project can significantly contribute to the overall sustainability of that particular development by making appropriate choices related to several aspects of the project. These choices include strategies, materials and technologies that can be summarised as follows:

- Ground improvement: several methods are available, but decisions should be supported by comprehensive analyses of the carbon footprint, life cycle and cost studies, and energy consumption analyses of each of the candidate methods in order to determine the one that proves to be the most sustainable. Such selection and implementation can lead to higher sustainability ratings.
- Earthworks: the main issues include the reduction of CO_2 emissions, waste control by reuse and the incorporation of the maximum amount of the excavated natural geomaterials as well as taking advantage of the long-term behaviour of treated soils. Other important aspects include, the optimisation of earthworks tasks by maximising productivity and minimising costs, as well as minimising energy consumption and emissions generated during extraction, processing, and transportation.
- Recycling and rehabilitation: promoting recycled material reuse through performance tests, including durability tests; and by taking advantage of engineering and environmental aspects that contribute to reduced greenhouse gas emissions and energy consumption, and to long-term economic benefits as well as conferring societal advantages. This is essential to facilitate the sustainable use of new materials in transportation infrastructure under various climatic and traffic (load and speed) conditions. The final goal is a holistic design approach addressing environmental, societal, economic, and resilience issues, through mechanistic approaches, life cycle analysis, as well as risk analysis. The use of

recycled and secondary materials should be promoted at the highest utility possible, albeit that maximum consumption of such materials will most likely require a mix of low, intermediate and high utility applications.
- Maintenance: if undertaken in a timely manner the service and structural life will be extended and resilience against the effects of extreme events for critical infrastructure will be enhanced.

In summary, this review of the application of geotechnical engineering in transportation infrastructure works highlights the transformation that has taken place in the industry in the last two decades from a traditional, low technology base to a much more sophisticated higher technology industry that fully takes account of sustainability issues. Sustainability can be improved by reducing energy consumption, greenhouse gas emissions, natural resource consumption, by increasing service life and by implementing more cost-effective solutions. However, it is not always easy to implement non-traditional practices, and it requires the dedication and perseverance of the entire project team including designers, builders and owners to select sustainable systems. Such practices will lead to the better use of sustainable systems in transportation infrastructure. However, in order to gain widespread acceptance, specifications must be developed to enable such techniques to be used on a regular basis.

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