Examining the carbon footprint and reducing the environmental impact of slope engineering options

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Abstract
Considerable progress has been made in the assessment, management and maintenance of existing earthworks and in the selection of methods of construction of new earthworks. Techniques involving multi-criteria analysis, carbon footprinting and life cycle assessment of competing schemes provide transparent methodologies for use in environmental impact assessment.

This review paper provides examples of use of the various techniques, and in particular concentrates on areas of innovation including:
- use of carbon calculators to choose between competing slope or earthwork stabilisation solutions
- methods of ground treatment to minimise earthwork impact (eg insitu soil strengthening, soil nailing, or green walls)
- combining performance-based design, under environmental load cases such as earthquake and flood, with carbon footprint and cost analyses.

Introduction
The EU Sustainable Development Strategy directive, renewed in 2006, has a three-part approach, setting the following objectives by 2020:
- to reduce greenhouse gas emissions by 20%
- to reduce primary energy usage by 20%
- to increase use of renewable forms of energy to 20% of the energy mix.

A recent Sustainable Development Commission report – ‘Prosperity without Growth’ – states that the world produces 770g of CO₂ per $ of income and that this figure must reduce to 6g per $ by 2050, if all 9 billion of us are to enjoy European income levels in 2050 and simultaneously stabilise atmospheric CO₂ at 450ppm.

It is generally agreed that construction activity contributes about 25% to global carbon emissions, and so it will be essential to reduce emissions in construction to pursue sustainable development.

Economic growth relies on the confidence of society in all its forms and the predictability of outcome of a certain course of action. There is thus a strong driver to put ground engineering activities into a context which can show improvements in these indicators of sustainable development. Relevant standards are ISO 14064 (2006) and 14065(2006). This paper provides the building blocks for embodied energy and equivalent carbon dioxide calculations associated with the most common forms of slope engineering. It places these calculations into the wider context of transport and resource planning.

Strategic guidance
In the UK, the Environment Agency has produced a carbon calculator for construction activities and this has been extended specifically for highway-related projects by the Highways Agency. These documents provide a framework from which an inventory of emissions in terms of CO₂ equivalents can be prepared for significant movements of earthwork and other materials. Such calculation systems enable broad decisions to be made, but are not sufficient to allow different methodologies to be compared.

O’Riordan and Phear (2009) observed that as confidence in carbon calculators grows, so such calculations can be incorporated into design, optioneering and value engineering activities. Infrastructure clients, designers, and contractors are all finding carbon accounting to be a useful tool, but in different ways. Designers are increasingly using this method in combination with traditional cost comparisons to decide between different schemes. Contractors are increasingly applying carbon accounting to their construction management systems.

This is because it has been realised that carbon reduction is a useful way to combine environmental management and “lean construction” methods. There

Figure 1: Energy consumption and equivalent carbon dioxide emissions, expressed in terms of PKT (passenger-km travelled) after Chester and Horvath (2010). Infrastructure components are shown in shades of red and orange, fuel production and consumption for a given vehicle use is shown in green and grey respectively and vehicle components are in blue.
is great legal and ethical pressure on contractors to manage and minimise the environmental impact of their work. There is also always great pressure to increase operational efficiency, reduce costs and make best use of resources. Both topics are concerned with controlling waste. Environmental impact from construction plant is closely linked to the efficient use, or otherwise, of that plant and carbon accounting is a good way to show this.

Good construction practice will also reduce both waste and environmental impact. Examples of this are co-ordinated planning of the different workstreams, for example by workspace booking, and by making good quality workmanship a key objective: poor workmanship increases waste, costs and the carbon footprint.

**Embodied energy, slope engineering and the provision of transport infrastructure**

Embodied energy is defined as the total energy (in Joules) that can be attributed to the use of an item or component. For the construction industry, embodied energy includes the energy used in extraction of the raw materials from the earth; the processing of that raw material into finished products; transportation to suppliers and then on to site; the construction process; the demolition and recycling; and the construction and maintenance of any associated temporary works.

Quantifying embodied energy is important because it encompasses associated environmental impacts such as resource depletion and greenhouse gas emissions. Research into the relationship between embodied energy and carbon dioxide shows a high correlation: 1 GI of embodied energy produces 0.098t of CO₂ (CSIRO, 2007). The Inventory of Carbon and Energy (Hammond and Jones, 2008) provides detailed sources of embodied energy coefficient data for most materials encountered in slope engineering, drawn from a wide range of publications. To provide greater accuracy to the associated carbon dioxide emission coefficients, the authors have carried out their own estimations rather than apply a common conversion factor across the whole dataset. As far as practicable, coefficients similar or identical to those provided by Hammond and Jones are used in calculations in this paper.

There is thus an emerging knowledge base that can be used and applied to slope engineering, and generally into ground engineering activities. By establishing energy usage and associated greenhouse gas equivalents for geotechnical processes, a common vocabulary can emerge that will facilitate dialogue across disciplines. For example, the CO₂ emissions consequences of choosing to provide a new road, on a particular route, to provide better mobility around a congested town can be compared with the construction and maintenance emissions associated with the road design and construction (O’Riordan and Phear, 2009). The consequences in terms of emissions of shorter or longer construction times, and the associated processes to achieve them, can be explicitly provided.

Similarly, maintenance decisions and processes can be examined. Using multi-criteria analysis (MCA) techniques, in which quantifiable parameters are used explicitly, geotechnical processes can be put into the context of sustainable design, construction and maintenance practice that up until now has concentrated on the end-user’s behaviour inside buildings. Therefore, although there are no direct environmental impacts associated with embodied energy, this link to carbon dioxide suggests a context for interpreting embodied energy data.

Fundamentally, there is little absolute knowledge of the energy footprint of current ground engineering operations. Reid and Clark (2000) developed a whole life cost (WLC) model for earthworks slopes based upon available failure information. The implications of this work were that slopes as shallow as 1 in 5 could be justified on economic grounds. Different conclusions could be reached using MCA in which emissions and/or energy consumption parameters are introduced into the assessment. More recently, Workman and Soga (2004) evaluated the embodied energy associated with the tunnel construction between the Stratford and the St Pancras terminus of the Channel Tunnel Rail Link project. This work has been extended into activities generally into retaining wall design and construction, railway trackbed design and maintenance, and embankment construction on soft ground (Chau et al, 2007, and O’Riordan, 2009).

Hughes et al (in press) describe a “bottom-up” approach to the carbon accounting of earthworks using detailed plant movements, and soil treatment options that can be aligned with bills of quantities. Examination of current practice can produce counter-intuitive results. For example Harbottle et al (2008) examine the performance of five remediation projects and conclude that on an emissions basis, the “best” overall solution is to provide a cover system, rather than use geotechnical processes such as soil stabilisation or washing, bioremediation or transport to landfill.

Recent work in the US (for example, Chester and Horvath, 2009) highlights the importance of an holistic approach to the provision of new transport infrastructure. Figure 1 puts into context the relative contribution, in carbon and energy terms, of the construction of the infrastructure on which the transport operates. The calculations for fuel consumption are based upon lifetime figures. As an example, for a given road alignment, an optimised vertical profile which seeks to minimise changes in gradient and associated fuel consumption would yield substantial environmental benefits beyond the construction choices embedded in the construction of the road itself.

**Slope engineering**

O’Riordan and Phear (2009) examine the background of performance-based design in the wider context of earthworks at large and the same principles can be applied to slope engineering. The use of probabilistic methods to establish the adequacy of a design enables more efficient and economic solutions to be developed. Embankment and cutting stability can conveniently be treated in this way (see, for example, Reid and Clarke, 2000). Chau and Soga (2007) report on a Japanese study in which various ground treatment methods were considered for highway embankments in the Tokyo area that have to accommodate high seismic forces. The parameters studied are shown in Figure 2 and the outcome of EE calculations shown in Figure 3. SCP denotes sand column piles and DJM is a form of deep soil mixing using the “wet” process (Hanson et al, 2001). By combining these figures with the probability of failure of the selected treatment method, the design earthquake Chau and Soga report the relationship in Figure »
Carbon footprinting of reinforced soil (mechanical stabilised earth) and soil nailed solutions

It can be seen from Figure 3 that the choice of treatment, in terms of movement of natural soil slopes in embankments and cuttings involves little variation in total embodied energy. However, with reference to Figure 1 and the demonstrable dominance of vehicular fuel usage, flatter gradients for a road or railway than would arise from a conventional balanced cut and fill are likely to alter the total energy and carbon balance of a particular piece of infrastructure.

In urban and developed landscapes, there are land acquisition constraints (Highways Agency, 2001). Flatter gradients require deeper cuttings, hence engineered slopes such as those involving soil nailing, reinforced soil and similar measures, are employed to minimise take.

Figure 5 is taken from a comparative study of a simple 4.5m high engineered slope using reinforced soil (MSE) and an equivalent mass concrete wall reported by Rafalko et al. (2010).

Not surprisingly, the dominant component, 85% of the total, lies in the manufactured elements, including imported selected backfill for the MSE wall. The wall, located at Washington Dulles Airport, is 40m long and we find that the energy associated with manufacturing amounts to 21.5 GJ/m or 4.8 GJ/m² retained material for the MSE wall and 55 GJ/m2 or 12.2 GJ/m² retained material for the concrete gravity wall.

By way of comparison with a soil nailing solution for the manufactured elements, we can consider a similar geometry to that of Figure 5, and assume that the stand-up time for the natural ground is sufficiently long for such a solution to be used. The leading parameters are:

- 70 degree, 5m high retained slope in stiff clay
- 20mm diameter, 6m long galvanised steel nails at 1.5m c/c
- Nail grouted into a 150mm diameter drilled hole
- 150mm thick sprayed concrete facing with mesh reinforcement (A142 or similar).

Using Hammond and Jones (2008) we find an energy requirement of 6.9 to 9.6 GJ/m, or 1.2 to 1.6 GJ/m² retained material height, is associated with the soil nail solution, substantially lower than for reinforced soil and an equivalent gravity wall. Similar calculations can be repeated for the manufactured elements of crib and gabion walling solutions.

Conclusions

Sustainable practice in slope engineering, design and construction can play a significant part in reducing energy use and carbon emissions. Tools for the calculation of carbon and embodied energy are readily accessible and these enable design and construction choices to be compared and evaluated.

Performance-based design methods, in which probability of failure/increased maintenance during the design life can be established, are well suited to carbon and energy accounting methods presented herein. Choices can be made transparent and readily communicated across the multiple disciplines involved, and the public at large.

**Figure 4. Life cycle Embodied Energy for different aseismic ground treatment designs (Chau & Soga, 2007)**

**Figure 5. Comparison of Embodied Energy and other indicators for MSE and concrete gravity wall (Rafalko et al., 2010)**

**References**


Environment Agency (2007), Carbon Calculator for Construction Activities


Highways Agency (2001) Road Improvement Within Limited Land Take, Highways Agency Advice Note HA 85/01.


