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An embodied carbon and embodied energy appraisal of a section of Irish motorway constructed in peatlands

Alan R. Duggan [a], Bryan A. McCabe [a,b,*], Jamie Goggins [a,b], Eoghan Clifford [a,b]

[a] College of Engineering and Informatics, National University of Ireland, Galway, Ireland
[b] Ryan Institute, National University of Ireland, Galway, Ireland

HIGHLIGHTS

- A novel life cycle assessment methodology for road construction is presented.
- This determines the environmental impact in areas of highly organic soils.
- This was applied to an Irish case study where excavate-and-replace was used for peat.
- In the case study, the biggest embodied carbon (EC) component was excavated peat.
- Alternative ground improvement scenarios of soil-mixing and piling were examined.

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ABSTRACT

In addition to the customary drivers of cost and timely project delivery, embodied energy (EE) and embodied carbon (EC) have come to prominence in recent years as major design considerations in all aspects of large-scale road construction projects. An assessment of road construction necessitating the excavation or alteration of peat should consider the impact on carbon stored within the peat and the greenhouse gases potentially released. A methodology for calculating the environmental impact of constructing roads on peat is presented in this paper. Furthermore, the paper describes the application of this methodology (focusing on EE and EC calculations) to a case study; a section of the M6 motorway in Ireland for which excavate-and-replace was the ground improvement method (Scenario ER). A range of peat-related factors impacting on EE and EC estimates were examined, including materials, transport and machinery, as well as more unfamiliar factors such as peat drainage, drainage systems, restoration, slope stability and clearance of vegetation/forest. Comparisons of total EC are investigated under various management practices and restoration techniques for peatlands, assessing their strength in terms of hydrology and carbon storage potential. The total EC and EE for road construction to the sub-base level (and implications thereof) of the 2.14 km section of the M6 discussed in this paper was 17,220 tCO_2eq (8047 tCO_2eq/km) and 54,541 GJ (25,487 GJ/km), respectively, with carbon loss from excavated peat accounting for 62% of the total EC. Two other ground improvement method scenarios for constructing this section of road were also considered: Scenario S, soil-mixing and Scenario ER + P, an appropriate combination of excavate-and-replace and piling. Scenario S gave rise to a total EC of 25,306 tCO_2eq (11,825 tCO_2eq/km) and a total EE of 164,364 GJ (76,806 GJ/km) while Scenario ER + P gave rise to a total EC of 17,048 tCO_2eq (7966 tCO_2eq/km) and a total EE of 92,706 GJ (43,320 GJ/km). In this study, Scenario ER was the preferred technique as it had EC comparable to Scenario ER + P and the lowest EE. On the other hand, Scenario S was the least favourable due to the high EC and EE of the binder. However, this paper shows that the EC and EE can be decreased dramatically by changing the binder proportions. Furthermore, the EC of Scenarios ER and ER + P can also be significantly reduced if alternative restoration techniques are employed for excavated peat.

1. Introduction and context of research

In the decade 2000–2010, the length of motorway and dual carriageway in the Republic of Ireland approximately quadrupled to a

* Corresponding author at: College of Engineering and Informatics, National University of Ireland, Galway, Ireland. Tel.: +353 91 492021.
E-mail address: bryan.mccabe@nuigalway.ie (B.A. McCabe).

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total of 1200 km [1]. Given that peatlands account for 13.8% of Ireland's land area [2], it was inevitable that peat would be encountered in large expanses on some of these projects. For geotechnical engineers, peat represents a challenge because of its high moisture content, low shear strength and high compressibility (especially its propensity for long-term creep settlements). Some form of ground improvement is normally required when it is encountered on road projects. The favoured option for road construction in Ireland to date has been to excavate the peat, particularly where the depth is no greater than 3–4 m [3] and replace it with competent fill material. However, in some road projects in Ireland, depths greater than 4 m were excavated, with local excavations reaching depths of up to 13 m [3]. Piling, on the other hand, because of its high cost, has generally been used only where settlement control was paramount. Some projects have also considered dry soil-mixing, whereby a dry binder (typically some combination of cement and ground granulated blast furnace slag) is injected into the peat to create a stabilised platform, but in most cases it was not deemed commercially viable because of the large amounts of binder required [4]. Surcharging, another option, is not currently permitted for peat soils by the National Roads Authority in Ireland. The use of any of these methods for supporting roads necessitates the generation of a substantial amount of construction materials, leading to the depletion of natural resources, the emission of greenhouse gases and damage to the local environment due to construction operations.

Ireland has an obligation to reduce its annual non Emissions Trading Scheme (non-ETS) greenhouse gases emitted to at least 20% below 2005 levels by 2020 or face significant fines under the legally-binding EU's '20-20-20' initiative [5]. In 2005, the Irish construction sector was domestically responsible for the emission of 8.11 $MtCO_2eq$ [6], amounting to 11.7% of the country's emissions of 69.3 $MtCO_2eq$ [5], where CO_2 equivalents (CO_2eq) include not only CO_2 but also other greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O) and perfluorocarbons (PFCs), taking account of their global warming potential as set out in the Kyoto protocol. Global warming potential is based on the relative amounts of heat trapped in the atmosphere by greenhouse gas; for example, CO_2 and CH_4 have global warming potentials of 1 and 25, respectively [7]. It is anticipated that Ireland will violate its non-ETS annual greenhouse gas emissions commitments from 2016 onwards, exceeding its EU 2020 target by between 4.1 (11%) and 7.8 $MtCO_2eq$ (21%) [5]. To combat these soaring emissions and comply with regulations, it is vital to be in a position to produce accurate calculations of construction-related energy consumption and emissions, including the geotechnical elements of projects. This will enable engineers to appraise various options with a view to minimising environmental impacts.

Recently, the geotechnical profession has taken steps to quantify energy consumption and emissions for construction projects. Egan and Slocombe [8] investigated the embodied carbon (EC) of several piling options on a range of construction projects, while Chau et al. [9] examined the embodied energy (EE) associated with the construction of sections of a UK rail tunnel. Both Milachowski et al. [10] and Chappat and Bilal [11] estimated the environmental impact of constructing roads. However, despite the increasing demands for sustainable engineering practices, there is a dearth of life cycle assessment (LCA) studies, methodologies and figures for geotechnical projects. This probably accounts for the absence of guidelines on how to determine the potential construction-related emissions (at planning and design stages) associated with road construction in areas of organic soil such as peat.

In this paper, a LCA methodology is outlined which allows a quantitative comparison of the potential environmental impacts of various ground improvement options for road construction on peat, including excavate-and-replace (ER), dry soil-mixing (S) and piling (P). The methodology was applied to a study section of a recent Irish motorway project for which the excavation and replacement of peaty soil was the chosen solution (Scenario ER). Results for total EE and EC for this case study are calculated. Alternative ground improvement scenarios that could have been considered on the same site were also examined, i.e. soil mixing (Scenario S) and a combination of excavate-and-replace and piling (Scenario ER + P). Only aspects of the road construction to the subbase level and related implications were included in the calculations. Pavement layers were common to all ground improvement scenarios considered and were therefore excluded in the interests of clarity.

2. EC/EE considerations in peatlands

2.1. Construction in peatlands

Peat is a soft organic soil formed in high water table environments where the supply of organic material to the surface surpasses the rate of decomposition due to anaerobic conditions [12]. Consequently, peat accumulates over time, slowly taking in carbon from the atmosphere in the process. In Ireland's three main bog types (raised bogs, blanket bogs, and fens), undisturbed peatlands have been sequestering carbon for thousands of years, exerting a net cooling effect on the world's atmosphere. Many of these peatlands are now disturbed and are net sources of CO_2.

Using existing EE and EC methods, it might be expected that the excavate-and-replace option would be less energy/carbon intensive than soil-mixing and piling, as replacement of peat with fill such as quarried material is relatively cheap and environmentally friendly. The EE associated with producing the binder in soil-mixing and the cement for the concrete in piles is energy intensive because of the additional manufacturing stage and, in general, high EE activities engender high EC. However, the excavation process and the extent of drainage due to construction have a negative impact as a drained peatland releases its stored carbon as CO_2 and other greenhouse gases and thereafter loses its ability to sequester carbon [13].

The higher the organic content of a soil, the higher the potential for loss of carbon as CO_2. In the absence of organic content values, the Scottish Natural Heritage [14] proposed that the carbon content of peat may be estimated at between 49% and 62% of its dry weight. Using this method, the carbon content of peat having a typical dry density of 0.1 g/cm^3 would lie between 0.18 and 0.23 tCO_2eq/m^3. However, it is preferable to quantify the organic content of the peat by the loss-on-ignition method [15]. Schumacher [16] suggests finding carbon content by dividing the organic content values by a factor, which has been derived by experiment and ranges between 1.724 (representing 58% carbon) and 2.5 (representing 40% carbon). In general, the range of organic contents found in peat soils is greater than the range of carbon contents found in the organic matter, thereby justifying the latter approach [16].

2.2. Life cycle assessment (LCA)

Environmental LCA tools involve quantifying and evaluating the environmental burden associated with a product or process by considering energy and material uses and releases into the environment. LCA tools can be utilised to implement opportunities to decrease the environmental cost of road construction. A LCA includes four phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment, and (iv) interpretation [17]. Having defined the LCA goal, the following are identified in Phase 1: functional unit (e.g. tCO_2eq/m^3, tCO_2eq/t, tCO_2eq/km),