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Factors affecting embodied carbon and embodied energy associated with ground improvement techniques for construction on peat

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ABSTRACT: In addition to the traditional drivers of cost and timely programme delivery, embodied energy (EE) and embodied carbon (EC) have emerged as major considerations in all aspects (including geotechnical) of large construction projects. Foundation engineers are beginning to undertake comparisons of the EE/EC associated with various piling and ground improvement options as part of an overall appraisal of scheme feasibility. Where construction involves the modification or removal of peat, these calculations become more challenging as allowances should be made for the impact on the carbon stored within the peat and the gases potentially released from peat.

Using a calculator developed at NUI Galway, research is underway to consider the EE/EC associated with piling, soil-mixing and excavate-and-replace—options that can facilitate road/motorway construction on peat. Several high-profile motorway projects in Ireland will provide data for the analysis. Also, with the help of scientists presently measuring Greenhouse Gas (GHG) emissions from peat, the research will investigate GHG emissions from peat under various management practices, restoration techniques, and mitigation against drainage methods, assessing their strength in terms of hydrology and carbon storage potential. This paper summarises a literature review carried out to identify specifically the ‘peat-related’ factors that will impact upon EE/EC calculations on construction of a road/motorway on peat.

KEY WORDS: Embodied carbon; Embodied energy; Ground improvement techniques; Road; Peat drainage.

1 INTRODUCTION

Peatlands account for approximately 20% of Ireland’s land area [1]. The advent of significant motorway projects in Ireland in the first decade of the 21st century (such as the M6 Athlone to Galway section) has required geotechnical engineers to consider carefully how to deal with the large volumes of peat encountered along these routes. Challenges posed by peat for highway construction over peatlands include its high moisture content, compressibility and creep, and low shear strength, which necessitate the use of ground improvement options such as soil-mixing, piling and excavate-and-replace methods.

As stricter environmental regulations are introduced in Ireland, it is imperative that energy and emissions associated with road construction are calculated accurately. Examples of moves towards quantifying the emissions and energy associated with geotechnical processes in the UK include Egan and Slocombe [2] and Inui et al [3]. In this type of study, it is usual to look at the embodied energy (EE) and embodied carbon (EC) of a product. EE can be taken as the total primary fuel and material costs, together with the refining, distribution, storage and retail of finished fuels and materials [5]. Using the EE/EC calculator produced by McCaffrey [6], which totals inputs, these indirect inputs can be quantified as EE intensities (MJ/kg) and EC intensities (kgCO$_2$e/kg) for materials and transport energy costs. With the aid of the aforementioned calculator and life cycle inventories such as the ICE V2.0 [4], direct and indirect inputs can be accounted for. Nevertheless, even when indirect inputs are included, similar results of EE and EC can be expected in the cited ground improvement techniques.

Generally, high EE produces high EC: the more energy used in a construction project, the more gas emissions created. Construction in peatlands poses an additional complication. While its excavation and replacement with more competent fill seems greener than the other methods, the excavation process and the extent of drainage due to construction have a detrimental effect on the carbon stored within the peat. This carbon is now released from the peat as CO$_2$ and other GHGs, and the peat is no longer able to absorb carbon.

Where information giving comprehensive representations of the dynamics of gas emission and removal are limited, the Intergovernmental Panel on Climate Change (IPCC) and other organisations have provided basic figures to estimate emissions from damaged peatlands [7]. Both Nayak et al. [8] and Hall [9] used these basic assumptions to estimate the
carbon cost of building a windfarm on peat and examined the
issues of drained peatlands and forest removal associated with
construction. Up to now, only simple calculations have been
applied to some peat–related factors in EE/EC summations.
This paper highlights the need for a robust software tool to
perform a life cycle assessment (LCA) to quantify EE and EC,
a model to calculate more accurately the cost of drained
peatlands and forest removal. As well as explaining these and
other potential factors that influence EC, the paper suggests
some means of reducing the total EC in a road construction
project.

The estimation of EC as a consequence of a particular
method of road construction depends on a wide range of
factors and construction activities that are the subject of this
paper. These include the following: construction operations,
peat drainage, peat stability, restoration of peatlands,
vegetation/forest, and the effect of climate change. When the
preceding factors are taken into account in EC summations,
the choice of method to use for ground improvement must be
reconsidered.

2 ROAD CONSTRUCTION OPERATIONS ON PEAT

Road construction on peat comes at a high energy and
environmental cost. Surcharging, a ground improvement
 technique often used on soft soils is not used, as settlement in
peat is difficult to predict and the duration required for it to
impact significantly on secondary consolidation is excessive.
Other ground improvement techniques must be used.

Since the 20th century, excavate-and-replace has been
considered the most reliable method available of building
major roads on peat, a method that involves peat removal and
replacement with low EE fills such as aggregates, thereby
providing a more stable and stronger platform to build the
road [10]. Complete removal of peat is undertaken by
machine if its thickness does not exceed 3–4m [11]. Dredging
of this material is not usually energy intensive because of the
semi-liquid state of the peat.

In peat deposits of between 4–10m deep, excavation and
replacement may be considered too expensive. ‘Peat-left-in
place’ techniques are used instead [10]; i.e., soil-mixing and
piling. Soil-mixing is becoming increasingly common as a
method of ground improvement and works by injecting
suitable binders into the ground, such as cement or
combinations of cement and ground granulated blastfurnace
slag (GGBS) for peat [12]. The binder creates a homogenous
mass in the peat structure, which in turn solidifies to
strengthen the peat and reduce settlement. Although
expensive, piling tends to be used in situations where
settlement control is critical.

The above techniques all require the removal of some peat.
If removed, it can be dried and burned as a fuel, and it can be
assumed that it will emit all its carbon, thus dramatically
impacting on EC summations. Excavated peat can be utilised,
also, in the landscaping of roadsides, in filling in borrow pits,
and it can be dried for agriculture purposes or laid on both
sides of a road in peat disposal areas to restore the disturbed
peat. Under anaerobic conditions, it could potentially retain a
large percentage of its carbon content, but peat laid on the
surface to dry will lose a high proportion of its carbon as
GHGs, increasing substantially the EC total.

3 DRAINAGE AND ITS IMPACT ON EC

3.1 Introduction to drainage

The excavate-and-replace technique requires peat to be
excavated, allowing the usual sources of water to enter the
excavation; namely, ground, surface and rain water. Ground
water flow enters the excavation, necessitating drainage of
some of the surrounding peatland and resulting in a water
table drawdown [13]. Even when the excavation is filled with
materials, drainage is still occurring in the surrounding
ground. This is due to the installation of drains along either
side of the road, resulting in a permanent lowering of the
water table. The extent of drainage can vary from less than a
1.5m radius to greater than a 50m radius [8]. Drainage of a
peatland drastically alters the hydrological regime, leading
to significant water loss, loss of habitat structure and subsidence
of the peatland [14]. The extent of the water table reduction
around the road and its likely impact on gas emissions need to
be estimated so that it can be included in EC summations.

In the absence of detailed measurements of peat
hydrogeology on a level site with uniform soil distribution,
the extent of drainage on each side of the road can be
estimated using the regression equation below [8]:

\[ E = 11.958 \times \log(k) - 9.361 \] (1)

where E is the extent of drainage around the road (m) and k is
the hydraulic conductivity (mm/d).

In the case of soil-mixing and piling, little or no peat is
removed during the operations, but drainage is still prominent
because of the drains placed at either side of the road. In soil-
mixing, the natural water content of the peat to be stabilised
prior to mixing could be over 500%; but because of the
reaction of water with the binder, the water content reduces
significantly. This hydration process affects drainage, but the
extent has not yet been ascertained. Irrespective of the extent,
however, CO₂ is released from the stabilised and surrounding
peat. Piling, on the other hand, has very little effect on the
peat itself, apart from initially applying lateral pressures on
the upper layers and, consequently, expelling pore water and
causing possible heave. Some peat may dry because of this,
but the extent is not known either.

To lower CO₂ emissions and thus EC, there are methods
available to mitigate the extent of drainage on the surrounding
peatland; such as, the installation of low permeability peat
plugs along a road, described by Gill [15].

3.2 Carbon dioxide

The addition of organic matter to the peat surface on pristine
peatlands exceeds decomposition losses as a result of
anaerobic conditions created by the high water table [16].
Consequently, peat gathers carbon and restricts aerobic decay.
Over centuries, intact peatlands slowly remove and store more
carbon from the atmosphere than they produce, exerting a net
cooling effect on the global climate [1]. Near-intact peatlands
in Ireland may sequester on average only 0.21 MtCO₂/yr as
80-95% of organic matter is still decomposed by aerobic
bacteria [17, 18]. Construction of a road will drain the nearby
peatland and reverse the peat storing process into emitting
carbon as CO₂.
Methane

Drained peat allows stored carbon to readily decompose due to the aerobic conditions created, releasing a substantial amount of CO₂, the level of which will need to be accounted for. CO₂ emissions vary mostly according to depth to water level, peat depth, and temperature [19]. Due to peat oxidation in the aerobic layer, intensified by the lowering of the water table, an area of raised bog damaged by extraction or cutting may emit as much as six to seven times more CO₂ than in a near-intact peatland [1]. Currently, damaged Irish peatlands may emit an estimated 9.68MtCO₂/yr [17]. The reason for such a large figure is that up to 100% of organic matter may decompose in the deep aerobic layer, in addition to organic matter that has been stored for many years. It is imperative that this accounted for in EC calculations.

3.3 Methane

Undrained healthy peatlands have negative effects, too, as CH₄ emissions are released in an intact peatland. CH₄ has a global warming potential (GWP) of 25 meaning that a large amount of heat is trapped in the atmosphere relative to CO₂, which has a GWP of 1 [19]. CH₄ can be released by three processes: diffusion across the air-water interface, bubble emissions, and transport via vascular plants (Figure 1) [7, 21].

![Figure 1. Methane release from a peatland site [22, 23].](image)

The IPCC [7] suggests that when conducting a basic calculation of CH₄ emissions it is satisfactory to count diffusive emissions. During cold periods when peat is frozen, CH₄ emissions are negligible [7, 23]; therefore, it is important to factor this into EC calculations. The IPCC have not released guidelines for calculating CH₄ emissions because pristine peatlands are not anthropogenic and, as such, are not relevant under the United Nations Framework Convention on Climate Change (UNFCCC) [22]. Restoration of a peatland, which may take place after road construction is, however, anthropogenic and must be reported. The emission factors shown below, produced by Couwenberg [22], are based on climate, water table, and vegetation.

Table 1 shows the necessity of calculating CH₄ released from restoring peatlands as part of road construction.

<table>
<thead>
<tr>
<th>Water table</th>
<th>Carbon dioxide</th>
<th>Methane</th>
<th>Nitrous Oxide (low emissions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undrained</td>
<td>18, 25-44</td>
<td>(18, 25)</td>
<td>(18, 25)</td>
</tr>
<tr>
<td>Drained</td>
<td>18, 25-40</td>
<td>(18, 25)</td>
<td>(18, 25)</td>
</tr>
<tr>
<td>Temperature</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>pH Low (&lt;7)</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Weather Wet</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Season</td>
<td>Winter</td>
<td>Summer</td>
<td>Summer</td>
</tr>
<tr>
<td>Vegetation</td>
<td>None</td>
<td>Vascular</td>
<td>Vascular</td>
</tr>
</tbody>
</table>

Note: Negligible: zero to low release except for nitrous oxide where negligible is close to zero release; medium to high release except for nitrous oxide where release is small.

3.4 Nitrous oxide

N₂O is even more damaging to the atmosphere than CH₄ and has a GWP of 298. N₂O emissions depend on many factors, not just on the water table position. Glatzel et al. [27] found N₂O release was higher at the edge of site than the centre despite the lack of a difference in water table. Factors influencing N₂O emissions include the presence of organic nitrogen, the degree of humification, the presence of vascular vegetation and pH [28]. Drainage permits bacteria to convert the organic nitrogen in peat to nitrates, which are then carried by leaching to the surface where they are finally reduced to N₂O [7]. According to Glatzel et al. [27], only cultivated or drained peatlands release >100μgN₂O m⁻² h⁻¹. Although it may seem that N₂O release should be highest in summer because of drier weather, N₂O release is negligible due to competition among plants for uptake of excess nitrogen and NO₃ [29,30].

N₂O emissions from Irish oligotrophic (nutrient-poor) peatlands are small or negligible because of their low nitrogen concentration [31]. Consequently, this is not a significant factor in emissions from road construction in Ireland, unless the site is a nutrient-rich fen. Klemedtsson et al. [32] reports that significant N₂O emissions can occur if the C/N ratio drops below 25; otherwise, they should be considered negligible in calculations.

In addition to the level of the water table, other factors such as peat properties, vegetation, weather and temperature will influence emissions. Table 2 lists research from several authors showing how each factor influenced emissions.

3.5 Peat stability

Soil disturbance should be minimised to prevent establishing aerobic conditions, which are ideal for decomposition and, therefore, the release of CO₂. There are many factors that may reduce the stability of the peat and impact on EC summations.
Water is the main cause of slope instability and acts in reducing the shear resistance of the underlying layer. Loading of the underlying material by saturation of the overlying layer may exceed the frictional resistance of the soil, causing it to fail. In peat excavate-and-replace, the water content of the peat on the excavation slope may exceed its liquid limit and collapse. Peat translational slides tend to occur where the slide’s base meets the peat-substrate interface because natural lines of drainage exist along this interface [33]. Artificial drainage lines may induce shear stresses and cause potential failures; so, too, can the presence of water in cracks, which are indicative of compression and tension [34, 35]. Peat stability may be critical in all drained peatlands, a potential factor to be considered after applying any of the three ground improvement methods mentioned. As a result of drying, cracks will start appearing, decreasing the peat’s strength to potential failure in heavy rainfall, as shown in Figure 2.

Figure 2. Typical water ingress through peat matrix [13].

The loss of surface vegetation due to construction leaves the peat surface fragile and without sufficient tensile strength [35]. Furthermore, loading of the peat mass by heavy machinery, structures, or overburden causes an increase in shear stress. Until pore pressures dissipate, peat stability is at its most vulnerable [13].

Peat stability and peat failures must be taken into account in the summation of emissions. Peat failures in blanket bogs and peat disposal areas due to construction have raised questions about the ability of the Environmental Impact Assessment (EIA) to fully assess the likely environmental impacts [1]. Blanket bogs are more prone to peat collapses than raised bogs because of their formation on slopes. Most slides occur in slope angles of 2-20°, where 20° appears to be the limiting gradient for deep peat [13]. Peat erosion has in the past decade been cited as a significant factor in losses of carbon due to peat disposal areas due to construction have raised questions about the ability of the Environmental Impact Assessment (EIA) to fully assess the likely environmental impacts [1]. Blanket bogs are more prone to peat collapses than raised bogs because of their formation on slopes. Most slides occur in slope angles of 2-20°, where 20° appears to be the limiting gradient for deep peat [13].

3.6 Restoration

Any improvement plan for restoring a peatland that has suffered because of road construction should demonstrate a high probability that peat hydrology will be restored, disturbance of peat minimised, and subsidence stopped [14]. Peatlands often have complex modes of water transport, and identifying these pathways is crucial if saturated conditions in the peat and its dependent ecology are to be restored to their original status of sequestering carbon.

To restore peatlands, simple techniques are used. Drains can be blocked to promote rewetting after construction [15]. Soft rushes and sphagnum can be planted to bind the peat together, which leads to a complete cover and stabilisation of the introduced peat [38]. Shade can be provided to lower the temperature and increase relative humidity near the surface, impacting on CO2 and CH4 emissions and thus EC. These techniques can be also used for peat disposal sites.

3.7 Vegetation/Forest

Another common practice after road construction is to continue drainage on disposal sites and drained lands and to plant trees on these sites. During the first few years, a net CO2 release occurs due to the exposure of soil carbon to aerobic conditions, but the uptake of carbon in vegetation and trees will somewhat offset oxidation losses. In 4–12 years after restoration, the site will become a net sink, the changeover varying according to vegetation dynamics, climate, peat depth and type, and site productivity [39]. This timeframe for emissions is shown in Figure 3. CH4 emissions will cease due to increasing aerobic conditions in the peat profile. In addition to this positive EC impact, the average loss of carbon due to decomposition decreases from 1 to 14.6tCO2·ha−1·yr−1 in the first rotation to a smaller figure after two or three rotations, which means that more carbon will be stored in the peatland forest annually [40]. During the first few rotations, though, some subsidence takes place depending on the bulk density of the peatland. Lindsay [23] found that this occurrence may extend up to 50–60m around the forest with time, somewhat draining the adjacent land and, inevitably, increasing GHG emissions.

![Figure 3. GHG balance of peatlands following afforestation. Values represent an annual flux of CO2/ha][39].](image)

For construction itself, it may be necessary to clear a forest, resulting in a CO2 loss, although the amount of carbon loss depends on the type of tree, the age of crop on felling and the end use of the timber. A drained peatland cleared of forest continues to release CO2. However, the trees are no longer present; therefore, there is no carbon uptake, which means a net loss of CO2 is taking place and must be accounted for [39]. It is essential, also, to evaluate the carbon and nitrogen content of the biomass layer as well as the peat [23]. The clearance of vegetation such as sphagnum and vascular plants due to road construction can lead to GHG emissions. Vegetation is a source of carbon and nitrogen and, if destroyed, harmful gases are released [41, 42]. Lindsay [23],
suggested that a 15 cm sphagnum layer has a carbon content of 183.3tCO₂/ha, while a damaged peatland dominated by vascular plants is thought to have a lower carbon content of 36.7tCO₂/ha. The reason for the difference is that the greater resistance to decay of sphagnum compared to that of vascular plants allows undecayed material to pass to the anaerobic zone, where the decomposition is so slow that peat accumulates carbon [23]. It would be advisable, therefore, to plant sphagnum rather than vascular plants to reduce EC.

4 VARIABILITY IN PEAT AND UNCERTAINTY OF EMISSIONS

As stated earlier, each peat site is different in climate, landscape, properties and characteristics. Aggregated emission factors from the IPCC only estimate emissions from an undrained or drained peatland and nothing in between; consequently, in calculating emissions from a near-intact peatland, there is little guidance. Site-specific equations developed by Nayak et al. [8] can be used to estimate GHG emissions from peat more accurately. Even with these, there are substantial inaccuracies in relation to emissions. For example, CH₄ takes at least a month to revert to producing emissions after restoration because of suppression of CH₄ due to methanogens requiring a long regeneration period following exposition to aerobic conditions [27, 44].

It is significant that peatland restoration over a short period of time may lead to higher GHG emissions than if it were in a drained state. The peatland may still be releasing CO₂ through the aerobic layer and, simultaneously, releasing CH₄ from rewetting areas, though CH₄ emissions will not generally exceed the emission levels of the original natural state [23]. A rising water table then stimulates growth of sphagnum and other vegetation, increasing carbon accumulation, raising the surface of the peatland and, in effect, lowering the water table, which leads to a slight decrease in CH₄ release. A near-intact peatland may be mildly contributing to climate change or global cooling on a 100 year timeframe [23]. It would appear crucial, therefore, that new published EC summation models take the above factors into account.

A sphagnum-rich peatland is likely to be beneficial to climate change, even if CH₄ is more damaging than CO₂. When CO₂, CH₄, and N₂O are discussed, it is vital to bear in mind that CO₂ is the biggest emitter even when GWPs are taken into account as shown in Table 3. Drained peatlands, therefore, should be avoided in road construction.

As climate change will have an impact on GHG release on peatlands affected by road construction, Holden et al. [45] predicts that temperatures will rise by about 1.68°C in Ireland by 2075. High rainfall sites will become more seasonally extreme through a decrease in rainfall in spring and summer and a slightly wetter autumn and winter.

5 PEATLAND’S RESPONSE TO CLIMATE CHANGE

Climate change will have an impact on GHG release on peatlands because of increased temperatures and lower water tables [21]. Additionally, the carbon cycling of degraded peatlands may be more affected by global warming and future climate changes than healthy peatlands, signalling the importance of peat restoration.

The annual range of CH₄ emissions seems to be strongly related to temperature. Higher CH₄ fluxes occur in years with the warmest and coldest seasons [16]. With climate change, this aspect warrants consideration.

Researchers have produced climate models showing that evapotranspiration will lead to a 100% increase in CO₂ emissions from peatlands because of increased temperatures and lower water tables [21]. Additionally, the carbon cycling of degraded peatlands may be more affected by global warming and future climate changes than healthy peatlands, signalling the importance of peat restoration.

The annual range of CH₄ emissions seems to be strongly related to temperature. Higher CH₄ fluxes occur in years with the warmest and coldest seasons [16]. With climate change, this aspect warrants consideration.

Nitrogen deposition is anticipated to increase [46]. N₂O fluxes were found to be high by Glatzel et al. [27] because the site in question had a history of drainage, experienced high atmospheric input and a rapid fluctuation in water table, which could be part of climate change and more extreme weather [46]. Dowrick et al. [47] furthered this notion by showing that an extreme drought caused an exponential increase in N₂O release compared to a moderate drought (water table at 8 cm below the surface).

If warm and dry weather occur prior to prolonged rainfall, peat that shrank and dried will not return to its original condition on rewetting. Alternating dry and wet weather periods puts great stress on the peat and may result in failure due to loss of shear strength [37], leading to further CO₂ emissions. Table 4 shows that the top metre of soil generally holds the most carbon, highlighting why erosion of the top surface must be stopped immediately and the peatland restored to ensure that this high level of carbon is not released as CO₂. Climate change is likely to have a negative impact on the environment and will increase EC.

Table 3. Rank of importance of GHG emitters.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Emission release generally dealt in (g, mg, μg) per m² per day</th>
<th>Rank</th>
<th>GWP</th>
<th>Effect on Environment (g, mg, μg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.001</td>
<td>2</td>
<td>25</td>
<td>0.025</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.0000001</td>
<td>3</td>
<td>298</td>
<td>0.000298</td>
</tr>
</tbody>
</table>

6 CONCLUSIONS

- A more accurate model for estimating EC and EE from construction on peat must be developed, taking all peat-related factors into account and using the most accurate databases and calculators available. The model could guide engineers in deciding which ground improvement techniques to use on a proposed road on peat, as well as how to mitigate environmental effects as more legislation is enacted.
- Large reductions of CO₂ and N₂O emissions can be achieved through restoration and rewetting of peatlands.
- Methods of mitigating lateral drainage need to be more thoroughly investigated in order to cut emissions.
- Afforestation could play a key role in the aftermath of peat disposal and drainage. As the need for timber increases, trees could be planted on drained peatlands and sustainably managed. Over the course of a tree’s lifespan, the area would lower CH₄ release and take in carbon, offsetting the carbon released from peat.
- Site-specific data could be used to enhance estimations of emissions.
ACKNOWLEDGMENTS

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