Quantifying the carbon footprint of coastal construction – a new tool HRCAT

Rudi Broekens[1], Manuela Escarameia[1], Clemente Cantelmo[1] and George Woolhouse[1]

[1] HR Wallingford, Wallingford, United Kingdom

Published in the proceedings of ICE Coastal Management Conference 2011, 15-17 November 2011, Belfast

Introduction

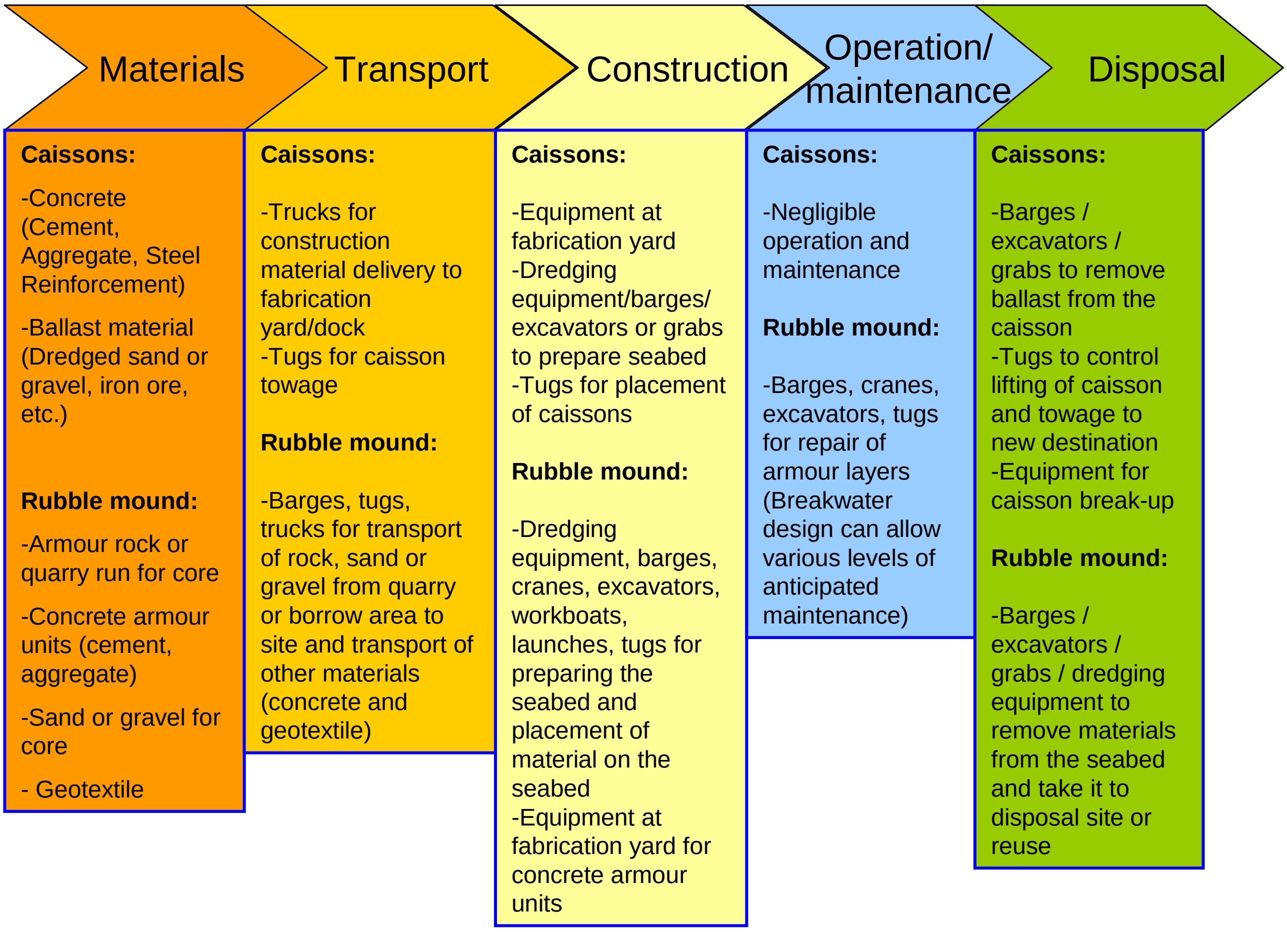
UK and European regulation aimed at achieving a low carbon society is currently not being sufficiently backed up by tools for the quantification of construction-related carbon emissions. Recent UK Government findings have highlighted that the amount of carbon emitted by construction and maintenance of infrastructure is largely unknown and that consistent carbon accounting is needed (BIS, 2010). It is expected that carbon accounting will become a standard requirement for engineering option appraisal and for any investment justification (be it project specific or at a national scale). Coastal schemes are no exception. Existing tools such as the Environment Agency Carbon Calculator are useful for the UK river and coastal protection market but currently lack the breadth of data and functionality required for the wider range of coastal construction works and for overseas schemes.

This paper explains the process of development of a new carbon accounting tool suitable for coastal construction schemes, illustrating its application on a real breakwater option appraisal.

Development of carbon accounting tool – HRCAT

HR Wallingford has developed HRCAT, a new tool for detailed estimation of carbon emissions of a range of construction schemes including coastal structures such as breakwaters and quay walls, and river and coastal protection (as well as conventional drainage and SuDS – Sustainable Drainage Systems). The development of the tool was underpinned by a thorough assessment of existing regulations and relevant documents, available literature and existing tools (EA, UKWIR, WRAP, Cap$_2$IT). This led to a methodology setting up the required boundaries and steps for the estimation of the carbon footprint of a scheme. Process maps were developed for each of the main subject areas (Figure 1), identifying the individual contributions to the total carbon emissions of the construction materials, transport to site, construction activities, operation and maintenance and disposal at the end of the scheme's design life.

An extensive dataset was gathered from reliable databases such as the Inventory of Carbon & Energy v1.6a (Hammond & Jones, 2008), complemented by manufacturers' own sources when available, the UK Defra/DECC's GHG (Green House Gases) Conversion Factors (Defra/DECC, 2009), as well as data specifically sourced for concrete armour units and rock, and construction and maintenance equipment (land and marine based) including dredgers. A critical assessment of the data was a vitally important aspect of the work to ensure consistency and reliability in the results. In some instances, literature values required some re-calculation before they could be used in the tool, for example to avoid double counting of costs.



	Materials	Transport	Construction	Operation/ maintenance	Disposal
Caissons:	-Concrete (Cement, Aggregate, Steel Reinforcement) -Ballast material (Dredged sand or gravel, iron ore, etc.)	-Trucks for construction material delivery to fabrication yard/dock -Tugs for caisson towage	-Equipment at fabrication yard -Dredging equipment/barges/ excavators or grabs to prepare seabed -Tugs for placement of caissons	-Negligible operation and maintenance	-Barges / excavators / grabs to remove ballast from the caisson -Tugs to control lifting of caisson and towage to new destination -Equipment for caisson break-up
Rubble mound:	-Armour rock or quarry run for core -Concrete armour units (cement, aggregate) -Sand or gravel for core - Geotextile	-Barges, tugs, trucks for transport of rock, sand or gravel from quarry or borrow area to site and transport of other materials (concrete and geotextile)	-Dredging equipment, barges, cranes, excavators, workboats, launches, tugs for preparing the seabed and placement of material on the seabed -Equipment at fabrication yard for concrete armour units	-Barges, cranes, excavators, tugs for repair of armour layers (Breakwater design can allow various levels of anticipated maintenance)	-Barges / excavators / grabs / dredging equipment to remove materials from the seabed and take it to disposal site or reuse

Figure 1: Process map for coastal protection using breakwaters

In the next sections a case study for estimating the carbon footprint of a breakwater construction project during an option appraisal phase is presented. Two different breakwater types are compared and a critical discussion of underlying data on carbon emissions associated with material use and construction activities is made. The paper focuses on a few key items – for an exhaustive discussion see Escarameia *et al* (2011).

Case study – breakwater

Description of scheme

This breakwater forms part of a marine terminal to be built in a remote overseas location with a design life of 50 years. It is detached from the shoreline and provides shelter to berths for ships used for the export of fossil fuels. Its length is approximately 1.4 km and the average seabed level is approximately 14 m below mean sea level. After an initial assessment of various forms of construction of the breakwater, the following breakwater types were selected for a further option appraisal:

1. a rubble mound breakwater using rock for the breakwater core and filter layers and a primary armour formed by concrete armour units in a single layer
2. a concrete caisson breakwater ballasted with sand and placed on a shallow rock foundation mound.

At the time of the option appraisal no suitable quarry for production of rock had been identified and rock was assumed to be produced in quarries at an average distance of about 500 km from the construction site. It was assumed that transport of rock from quarry to site would be carried out over land using trucks with a 32 tonne payload, which would be fully loaded when carrying rock from the quarry to the site and would be empty when returning to the quarry. Concrete caissons were assumed to be fabricated off-site and transported over sea to the site over a distance of about 2500 km. Sand for ballasting of caissons was assumed to be won in a near-by marine borrow area using dredging equipment. Figure 2 shows a schematic of the two breakwater options.

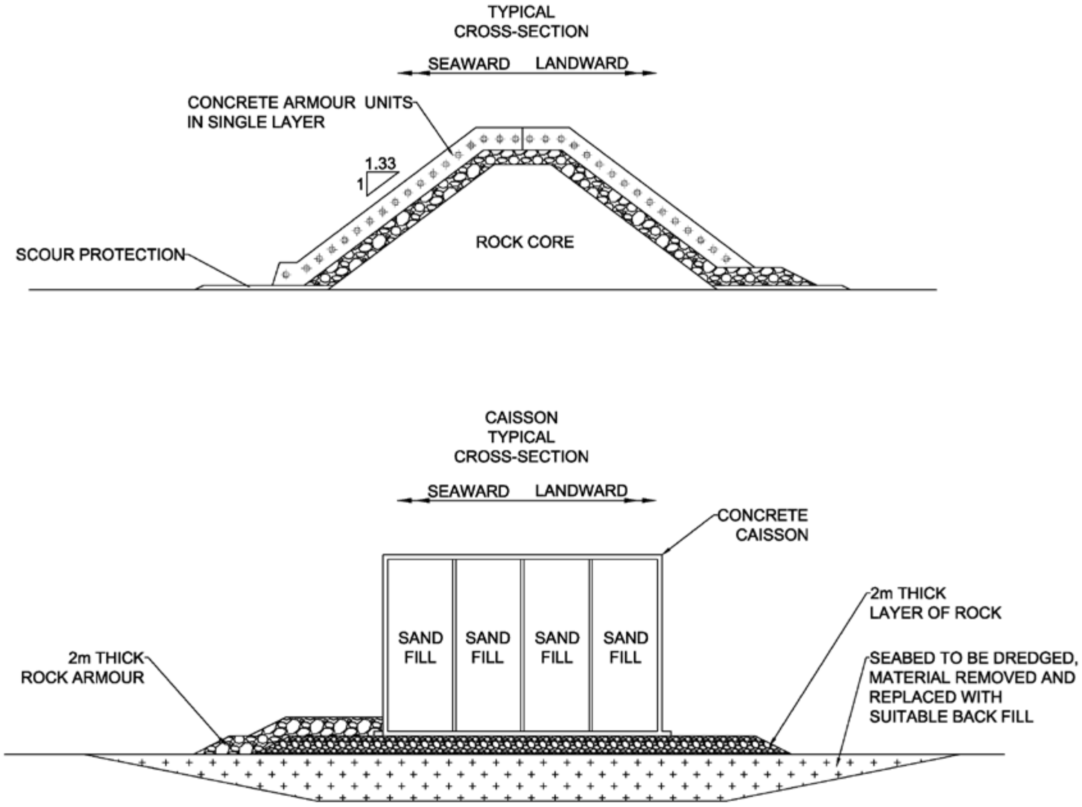


Figure 2: Schematic of breakwater options

HR Wallingford’s methodology

A process map for breakwaters has been developed and is presented in Figure 1. As the present case involves an option appraisal at an early design stage, a “cradle to built asset” approach was used (maintenance, operation and disposal were not included in the assessment as these were assumed not to have a significant effect on the outcome of the appraisal). In practice breakwaters, like other large structures such as bridges, are not normally disposed of completely at the end of their design life, but establishing the carbon footprint of disposal (which may not be insignificant) may be relevant in a more detailed option appraisal exercise.

A detailed description of definitions of various parameters associated with carbon footprinting used in available literature is provided by Escarameia *et al* (2011), as well as a description of exclusions (e.g. CO_2 emissions in manufacturing of equipment used for breakwater construction have not been taken into account). It is also noted that both CO_2 and CO_{2e} (equivalent CO_2) are being used in published literature, the latter taking into account green house gases other than CO_2. HRCAT currently does not make a distinction between CO_2 and CO_{2e}, as at present there is insufficient clarity in the available data to make such a distinction.

The carbon emissions associated with the construction of the breakwater have been divided into three main categories:

- production of materials to be used in construction
- transport of materials from where materials are produced to the breakwater site
- construction of the breakwater.

For production of materials the emission is calculated by multiplying the rate of embodied carbon (EC) per material quantity (e.g. $kgCO_2$/tonne) and the estimated total quantity in the scheme. Similarly, the emission associated with transport of materials is calculated by multiplying a rate of EC per quantity of equipment use and the quantity of equipment use. For road transport (trucks) the rate of EC per quantity of equipment use has been defined as $kgCO_2$ per travelled distance. For sea transport this rate has been defined as $kgCO_2$ per energy use ($kgCO_2$/kWh). The latter method has often also been used for calculating emissions related to construction equipment.

Discussion of data values

Material: Rock

A literature search on the carbon emissions associated with production of armour rock or quarry run that are typically used for breakwater construction indicated limited current knowledge. Hammond & Jones (2008) present an embodied carbon (EC) value for “general stone” of 56 $kgCO_2$/tonne. It is not certain whether this value is supposed to be representative of armour rock or of quarry run (or both) and the authors note that data on stone is generally poor. The authors also present values for granite and limestone, both of which can be used for armour rock or quarry run in coastal construction projects. For granite, a wide range of values is presented from 6 to 781 $kgCO_2$/tonne whereas for limestone a value of 17 $kgCO_2$/tonne is given. The upper limit for granite however applies to dimension stone and is based on values presented by Lawson (1996). Therefore this upper limit is most likely not representative of production of armour rock or quarry run. No context for the value for limestone was found.

For a better understanding of the carbon emissions associated with armour rock and quarry run it is necessary to consider the production process in somewhat greater detail. Rock for breakwater construction is typically sourced in either aggregate quarries, dimension stone quarries or dedicated armourstone quarries (CIRIA/CUR/CETMEF, 2007). Carbon emissions for the production of rock may vary significantly depending on the type of quarry that is used. For instance, in a dimension stone quarry, where armour rock is recovered from waste resulting from the production of dimension stone, the EC for production of armour rock is small since most of the energy use of the quarry is taken into account in the production of dimension stone. The EC of rock produced in a dedicated armourstone quarry may be larger than for a dimension stone or aggregate quarry, as there will be energy use associated with setting up the quarry e.g. removal of overburden and there may be energy use associated with the production of waste material, i.e. rock with unsuitable grading. Finally it should be noted that the type of rock (e.g. granite, basalt or limestone) may also affect the EC value.

Some guidance on dimension stone quarries can be derived from EC values of natural dimension stone published by Historic Scotland (2010), indicating that for granite stone the total “cradle to gate” value is 93 $kgCO_{2e}$/tonne, including cutting, polishing, internal transport on site and production of stone waste. The data also indicates that most of the emissions originate from processing the stone (i.e. cutting and polishing) and that only about 20 $kgCO_{2e}$/tonne is associated with extraction at the quarry. It may be argued that if armour rock resulted from waste produced at such a quarry, a value significantly lower than 20 $kgCO_{2e}$/tonne could be achieved. Data provided by STEMA Shipping (2011), distributors of armour and core rock in Northern Europe from a dimension stone quarry in Larvik (Norway) suggest a low value of 0.87 $kgCO_2$/tonne for production of armour rock and 0.99 $kgCO_2$/tonne for production of core rock. A slightly smaller value for armour rock is suggested than for core rock because no crushing is involved in its production.

No specific EC value for rock from an aggregate quarry has been found. For the purpose of the present case study it has been assumed that the EC value for rock from an aggregate quarry is similar to the value of aggregate produced in the same quarry. Hammond & Jones (2008) present a value of 5 $kgCO_2$/tonne for aggregate. Also no data has yet been found on dedicated quarries nor has a clear understanding been developed on the effect of the type of rock on EC estimates. For the present case study a value of 5 $kgCO_2$/tonne was adopted for both armour rock and quarry run, being within the range of values found.

Material: Concrete

As can be seen in data published by Hammond & Jones (2008), the carbon footprint of concrete is strongly dependent on the following factors:

- the compressive strength class of concrete (the underlying reason for this dependency is that cement has a higher EC value than aggregate and that usually a higher cement content is required for concrete with higher compressive strength)
- the amount of cement additions, such as fly ash or ground granulated blast furnace slag (ggbs)
- the amount of steel reinforcement.

Therefore it is important to consider the above factors when developing the EC estimate for concrete material use. Two different structural concrete elements are present in the case study: concrete armour units in the rubble mound option and concrete caissons in the caisson option.

Various types of single-layer concrete armour units may be used for construction of a rubble mound breakwater and their design and construction specification is usually controlled by various licence holders. At the option appraisal stage the required concrete specifications were not available. It has been assumed that a concrete compressive strength class of C25/30 will be required for the armour units. For the amount of cement additions, a low and a high amount of cement additions were selected representing a range suitable for concrete in a marine environment (CIRIA 2010). EC values were calculated using data in Hammond & Jones (2008) - see Table 1. Usually armour units are not reinforced and therefore no additional EC component for steel reinforcement was added.

Table 1: Characteristics of cement for concrete armour units

Cement type	Assumed addition material and percentage	Compressive strength class	EC value unreinforced concrete ($kgCO_2$/tonne)
CEM II B - V	21% fly ash	C25/30	112
CEM III B	80% ggbs	C25/30	51

The Table indicates that the lower limit of the EC range is approximately half the value of the upper limit. The lower limit compares well with the value presented by Van der Horst *et al* (2007) of 110 $kgCO_2/m^3$ (approximately 46 $kgCO_2$/tonne) for the use of CEM III B cement for the fabrication of Xbloc® armour units. Due to the lack of specification, for the present case study an average value of 80 $kgCO_2$/tonne was adopted.

Caissons are usually built using reinforced concrete and a typical concrete strength class of C40/50 was assumed. Again two types of cement were considered in order to establish a range of EC values for reinforced concrete. From experience on similar projects, it was assumed that the amount of steel reinforcement is approximately 0.3 tonne/m^3concrete. EC values were calculated using data in Hammond & Jones – see Table 2.

Table 2: Characteristics of cement for caissons

Cement type	Addition	Compressive strength class	EC value unreinforced concrete ($kgCO_2$/tonne concrete)	EC value steel reinforcement ($kgCO_2$/tonne*)	EC value reinforced concrete ($kgCO_2$/tonne concrete)
CEM II B - V	21% fly ash	C40/50	138	216	354
CEM III B	80% ggbs	C40/50	60	216	276

*EC values are in $kgCO_2$ per tonne reinforced concrete

The Table indicates that the EC value for steel reinforcement is the dominant element for reinforced concrete. For the case study an average value of 300 $kgCO_2$/tonne was adopted for reinforced concrete.

Transport: land transport of rock

The CO_2 emissions associated with truck transport were calculated using data on emission factors for freight transport provided by DEFRA/DECC (2009). This source presents data for carbon dioxide emissions per km for various diesel HGV road freight vehicle classes - see Table 3.

Table 3: CO2 emissions for road transport

	0% weight laden	100% weight laden	Average
Rigid truck (>17tonne)	0.96 (kgCO2/km)	1.38 (kgCO2/km)	1.17 (kgCO2/km)
Articulated truck (> 33tonne)	0.85 (kgCO2/km)	1.40 (kgCO2/km)	1.13 (kgCO2/km)

Table 3 indicates that the emission rates per km for the two different truck classes are similar. Based on the above numbers a value of 1.1 $kgCO_2/km$ was adopted for the case study.

Construction: land based equipment

Land based equipment required for breakwater construction includes wheel-loaders, bulldozers, cranes and excavators. Carbon emission data for land based equipment were taken from the Department of Transport (2004), indicating a fuel consumption rate in terms of grams of diesel per amount of applied power for various types of equipment. It was concluded that the variability of these rates for the various types of equipment is fairly small. The average value was about 260 g diesel/kWh (about 1 $kgCO_2/kWh$). The above reference further provides information on typical loading factors (i.e. the ratio between rated power of equipment and applied power during use of the equipment) for various types of equipment, again indicating a fairly small variability for typical construction equipment and a best estimate of about 30% for most types of plant.

The World Ports Climate Initiative (2009) presents a methodology for estimating greenhouse gas emissions associated with the construction of new port facilities. Their methodology is essentially similar to the one adopted for the present case study as are the EC rates of construction equipment (for example the applied rate for use of a bulldozer is only about 10% higher than the rate used in the present case study).

Construction: Marine equipment

For application of marine equipment the same methodology was used as for land based equipment. Typical loading factors for marine equipment including workboats (45%), tugboats (31%) and ocean tugs (68%) have been presented by the World Ports Climate Initiative (2009). An approximate emission rate of 0.65 $kgCO_2/kWh$ was adopted for these types of marine equipment, also based on the above data.

Results

Using data values as those described in the previous section, estimates of the carbon dioxide emissions were made for the two breakwater options – see Tables 4 and 5.

Table 4: Summary of EC for various construction materials

		Rubble mound breakwater		Caisson breakwater	
Material	**EC ($kgCO_2$/tonne)**	**Quantity (tonne)**	**EC (million $kgCO_2$)**	**Quantity (tonne)**	**EC (million $kgCO_2$)**
Rock	5	3,650,000	18.3	510,000	2.6
Concrete (armour units)	80	550,000	44.0		
Concrete (caissons)	300			342,000	91.8
Sand	2*			1,300,000	2.6
Total			**62.3**		**97.0**

* includes transport from borrow area to breakwater

The EC contribution of the use of geotextile was found to be negligible.

Table 5: Carbon footprint of different breakwater types

	Rubble mound with concrete armour units	Caisson
Materials (million kgCO_2)	62	97
Transport (million kgCO_2)	133	76
Construction (million kgCO_2)	17	15
Total (million kgCO_2)	**212**	**188**

It is concluded that for the selected case study the caisson breakwater has a smaller carbon footprint than the rubble mound breakwater with concrete armour units, mainly due to a large contribution of transport for the rubble mound breakwater, associated with road transport of rock over a long distance. For the caisson breakwater option the use of reinforced concrete is the dominant element in the carbon dioxide emission estimate. It should however be noted that these results are strongly dependent on specific circumstances for the present case study that affect the design of the breakwaters (e.g. the average water depth) or the breakwater construction (e.g. the distance between rock quarry and breakwater site). Therefore it cannot be concluded that in any option appraisal the caisson option will have a smaller carbon footprint than the rubble mound option. The results also indicate that the contribution of construction related emissions is fairly small. At this point this is not fully understood and a carbon footprint estimate for a case study in the detailed design or construction phase would be helpful to gain a better understanding of these emissions.

Uncertainty

HRCAT enables an estimation of the level of uncertainty in predictions as a qualitative rating of the estimates for each construction scheme element (materials, transport and construction) based on the following criteria:

- knowledge basis (how “good” the data is)
- applicability (how well knowledge can be applied) and
- scheme information (how much detail is available to allow calculations and how much needs to be assumed).

With regard to materials, in the present case study the scheme information is reasonably accurate, as the major quantities have been defined in the conceptual designs of the two breakwater options. On the other hand, the knowledge basis and applicability of materials varies per material: for concrete there small uncertainty but for rock a large variability has been found in published data suggesting a large uncertainty.

With regard to transport the scheme information is quite inaccurate as no quarries had yet been identified and the quarry location will have a major impact on CO_2 emissions. The knowledge basis and applicability of data is thought to be fairly accurate, as variability in data on CO_2 emissions related to road transport is small.

With regard to construction the scheme information is somewhat inaccurate, as no detailed plan has been developed for type, number and duration of use of equipment. The knowledge basis and applicability for construction seems fairly accurate, although more data on loading factors of equipment and emissions associated with temporary works or use of temporary materials such as formwork would be helpful to improve accuracy.

A graphical illustration of uncertainty is presented in Figures 3 and 4.

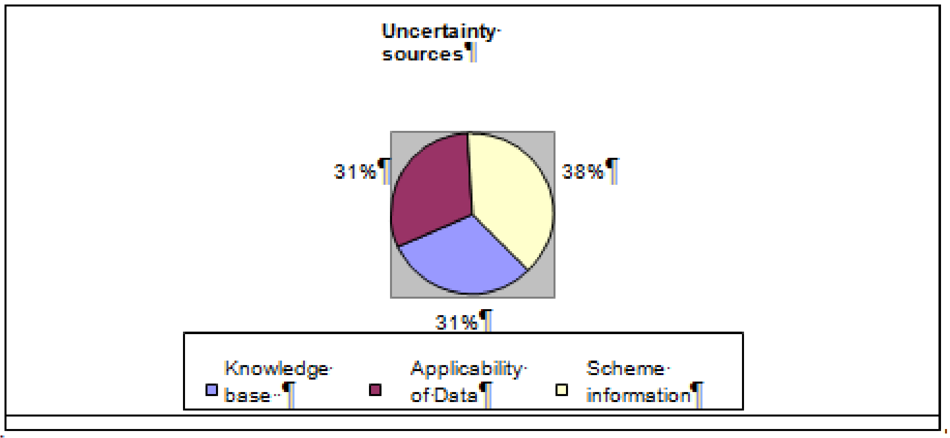


Figure 3: Uncertainty sources per criterion presented by HRCAT

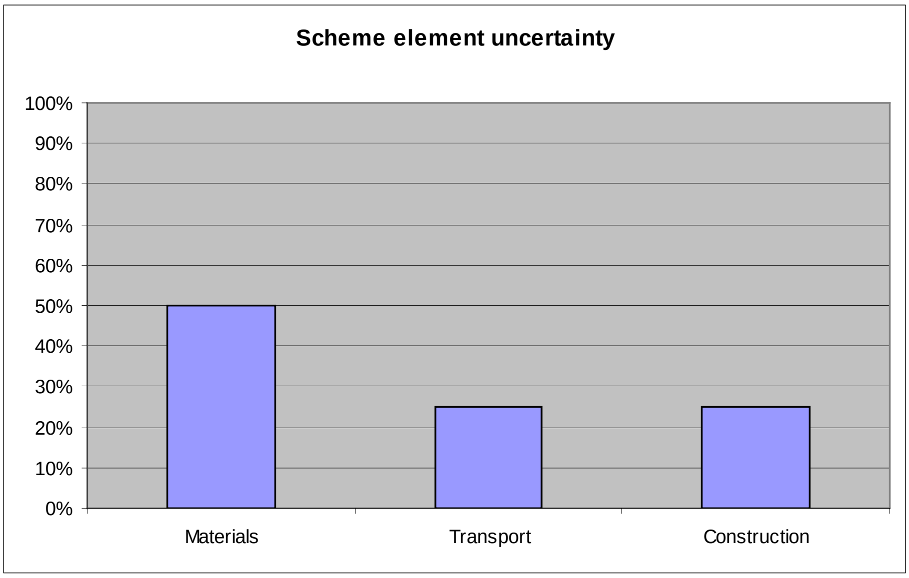


Figure 4: Uncertainty sources per scheme element presented by HRCAT

Discussion and conclusions

Development of HRCAT

HRCAT enables the user to estimate the whole life carbon cost of a coastal construction scheme (as a total or split into its contributing elements), and the level of uncertainty associated with the predictions. The versatility of the tool enables application to various types of coastal construction works and can be extended to include softer coastal management schemes in the future. It can help identify the relative contributions of materials, transport, construction and operation for each construction scheme element.

HRCAT has been tested on a case study for the calculation of the carbon footprint of two different breakwater types. The case study enabled further development of the tool in terms of input/output and its database of embodied carbon (EC) values associated with production of materials and use of construction equipment. HRCAT can support the designer and local authorities in estimating the carbon footprint of various elements of coastal developments, enabling them to focus on the key elements and informing a design with a smaller carbon footprint.

Accuracy and uncertainty

During the development of HRCAT, a critical assessment of published data on EC values related to use of materials and equipment has been carried out. In some key areas of a typical coastal construction project, there can be a wide variability in published values. An example is the large variability in published EC values for the production of rock. This is likely due to inadequate consideration of the processes involved. It was found that different quarry products (e.g. dimension stone, aggregates or rock used in typical coastal construction projects such as armour rock and quarry run) produced in different quarry types (dimension stone quarry, aggregate quarry or dedicated quarry) may have quite different associated EC values. The present variability is illustrated by a comparison of the adopted value for the present case study with the value adopted by Bruce & Chick (2009), who presented a methodology and a worked example for the assessment of breakwater construction. The latter value is 56 kgCO_2/tonne (i.e. the value for general stone presented by Hammond & Jones (2008)), whereas the value adopted for the present case study is about 10 times smaller (5 kgCO_2/tonne).

It is expected that, as more data becomes available in the coming years on the use of construction materials and equipment, the accuracy of published EC values will improve. It may however be useful to look at the accuracy of carbon footprint estimates in the context of accuracy of cost estimates. At a typical option appraisal stage of a civil engineering construction project, the accuracy of a cost estimate would be about +/-30%. It may be assumed that, in view of limited experience in the construction industry, the accuracy of a carbon footprint estimate is currently lower than that. Although this could of course improve in the future, carbon footprint estimates may remain somewhat less accurate than cost estimates for some time. Contrary to costs, the exact carbon footprint of completed works are likely to remain unmeasured in many cases, which may limit the build-up of reliable data over the years.

Reducing the carbon footprint of a coastal construction project

Whilst not the focus of the present case study, inevitably some insight has been gained on how to reduce the carbon footprint of a coastal construction project. Not surprisingly, and similar to reducing the construction cost of a breakwater, the primary focus should be on optimising the design and construction process in order to minimise use of materials and equipment. On a secondary level, the case study has showed that when a project includes concrete works, two design options for concrete stand out that seem to be effective in reducing CO_2 emissions:

- using cement with a high percentage of additions (e.g. fly ash, ggbs)
- minimising the amount of steel reinforcement.

Context

Bruce & Chick (2009) provide some context to carbon emissions related to breakwater construction, indicating for example that the construction of 1 km of their example breakwater would have a CO_2 emission equal to approximately 0.035% of the UK's annual emission. Adding to their example, the present case study involves a breakwater for a marine fossil fuel export terminal. The amount of embodied energy in the fossil fuel that could typically be exported through such a terminal during its lifetime has been estimated as approximately 2×10^{10} GJ and the associated CO_2 emissions have been estimated at 1×10^{12} kg, assuming that all fuel will be used for combustion. The CO_2 emissions associated with the construction of the breakwater would therefore be of the order of 0.02% of the emissions eventually resulting from combustion of the fossil fuel exported through the marine terminal of which the breakwater forms a part.

References

BIS (2010). Low Carbon Construction - Emerging findings. Department for Business, Innovation and Skills, HM Government, UK.

Bruce T. and Chick J. (2009). Energy and Carbon Costing of Breakwaters. Coasts, Marine Structures and Breakwaters 2009, 16–18 September 2009, Edinburgh International Conference Centre, UK.

CIRIA (2010). The use of concrete in maritime engineering – a guide to good practice. Construction Industry Research and Information Association, London.

CIRIA/CUR/CETMEF (2007). The Rock Manual – The use of rock in hydraulic engineering. C683, London.

Defra/DECC (2009). 2009 Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors. Web site accessed in November 2009.

Department for Transport (2004). Non-Road Mobile Machinery. Usage, Life and Correction Factors.

Escarameia M., Woolhouse G., Udale-Clarke H., Woods-Ballard B., Broekens R. (2011). Developing of HR Wallingford carbon footprinting capabilities for hydraulic engineering schemes. April 2011.

Hammond G. and Jones C. (2008). Inventory of Carbon & Energy (ICE), version 1.6a, Sustainable Energy Research Team (SERT), Department of Mechanical Engineering, www.bath.ac.uk.

Historic Scotland (2010). Embodied Carbon in Natural Building Stone in Scotland, Technical Conservation Group, Technical Paper 7 by Chishna N., Goodsir S., Banfill P. and Baker K., March 2010.

Lawson, B. (1996). Building Materials, Energy and the Environment – Towards Ecologically Sustainable Development, School of Architecture The University of New South Wales.

STEMA Shipping (2011), personal communication.

Van der Horst A.Q.C., Van Gaalen J.M. and Van der Vorm-Hoek C.V.A. (2007), "Duurzame toepassing van Xbloc® wereldwijd" (in Dutch).

World Ports Climate Initiative (2009). Carbon Footprinting for Ports, Draft Guidance Document.