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Embodied Energy: Soil Retaining Geosystems

Kenichi Soga*, Chris Chau, Duncan Nicholson***, and Heleni Pantelidou******

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Abstract

Embodied energy is defined as the total energy in joules that can be attributed to bringing an item to its existing state. This paper attempts to quantify the amount of energy that is put into constructing geotechnical structures. In this study, several common retaining wall options are designed for (i) a hypothetical highway widening project based on a typical condition in London, (ii) basement construction of actual high rise buildings in London and (iii) embankments and cuttings as part of an actual highway road widening project. The embodied energy of each design was computed. Results show that the largest variance on embodied energy is the design solutions and within a given design the materials energy dominates over the installation energy and the transportation energy. The choice of Embodied Energy Intensity (EEI) of materials, particularly steel and concrete, is shown to have a large influence on the magnitude of embodied energy. When comparing among different designs of soil retaining structures, a recycled steel wall system generally has less embodied energy than the equivalent concrete wall system, which is more efficient than the equivalent virgin steel system. Results of the three case studies collectively indicate that minimizing materials usage is the key for reducing embodied energy in soil retention projects.

Keywords: *embodied energy, soil retaining structures, material energy, transportation energy, installation energy, geotechnical design*

1. Introduction

Embodied energy is defined as the total energy in joules that can be attributed to bringing an item to its existing state. It sometimes includes the energy required to operate and demolish the item. Study into embodied energy can be important because embedded into the measurements are associated environmental implications such as resource depletion and greenhouse gases. As part of sustainable development, successive improvements in the construction of modern buildings through higher standards of insulation and more efficient control systems have reduced energy consumption and emissions during the whole life cycle of a building (Cole and Kernan, 1996; Fay *et al*., 2000). The embodied energy calculation allows evaluating such improvements in quantified manner and substantial embodied energy data now exists for a wide range of buildings and common construction materials such as steel, concrete and aggregates (Hammond and Jones, 2006; Howard *et al*., 2000; Kiani, 2006). Research also shows high correlation between embodied energy and embodied carbon, which is the main contributor of the greenhouse gases (Morigunchi and Namsai, 1998; Hammond and Jones, 2006). Therefore, although there are no physical environmental impacts associated with embodied energy, it has a tangible meaning that can shed light on how it can be interpreted.

In recent years embodied energy calculation has been carried out as part of a life cycle analysis. Taking as an example of geotechnical construction, the boundary would start from the energy used in (i) extraction of raw materials from the earth, (ii) the processing of the raw materials into finished products, (iii) the transportation to the suppliers and then to the site, (iv) the construction processes, including any associated temporary works, (v) the maintenance, and (vi) the demolition and recycling. Embodied energy analysis results may be interpreted in at least the following four ways.

(a) It could give greater understanding of how much energy and raw materials are used at each stage of the product's life.
(b) It could serve as an indicator for the overall environmental impact.
(c) It could provide an indication of the degree of depletion of fossil fuel resources in countries that are heavily dependent on them for energy.
(d) It could become an indicator of greenhouse gas emissions (primarily CO_2) and hence contribution to global warming.

Past research in relation to embodied energy analysis focused on optimisation of residential building design (e.g., Suzuki and

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*Professor, Dept. of Engineering, University of Cambridge, Cambridge, UK (Corresponding Author, E-mail: ks207@cam.ac.uk)
**Ph.D. Student, Dept. of Engineering, University of Cambridge, Cambridge, UK (E-mail: ta1hung@hotmail.com)
***Director, Arup Geotechnics, London, UK (E-mail: Duncan.Nicholson@arup.com)
****Associate, Arup Geotechnics, London, UK (E-mail: heleni.pantelidou@arup.com)

Oka, 1998; Guggemos and Horvath, 2006). The application of a detailed embodied energy calculation approach to civil engineering infrastructure is so far limited (e.g. soil retaining walls by Chau *et al*., 2006 and Inui *et al*., 2011; basement construction by Chau *et al*., 2008; earthworks by Hughes *et al*., 2011; tunnels, piled foundations and embankments by Chau *et al*., 2011). Perhaps it is because such studies appear to be more complicated and less meaningful than ones for the buildings for the following reasons (Inui *et al*., 2011): (1) the design option is strongly site-specific, (2) less design varieties are available, (3) installation processes described at the design stage often does not reflect what actually happens on sites, partly due to complicated geotechnical profiles and/or conditions around the site; and (4) their service lives are long compared to buildings, and relatively negligible amount of operational energy is required, i.e. much more energy consumed for lighting and heating of buildings than painting or galvanising of retaining walls. In order to encourage efforts by practicing engineers to reduce the environmental impacts as the industry, it is necessary to develop a simple methodology that allows optimisation of geotechnical design with an objective to reduce the energy inputs.

In this study, several common retaining wall options are designed for (i) a hypothetical highway widening project based on a typical condition in London, (ii) the basement construction of actual high rise buildings in London, and (iii) embankments and cuttings as part of an actual highway road widening project. Some details are already reported in Chau *et al*. (2006, 2008) and Inui *et al*. (2011). This paper aims to assess the data collectively to facilitate the investigation on some fundamental geotechnical infrastructure functionalities as well as scenarios that single out key attributes which affect design solutions. By doing so, the study identifies abatement strategies for more energy efficient construction of geotechnical structures.

2. Methodology

In this paper, three case studies are presented. For this study on embodied energy calculation of geotechnical structures, it is only pragmatic to set a narrow boundary in order to assess the possible effects of a selection of the essential factors. Therefore, the performance requirement is adopted as specified in each case study, and the life cycle of a structure is considered as an aspect that determines the design requirement and its finishing such as corrosion protections. The location conditions are pragmatically simplified unless otherwise stated according to particular case studies. The study does not consider for the end of life scenarios (e.g., energy required for demolition). The probability of any natural disasters and related mitigation efforts is not considered.

Fig. 1 illustrates typical key process stages during the life cycle of a geotechnical structure and the shaded cells refer to the processes included within the boundary of this study. The conceptual process boundaries are similar in that they start from the extraction of raw materials and end with the completion of the structures; ignoring the recurring processes such as maintenance and uncertain processes such as end of life scenarios.

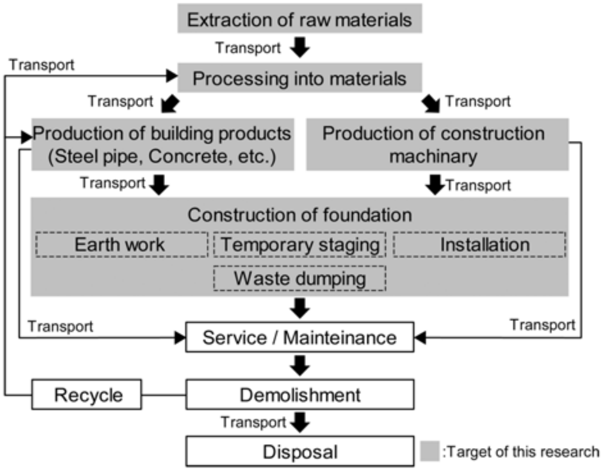


Fig. 1. Key Process Stages during the Life Cycle of a Civil Construction (after Inui *et al*., 2011)

Once the goals and the study boundaries are established, it is followed by a systematic examination of all the stages involved in the construction. Then detailed data acquisition is required to assess the quantities of materials or machinery used, transportation distances, construction processes and duration of machinery usages for each process stage; followed by the embodied energy evaluation for each process stage. For the ease of analysis, this study categorises the processes into three types: (a) materials, (b) transportation, and (c) installation. The basic calculation rationale is as follows:

(1) Material energy is found by the total volume of each material used, hence the weights and multiplying them by their respective Embodied Energy Intensity (EEI) value (see Table 1).
(2) Transportation energy includes the moving of the machinery and the materials used, and thus is calculated using the

Table 1. Embodied Energy Intensity Values (Inui *et al*., 2011)

Material	Unit	EEI (MJ / unit)		
		Mean	Maximum	Minimum
Steel (Virgin)[1]	kg	37	63	12
Steel (Recycled)[1]	kg	13	23	6
Concrete[2]	kg	1.8	2.0	1.5
Cement mortar[1]	kg	1.54	3.5	0.1
Diseal Fuel[3]	L	37.2	41.2	35.4
Geotextile	kg	78.1[1]	103[2]	52.5[2]
Granular	kg	0.15[1]	1.0[2]	0.05[4]
Electricity[4]	kWh	9.75	N/A	N/A
Construction Machinary[3]	kg	52.6	N/A	N/A

[1] Hammond and Jones (2008), [2] Kiani (2006), [3] Architectural Institute of Japan (AIJ) (2003), [4] Howard, Edwards and Anderson (2000)

litres of fuel consumed by the vehicles multiplied by the EEI of fuel. Alternatively, some EEI values are presented as simple MJ/tonne-km values. Calculations are based on an assumption of returned journey for means of transport except shipping, which is seldom returned empty. This assumption represents conservative estimation.

(3) Installation energy is the amount of energy consumed on site to operate the machinery for the main installation as well as the construction and removal of the temporary staging. This is evaluated as the product of the amount of fuel and/or electricity consumed and their EEI value

The sum of the material, transportation and installation energy would give the total embodied energy. Embodied energy calculation typically ignores the contribution from manual labour. This is because the lack of valid ways to evaluate human's energy contribution. Also labour is often related to the cost of construction. By excluding labour, the embodied energy values evaluated will provide an index for optimising construction processes in addition to cost.

3. Case Study 1: Retaining Walls for Railway Embankment Widening

3.1 Case Description

An embodied energy study was carried for a railway embankment widening project with the embankment being approximately 5 m high. The ground is a hypothetical profile with an underlying London Clay stratum. The construction methodologies and rates are based on UK construction practice and equipments (details in Chau *et al*., 2006; Inui *et al*., 2011).

For the study, a 1 in 2 railway embankment cross section is considered. The settings and respective loads are summarised in Fig. 2. A typical London Clay soil profile and ground water condition are used and the embankment profile consists of 9 m of granular fill, underlain by London clay. A surcharge is used to model a 2 m high upper slope dead load and a railway live load of 50 kPa is placed 5m behind the wall.

The four wall designs considered are (i) a cantilever pressed-in steel tubular pile, (ii) a cantilever secant pile wall, (iii) a tied back sheetpile wall with a row of tension piles, and (iv) same as (iii) but with reinforced concrete mini-pile wall. The sections through the propped and cantilever walls are shown in Fig. 2(a) and (b), respectively. The walls are designed according to BS8002 (1994). For UK designs the serviceability requirement is based on lateral wall deflections of less than 100 mm as Serviceability Limit State (SLS) conditions. Partial factors are applied to soil parameters to assess the walls for Ultimate Limit State (ULS) conditions. Different systems are chosen for either their ULS or SLS constraints: the maximum horizontal movement for the cantilever cases and the maximum ULS bending moment for the propped cases.

The walls are assumed to be left in place at their end of their design life of 120 years and corrosion is taken into account. Corrosion allowances are made to increase the steel wall thickness. For the exposed section of retaining wall the retaining specification includes for water tightness to the Institute of Civil Engineers (ICE) wall specification (1996): that is, allowing damp conditions but no running water.

3.2 Embodied Energy Calculations

For the two steel pile designs, two different installation methods are considered; 1) conventional driven method and 2) less general pressed-in method where the piling machine runs on top of the piles and requires no temporary staging (e.g., Giken silent piler). The soil removal and temporary works are also considered. For installing the piles, a temporary embankment is needed for operating the construction machinery. It has a slope angle of 1:2 and is constructed adjacent to the pile top and covered by granular material. The widths of the temporary embankments are 15 m for the secant piles and the conventional driven piles, and 5 m for the propped piles. The pressed-in cantilever tubular steel wall and the pressed-in sheet pile wall do not require any temporary staging.

The soil removal process entails the fuel energy consumed to remove the existing slope embankment onto trucks and to transport these trucks to and from the construction and dump sites. In this study, a list of distance from a typical London construction site to suppliers is chosen: cement and aggregates are estimated to be transported from 96 km (60 miles) away, construction machinery and steel are from 48 km (30 miles) away, and the disposal area and concrete batching plant are located 16 km (10 miles) away. Installation processes inputs are estimated, wherever possible, from a document published by the Ministry of Land, Infrastructure and Transport of Japan (2006).

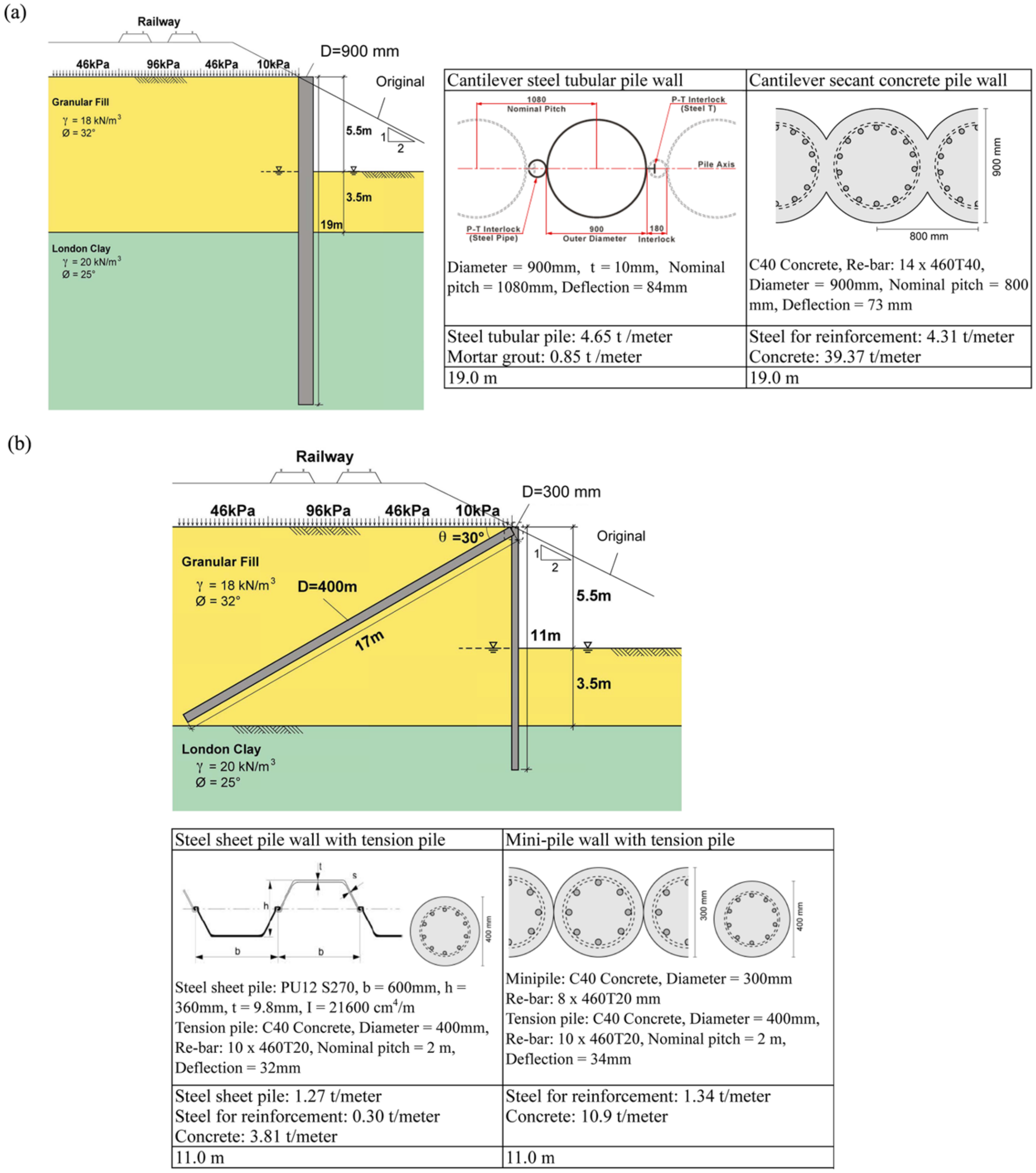
Further details of the embodied energy calculation can be found in Chau *et al*. (2006) and Inui *et al*. (2011).

3.3 Results and Discussion

Fig. 3 shows the embodied energy (GJ/m-run: energy in joules for every meter of wall length) for the four retaining wall designs and the two installation methods for the steel tubular piles. The total energy consumed in a meter run of wall on average is approximately 100 GJ/m. This is approximately 1.6 times the UK average annual household energy consumption from 2005 (National Statistics & Defr, 2006). Comparing within the same site, the maximum difference in embodied energy between the most energy consuming and efficient walls is in the order of 200 GJ/m. This shows that careful choice of retaining wall designs can contribute significantly in reducing the embodied energy.

Within each design, material production occupies the largest proportion of embodied energy. In particular, the energy used for tubular and sheet piles or reinforced concrete piles governs the overall magnitude of the material energy, even though the mass of steel used is relatively small compared to concrete, as shown in Fig. 2. This is primarily due to the large EEI of steel compared to that of concrete.

Comparing across designs, the propped systems with pressed-



Cantilever steel tubular pile wall	Cantilever secant concrete pile wall
Diameter = 900mm, t = 10mm, Nominal pitch = 1080mm, Deflection = 84mm	C40 Concrete, Re-bar: 14 x 460T40, Diameter = 900mm, Nominal pitch = 800 mm, Deflection = 73 mm
Steel tubular pile: 4.65 t /meter Mortar grout: 0.85 t /meter	Steel for reinforcement: 4.31 t/meter Concrete: 39.37 t/meter
19.0 m	19.0 m

Steel sheet pile wall with tension pile	Mini-pile wall with tension pile
Steel sheet pile: PU12 S270, b = 600mm, h = 360mm, t = 9.8mm, I = 21600 cm^4/m Tension pile: C40 Concrete, Diameter = 400mm, Re-bar: 10 x 460T20, Nominal pitch = 2 m, Deflection = 32mm	Minipile: C40 Concrete, Diameter = 300mm Re-bar: 8 x 460T20 mm Tension pile: C40 Concrete, Diameter = 400mm, Re-bar: 10 x 460T20, Nominal pitch = 2 m, Deflection = 34mm
Steel sheet pile: 1.27 t/meter Steel for reinforcement: 0.30 t/meter Concrete: 3.81 t/meter	Steel for reinforcement: 1.34 t/meter Concrete: 10.9 t/meter
11.0 m	11.0 m

Fig. 2. Retaining Wall Designs for a Road Widening Project (After Inui *et al*., 2011): (a) Cross-section of Cantilever Wall Systems, (b) Cross-Section of Propped Wall Systems

in piles and mini pile have less embodied energy than the cantilever systems by a factor of approximately three when virgin steel is used. This is mainly because the propped systems require much less amount of steel and concrete. Within the cantilever designs, all steel options (virgin or recycled, hammer or press-in) are less energy intensive than the concrete secant walls. However the advantage of steel over concrete is not evident in the propped case, deterring a conclusive argument for steel. It is hypothesised that this is due to the tension bearing capability of steel over concrete, where this efficiency becomes increasingly important when the maximum bending moment of a design increases.

The use of recycled steel can reduce the overall embodied energy significantly in all cases, particularly for the cantilever systems. The embodied energy intensities for steel production vary significantly and the quoted result values are highly sensitive

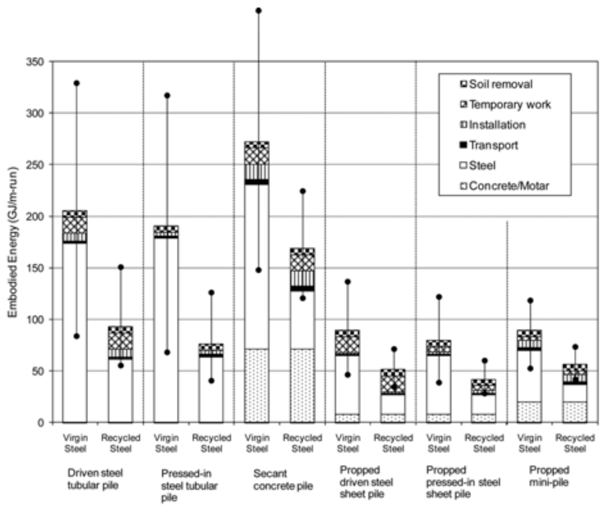


Fig. 3. Embodied Energy of Different Retaining Wall Systems

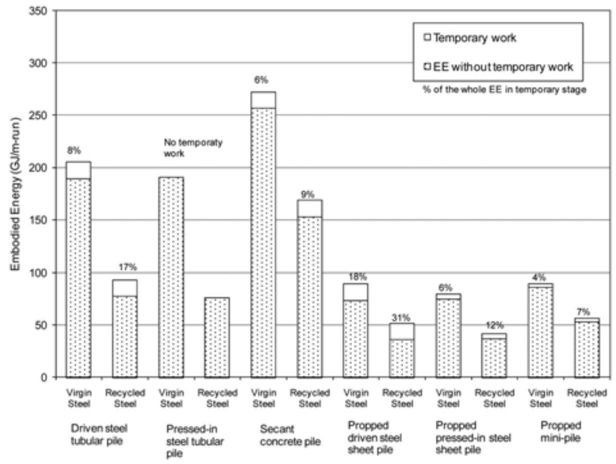


Fig. 4. Contribution of Temporary Staging

when evaluated using the upper or lower bounds of the published EEIs of steel as shown with the error bars in Fig. 3. Further discussion on this issue will be made later. However, the fact that materials, in particular steel, are the most significant energy consumer does not change even when the lower bound EEIs are used.

The embodied energy for the transportation of materials and construction machinary are small compared to the other stages and proportional to the mass of material used per unit-run wall. The values of installation energy (including soil removal and temporary staging) are approximately 10 GJ per m-run except for the concrete secant pile wall and the driven pile walls, which need a relatively large-scale soil berm as temporary staging.

Within the operational energy, temporary staging occupies a relatively larger portion. For the steel tubular pile and the propped steel sheet pile, the driven method is subject to more embodied energy than the pressed-in method. The difference comes mainly from the temporary staging for the driven piling machine and the crane. Fig. 4 is a reinterpretation of the result highlighting the proportion of embodied energy associated with temporary staging. The actual energy values are very similar for the various installation needs. Therefore the extent of its influence is inversely proportional to the energy associated with the sum of energy of the rest of the processes excluding temporary staging. The temporary staging constitutes to be around 10% of total for the cantilever designs or when virgin steel is used. In the extreme case of the propped sheet pile wall with recycled materials, the temporary staging energy proportion constitutes almost one third of total. This serves as a strong case favouring the use of self-erecting press-in machines, but the total energy of this design is still below that of the cantilever options. This implies that, by energy alone, temporary staging is not universally the dominant factor for design optimisation.

4. Case Study 2: Basement Retaining Wall for a High-rise Building

4.1 Case Description

This case study calculates the embodied energy of basement perimeter wall designs and anchoring system alternatives based on two real sites in London near the river Thames. At Site1, the proposed building to be built at this site is 40 storeys and has a three level basement at about -6 m, where the ground level is at +5 m, resulting in an expected 11m dig, with the toe of the retaining wall at close to -12 m. This site has a layer of made ground and terrace gravel overlaying the Lambeth clay and sand, and an underlying layer of Thanet sand (details in Chau *et al.*, 2008).

At Site2, the proposed development involves six commercial buildings varying between 6-50 storeys high and seven residential buildings varying between 30-50 storeys high. The study takes an average of the buildings so that a 40 storey building was evaluated for easier comparison with Site1. There will be three level basement at +0.0 m, where the ground level is at +5.4 m. This site has a layer of made ground, a thin layer of alluvium, then terrace gravel and an underlying Lambeth clay layer. At both sites, a basement perimeter wall is designed for the car parks of a commercial building. In reality, extra layer of internal walls is sometimes inserted to give a more presentable finish. For this purpose of this study. In this study, however, this has been excluded.

The retaining walls for the basement construction are designed according to BS 8002 (1994). The walls are assumed to be left in place at their end of their design life of 120 years and corrosion is taken into account. No maintenance work is assumed to be required during the service life. The serviceability requirement is based on lateral wall deflection of less than 50 mm during any point of the construction. For the exposed section of the retaining walls, the specification includes water tightness according to the ICE wall specification (1996): allowing damp conditions but no running water. Corrosion allowances are made to increase the steel wall thickness.

4.2 Wall Designs and Embodied Energy Calculations

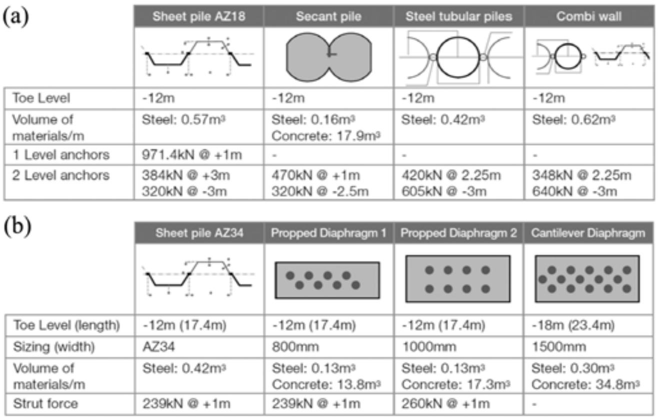
As with all large basement projects, different design options are required around the perimeter of the wall. This is due to the varying profiles, surrounding structures and water conditions. Fig. 5 shows the configurations and sizes of the wall designs considered, the volume of materials used, and the design forces for anchors.

Site 1 is far away from the river and other underground structures and has enough room behind the wall for anchorages. Therefore, four standard retaining wall options are is considered for this site: sheet pile, secant pile, steel tubular piles and combi walls. For each design, a two level anchorage is considered. Additionally, the sheet pile option is used as an example to further investigate the embodied energy of six anchor design options most commonly used in industry: three standard sizing of anchors (0.12 m, 0.15 m or 0.20 m in diameters) arranged in either one or two level of anchors.

Site 2 is close to the river with an aging canal wall that has to be either strengthened or replaced. Hence three propped options and a cantilever option are considered for this location. Excavations for the propped options are completed by tying the props across to the existing canal wall using the sheet pile option or the two options for diaphragm walls all with their toe levels at around -12 m. For the cantilevered option, a diaphragm wall is considered with its toe level at approximately -18 m resulting in a 23 m wall.

The inputs for materials are taken from the construction drawings and the bills of quantities to measure its materials usage. Transportation and installation energy inputs are taken from receipts, records or work schedules, to capture data such as types of machinery or vehicle, distances travelled and duration of operations. Transportation calculations are based on returned journey for all land transportations except shipping, which is seldom returned empty; this represents the conservative estimation.

Further details of the embodied energy calculation can be found in Chau *et al*. (2008).



(a)

	Sheet pile AZ18	Secant pile	Steel tubular piles	Combi wall
Toe Level	-12m	-12m	-12m	-12m
Volume of materials/m	Steel: 0.57m³	Steel: 0.16m³ Concrete: 17.9m³	Steel: 0.42m³	Steel: 0.62m³
1 Level anchors	971.4kN @ +1m	-	-	-
2 Level anchors	384kN @ +3m 320kN @ -3m	470kN @ +1m 320kN @ -2.5m	420kN @ 2.25m 605kN @ -3m	348kN @ 2.25m 640kN @ -3m

(b)

	Sheet pile AZ34	Propped Diaphragm 1	Propped Diaphragm 2	Cantilever Diaphragm
Toe Level (length)	-12m (17.4m)	-12m (17.4m)	-12m (17.4m)	-18m (23.4m)
Sizing (width)	AZ34	800mm	1000mm	1500mm
Volume of materials/m	Steel: 0.42m³	Steel: 0.13m³ Concrete: 13.8m³	Steel: 0.13m³ Concrete: 17.3m³	Steel: 0.30m³ Concrete: 34.8m³
Strut force	239kN @ +1m	239kN @ +1m	260kN @ +1m	-

Fig. 5. Basement Retaining Wall Designs for a High-rise Building: (a) Site 1, (b) Site 2

4.3 Results and Discussion

Figure 6 shows the embodied energy per metre-run of the four respective basement wall designs for Site 1 and 2. The total energy consumed in a meter run of wall on average is approximately 150 GJ/m, which is slightly greater than the values evaluated in case study 1 due to the height difference. Both cases adopt similar construction methods. Comparing within the same site, the maximum difference in embodied energy between the most energy consuming and efficient walls is in the order of 200 GJ/m. For an average 200 m perimeter wall for a commercial building with an approximately 250 m^2 area, this difference would result in an extra embodied energy of 50 TJ or 785 annual household equivalent in joules.

The material energy is the greatest contributor to the overall embodied energy value in all cases. Results from Site 1 suggest that the embodied energies of the steel based designs such as sheet pile, steel tubular piles and combi walls built purely from recycled steel are significantly less than those of the other retaining wall options. The opposite is true when only virgin steel is available. This again stresses the choice of steel used in the

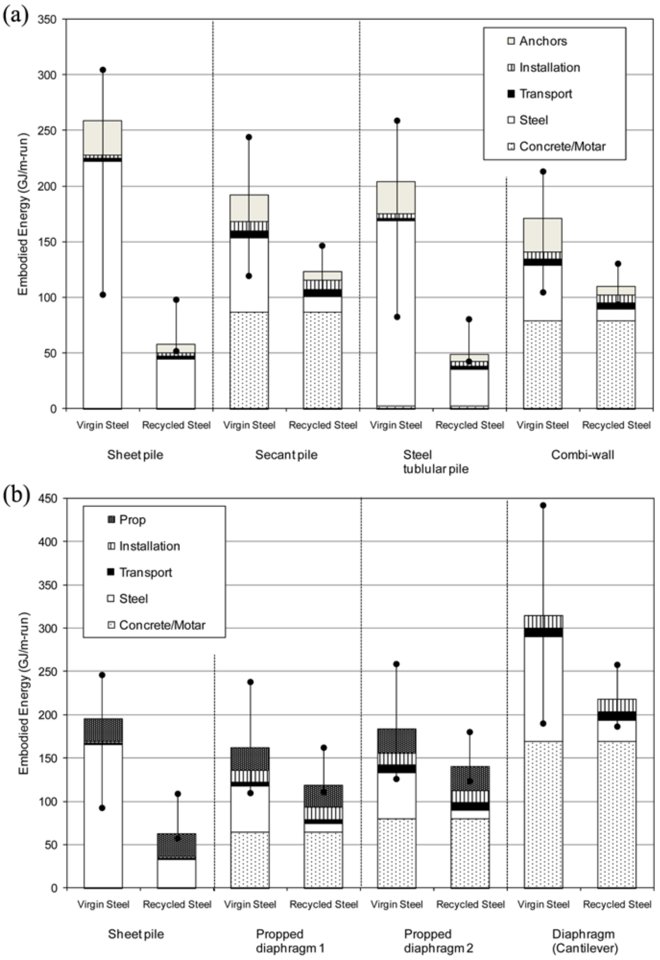


Fig. 6. Embodied Energy per Metre-run of the Four Respective Basement Wall Designs: (a) Site 1, (b) Site 2

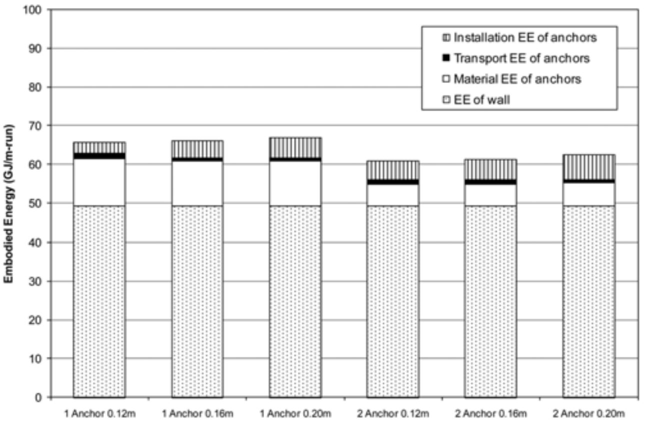


Fig. 7. Effect of Anchors on Embodied Energy

construction industry.

Results from the two sites collectively show that the cantilever diaphragm wall systems have much more embodied energy than any of the propped systems. This is because a cantilever system will always have to be founded with a deeper toe level, resulting in the use of much more materials.

Figure 7 shows the embodied energy comparison of the different anchoring systems using the same sheet pile wall from Site 1. Comparatively, the designs with two rows of anchors rather than one row consume less energy. This is because the required anchoring force for a one-row design is larger than the sum of the required forces from the two rows of anchors. Therefore, the length of anchors on the one row design is much longer resulting in more use of materials. As on average the anchoring systems are approximately 25% of the total energy, the difference between one and two row systems is relatively small. Therefore, it can be argued that the decision between choosing one row or two rows of anchors should be based on the practicality of the solution rather than the contribution to the embodied energy.

5. Case Study 3: Embankments and Cuttings for Highway Widening

5.1 Case Description

This case study investigates a range of soil retention options considered for a section of a UK highway widening project, which improves approximately 80 km of one of their highways by widening the three lanes sections to four lanes on each carriageway. For the widening, no land outside of the highway boundary will be used for the permanent works, and the additional space required for the new lanes will be provided by modifications to cuttings and embankment slopes including the steepening or shifting of the slopes.

A geotechnical consulting company carried out some geotechnical designs for numerous options for cuttings and embankments and this case study examines the embodied energy for five embankments retention options and four cuttings options.

The existing embankments are 40 years old, with a mature vegetation cover. The embankment heights are up to 12 metres, with side slopes generally 1V to 3H or flatter. The embankment fill comprises a mixture of granular and cohesive materials, with the strength of the fill varying along the scheme. Typically the retained height is one metre or less and, in most cases, the new pavement remains on top of the existing embankments. The retention options considered for the embankments are (a) Granular wedge with 1V to 1.5H side slope and topsoil retention system, (b) Bored spaced piled wall and pre-cast panels with varying pile spacing, (c) Bored piled walls with plunge H columns and pre-cast panelling, (d) Reinforced L-shaped cantilever retaining wall, and (e) Embedded Sheet pile wall.

The existing cuttings are typically 6 metres high, extending locally up to 13 metres. Their side slopes are typically 1V to 3H. The retained heights are between 1 and 2 metres, extending up to 5 metres at slip roads. The options considered are (a) Soil nailing, (b) Embedded Sheet pile, (c) Contiguous bored pile wall and (d) Reinforced L-shaped cantilever retaining wall.

Fig. 8 shows the schematics for the nine retention options. The schematics for the sheet pile wall and the cantilever wall (Fig. 8(e) and 8(c) respectively) are similar when used for both embankments and cuttings, so there are only seven figures for the nine options. The several options considered are designed for the same retained height and particular ground conditions to provide a meaningful comparison. This case study calculates only the energy of a typical steel value instead of hypothesizing the virgin and recycled conditions.

5.2 Embodied Energy Calculations

For the materials energy, the volumes are taken from the bill of quantities documents for each soil retention option, which provides the quantities of the materials used per linear metre of the structures. All materials come from the UK, while the transportation distance is 24 km (15 miles) for the precast concrete units and 80 km (50 miles) for the soil nails. For the steel, 80 km (50 miles) is selected for the analysis. For the rest, the range of transport distances is between 16 km (10 miles) and 48 km (30 miles) and a distance of 24 km (15 miles) is used in the analysis; this is considered to be reasonably reflective of the average transport distances of all other materials.

The machinery used in construction comes from all over the UK, with transportation distances varying from 16 km (10 miles) to 160 km (100 miles). Based on the information provided, the distance is assumed in the analysis as 48 km (30 miles).

The retaining wall construction involves large excavations both in embankments and in cuttings. The spoils are not disposed of directly during the excavation, but are collected in designated stockpile areas of the site using dump trucks. The maximum distance between any soil retention option under construction and a stockpile area is 0.5 km. The excavated material is not disposed of in a landfill, but rather in an old quarry located 16 km (10 miles) away from the site.

The durations of machinery operation for the three built soil

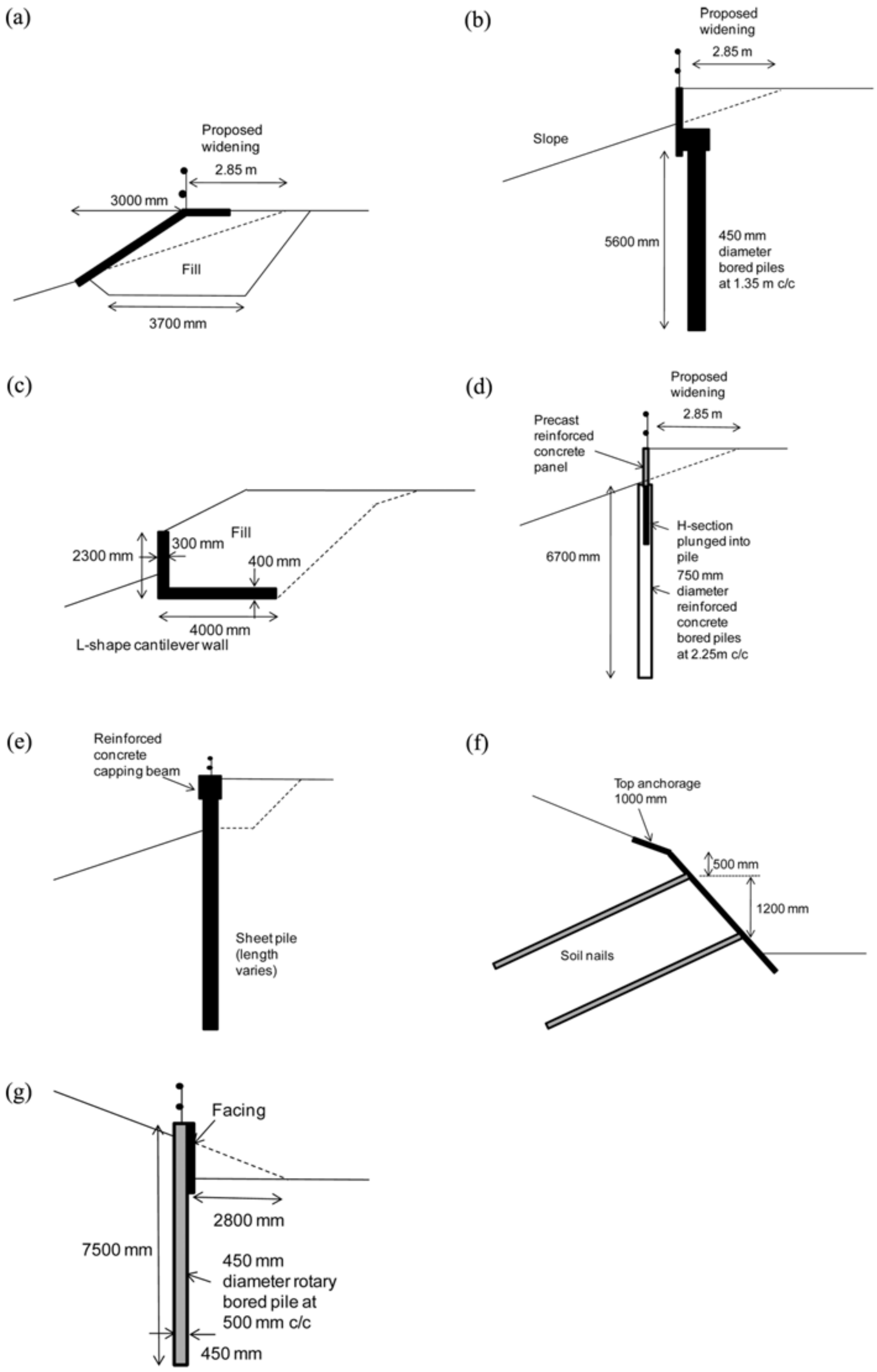


Fig. 8. Soil Retention Options: (a) Granular Wedge, (b) Bored Spaced Pile Wall, (c) L-shaped Cantilever Wall, (d) Bored Space H-section Pile Wall, (e) Embedded Sheet Pile Wall, (f) Soil Nailing, (g) Contiguous Bored Pile Wall

retention options, the soil nailing (1 m retention), the bored pile wall (2 m retention) and the granular wedge (2 m retention) are derived from the chainage-time bar chart.

5.3 Results and Discussion

The computed embodied energies per m-run of the soil retention options are shown in Figs. 9(a) and (b) for the embankments and the cuttings, respectively. For the embankment options, the order is "Granular Wedge", followed by "Bored Spaced Pile", "Bored Spaced H-section Pile", "Embedded Sheet-pile" and finally "L-shaped Cantilever Wall". For the cutting options, the most favourable option is the "Soil Nailing", followed by "Contiguous

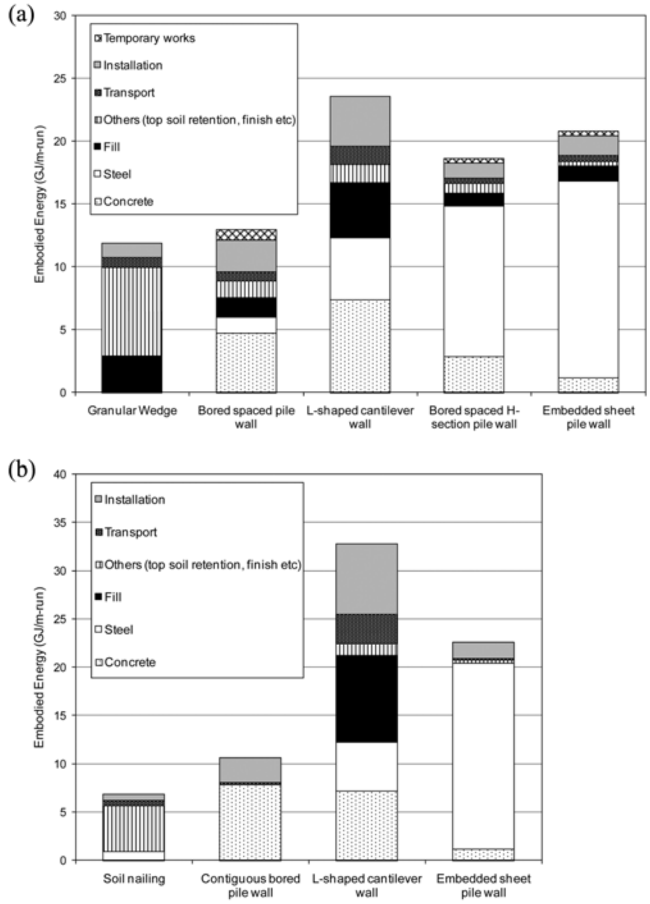


Fig. 9. Embodied Energies per m-run of the Soil Retention Options: (a) Embankments, (b) Cuttings

Bored Pile", "Embedded Sheet Pile Wall" and finally "L-shaped Cantilever". Consistent to the results in case study 1 and 2, the materials energy dominates the contribution for all designs.

The three bored pile options are similar and the design is similar to the anchoring system shown in case study 2. The embodied energy values are approximately 10-20 GJ/m-run for 1-2 m retention in this case study, compared to over 100 GJ/m-run for 5-10 m retention in case study 1 and 2. The active soil pressure is a function of the square of the retention height H; the rate of increase of the size of the piles (and hence the additional quantities of materials required) will at least be the rate of H^2.

The design solutions of the two L-shaped cantilever walls are identical between the embankment and cutting options and their retained heights differ only by one meter. Their embodied energies are different (embodied energy = 23.4 GJ for the embankment option and 33 GJ for the cutting option) for two reasons: (1) due to the proportions of the two sides on the L-shape which amounts to a difference in the quantities of fill materials required as the retention height increases and (2) the energy consumed in the "cutting" process constitutes to a large proportion of the total.

6. Discussion on Uncertainty

All resulting plots show the dominance of materials energy. The key outcome in this comparison is the call for geotechnical engineers to assess for the optimal point for spacings, lengths, and reinforcements in order to achieve materials quantity minimisation when optimising the design for a certain retention height. The dominant energy in materials in theory should help to achieve this, but equally significant is the contribution of uncertainty in EEI values as shown in the large error bars in Figs. 3 and 6.

The database for concrete by Hammond and Jones (2008) demonstrates a fundamental problem with EEI in that limited information is available from each source. For example, there is a doubtful inclusion of the concrete EEI values being 0.07 and 92.5 MJ/kg, when the average and the standard deviation of 122 records are 2.9 MJ/kg and 8.7 respectively. The embodied energy results in this study show that the concrete options have a much larger uncertainty in the results. This is because of the vast quantities by weight, making it sensitive to the differences in EEI. The vast range of these data presents a hurdle to a definitive and un-bias conclusion.

When comparing between steel and concrete designs, steel has a significant saving over concrete for the cantilever system. For the propped system, the embodied energy values are similar with different mixtures of the two materials. This implies that, even when using an average steel value (instead of a separate virgin and recycled value), there seems to be no clear winner between the two materials, but a case specific matters.

What complicates the matter is the existence of recycled and virgin steels. These two steels have almost indistinguishable by physical properties but their difference in process and raw materials use means that their EEIs are very different. Inui et al. (2011) state that a notable difference is observed between the steel produced via the Electric Arc Furnace (EAF) route compared to the integrated steel making route, which is based on the Blast Furnace (BF) or Basic Oxygen Furnace (BOF). The former uses primarily recycled scrap iron and steel and electricity, while the latter uses raw materials including iron ore, coal, limestone and some recycled steels. Moreover the recycled steel can be grouped into three types according to its source: 1) home scrap from within the steel mill itself, 2) prompt scrap from the production of finished goods and 3) obsolete scrap from steel products at their end-of-life. The three types of recycled steel have different return cycles: home scrap usually returns to the steel mill within weeks, prompt scrap returns within several months while obsolete scrap depends on the lifetime of the products, which may take decades. The average typical EEI of steel via the BF or BOF routes are roughly 10 and 24 GJ/t, with ranges of 10-19 GJ/t and 20-60 GJ/t, respectively. The construction steel one purchases in the form of rebar or sheetpiles would generally consist of a variable steel mix produced via both routes depending on availability.

This study evaluates the cases of recycled and virgin steel separately to depict the upper and lower bounds values. It is aimed to discuss the effect of the use of recycled steel on embodied energy reduction, even though the contractor cannot always choose the type of steel to purchase in reality. Results in this study show that the recycled steel designs are in most cases more energy efficient than the concrete designs, which in turn are more favourable than the virgin steel designs. Take for example Fig. 3, the most energy efficient designs are the recycled tubular pile and the recycled sheet pile, while the design with the largest embodied energy value is clearly the virgin steel sheet pile. This observation is consistent in all cases, but it has limited practical value because at present the chose for a type of steel is not an option when purchased from a steel maker.

In summary, when comparing steel and concrete in the aim to conclude on a preferable construction material for geotechnical structures in terms of embodied energy, it is largely inconclusive due to the large uncertainties associated with materials EEI. This implies that the energy efficiency push for steel usage requires clarifications from the steel industry. A possible suggestion may be the introduction of an explicit specification on the recycled properties and/or recyclability of steel or the documentations on the quantities of steel used in a geotechnical design in order to stipulate the treatment of steel at its end of service lives. These actions will have an impact on steel price models which will require careful identifications. While for concrete designs, there are more options that can be determined by engineers and contractors. However, the key to an embodied energy efficient design lies in the minimisation of material usage for any particular design.

7. Conclusions

This paper consists of several case studies that evaluate soil retention designs based on their embodied energy. The embodied energy is categorised into materials, installation or transportation. The purpose of the paper is to raise awareness of environmental quantification of designs and to provide possible directions to exercising the awareness.

For soil retention projects, the largest variance on embodied energy is the design solutions and within it, materials energy over installation energy or transportation energy. The design solutions often have many project specific and uncontrollable constraints (retained height, ground conditions and access etc.), which makes a rigid standard for energy efficient design inherently difficult to produce. However, results show that there are opportunities to produce energy efficient designs by geotechnical engineers.

The choice of EEI values of materials (particularly for steel and concrete) is shown to have considerable influence on the results of embodied energy calculation. When comparing the materials within the designs, a recycled steel wall system generally has less embodied energy than the equivalent concrete wall system which in turns is more efficient than the equivalent virgin steel system. This suggests for the need for more clarification for the type of steel being used. Although there are gaps in the analyses of the case studies presented in this study, evidences collectively indicate that minimisation of material usage is the first aim to have a retaining wall with small embodied energy.

In order to encourage efforts by practicing engineers to reduce the environmental impacts as the industry, it is necessary to develop a simple methodology that allows optimization of geotechnical design with an objective to reduce energy inputs or carbon emissions. For further works, there should be an investigation into a larger range of geotechnical projects of different sizes: e.g. cofferdams, foundations, large embankments, tunnels as well as a larger range of retention options. For example Chau *et al*. (2011) and Hughes *et al*. (2011) present embodied energy or embodied carbon calculation examples of other types of geotechnical infrastructure. Furthermore, the materials requirement for each geotechnical structure in a large range of ground profiles should be tested, e.g. range of weak cohesive and granular soils. Then the design guidelines for geotechnical structures with small embodied energy may be established.

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