Greenhouse Gas Emissions from Excavation on Residential Construction Sites

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Abstract

Despite considerable research concerning the manifestation of greenhouse gases in the usage of buildings, little has been done concerning emissions arising from the construction process itself. This paper specifically examines emissions arising from cut and fill excavation on residential construction sites. Even though such excavation is often seen as being economical in terms of providing a flat base for concrete raft slab construction, the environmental consequences of this approach need to be considered more fully in terms of impact on the environment. This is particularly important when steeply sloping sites are involved and for different soil types. The paper undertakes a study that quantitatively assesses the cumulative greenhouse gas emissions caused by cut and fill excavation on 52 residential projects in Australia for a range of slope and soil types. The paper presents results from the study and concludes that greenhouse gas emissions increase as site slope increases; the building footprint area (as distinct from Gross Floor Area), exposes the need to reduce the area of the building to reduce greenhouse gas emissions; excavation of rock soils creates higher emissions than other soil types; and cut and fill excavation on steeply slope sites increase emissions. Potential alternative construction includes suspended floor construction systems which involve less excavation.

Keywords: Life-cycle analysis, Greenhouse gases, residential construction, excavation, floor construction

Introduction

The building construction process is well known as a source of excessive resource consumption, pollution and a threat to biodiversity (Dimoudi & Tompa 2008). There is subsequently a distinct need to strike a balance between the act of building and the environment it impacts on. Construction involves complex processes in transforming land into habitable environments but such impacts represent a relatively underdeveloped area of knowledge. Part of the construction process involves excavation, which is asserted here as being an important area to study, given that it intrinsically involves changing the site in terms of revealing, disturbing, removing and depositing soil and vegetation.

It is notable that some forms of construction touch the ground more heavily than others, and this is considered to be the case with cut and fill excavation. It is commonly used in conjunction with concrete raft slab construction on sloping sites in Australian residential construction. It meets certain practical and economic needs during construction, but in extreme situations (as shown in Figure 1) it also represents a relatively disruptive change to the topography of the site – especially where alternatives such as suspended floor construction potentially have reduced impact.

Ostensibly, cut and fill excavation provides a level building platform whereby half of the slope is typically cut away over the building footprint area, and the spoil from this excavation is

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then used to fill the other half of the building footprint, thus providing a level platform. In addition, the cut and fill area normally involves retaining wall construction and associated drainage to stabilize the perimeter of the disturbed area.

The excavation process is particularly machine intensive due to the reliance on excavators, rollers and other equipment to remove, place and prepare soil; and for trucks to carry waste soil offsite for disposal. This machine intensive approach takes longer depending on the soil type and the steepness of the site. As a result of these issues, the research chooses to focus on greenhouse gas (GHG) emissions caused by cut and fill excavation for residential construction, on a range of slope and soil types. Further, the process and the context in which it occurs has meant that the research focuses specifically on the three major gases associated with GHG including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Even though only three gases were assessed in the study, the term GHG is still used throughout the paper, as the other gases were not considered significant in the cut and fill construction process.

Figure 1: Example of a new residence under construction on a steeply sloping site
(Note: Photograph attributed to Alistair Woodard)

A life cycle assessment (LCA) approach has been used in providing an underpinning methodological framework for executing the study. This approach is considered to offer the best way to obtain a full and quantitative understanding of the issues involved. The study is considered to be a first step in comparing different forms of construction concerning GHG performance. The study also aims to be of use to both building designers and those involved in environmental policy formulation, concerning urban development and the built environment.

A Review of LCA and GHG in the Context of Construction Processes

Consistent with the previous discussion, the LCA framework is appropriate because it offers a methodology for assessing the environmental impacts associated with products and processes, from the extraction of raw materials to the ultimate disposal of waste from products or processes (Klöpffer 2006). LCA can yield vital information on a variety of outputs but of particular interest in this study is GHG emissions and how related information can best be used as part of an integrated design process (Kohler & Moffatt 2003). Specifically, LCA can assist construction decision-making by identifying and addressing problems ranging from excessive consumption of resources to the pollution of the surrounding environment

(Ahn et al. 2010). Such principles are encapsulated in the ISO 14040 series of standards (ISO 2006a & b) which provide guidelines and principles on the LCA methodology. Global warming potential (GWP) is commonly used to express the impact of GHG contributing to global warming. CO_2 is adopted as a reference point to convert different gases into CO_2 equivalence ($CO_{2\text{-}e}$).

In this context, Yan et al (2010) define four sources of GHG emissions relating to building construction including: the manufacture and transportation of building materials; energy consumption of construction equipment; energy consumption for processing resources; and disposal of construction waste. These have been taken into account in the current research but key issues of note include the impact of equipment on excavation processes and the removal of any spoil taken off site.

Two common methods are cited in the literature for calculating environmental impacts and GHG emissions including: process-based analysis (Guggemos & Horvath 2005) and economic input–output based analysis (Gerilla, Teknomo & Hokao 2007). As Yan et al (2010) point out, the former models the environmental impacts from products and services around process flow diagrams, whilst the latter includes both direct and indirect impacts such as those that may arise from upstream supply chains (there is a relatively short supply chain in the given study setting). In this research the focus is on process management and so the chosen methodology follows this theme.

Specific studies focusing on GHG deal with different aspects of a building's life cycle. A number of studies have focused on saving emissions during the operational life of the building including work by Zhang et al (2011) on green property, and Su et al (2010) on the strategic apportionment of window to wall ratios. Chen et al (2001) focused on specific building typologies such as multi storey residential buildings. However these and similar studies appear to have largely neglected investigation of the environmental impact of the construction process itself (Bilec, Ries & Matthews 2009; Li, Zhu & Zhang 2010). With a greater emphasis on construction, Cole (1998) investigated a selection of alternative wood, steel and concrete structural assemblies. Others have concentrated on specific construction materials such as Gustavsson and Sathre's (2006) investigation of wood and concrete and Goggin's (2010) study on the use of blast furnace slag to reduce emissions from concrete. Still others have considered the prospect of curbing emissions via the use of industrialised methods of construction and found that prefabrication provides lower emissions than traditional methods of construction (Mao et al. 2013). Similarly, Monahan and Powell (2011) compared a novel off-site panelized timber frame system with two traditional alternatives and found that embodied carbon for a semi-detached house was 34% less than the comparative traditional methods.

However there is very little attention being paid to site excavation. Therefore for this study, the focus is less on the selection and use of competing construction materials, but more on the extent of re-shaping the existing topography (including potential impacts on bio-diversity). Consequently, there is the obvious concern that the greater the re-shaping of a site, the greater the impact on emissions. Virtually no published research could be found concerning the application of LCA and the extraction of GHG data for excavation. As such, the current study is thought to represent a new contribution to the body of knowledge especially concerning the key emissions from excavation.

Methodology - Assessing GHG Emissions Using a Life Cycle Framework

ISO 14040 (2006a) and ISO 14044 (2006b) were used as a basis for undertaking the study and have influenced the structure and process undertaken in the research. These standards have the inherent benefit of offering a standardised and repeatable process that operates under a known and accepted framework. The subheadings below broadly comply with those used in the above Standards but reporting has been modified somewhat to suit the flow of discussion and the structure of the research paper.

The Project and Sampling Details

The project was undertaken in terms of comparative studies on a range of soil and slope types (as shown in Table 1) in order to identify and quantify emissions. Design documentation was obtained for 52 detached residential housing projects in the greater Sydney basin. The gross floor area of these projects ranged from 154m^2 to 1,020m^2. As part of the study, slope was included as the main variable impacting upon the amount of cut and fill arising from each individual site. Soil type was included because the work rate of excavation equipment would likely change under different soil types i.e. for rock, clay and sand sites. The soil classification used in the study reflected the same classification system as used in Australian Standard AS2870 being the Residential Slab and Footings Code (SAI Global 2011).

Table 1: Summary of projects by soil and slopes type

Soil type **Slopes type**	**Sand**	**Clay**	**Soft soil**	**Rock**
1 in 10	5 Sites	5 Sites	4 Sites	1 Site
1 in 6	3 Sites	7 Sites	5 Sites	2 Sites
1 in 4	6 Sites	3 Sites	2 Sites	3 Sites
1 in 2	-	-	-	6 Sites
Totals	14 Sites	15 sites	11 Sites	12 Sites

From Table 1, it is evident that only a small number of instances were obtained for the slope ratio of 1 in 2. This was because in practice, such steeply sloping sites were found to be largely untenable or uneconomical to construct, except occasionally where solid rock excavation was involved. In these instances, the majority of the excavation was heavily biased towards cutting rather than equal cutting and filling (solid rock is often self-supporting thus allowing a large cut).

Life-cycle Assessment Framework

The study adopted an LCA framework which is considered as a ‘cradle to grave’ approach. It is used to analyse the impact from the acquisition of raw materials for the manufacturing of building products/components for construction to final disposal of the building, and the plant/equipment used for cut and fill activities on site. Specifically, the study aims to establish a methodology for assessing environmental impacts from cut and fill activities and the related GHG emissions for the construction of residential development on sloping sites.

A functional unit was established to conduct the measurement of functional outputs of the product system. The primary function of cut and fill excavation (being the product system) was to level the ground for construction of a concrete slab, including the related retaining wall structure and subsoil drainage used to maintain the stability of the excavation.

On this basis, the project was defined in terms of detached residential dwellings having an assumed life span of 60 years. An area of 1m^2 of the ground floor area of the building was set as the functional unit for the cut and fill study. Additionally, a 10m^2 wall area was used as the functional unit for the associated retaining wall and subsoil drainage construction (including linked excavation and footing construction works). However the retaining and drainage construction not intimately linked to the cut and fill excavation for the dwelling such as for general landscaping was omitted from the study. In providing further detail about the projects studied, it was found that some of the sites had a bias towards “cut only” or “fill only”. Therefore excess cut materials were assumed to have been deposited at the nearest landfill site and any additional backfilling materials were purchased from the nearest wholesale supplier.

The project focused specifically on the material and associated GHG emissions (with a focus on carbon, methane and nitrous oxide). Other emissions such as non-methane volatile organic compounds and particulates were excluded from the study. The cut and fill activities relied heavily on the operation of machines such as excavators and trucks. These machines consume electricity and diesel fuel. Consequently, resource depletion and associated emissions relating to the production of electricity and petroleum were considered in the study.

Inventory Analysis

Inventory analysis is derived from the logic that an increase in global temperature is related to the amount of GHG in the atmosphere. Climate change is often seen as an outcome of global warming and as mentioned previously, it is therefore appropriate to consider this in terms of GHG emissions. GHG is a measure of all gases set in relative terms to carbon dioxide which has a GHG of 1 kg. This enables all variables to be identified in terms of the common denominator. There is also the need to identify the time period to calculate GHG emissions and a 100 year period was adopted for the study.

Table 2: Inventory data of key materials/activities for the study

Material/activities	Quantity
Excavator for cut & fill activities on site (Litre/hr)	15 litres/hr (output rate vary to soil and slope type)
Transport excess excavated materials to landfill (Litre/km)	40 litres/1000kms
Transport filling material to site (Litre/km)	40 litres/1000kms
Retaining wall & subsoil drainage construction (kg):	
Concrete block	2,808
Cement	1,680
Sand	4,189
Aggregate	6,709
Lime	92
Steel	266
Water	1,086
Blue metal	4,172
Treated timber	981
PVC pipe	20
Geofabric	2

Data collection for the study was undertaken for the three standardised stages of a building namely: initial construction, building operation and end-of-life. For initial construction, material quantities and related work rates involved in processing the materials were estimated from the design documentation for each of the 52 residential building projects. In parallel with this, data was collected on various inputs and outputs of the product system. Table 2 summarizes the inventory data of key materials/activities for the study. The study included the three types of retaining structure encountered across the 52 projects (i.e. treated timber logs, concrete block and steel posts with timber log infill). For all the projects a quantity take off was undertaken for all the processes and materials pertaining to cut and fill construction and the associated retaining structure and subsoil drainage. The quantities were tabulated in an Excel spreadsheet for an LCA analysis. The LCA model was created using the GaBi software and its integrated LCI database that helps to establish environmental profiles and associated impacts. Finally, Government published literature was also used for this purpose including IPCC (1995), DCCEE (2010) and DEH (2006a, 2006b) publications.

At the operation stage, maintenance and replacement occur, however this was considered to be a null variable for cut and fill excavation. Similarly, the three different types of retaining walls (including drainage) were found to require virtually no regular or scheduled maintenance during the 60 year life of the dwelling. However, this was subject to the use of durable materials, especially the use of timber suitable for in-ground application.

At the end of the building life cycle, the building was assumed to be demolished and sent to landfill. The study only included the demolition of retaining wall and subsoil drainage using manual methods and transportation of waste to the nearest landfill station. No allowance was made for the recycling of waste or for any further emissions relating to the operation of the landfill station. The demolition of the building has also been excluded as it is a larger system that is not within the scope of the study.

Findings

The life cycle impact assessment results were calculated for the GHG emissions for all projects in the sample. Cut and fill excavation was measured based on the design documents received for each project. Table 3 summarizes the average quantities of cut and fill by soil and slope type. The volume of cut and fill was measured based on the differences between site topography and the required platform level. The table demonstrates a high variance in the volume of cut and fill – especially where rock sites with a slope of 1 in 2 were concerned. From the study it was realized that cutting generates more GHG than filling due to the high energy related process. Therefore variances in the proportion of cut and fill can cause significant differences in the associated GHG emissions in the process.

Table 3: Summary of average cut & fill by soil and slopes types

Soil / **Slope**	**Sand (m^3)**		**Clay (m^3)**		**Soft soil (m^3)**		**Rock (m^3)**	
	Cut	Fill	Cut	Fill	Cut	Fill	Cut	Fill
1:10	71	46	81	77	50	44	35	40
1:6	402	70	107	84	136	21	44	35
1:4	424	153	126	46	39	-	77	124
1:2							507	32

Based on the estimate of cut and fill excavation and the associated retaining structure, the life cycle impact assessment of GHG emissions was calculated and summarized in Table 4. It presents results in two contexts:

1. Cumulative GHG per metre square of gross floor area (GFA) - which represents the total floor area of the building including multiple floor levels.
2. Cumulative GHG per square metre of building footprint (BF) - which represents only the floor area that interfaces with the ground i.e. the ground floor area only.

The reason for this is simply because the BF is the area in touch with the ground and is therefore the primary area affected by excavation, retaining wall and drainage construction. Consequently, the BF method of measurement is potentially more accurate in measuring impacts especially where comparing single storey and multi-storey construction i.e. a multi storey dwelling may have the same GFA as a single storey dwelling, but the former will have a much smaller BF.

Table 4 summarizes the GHG emissions by soil and slope type for the 52 projects per BF and GFA. From the table, the data shows that in general, GHG increases as slope steepness increases. However as shown in the table, GHG emissions per square metre of GFA is lower than GHG emission per square metre of BF, in all cases. The results indicate that working towards a smaller footprint will reduce GHG emission - this is particularly the case for steeply sloping rock sites. The GHG per square metre for rock sites with a slope of

1 in 2 was three times lower for GFA compared to BF. Therefore reducing the building footprint by constructing multi-level dwelling can help to reduce environmental load on cut and fill construction.

Table 4: Average GHG per m^2 of building footprint and gross floor area by soil and slope types

Item / Slope	Sand		Clay		Soft Soil		Rock	
	BF	GFA	BF	GFA	BF	GFA	BF	GFA
	($kgCO_2$-e/m^2)		($kgCO_2$-e/m^2)		($kgCO_2$-e/m^2)		($kgCO_2$-e/m^2)	
1:10	72.0	44.7	39.1	30.8	19.7	10.4	137.4	81.6
1:6	224.5	98.1	80.9	54.7	100.7	49.2	189.7	164.8
1:4	248.4	99.2	116.3	72.0	43.1	20.8	260.4	145.6
1:2	-	-	-	-	-	-	2394.7	892.5
Note: BF – Building footprint GFA – Gross floor area								

The research results were also presented graphically, as shown in Figure 2. It presents the analysis of GHG by soil and slope type per building footprint. The figure demonstrates consistent results showing GHG emissions increase with increase in slope steepness. The steeper the slope the higher the GHG emissions per square metre of BF. However the trend is not a smooth and evenly spaced progression. Soft soils demonstrated the most inconsistent results relative to the other soil types. This appears to be a result of more cut and fill activity per square metre of floor area relative to the other soil types. It may also be a result of the site specific nature of soft soil sites (associated with problematic soil conditions) relative to the consistency of other soil types.

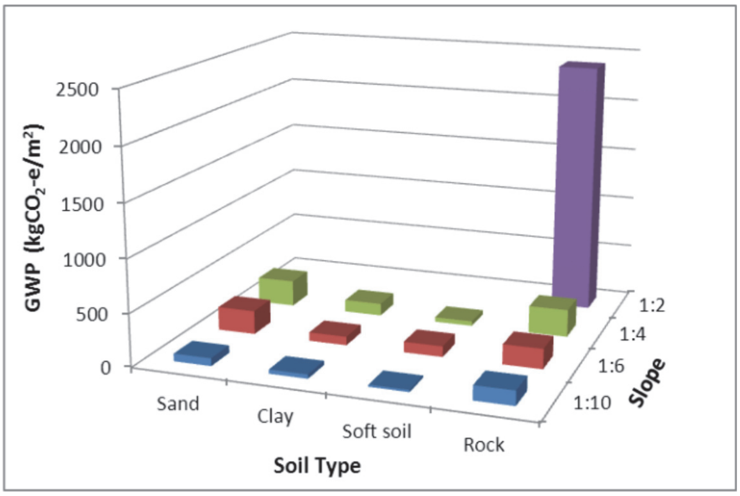

Figure 2: GWP ($kgCO_{2\text{-}e}/m^2$) per building footprint by soil and slopes type

For the most part, excavation of rock soils created higher emissions relative to the other soils in the same slope category. It is also evident that rock sites with a slope of 1 in 2 created higher emissions per square metre relative to the other soil types. The extremely high GHG emission for rock sites with a 1 in 2 slope was primarily due to the massive amount of cut for these sites. Extensive time and energy was required by the excavator during the cutting and associated rock breaking processes because it is harder and slower to remove than other soils.

Some of the other data also follows non-linear trends. Reasons surrounding these issues are discussed further below:

- Some steeply sloping sites (mainly involving soft soils as categorised in Table 4) were only excavated over a small proportion of the overall GFA and only involved a very small BF relative to the GFA. This typically involved situations where the cut was used to create a levelled area for single or double garage construction. The main dwelling was built on top of the garage structure but then bridged out over the sloping site to an upper section of the slope. These specific circumstances resulted in trends in the calculations that differed from the other double storey projects where the lower and upper floors were similar in area. Therefore it appears that the small BF of the garage construction had an independent effect on the GHG calculated for such sites.
- Cutting generates considerably more GHG than filling during the cut and fill process. It is notable that not all sites involved equal proportions of cut and fill and so a bias towards additional cut not only increased the amount of work in extracting soil but also additional cartage of spoil away from the site – thus causing differences in cumulative GHG emissions relative to other sites. This mainly occurred on rock sites.
- The levelled excavation area generally included the building footprint plus an additional levelled apron area around the footprint perimeter that was in the order of 1.0 to 1.2m wide. However, where an “L” shaped footprint was involved, extra excavation often took place in the re-entrant corner on the inside of the “L”. This may be levelled to create an outdoor entertaining area and thus creating a variance in excavation, retaining and drainage quantities in these situations.
- The shape, size and orientation of the dwelling had a changing impact on the amount of excavation work required from one site to the next and this subsequently impacted on cumulative GHG calculations.

Conclusion

The research quantifies the main inputs and outputs of constructing dwellings on sloping sites with regard to cut and fill excavation, retaining wall construction and related subsoil drainage works. The results indicate that slope has a positive correlation with cumulative GHG emissions. Rock has higher cumulative GHG emissions than other soil types.

The study analysed GHG emissions under two distinct scenarios including the rate of emissions relative to Building Footprint (BF) area, and relative to Gross Floor Area (GFA), for each dwelling The results indicate that the former is in many ways the most appropriate performance measure of the two because it more directly exposes the need to reduce cumulative GHGs emissions associated with construction on sloping sites by minimising the part of the dwelling in touch with the ground. Here, multi-level dwellings will perform better than single storey dwellings (all other things being equal).

Further, whilst the average GHG emissions for Building Footprint (as taken from Table 4) equates to 265 kgCO_2-e/m^2, the real issue is the degree of variance depicted by both slope and soil type. For instance, the lowest value of 72 kgCO_2-e/m^2 occurs on sand sites with a slope of 1:10, whilst the highest value of 2,395 kgCO_2-e/m^2 occurs on rock sites with a slope of 1:2. This degree of variance suggests that slope and soil type are useful variables in explaining the GHG emissions associated with site excavation. In future studies, these same variables may well be useful in explaining the GHG emissions associated with more holistic floor construction systems, as well.

It was evident that a steep slope substantially increases the burden arising from cumulative GHG emissions. Alternative solutions such as suspended flooring systems may minimise the disturbance to the site environment and this may in turn create broader based environmental benefits. Whilst such options should be considered in future research, they should be compared with cut and fill excavation coupled with the concrete raft slab construction mentioned earlier in this paper. Even so, any such comparisons should additionally consider life cycle cost analysis to ensure a balanced perspective of not only environmental protection but return on investment as well. This study does not provide a proportional perspective concerning how much cut and fill excavation contributes to the overall GHG emissions in constructing an entire dwelling. This would provide a relative and contextual understanding of the findings presented in this study.

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