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A Framework for Cost and Carbon Assessment : Liquefaction Effects on Lightweight Structures

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A Framework for Cost and Carbon Assessment: Liquefaction Effects on Lightweight Structures

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in

Structural Engineering

by

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The Thesis of Manasa Vijayakumar is approved and it is acceptable in quality and form for publication on microfilm and electronically:

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ABBREVIATION AND ACRONYMS

C, c	Carbon Emission
CLE	Contingency Level Earthquake
Constr. Act.	Construction Activity
cov	Coefficient of Variance
EF	Emission Factor
E_i	Seismic Events
EIO	Economic Input Output
EIO-LCA	Economic Input Output Life Cycle Assessment
FCR	Fuel Consumption Rate
FEF	Fuel Economy Factor
GHG	Greenhouse Gas
GI	Ground Improvement
GI-CLE	Ground Improvement for Contingency Level Earthquake Event
GI-MCE	Ground Improvement for Maximum Considered Earthquake Event
L	Length
LCA	Life Cycle Assessment
LMG	Low Mobility Grout
LN	Lognormal Distribution
MCE	Maximum Considered Earthquake
N	Normal Distribution
O&P	Unit Cost including Overhead & Profit

PACT	Performance Assessment Calculation Tool
P-LCA	Process Life Cycle Assessment
Q	Unit Quantity of Construction Item
Q_c	Unit Quantity of Construction Item for Carbon Calculation
S, s	Settlement
Trans.	Transportation

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ABSTRACT OF THE THESIS

A Framework for Cost and Carbon Assessment:
Liquefaction Effects on Lightweight Structures

by

Manasa Vijayakumar

Master of Science in Structural Engineering

University of California, San Diego, 2015

Professor Ahmed Elgamal, Chair

Sustainability is increasingly becoming a major concern in construction and development of the built infrastructure. Systematic inclusion of environmental impact and cost as metrics in performance-based engineering frameworks is a primary objective of this research. In this study, this objective is addressed within the context of ground improvement in seismic regions, as a geotechnical application of major economic and environmental consequence. For a representative lightweight structure such as a residential house built on potentially liquefiable ground, three cases are considered. In the first case, the structure is built, and potential settlement damage resulting from seismic activity is repaired thereafter (by re-levelling the structure). The other two cases include a ground improvement countermeasure before construction of the structure, to mitigate such potential settlement damage. Based on a corresponding specific seismically-induced settlement scenario, this study aims to develop a pilot framework for assessment of cost and carbon emissions associated with these three cases. For the stakeholder, the initial as well as potential post-earthquake cost and carbon emissions are assumed to be factors of interest. As such, the framework is presented along with the necessary underlying computations and outcomes. Carbon emissions are computed via two life cycle assessment (LCA) approaches: (i) process-based (P-LCA) and, (ii) a hybrid approach which uses P-LCA and economic input-output LCA. The a priori ground improvement technique considered for this study is vibro stone columns and the method for post-earthquake re-levelling of the residence is compaction grouting. Potential benefits and shortcomings in terms of cost and carbon emissions are contrasted, as a primary element of an overall decision-support process.

1 Introduction

In the last few decades, studies have been conducted on sustainability in the infrastructure industry (Ding 2007, Ortiz et al. 2008). Inclusion of sustainability in the field of geotechnical engineering is becoming more imperative to contribute to the existing environmentally-conscious society (Shillaber et al. 2014, Keaton 2014). Emissions such as carbon dioxide from the construction industry contribute to almost 39% of the total emissions in the United States per year (EESI 2015). These emissions are believed to be the highest during the start of the project, generally during geotechnical work (Jefferis 2005, Jefferson et al. 2010). Certainly, the impact on sustainability will be of particular significance when dealt with during this stage of the project. Soil stabilization or ground improvement arguably is a significant element of geotechnical work in areas prone to earthquake hazard and associated liquefaction. Indeed, earthquake-induced liquefaction remains a major contributor to the observed infrastructure damage worldwide. As such, this report will be concerned with carbon emissions incurred during ground improvement, as an additional component of a simple decision support framework.

Major liquefaction effects have been witnessed recently during the 2010 and 2011 Christchurch Earthquake, and the 2011 Great East Japan Earthquake (Cubrinovski et al. 2011a, Tokimatsu et al. 2012, Yasuda et al. 2012a, Bray et al. 2014). In lightweight structures (Martin and Lew 1999) such as residential properties and small footprint warehouses, pervasive settlement was observed. Devastating damage was seen during the 2011 Great East Japan Earthquake affecting as many as 27,000 houses only in Tohoku and Kanto districts (Yasuda and Ishikawa 2011, Tokimatsu et al. 2012, Yamaguchi et al. 2012, Yasuda et al. 2012a, 2013, 2014a, 2014b) and many more houses in the surrounding areas. Similarly, in the Christchurch, New Zealand earthquakes during September 2010 and December 2011 thousands of residential houses (Figure 1) and these properties required extensive restoration due to liquefaction (Yamada et al. 2011, Cubrinovski et al. 2011a, 2011b, 2012, Bray et al. 2014, Van Ballegooy et al. 2014).

As a result of the observed impacts, these events provide motivation to mitigate hazard due to liquefaction in lightweight structures, in particular for residential buildings (Boulanger 2012). Following the earthquake, if salvageable, repairing the house may not only involve re-levelling but possible further retrofitting of the foundation, interiors, lifelines and the surrounding landscaped area. Related representative repair guidelines are discussed in MBIE (2012, 2013) for houses that experienced settlement after the Canterbury earthquakes.

For new construction, this potential damage may be mitigated by implementing appropriate ground improvement techniques (Baez and Martin 1995, Adalier 1996, Mitchell and Jardine 2002, Adalier and Elgamal 2004). Conversely, the damage can be repaired after the anticipated earthquake event occurs. As such, this study investigates the cost, and environmental impact due to carbon emissions in both alternatives for a representative lightweight structure such as a residential building. The a priori ground improvement method for the residential house is vibro stone columns and the method for re-levelling post-earthquake is compaction grouting. Repairs to the structure are based on the guidelines from MBIE (2012, 2013). The analysis for carbon emission follows the process-based life cycle assessment (P-LCA) procedures presented by

Harmouche et al. (2012). These emission estimates are compared to the results found through a hybrid P-LCA and EIO-LCA procedure.

The following report essentially focuses on residential structures, although the assessment approach can be applied to other lightweight structures. The remainder of the document provides a brief background concerning liquefaction effects along with the corresponding countermeasures and resulting carbon emissions. Relevant information about post-event repair of a structure that has settled due to liquefaction is included. Scope and methodology for calculating cost and carbon emissions for a specific earthquake-induced settlement scenario are described. The framework is further extended in order to represent the settlement, cost and carbon emission by probabilistic distributions. The calculations and results are presented, followed by a summary and the drawn conclusions.

2 Liquefaction and countermeasures

2.1 Liquefaction and house settlement

During the recent earthquakes in Japan and New Zealand, many buildings experienced settlement and differential settlement due to the soil liquefying beneath the foundation (Figure 2). Figure 3 shows typical damage seen in house foundations due to liquefaction, of which in this report, primary attention will be given to uniform and differential settlement. Such settlements demonstrate the necessity for ground improvement to mitigate liquefaction-induced damage. A survey carried out by Tokimatsu et al. (2012) after the 2011 Great East Japan Earthquake showed that many areas where ground improvement work had been carried out manifested no liquefaction including Tokyo Disneyland, displaying effectiveness of liquefaction countermeasures despite a strong intensity earthquake.

In the U.S., based on field investigation for liquefaction potential, if the site demonstrates even a reasonable expectation of liquefaction hazard, the reviewing agency suggests suitable mitigation techniques via ground improvement for certain classes of structures before being constructed (CDMG 2008). Depending on the building performance, the permitting agencies may set certain levels of protection prior to project approval (CDMG 2008). As such, the potential for limited repairable settlement may be tolerated for certain lightweight structures.

The surveys conducted in Japan (Tokimatsu et al. 2012) conversely showed several areas affected by liquefaction leading to settlement and tilting of the buildings (Figure 4, Figure 5). According to Kazama and Noda (2012), the estimated cost of repair for lightweight structures was found to be more than one-half the total rehabilitation cost incurred including lifelines, transportation infrastructure etc. during the 2011 Great East Japan Earthquake (Figure 6). Among other investigations conducted after the earthquakes, Figure 7 shows a representative number of damaged residential houses in different cities of Japan. Figure 8 indicates the vast area affected by liquefaction as one of the primary earthquake hazards in New Zealand.

Studies of past earthquakes such as the Tottoriken-Seibu Earthquake in 2000 (Yasuda and Ariyama 2008) discuss the potential damage to houses due to liquefaction. Yasuda (2010) found that the houses with the largest inclination and differential settlement in Yonago City were located where sand boils were induced. This indicated that the damage was mainly due to liquefaction. According to Yasuda (2010), restoration is needed if the angle of inclination is between 5/1000 and 15/1000 (Figure 9). As shown in the Figure, differential settlement is referenced against the corner with the smallest settlement. The largest settlement relative to this corner is divided by the distance (L) to obtain the inclination angle. Yasuda (2010) recommends using the angle of inclination of the house and differential settlement as indicators if the house requires re-leveling. Figure 10 and Figure 11 show a representative number of damaged houses based on angle of inclination, settlement and degree of damage.

As mentioned earlier, MBIE (2013) provides guidelines on repairing houses that have experienced settlement damage from the Canterbury earthquakes. However, the guidelines are based directly on the amount of differential settlement as shown in Table 1, which as mentioned before is related to inclination.

2.2 Ground improvement and re-levelling techniques

2.2.1 Vibro Stone Columns

Vibro stone columns or vibro replacement (Priebe 1995, Baez and Martin 1995, Priebe and Grundbau 1998, Mitchell and Jardine 2002, Adalier et al. 2003, Adalier and Elgamal 2004) is a type of ground improvement technique to improve the bearing capacity of soil and reduce settlement (Figure 12). Vibro stone columns densify the soil by injecting dense stone aggregate columns in a grid pattern into the soil (Mitchell and Jardine 2002, Jefferson et al. 2010, Pinske 2011). Generally, the vibrating probe is first inserted into the ground to the desired depth of the column. Once the probe is at the desired depth, stone is backfilled into the feeder. The stone fills the voids created by the probe as it is vibrated and is lifted out of the ground. Other construction methodologies and procedures are briefly summarized in Jefferson et al. 2010.

2.2.2 Compaction Grouting

Compaction grouting (Baez and Henry 1993, Boulanger and Hayden 1995) using Low Mobility Grout (LMG) is one of the ground improvement methods recommended by MBIE (2012) to re-level structures (Figure 13). This method involves injecting thick LMG (or thixotropic grout) into the soil pores to densify the soil (Andrus and Chung 1996, Yasuda 2005, 2007, MBIE 2012). The grout is injected by inserting a grout pipe into the soil and injecting bulbs of grout as the pipe is lifted a certain specified distance after each injection (Miller and Roycroft 2004, Haramy et al. 2012) (Figure 13, Figure 14). The grout column densifies the soil due to the grout mass expanding and displacing the surrounding soils. The expansion of the grout mass raises the building and also increases the bearing capacity of the soil (Andrus & Chung, 1996, Wilder et al. 2005).

Andrus and Chung (1996) advises not using this technique for thick, saturated clayey soils and soils with silt deposits. However, Cleveland et al. (2012) provides three case studies where compaction grouting using LMG successfully remedied settlement in moderate to high plastic fine grained cohesive soils. There has also been an increase of studies to quantify and assess the effectiveness of the method as a ground improvement technique (Nishimura et al. 2011, Haramy et al. 2012).

3 Life Cycle Assessment

A vast amount of research exists about life cycle assessment (LCA) models to quantify the environmental impact for the constructed infrastructure (Hendrickson and Hovarth 2000, Ochoa et al. 2002, Bilec et al. 2006, Junnila et al. 2006, Säynäjoki et al. 2011, Tatari and Küçükvar 2012a, Küçükvar and Tatari 2013). For the constructed infrastructure, LCA studies address many environmental impact issues, such as greenhouse gas (GHG) emissions, toxic air emissions and hazardous waste. Of the various phases of a structure's life, material, construction, usage, maintenance and end-of-life, usage phase has been the most studied. This is due to the usage phase disproportionately contributing more to energy consumption, energy use and greenhouse gas emissions (Ochoa et al. 2002, Junnila et al. 2006).

LCA studies investigating emissions are finding that the overall environmental impact of construction (including GHG emissions) should not be overlooked. Of the different GHG emissions such as methane, nitrous oxide and other fluorinated gases, carbon emissions contributed to majority of the released total chemical emissions (Säynäjoki et al. 2011). According to U.S. Environmental Protection Agency (EPA 2013) emissions due to carbon dioxide is about 82% of the total GHG emissions.

In particular, there are studies that focus on the environmental impact of residential buildings. Ochoa et al. (2002) uses an EIO model to investigate the environmental emissions for the residential buildings sector. The study revealed that the construction phase was the largest contributor to economic activity, hazardous waste and toxic air emissions. The study also found that the GHG emissions from the construction phase are significantly low relative to the other life cycle phases. However, according to Säynäjoki et al. (2011), these GHG emissions should not be overlooked. This is because the construction phase releases a large amount of GHG emissions in a short period of time. For example, a new low energy building that has a 50 year life span is unable to help mitigate climate change because the construction of other structures are releasing GHG emissions at a faster rate than the benefits of one low energy building that can help mitigate emissions.

Life cycle assessment provides many approaches to evaluate the environmental impact of structures. Carbon emission is one of the many environmental impacts that are addressed by the LCA methodology. Out of many existing LCA models, this study uses three popular approaches: process-based life cycle assessment (P-LCA), economic input-output life cycle assessment (EIO-LCA), and hybrid model that combines the first two models (Suh et al. 2004). The first two models have their advantages and disadvantages (Bilec et al. 2006). The hybrid model is used in an attempt to combine the advantages of both approaches. Different hybrid LCA models can vary by the adopted proportion of process and input-output data. Bilec et al. (2006) provides more detail on the different types of hybrid LCA models.

The P-LCA, EIO-LCA and hybrid LCA approaches are used for computing carbon emissions. All approaches can be used potentially for calculating the direct and indirect emissions from various greenhouse gases (GHGs) related to the production chain of all the materials used and the involved energy inputs.

3.1 Process-Life Cycle Assessment

P-LCA analyses the life of the product by breaking it down stage by stage (e.g., construction, service and removal) in order to analyze the various factors that go into the associated processes. Each individual process might involve interactions with the overall scope, which should be addressed. The life cycle phases are extraction of material, manufacturing/construction, usage phase and end-of-life (Ochoa et al. 2002). Harmouche et al. (2012) categorizes the carbon emissions into three phases: embodied carbon, transportation and construction activity.

For P-LCA, one possible approach for computing the carbon emissions is based on materials used. Carbon emission factors (EF) convert the amount of material used to the associated released carbon emissions (Hammond and Jones 2008). The University of Bath's *Inventory of Carbon and Energy (ICE)* (Hammond and Jones 2008) provides a reliable database of these EFs for over 400 construction materials that came from either secondary data resources or derived from known information. The EFs from *ICE* only account for emissions due to production and manufacturing. The boundary condition for the EFs is therefore, cradle-to-gate. The emissions due to transportation are computed separately since this can vary from project to project.

Accuracy or detail of the data collection for P-LCA is determined by the investigator. In Harmouche et al. (2012), the calculator to compute the carbon emissions for the construction of a building requires specific information from the suppliers and contractors about the production of the material, transportation of the material and equipment used on site. As such, P-LCA requires more time to collect the data as the level of detail of the analysis increases.

Aside from the subjectivity of the level of accuracy of the data collected, the boundary of P-LCA is also chosen subjectively (Bilec et al. 2006). This is a disadvantage since the minimum boundary of P-LCA is computing only the direct emissions and the expansion of the boundary is limited to the amount of indirect emissions chosen to be considered. In contrast, the EIO-LCA eliminates the boundary problem, since it accounts for all direct and indirect emissions (Bilec et al. 2006).

3.2 Economic Input-Output Life Cycle Assessment

EIO-LCA was initially theorized and introduced by Wassily Leontief in the 1970s, for which he won the Nobel Prize in economic sciences in 1973 (Leontief 1970). EIO-LCA is composed of individual sectors and their interactions within an economy. The interactions are quantified as inputs and outputs which are considered as monetary transactions between the sectors. In the U.S., the Bureau of Economic Analysis publishes the relevant data for as many as 428 different sectors (BEA 2010).

The EIO-LCA model is based on the cost of the materials and EIO-multipliers. The EIO-LCA model uses EIO-multipliers to convert the dollars spent into emissions generated. The EIO-multipliers are derived from an algorithm that accounts for the 428 industry sectors that contribute indirect emissions (Hendrickson et al. 2005). As such, this methodology quantifies the environmental impacts of the products or processes of direct and indirect suppliers at the level of the U.S. economy (Tatari et al. 2012a, Küçükvar and Tatari 2013).

Because EIO-LCA models are based on cost, collecting the data is less time consuming and thus, the analysis is more time efficient. However, the EIO-LCA model does have some disadvantages (Matthews and Small 2001, Bilec et al. 2006). For a specific or specialized product, this model is not as accurate since the data represents a general product scenario. It is also difficult to determine which process or stage influences the carbon emissions the most since it does not relate the estimated emissions to the individual ingredients (e.g., extraction, production, transportation, construction) as done for the P-LCA models.

3.3 Hybrid Life Cycle Assessment

More recent studies are using hybrid models to improve LCA for the various components of construction (Bilec et al. 2006, Säynäjoki et al. 2011). It should be noted that the hybrid models can be more convenient, since the available data for a certain type of LCA model might be inadequate. For example, Säynäjoki et al. (2011) uses P-LCA data to compute the emissions for construction materials that had the most carbon emissions for a residential construction project in Finland. The P-LCA data provided more accurate information about the production and transportation of the local materials. The EIO data was used to account for other indirect emissions not captured by the P-LCA data. The hybrid model is generally designed as a combination of two or more LCA models to make the overall approach simpler and at the same time most accurate. The level of accuracy is determined by the investigator.

3.4 Life Cycle Assessment and Ground Improvement

Studies have been performed to assess the carbon emissions from different ground improvement techniques designed to strengthen the original surficial ground strata (Gaterell 2005, Holt et al. 2010, Pinske 2011). Among those, the vibro stone column technique was addressed with emissions compared to those corresponding to the deployment of a deep foundation system as an alternative solution (Chawla et al. 2010). Along with production of the stone aggregate, transportation was noted as a main contributor to the overall emitted carbon (Gaterell 2005, Pinske 2011).

Some recent studies further drew the attention to: (i) sensitivity of the estimates to the underlying input variables and assessment technique, and (ii) the need for inclusion of additional considerations for more accurate estimates of the overall environmental impacts i.e. broader framework when estimating the overall environmental impacts (Jefferson et al. 2010, Mitchell and Kelly 2013).

4 Scope of Study

For new residential structures that may be built on potentially liquefiable ground, three cases are considered. In the first case, the structure is built, and potential settlement damage resulting from seismic activity is repaired thereafter (by re-levelling the structure). The other two cases include a ground improvement countermeasure before construction of the structure, to mitigate such potential settlement damage. For the developer, the initial as well as post-earthquake cost and carbon emissions are assumed to be factors of interest towards a decision as relates to the potential a-priori countermeasure deployment.

This study starts with a deterministic postulated specific earthquake-induced settlement outcome. It aims to develop a pilot framework for the assessment of cost and carbon emissions associated with the three cases. The framework is presented along with the necessary underlying computations and representative results of significance for the process of decision support. The cost and carbon emissions considered are those due to material production, transportation to and from the site, and construction activity on site. The above discussed framework is further extended in order to represent the settlement, cost and carbon emissions by probabilistic distributions.

Carbon emissions are computed using two life cycle assessment (LCA) approaches: process-based (P-LCA) and a hybrid approach which uses P-LCA and EIO-LCA. The ground improvement (GI) method considered for this study is vibro stone columns and the method for post-earthquake re-levelling of the residence is compaction grouting.

5 Cost and Carbon Computation Methodology

Figure 15 presents the steps for computing the cost, and carbon emissions for both P-LCA and EIO-LCA. Construction items such as materials, equipment etc. are first defined. Based on the scope of the construction project, the necessary quantities (Q) of each construction item are computed. An item may have more than one quantity and thus, more than one cost associated with it. For example, re-grading and resurfacing requires two different quantities - concrete and the equipment, that represent this item. One of the LCA methodologies considered in this document is based on economic equivalents, therefore the unit cost is needed for all construction items. Unit costs of materials can be obtained from available databases or from the contractor on the project. The RS Means provides national averages for such unit costs. The unit costs used herein only includes the material/production cost for the LCA model.

5.1 Cost Calculation Methodology

To compute the total cost for the project, the quantities (Q) calculated are multiplied with the unit costs that includes material cost and overhead & profit (O&P). The unit cost data are collected from available sources. Equation (1) displays the formula for total cost:

$$Cost = \sum_{i=1}^{I} Q_i \times (Unit\ Cost\ _i) \tag{1}$$

where, I is the total number of items and Q is the quantity of material. Herein, the majority of unit costs are taken from the RS Means (2008, 2010, 2013, 2015). In this reference, all the reported unit costs correspond to the year 2002 since the EIO-multipliers are based on monetary values from 2002. Cost data taken from elsewhere and not based on the year 2002 were adjusted for the year 2002 values using an inflation calculator (Coin News, 2014), which uses the National Consumer Price Index data provided by the U.S. Bureau of Labor Statistics. It should be noted that the cost is assumed to stay constant regardless of the amount purchased in order to simplify the analysis.

5.2 P-LCA Methodology

In this P-LCA study, carbon footprint is defined as the amount of carbon dioxide emissions directly and indirectly emitted from cradle-to-site (Hammond & Jones (2008)), and thereafter the construction and usage (Ochoa et al. 2002). Other GHG emissions are neglected. As presented in Harmouche et al. (2012), the emissions generated are categorized into three phases: (1) the embodied carbon or the raw material emissions are those generated during the production of the material, (2) the construction activity emissions are those generated during construction on site, and (3) the transportation or tail pipe emissions are those generated during transportation of the material. The methods for computing each of these emissions are summarized in Figure 16. Apart from the above three phases, the Figure shows a separate category to illustrate that the diesel production emissions are related to the combined transportation and construction components. Additional details related to Figure 16 are presented below.

5.2.1 Embodied Carbon

The carbon emissions from the raw materials are also known as the embodied carbon (Harmouche et al. 2012). The quantities Q are first converted into standard carbon calculation quantities (Q_c), essentially the weights for which EFs are readily available. For example, the Q for grout used for compaction grouting is in units of cubic volume. This Q is multiplied by the density of grout to obtain Q_c, which has the appropriate units so that when it is multiplied by its corresponding EF the amount of carbon emissions is obtained.

The embodied carbon EFs are taken from the *ICE* database (Hammond and Jones 2008). It should be noted that using *ICE*'s carbon EFs for analyzing structures in the U.S. are somewhat approximate since the available EFs (Hammond and Jones 2008) are based on the construction materials in the UK; and the fuel mixes used to produce the product vary from country to country.

5.2.2 Transportation Emission

As shown Figure 16, tail-pipe emissions i.e. the direct carbon dioxide emissions from combustion of fuel are quantified based on the emission factors provided by the U.S. Energy Information Administration (EIA 2014). According to EIA, about 22.38 pounds of carbon dioxide are produced by burning a gallon of diesel fuel i.e. 2.68 kg of carbon dioxide per liter. As shown in Figure 16, the amount of fuel consumed for the distance travelled by a vehicle is multiplied by the emission factor of the fuel (kgCO$_2$/liter) to determine the tail pipe emissions. The fuel consumed by vehicles during transportation is estimated by summing over employed vehicle types (k) i.e. number of employed vehicles × distance in km ÷ fuel economy factor (FEF) (EPA 2008). The distance travelled by the vehicles is assumed judiciously. For example, the approximate distance of stone quarry from the site is taken as 113 km one way. The emission factors for carbon dioxide taken from the database is 2.68 kgCO$_2$/liter (EIA 2015). In the above, the number of required highway trucks is simply equal to total weight to be transported divided by the weight carrying capacity of the employed truck.

5.2.3 Construction Activity: Off-Road Diesel Engine Emissions

To calculate the carbon emissions during construction, the amount of consumed fuel in liters is estimated first. For that purpose, the hours of equipment operation are multiplied by an appropriate fuel consumption rate (Harmouche et al. 2012). The fuel consumption rate (FCR) differs depending on the type of construction equipment. Frey et al. (2010) provides FCRs for different construction equipment. These FCRs are based on the various activities the equipment performs. As such, the amount of fuel for construction is defined by summation over the involved parameters (equipment (m) × hours of operation$_m$ × FCR$_m$). The mass per fuel emission rate (emission factor) of 2.68 kgCO$_2$/liter (EIA 2015), shall be used to calculate the carbon emission due to consumption of the construction fuel as shown in Figure 16. Also, carbon emission produced by the crew members (laborer) on site is included under construction activity. This is calculated by multiplying the number of crew members by the carbon emission produced per person per day. An approximate emission factor per person based on United Nations Statistics Division (UNSD 2015) is taken as 15 kgCO$_2$/day.

5.2.4 Diesel Production for Transportation and Construction Activity Emissions

To calculate the carbon emissions due to the production of the fuel that is used to transport the material and to run the construction equipment, the employed emission factor for diesel production is 0.06 kgCO$_2$/liter (NREL 2010). Carbon emission from production of fuel is included to the total carbon emission during transportation and construction activity. The total amount of fuel for construction activity and transportation is calculated using the method discussed in the previous sections.

5.3 EIO-LCA Methodology

The EIO-LCA computes the carbon emissions through a conversion factor based on the monetary value of the quantities called EIO-multiplier in kgCO$_2$/\$ (CMU 2008). These multipliers are obtained from the EIO-LCA tool for the U.S. 2002 benchmark producer price model (CMU 2008). As mentioned earlier, EIO-multipliers account for emission within the context of “cradle-to-gate.”

As shown in Figure 15, the costs for the construction quantities Q are first obtained. The cost of the quantities is found by multiplying the Q by its associated material/production cost, which does not include the overhead and profit (O&P). The total cost of the quantity Q is then converted to equivalent carbon emissions by multiplying its EIO-multiplier, as summarized in Equation (2):

$$CO_2 Emission = EIO\ multiplier_{Quantity} \times Production\ Cost_{Quantity} \qquad (2)$$

Figure 17 shows only the EIO-LCA approach for computing raw material and diesel production emissions.

5.4 Hybrid (P-LCA and EIO-LCA) Methodology

The hybrid LCA model is a combination of the P-LCA and EIO-LCA models. As mentioned earlier, this approach allows for more flexibility and potentially more accuracy in estimating carbon emissions. This hybrid model consists of computing the emissions from raw material and diesel production through an EIO-LCA, while computing the tail pipe emissions and on-site construction activity emissions through a P-LCA. The P-LCA model comprehensively assesses the direct emissions from the two phases mentioned above which largely comprises of emissions from diesel. It does not include the indirect emissions produced down the supply chain line which the EIO-LCA approach accounts for.

6 Case Study

6.1 Residence on Liquefiable Ground

According to the U.S. Census Bureau (2013), the majority of new single-family homes have a slab-on-grade foundation. For this study, the idealized residential house considered is a two-story wood frame structure supported on a slab-on-grade foundation with a footprint of 10.7 m by 10.7 m (approximately 240 m^2 area for 2 stories). The hardscape around the residence is assumed to be 50 m^2.

In order to benchmark the magnitude of ground improvement cost and carbon emissions, these parameters will be referenced to those resulting from construction of the residence. The average sale price of a residential house is $298,000 for an average space of 240 m^2 (U.S. Census Bureau 2013). This cost is used as the estimated price of the house in the case study. According to Salazar and Meil (2009), the LCA carbon footprint estimate of a wood frame residential house is approximately 60,800kg-CO_2e.

In order to define and illustrate the elements involved in calculation of cost and carbon, the scenario of a house is studied, built on liquefiable ground and thereafter exposed to an earthquake shaking event. On this basis, the following three cases for construction (with or without a priori ground improvement) and post event settlement/repair are considered:

(1) no ground improvement implemented with a post-event settlement of 0.15 m,

(2) ground improvement implemented as a countermeasure against moderate levels of shaking such as those corresponding to a Contingency Level Earthquake (CLE, an event with a 10% chance of exceedance in 50-years (USGS 2007)) with a post-event settlement of 0.06 m, and

(3) ground improvement implemented as a countermeasure against higher levels of shaking such as those corresponding to a Maximum Considered Earthquake (MCE, an event with a 2% chance of exceedance in 50-years (USGS 2007)) with practically no post-event settlement.

Strictly for the purpose of this study, the above postulated levels of ground improvement will be termed as GI-CLE and GI-MCE in the following sections. In all three cases, the ground is initially poor, and thus easily liquefiable. The properties of the soil on which the structure is built is defined in Table 2. The ground improvement technique prior to building the house is vibro stone columns. On occurrence of an earthquake, the house that experience post-event settlement shall be re-levelled via compaction grouting. As mentioned earlier, the settlement values are taken from MBIE (2013), a guideline for house that experienced settlement after the Canterbury earthquakes. The term settlement herein is assumed to implicitly also account for differential settlement, which being a primary concern while discussing liquefaction hazard. In effect, “settlement” is the total of uniform and average differential settlement that the structure experiences.

6.2 Ground Improvement Prior to Construction

6.2.1 Construction Item Quantities

The ground improvement technique used prior to building the house is vibro stone columns. The stone columns are presumed to have a unit weight of 1600 kg/m^3 and a depth of 8 m for Case 2 and 12 m for Case 3. After the construction of stone columns, a stone bed (depth of 0.54 m for Case 2 and 0.80 for Case 3) is laid on the ground spread over the entire footprint. The cost and carbon emissions are computed by the process outlined in Figure 15 through Figure 17. For the three cases under consideration, each GI case has a defined group of construction items. Each item has an approximate amount of quantities required, Q and Q_c. As shown in the flow chart in Figure 16, the quantity Q of each construction item is first calculated as it is required for computing the cost, and the quantity for carbon calculation Q_c. It should be noted that only the results for Case 2 and 3 are reported, since Case 1 requires no action taken for improving the ground initially.

The design parameters required for the construction of stone columns are shown in Table 3. Additional information required such as density and unit weight of the materials (for carbon computation) are provided in Table 4. Based on the design, Table 5 lists the construction items for the three phases: raw materials, construction activity, and transportation. The Table displays the procedure to compute the quantities Q & Q_c for all the items under each phase. The volume of the raw materials required for stone column and stone bed i.e. aggregates can be calculated as shown in the Table.

The Table lists the equipment required to execute the work on site. A crane-suspended downhole vibrator is used to construct the stone column (Hayward Baker Inc.). A compact track loader is used throughout the construction time to load the vibrator with aggregate and clear the site off excess material. A grader is used to level the surface once the stone bed is laid. Fuel consumption rates for the equipment (Table 6) are used to find the total quantity of fuel required to run the equipment on site. Electricity on site is assumed to be generated using diesel generators instead of a power grid. The fuel consumed by the generator and other equipment is calculated based on the hours of operation. Crew members or laborers required to execute the work on site shall be six members per day (including chief of party, driver, equipment operators and skilled laborers). The cost for equipment rental and mobilization (i.e. site preparation & tear down such as staging of on-site material & equipment, storage facilities, access road construction, site cleaning and grubbing, surveying, fencing, temporary site office etc.) are included under construction activity.

For the transportation phase, it is assumed that a 10-wheel truck and a combination truck will be used to carry materials and equipment required, respectively to the site from their sources and back. Table 7 provides the Fuel Economy Factor (FEF in kilometer per liter), load capacity and an approximate distance travelled by the vehicles to find the total fuel consumed by the vehicles during transportation. As stated in the methodology to compute the total diesel for transportation, the total number of vehicles is estimated by dividing the total weight of material by the load capacity of the vehicle. The number of 10-wheel trucks required is based on the total quantity of stone aggregates required. In this study, it is assumed that one combination truck will be used to transport all the equipment. Table 9 shows an elaborate computation of the total diesel required to transport the equipment and materials to the site and back. The total diesel quantities Q and Q_c for transportation are found in units of liter.

6.2.2 Cost Computation

For the effort, the quantities Q and Q_c of each construction item are provided in Table 8 and the associated unit costs including O&P, and production costs are listed in Table 10. The above mentioned two parameters i.e. the quantity Q and corresponding unit cost including O&P are each multiplied (Equation (1)) and summed over all the construction items to compute the total cost incurred during the ground improvement process. The quantity Q_c required for carbon calculation and the production cost will be used to compute the carbon emission and has been discussed in the subsequent carbon computation section. The itemized GI quantities Q and Q_c calculated and their corresponding costs (unit cost including O&P and production cost) are tabulated in Table 11.

6.2.3 Cost Results

The total GI cost details for the three cases are summarized in Table 12. As in Case 1 does not undergo any ground improvement, there is no cost incurred. It can be expected that as the level of ground improvement increases, the corresponding cost will increase accordingly. True to form, the cost of Case 3 is higher than that of Case 2. More importantly, the Table shows the cost incurred during each phase of construction namely material, construction activity and transportation. This can be better understood from Figure 18 which illustrates the cost contributions from different phases for Case 2 and Case 3 in the form of a pie chart. For Case 2, 89% of the cost is incurred during the construction activity phase, followed by 9% due to materials and 2% due to transportation phase. Similarly, Case 3 shows that 82% of the cost is spent during construction activity, 14% on materials and 4% during the transportation phase. It is evident that construction activity is the most expensive phase which includes the cost of equipment rental, mobilization, labor and diesel for on-site equipment and electricity, whereas the costs of material and transportation are relatively insignificant.

6.2.4 Carbon Emission Computation

To compute carbon emissions via P-LCA model, the approach outlined in Figure 16 is followed. The assessment is broken down by computing the carbon emissions in four phases; raw material (embodied carbon), construction activity, transportation (tail pipe CO_2), and diesel production. Table 13 lists the emission factors for each construction item. To find the carbon emitted, the quantity Q_c from Table 8 is each multiplied by its corresponding emission factor and summed over all the construction items. The total carbon emission computed using the P-LCA model is itemized in Table 14 and the total carbon emission for each construction phase is summarized in Table 15.

For the hybrid LCA model, the emissions from transportation and construction activity are found using P-LCA as described above while the emissions due to embodied carbon and diesel production are computed using EIO-LCA model. The total material/production cost of each construction item is calculated by multiplying the quantity Q_c by the corresponding production cost. The carbon emission using the EIO-LCA model are computed by inserting the EIO-multipliers of each quantity (Table 16) and corresponding total production cost (Table 11) into Equation (2). Table 17 summarizes the total carbon emissions computed with the hybrid LCA model.

6.2.5 Carbon Emission Results

The carbon emission produced during ground improvement for the different cases are found using P-LCA and hybrid LCA models and are summarized in Table 15 and Table 17. As mentioned during cost analysis, Case 1 does not undergo ground improvement and therefore there is no carbon emission produced. As expected, Case 3 produces more carbon than Case 2 and this is reflected via both the LCA approaches. In general, the P-LCA computed carbon emissions to construct the vibro stone columns in this case study are in parallel with studies performed by Chawla et al. (2010).

Comparing the P-LCA and hybrid LCA carbon results for Case 2, it is apparent that the emission found via hybrid LCA model is much larger than that using P-LCA model. This similarity is prominently seen in both cases i.e. Case 2 and Case 3. The emission found via hybrid LCA is about 37% higher than that of P-LCA model in both cases. This is due to the fact that the former provides a more holistic assessment by using EIO-LCA model (within hybrid LCA) which accounts for other indirect emissions down the supply chain that P-LCA does not include (Säynäjoki et al. 2011, Küçükvar et al. 2013). For instance, P-LCA underestimates carbon emission from production of diesel at refinery when compared with the hybrid LCA.

These Tables are further presented in form of pie charts showing the breakdown of carbon emissions for each case of GI construction. The breakdown for Case 2 (Figure 19) via P-LCA model shows that 49% of the emission is produced during construction activity, followed by 35% during transportation and 17% from materials. For the same case, the hybrid LCA model presents similar results of 49% emission from construction activity, 37% from transportation and 14% from materials. Similarly, the carbon emission produced in Case 3 can be found in Figure 20 which shows that results from P-LCA model is comparable to that found via hybrid LCA model. These comparisons elaborate the fact that although the emissions computed via P-LCA and hybrid LCA models are quantitatively different, the ratio of contribution from the three phases of construction are similar.

6.3 Post-event Repair

6.3.1 Construction Item Quantities

Similar to the GI cases, the cost and carbon emissions are computed by following the process outlined in Figure 15 through Figure 17. For each of the three Cases considered, the house experiences a certain level of settlement, as discussed earlier in Section 6. For each settlement limit, there is an associated repair effort. Each repair effort, similar to the GI cases, has a set of construction items (for Cases 1 and 2, as Case 3 does not require any repair). It should be noted that the post-event repair quantities discussed in this report are specific to this case study. Based on the repair quantities (Q and Q_c), the cost and carbon emissions are computed.

All the input parameters required to estimate the quantities of repair items are laid out in Table 18. Additional information such as density and unit weight of materials used are provided in Table 4. Table 19 lists the three phases of construction items for post-event repair: materials, construction activity and transportation. In this study, the raw materials required to repair the house include grout to re-level the foundation, concrete to re-grade the hardscape area around the house, and reparation or replacement of damaged representative non-structural components. In this study emphasis is placed on house re-levelling, and thus only a small list of non-structural components is included (repair for flooring, door, and chimney).

6.3.1.1 Relevelling Related Materials

The volume of grout required obviously exceeds that needed exactly to offset the incurred settlement and bring the structure back to its original level (due to soil compressibility, and grout migration outside of the immediate house footprint for instance). For that reason, in this study, the estimate for grout volume shall be 2 × house footprint area × settlement (i.e., a factor of 2 is assumed). In addition, based on the level of damage, it is assumed that a certain percent of total hardscape area requires re-grading and the corresponding concrete quantity is estimated (Table 18).

6.3.1.2 Non-Structural Components Materials

To estimate the potential damage caused to representative non-structural components of the house, judicious assumptions are made for certain quantities while others are based on the Performance Assessment Calculation Tool (PACT 2012), a guideline provided by Federal Emergency Mitigation Disaster (FEMA). As mentioned above, the representative non-structural components in this study are floor finishes (carpet), external door, and chimney.

PACT provides a normative quantity of tile flooring in a residential building as 0.212 square meters per gross square meter. Based on an assumption that the rest of the area within the house will be covered with carpet flooring, the normative quantity of carpet flooring is 0.788. A judicious assumption is made to estimate the damage caused to the flooring.

For the specific purpose of this study, it is assumed that the entire chimney is replaced (if any appreciable settlement is incurred). Similarly, one door is replaced if settlement occurs. It should be noted that not all non-structural components that are liable to damage are accounted for in this case study. As mentioned earlier, the non-structural components used in this study are only representative of such elements that may require repair. Ideally a comprehensive list of all non-structural elements that require repair due to the earthquake should be prepared and analyzed for cost and carbon.

6.3.1.3 Construction Activity and Transportation

The machinery required for compaction grouting includes drilling, mixing, pump and delivery systems (Hayward Baker Inc.). Besides, a grader is used for regrdaing and resurfacing the pavement. The equipment required to repair the non-structural damage in the house shall use a diesel generator throughout the process. The fuel required to run all the above mentioned equipment on site can be computed using the corresponding fuel consumption rates (FCR) tabulated in Table 6. Items such as equipment rental, mobilization, labor and electricity are included under construction activity similar to the GI method.

To compute the total diesel for transportation, the total number of vehicles is estimated as presented in the previous section (Table 21). Table 7 provides the FEF, load capacity and approximate distance travelled by each vehicle. The number of concrete mix truck is based on the total amount of concrete and grout required for construction. It is assumed that a pick-up truck is used for transporting non-structural components and other miscellaneous materials. A combination truck is used to transport the equipment to the site and back. The total diesel for transportation of materials and construction equipment is obtained following the method used in GI. The total diesel in liters is used for cost and carbon calculations, as shown in Figure 13. Table 20 provides the Q values of each item to compute the cost.

6.3.2 Cost Computation

The material quantity Q for each construction item is in provided in Table 20. For the effort, the associated unit cost including O&P are provided in Table 10. The above mentioned parameters, i.e. material quantity Q and the corresponding unit cost including O&P are inserted into Equation (1) to compute the total cost, itemized in Table 22.

6.3.3 Cost Results

The total repair costs for the three cases have been summarized in Table 23. Predictably, based on the amount of post-event repair executed, the cost incurred during Case 1 is greater than Case 2. Case 3 perceived no settlement and therefore no is cost incurred. Figure 22 illustrates the cost contributions from different phases for Case 1 and Case 2 in form of a pie chart. In case of post-event repairs for Case 1, approximately 58% of the cost is resulted from construction activity, 41% from materials and less than 1% from transportation. Similarly the cost distribution of Case 2, approximately 54% of the cost is from construction activity, 46% from materials and less than 1% from transportation. In this particular instance, it can be seen that the cost of materials and construction activity phase are very similar. Although the cost from transportation phase is insignificant, it cannot be omitted from carbon analysis as it contributes a significant amount of carbon emission.

6.3.4 Carbon Emission Computation

The P-LCA procedure implemented for computing the GI emissions is applied to obtain the post-event repair emissions. To find the carbon emitted, the material quantity for carbon calculation Q_c (Table 20) is multiplied by its corresponding emission factor and summed over all the construction items. The EFs for all the items are provided in Table 13. The total carbon computed with the P-LCA model is itemized in Table 24 and the total carbon emission for each phase of construction is summarized in Table 25.

Similarly, the hybrid LCA model is implemented for computing the GI emissions to achieve the post-event repair emissions. The total production cost of each construction item is computed by multiplying the material quantity Q_c with the corresponding material/production cost. The EIO-multipliers for the repair items (Table 26) and corresponding total production cost (Table 22) are multiplied to find the carbon emissions using the EIO-LCA model. As mentioned earlier, emissions from transportation and construction activity are computed via the P-LCA model, whereas raw materials and diesel production at the refinery are computed using EIO-LCA model. Table 27 summarizes the total carbon emissions computed with the hybrid LCA model.

6.3.5 Carbon Emission Results

The carbon emission produced during post-event repair computed via P-LCA and hybrid LCA models are summarized in Table 25 and Table 27. As expected, emission from Case 1 is higher than Case 2. The tabulated results can be better perceived from Figure 23 and Figure 24 (for Cases 1 and 2) which shows the carbon emission contributed from each of the three phases of construction via P-LCA and hybrid LCA models. For Case 1, the P-LCA model shows emission from materials (embodied carbon) dominated by 77%, followed by 19% from construction activity and 4% from transportation phase (Figure 23). The Figure also demonstrates a contribution of 87%, 11% and 2% from materials, construction activity and transportation, respectively via hybrid LCA model.

Similarly, the carbon emission contribution from three phases for Case 2 can be seen in Figure 24. In both cases, the largest emission is contributed from embodied carbon or raw materials. As discussed earlier, the minor variation in the contribution ratio in post-event repairs can be attributed to the difference in emission factors and EIO-multipliers pertaining to the raw materials and diesel production. These results are in parallel with studies performed by Harmouche et al. (2012) on construction, primarily using cementitious materials where the emission from transportation and construction activity are relatively insignificant compared to the embodied carbon.

6.4 Representation of settlement, cost and carbon by probabilistic distributions

6.4.1 Probabilistic Analysis Computations

The above discussed framework is further extended in order to represent the settlement, cost and carbon emission by probabilistic distributions. This section of the study will analyze the benefits and shortcomings in terms of cost and carbon for the three cases, on the basis of probability of seismic event induced settlement occurrence. The following section presents a framework that is based on total probability theorem, along with necessary assumptions and parameters chosen for this study.

The framework for computing the probability of exceeding a certain cost or carbon footprint is displayed in Figure 21. Each step in the flow chart is explained in detail below.

1. The first step is specifying the seismic events, E_i. For this study three events are considered (in terms of incurred settlement in each): E0 resulting in relatively small settlements, E1 resulting in relatively moderate settlements, and E2 resulting in relatively large settlements. In general, the probabilistic analysis can be conducted for any number of events and their probabilities of occurrence.

2. Step 2 specifies the probability of occurrence for each earthquake event. For instance, the probabilities of E0, E1, and E2 occurrence can be taken as 85%, 10%, and 5%, respectively. To further illustrate the impact of these probabilities, results will be presented as well for the probabilities of 70%, 20% and 10%.

3. Step 3 defines a settlement probability distribution, for each of these events. As described in the flowchart, a log-normal (*LN*) distribution is employed with a specified value for the mode ($\hat{\mu}_S$) for each of the three cases analyzed (and a coefficient of

variance, cov δ). The parameters for each of the three cases are listed in Table 28. Using this distribution, the conditional probability of a settlement *S* occurring given that earthquake E_i occurs is defined by $P(S|E_i) = LN(\hat{\mu}_{\boldsymbol{S}|\boldsymbol{E_i}}, \delta)$.

4. Using Steps 2 and 3, the probability of settlement *s* being less than settlement *S* can be computed as $P(s < S) = \sum_{i=0}^{I} P(s < S|E_i) \times P(E_i)$.

5. In discrete form, the results of Step 4 are used to define the probability of a particular settlement event S_j occurring. This probability $P(S_j)$ is defined by $P(S_{j-1} < s < S_j)$, that being the difference of $P(s < S_j)$ and $P(s < S_{j-1})$. For this study, eight discrete settlement events S0 to S7 are used, representing settlements starting from 0.003 m to 0.24 m with a 0.03 m increment (Table 29). Whenever warranted, employment of additional settlement events (with closer increment) may lead to further accuracy in the computations.

6. This step determines the probability distribution of cost given a settlement event S_j. This probability is assumed to be Normally distributed (*N*), characterized by a mean cost, μ and a coefficient of variance, cov. The cost parameters for each of the three cases are listed in Table 29. This distribution provides the conditional probability of incurring the cost C, given that settlement S_j occurs, $P(C|S_j) = N\left(\mu_{C|S_j}, \delta\right)$.

7. From Steps 5 and 6, the probability of cost exceeding a certain cost C can be found using $P(c > C) = \sum_{j=0}^{J}\left[1 - P(c < C|S_j)\right] \times P(S_j)$. The same procedure is repeated for finding the carbon exceeding a certain carbon and the necessary carbon parameters are listed in Table 30.

As shown in the Tables, the coefficients of variance for settlement are taken as 0.3, merely as representative values in this study. In effect, these values can be better defined based on potentially available liquefaction-induced house settlement earthquake reconnaissance data. Similarly, cost and carbon emission coefficients of variance are taken as the representative value of 0.2 throughout, with other values possible whenever substantiated by actual related data. For illustration, the effect of coefficient of variance on the outcomes will be touched on briefly in the subsequent results section below (a scenario with coefficient of variance = 0.5 for all involved quantities, settlement, cost, and carbon).

6.4.2 Probabilistic Analysis Results

The probability of exceeding a certain cost and carbon (i.e. $P(c > C)$) are shown in Figure 27 and Figure 28 for the P(E) of 85%, 10% and 5% and the P(E) of 70%, 20% and 10%, respectively (cov of 0.2 for settlement and 0.3 for cost and carbon). Figure 27a shows the probability of exceeding a certain repair cost for the three cases. The graph shows that the probability of exceedance decreases from Case 1 to Case 3. For instance, the $P(c > C)$ for a repair cost of \$75,000 is 28% for Case 1, 4% for Case 2 and 1% for Case 3. Similarly, Figure 28a shows that the probability of the $P(c > C)$ for a repair carbon of 15,000 kg is 57% for Case 1, 10% for Case 2 and 3% for Case 3. The marked decreases in probability for Cases 2 and 3 highlights the significance of a priori ground improvement in reducing the potential for additional cost and carbon production. For a slightly higher potential of settlement (P(E) of 70%, 20% and 10%), Figure 27b shows that the corresponding cost probability is somewhat increased to 33%

for Case 1, 7% for Case 2 and 1% for Case 3, and Figure 28b shows the corresponding carbon has also increased to 62% for Case 1, 16% for Case 2 and 4% for Case 3.

To illustrate the impact of a higher cov (e.g., 0.5 for settlement, cost and carbon), Figure 29 and Figure 30 show a more gradual reduction in probabilities as expected compared to Figure 27 and Figure 28. Considering the P(E) scenario of 85%, 10% and 5%, the probability of exceeding the repair cost of $75,000 has increased from 28%, 4% and 1% (Figure 27a) to 44%, 22% and 19% (Figure 29a) for Cases 1, 2 and 3, respectively. Similarly, the probabilities of exceeding the repair carbon production of 15,000 kg has increased from 57%, 10% and 3% (Figure 28a) to 59%, 28% and 24% (Figure 30a) respectively. For the slightly higher potential of settlement (P(E) of 70%, 20% and 10%), Figure 29b shows that the corresponding cost probability has increased to 46%, 25%, 19% for Cases 1, 2 and 3, and Figure 30b shows the corresponding carbon has also increased to 61%, 32% and 24%.

7 Overall Results and Discussion

7.1 Deterministic Analysis Results

Table 31 shows a summary of the total project cost results (including GI, construction of the house and post-event repairs) calculated for the three cases considered. Among the three cases, the cost incurred during Case 3 is found to be the least. Costs of Case 1 and Case 2 are comparable and each about 10% higher than Case 3. More importantly, considering the cumulative GI and post-event repair costs for the three cases, Case 3 again reveals to be the most economical in this study. A comparison between the cumulative costs for Case 1, 2 and 3 (Figure 25) shows that Case 1 and 2 are comparable, and higher than Case 3 by 78%.

Carbon analysis for the total project via P-LCA and hybrid LCA models shows that Case 1 produces the most carbon emission (Table 32). Considering the carbon emissions from cumulative GI and post-event repairs, the results from the P-LCA & hybrid LCA models vary by about 132%, 123% and 38% for Cases 1, 2 and 3, respectively (Figure 26). As discussed in earlier sections, one of the reasons for this vast difference in emissions (especially for Case 1 and 2) could be attributed to the large quantity of raw materials and diesel used along with their high emission factors/EIO-multipliers.

Based on the discussions above, it can be inferred that Case 3 is the most viable option for a structure if a seismic event occurs. In general, Case 3 may not always be the most appropriate option, as the situation depends on the expected level of seismicity, and the risk that the stakeholder is willing to assume. Nevertheless, this framework aids the overall decision-making procedure such that the stakeholder can evaluate the potential benefits and shortcomings in terms of cost and carbon.

7.2 Probabilistic Analysis Results

As mentioned earlier, the probability of exceeding a certain cost and carbon for the three cases are shown in Figure 27 through Figure 30 for the different investigated scenarios. Expectedly, for any specified cost, the probability of exceedance decreases from Case 1 to Case 3 (Figure 27 and Figure 29). Case 1 shows the highest probability of exceedance for a given settlement event. This is because the probability of large settlements occurring is high when the soil is not modified prior to construction. Likewise, Figure 28 and Figure 30 show the probability of exceeding a certain carbon emission for the different scenarios.

In effect, this framework helps to assess the probability of incurring additional cost and carbon emissions, given the corresponding initial construction quantities. For Case 1 where no initial ground improvement is done, the initial investment to build the house is \$298,000. Given a particular postulated hazard scenario (e.g., P(E) of 85%, 10% and 5% with cov of 0.2 for settlement and 0.3 for cost and carbon shown in Figure 27a), the probability of exceeding a repair cost for instance of \$72,000 is 34%. Similarly, for Case 2, the initial investment including a GI-CLE ground improvement is about \$330,000 and the probability of exceeding this cost is 6%. In Case 3 with GI-MCE ground improvement, the initial investment is about \$345,000 and the probability of exceeding this cost for additional repair is 4%. Similar logic applies to the emitted carbon as depicted in Figure 28a, the probability of exceeding a repair carbon for instance of 18,000 kg, Cases 1, 2 and 3 probabilities are 34%, 4% and 0% with the initial quantities being about 60,000 kg, 68,000 kg, and 75,000 kg, respectively.

7.3 General Remarks and Suggestions for Additional Research

1. The above discussed results for Cases 1 and 2 (which underwent post-event repair) were obtained without including cost/carbon associated with any disruption of function or temporary relocation incurred to the residents. This issue would increase the cost and carbon computed in the study.

2. This study does not attempt to account for all damage possibilities that might occur to the property. As mentioned earlier, only a small representative set of non-structural components are included in this study. In effect, a comprehensive list of damaged non-structural components can be included for a more detailed analysis.
3. The framework can be refined to employ a quantitative analytical/numerical approach for estimating the expected settlement.
4. The framework of this study can be extended in a straightforward fashion to assess cost/carbon considerations for an entire housing development rather than a single-family house. Studying such a more realistic community situation would yield more insights as pertains to the decision-support process.

8 Summary and Conclusion

This study is concerned with cost and environmental impact due to carbon emission as metrics in a performance-based assessment framework. For that purpose, focus is placed on the scenario of a lightweight structure in a seismic zone, built on a potentially liquefiable soil. Three cases are considered: (1) repair the liquefaction-induced settlement damage by re-levelling the structure after the possible occurrence of seismic activity, or (2) implement a priori a ground improvement countermeasure to mitigate such damage (two different scenarios studied). The considered a priori ground improvement technique is vibro stone columns. Re-leveling the structure that has experienced settlement is based on the compaction grouting procedure. This study sets up a pilot framework to evaluate and contrast the cost and carbon emissions associated with these three cases.

In order to define and integrate the salient elements of the framework, three cases of ground improvement and their corresponding settlements are considered for the structure (taken herein as a residential house): 1) no ground improvement with a post-earthquake settlement of 0.15 m, 2) ground improvement for GI-CLE event with a post-earthquake settlement of 0.06 m, and 3) ground improvement for a GI-MCE event with no significant post-earthquake settlement. The house that experiences a settlement of 0.06 m or greater undergoes a certain level of re-levelling and repair depending on the amount of settlement. Cost estimates are derived from existing databases for construction items. Carbon emission for each case is computed using two models: (i) P-LCA and, (ii) a hybrid approach which is a combination of P-LCA and EIO-LCA models. The results of carbon emission from the two models are contrasted.

As such, the above described phase of the study introduces and integrates the various components of the framework, in that the incurred settlement as well as the cost and carbon emission computations are all based on specific quantities, within a deterministic framework. In addition, it provided the basis for probabilistic assessments as will be highlighted further below.

For the above mentioned three cases, the deterministic analysis showed that the GI-MCE case resulted with the least incurred overall cost. This is because the house in this case does not experience any settlement and therefore does not require a post-event repair. Although the cumulative cost of initial ground improvement and post-event repair for the other two cases (house with no GI and GI-LCE event) was comparable, it was found to be significantly higher than the GI-MCE case.

Similarly, the carbon assessment for this study showed that the GI-MCE case produced the least carbon emission. Conversely, the house that was not subjected to a priori ground improvement eventually underwent large settlement repair, resulting in the most carbon emission. Comparing the two models i.e. P-LCA and hybrid LCA, the hybrid LCA model consistently estimates a larger amount of emission than P-LCA. This is due to the fact that P-LCA neglects the indirect emissions that the hybrid LCA accounts for within the EIO-LCA model which provides a more holistic approach to the study.

Furthermore, the above framework provided a basis for assessment of the outcomes under the conditions of a probabilistic earthquake induced settlement scenario. In addition, in this assessment phase, cost and carbon were represented by probability distributions. On this basis, settlement for the three cases was represented by a log-normal distribution and the corresponding cost and carbon were characterized by normal distributions. For the above scenario, the results showed that the probability of exceedance of a specified cost or carbon decreases as the amount of initial ground improvement increases. As such, a range of cost/carbon emission is displayed for the stakeholder to consult within the overall risk assessment decision support framework.

In general, this study provides a first attempt to develop a cost and carbon emission performance-based framework for mitigating the settlement consequences of ground liquefaction. While the emphasis was placed on the residential house scenario, this developed framework can be easily extended and applied to other lightweight residential/commercial structures, as well as to an entire housing development or commercial complex.

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APPENDIX - TABLES AND FIGURES

Table 1: Damage Limit for Settled Wood Frame Residential Structure (Modified from MBIE 2012)

Limit Description	Repair Method
Variation in floor level <50mm & Floor slope < 1 in 200 between any two points >2m apart	Repair not required
Variation in floor level >=50mm and <150mm	Re-level existing foundation, via compaction grouting
Variation in floor level >=150mm	Replace foundation, partial or full
House has fully or partially collapsed off the piles and repair is uneconomical, or vertical differential settlement	Demolish and replace structure. May need to relocate for a long period of time.

Table 2: Soil Parameters

Thickness of liquefiable layer	10 m
Clay crust above liquefiable soil	0.5 m
Bearing pressure of soil	20 kPa
Residual shear strength of liquefiable soil	2 kPa

Table 3: Ground Improvement Design Parameters

Raw Materials	Property	Case 2	Case 3
Stone Column	Height of stone column (m)	8	12
	%[1] of total footprint area treated with stone columns	10%	20%
	Diameter of stone column (m)	0.9	0.9
	Area of stone column (m^2)	0.66	0.66
	No. of stone columns	18	35
Stone Bed	%[1] of footprint length	5.0%	7.5%
	Depth of stone bed = % of footprint length * footprint length (m)	0.54	0.80
Construction Activity		Case 2	Case 3
Mobilization / Construction of Stone Column, Stone Bed / Regrading	No. of hours per day	8	8
	No. of days - Mobilization	3	3
	No. of days – Stone Column	3	6
	No of days – Regrading	2	2
	Total no. of days	8	11
Labor	# of crew members	6	6

[1] Assumed Percent

Table 4: Density of Materials

Raw Material	Density (kg/m^3)
Stone Aggregate	1600
Grout	2162
Concrete	2400
Carpet – General	284
Wood	540
Chimney – Masonry	1920

Table 5: GI Construction Items and Corresponding Quantities for Case 2 and 3

GI	Construction Item	Unit	Quantity, Q	Unit	Quantity, Q_c
Case 1: No Ground Improvement	-	-	-	-	-
Case 2: Moderate Ground Improvement & Case 3: Substantial Ground Improvement	Stone Column	tonne	No. of Stone Column[1] × Cross Sectional Area[2] × Height[2] × Density of Stone	kg	$Q \times 1000$
	Stone Bed	tonne	Footprint Area × Depth[3] × Density of Stone	kg	$Q \times 1000$
	Mobilization – Site Preparation & Tear Down	lump -sum	1	liter	No. of working hours x FCR[4] of generator
	Diesel for m # of Equipment[5]	liter	Equipment$_m$ × Operation Hours per Day$_m$ × # of Days$_m$ × FCR$_m$ [4]	liter	Q
	# of Crew Members or Laborer	Ea	Number of Members Working per Day	Ea	Q
	Diesel for Transportation	liter	Vehicle$_k$ x Number of Trip$_k$ x FEF$_k$ [4] x Distance Travelled in a Two-Way Trip$_k$	liter	Q

[1] No. of stone column - Table 3

[2] The cross sectional area and height refers to that of the stone column - Table 3

[3] Depth refers to that of stone bed - Table 3

[4] Fuel Consumption Rate - Table 6

[5] Equipment includes stone injector, grader, compact track loader and diesel generator

Table 6: Fuel Consumption Rate for Equipment

Equipment	FCR (liter/hour)	Reference
Stone Injector	10.60	Frey et al 2010, similar to excavator
Grader	9.46	Frey et al. 2010
Compact Track Loader	10.98	Frey et al. 2010
Generator	4.54	Frey et al. 2010
Drilling Equipment	9.46	Frey et al. 2010, similar to move rock
Grout Injector	10.60	Frey et al. 2010, similar to excavator

All FCR given in gal/hour are converted to liter/hour assuming 1 gallon = 3.785 liter

Table 7: FEF and Load Capacity of Vehicles for GI & Repairs

Vehicle	Fuel Economy Factor (FEF) (km/l)	Load Capacity	Distance- one way (km)
10 Wheel Truck	2.55[1]	25 tonne	113
Combination Truck - Equipment Transporter	2.51[2]	-	80
Concrete Mix Truck	2.59[3]	13 m^3 [4]	48
Pick-up Truck	9.35[5]	3 tonne[5]	80

[1] http://www.popularmechanics.com/cars/trucks/g116/10-things-you-didnt-know-about-semi trucks/?slide=5

[2] EPA 2008

[3] http://www.ehow.com/list_7668977_specs-mileage-class-8-trucks.html

[4] http://www.nrmca.org/aboutconcrete/howdelivered.asp

[5] http://www.autotrader.com/research/article/best-cars/148600/top-6-fuel-efficientpickups.jsp

All units converted to SI units

Table 8: Ground Improvement Quantities (*Q* & *Qc*)

	Quantity, *Q*			Quantity, *Qc*		
Construction Item	Unit	Case 2	Case 3	Unit	Case 2	Case 3
Stone Column	tonne	151	441	kg	146547	439642
Stone Bed	tonne	98	147	kg	98003	147005
Diesel for Stone Injector	liter	254	509	liter	254	509
Diesel for Track Loader	liter	263	527	liter	263	527
Diesel for Grader	liter	151	151	liter	151	151
Diesel for Diesel Generator	liter	291	400	liter	291	400
Diesel for Mobilization	liter	109	109	liter	109	109
# of crew members	Ea	6	6	Ea	6	6
Diesel for Transportation – (Table 9)	liter	948	2185	liter	948	2185

Table 9: Diesel required for Transportation

Vehicle	FEF[1] kmpl	Distance – one way[1] km	Load Capa-city [1]	Quantity	Case 1	Case 2	Case 3
10 Wheel Truck	2.55	113	25 ton	Stone (ton)[2]	-	249	588
				# of trucks[3]	-	10	24
				Diesel[4] (liter) = [a]	-	884	2121
Combination Truck - Equipment Transporter	2.51	80	-	Equipment[5] (Ea.)	-	1	1
				# of trucks[3]	-	1	1
				Diesel[4] (liter) = [b]	-	64	64
				Total Diesel (liter)= [a]+[b]	-	948	2185

[1] Vehicle Specifications- Table 7

[2] Stones used for stone column + stone bed - Table 8

[3] $\# \ of \ trucks = Total \ Material \ Quantity/Truck \ Load \ Capacity$

[4] $Diesel = \# \ of \ trucks \times distance \ traveled \ in \ a \ two \ way \ trip \div FEF$

[5] List of equipment - Table 6

Table 10: Unit Cost of Ground Improvement and Post-Event Repair Items

Construction Item	Unit	Production/Material Cost per Unit	Total Cost including O&P per Unit
Raw Materials			
Stone Aggregate[1]	tonne	$ 5.57	$ 11.14
Low Mobility Grout[2]	m^3	$ 728.37	$ 1107.11
Concrete[2]	m^2	$ 22.29	$ 50.17
Floor finishes – Carpet[2]	m^2	$ 19.70	$ 24.65
Exterior Door[2]	Ea	$ 83.33	$ 144.38
Masonry Chimney[3]	Ea	$ 6,502	$ 7,225
Construction Activity			
Mobilization[4]	lumpsum	-	$ 8,000
Equipment – Stone Injector[2]	day	-	$ 1,400
Equipment - Install Grouting Pipe[2]	day	-	$ 389
Equipment – Grouting Pump[2]	day	-	$ 85
Equipment - Grader[2]	day	-	$ 438
Equipment – Track Loader[2]	day	-	$ 273
Equipment – Diesel Generator[2]	day	-	$ 102
Total labor cost[2]	day	-	$ 1,559
Diesel[5]	liter	$ 0.65	$ 0.81
Transportation			
Diesel[5]	liter	$ 0.65	$ 0.81

[1] USGS

[2] RS Means 2008, 2010, 2013, 2015

[3] PACT, 2014

[4] Andrus & Chung 1996

[5] EIA 2013

Table 11: Ground Improvement - Material Cost and Total Cost including O&P

		Total Cost including O&P			Material/ Production Cost		
Construction Item	Unit	Unit Cost	Case 2	Case 3	Unit Cost	Case 2	Case 3
Stone Columns	tonne	$ 11.14	$ 1,686	$ 4,916	$ 5.57	$ 843	$ 2,458
Stone Bed	tonne	$ 11.14	$ 1,092	$ 1,638	$ 5.57	$ 546	$ 819
Mobilization	Lump -sum	$ 8,000	$ 8,000	$ 8,000	-	-	-
Injector & loader – Equipment Rental Cost	Ea	$ 1,673	$ 5,019	$ 10,038	-	-	-
Grader - Equipment Rental Cost	Ea	$ 438	$ 876	$ 876	-	-	-
Diesel Generator - Equipment Rental Cost	Ea	$ 102	$ 816	$ 1,122	-	-	-
Cost of Diesel used in Equipment[1]	liter	$ 0.81	$ 864	$ 1,371	$ 0.65	$ 692	$ 1,098
Labor Cost	Ea	$ 1,559	$ 12,472	$ 17,149	-	-	-
Cost of Diesel used during Transportation	liter	$ 0.81	$ 767	$ 1,769	$ 0.65	$ 614	$ 1,415
Total Cost			$ 31,592	$ 46,878			

[1] Equipment include stone injector, loader, grader, diesel generator for electricity and mobilization

Table 12: Summary of Costs for each GI states (including O&P)

Case	Material	Transportation	Construction Activity	Total Cost
1	0	0	0	0
2	$ 2,777	$ 767	$ 28,047	$ 31,592
3	$ 6,554	$ 1,769	$ 38,556	$ 46,878

Table 13: P-LCA: Carbon Emission Factors for GI & Repair Items

Construction Item	Emission Factor	Reference
Stone Aggregate	0.005 kgCO$_2$/kg	Hammond and Jones (2008)
Grout	0.213 kgCO$_2$/kg	Hammond & Jones (2008)
Concrete	0.13 kgCO$_2$/kg	Hammond & Jones (2008)
Carpet	3.89 kgCO$_2$/kg	Hammond & Jones (2008)
Wood – Plywood	0.81 kgCO$_2$/kg	Hammond & Jones (2008)
Chimney - Brick	0.62 kgCO$_2$/brick	Hammond & Jones (2008)
Diesel for Equipment and Transportation	2.68 kgCO$_2$/liter	Frey et al. (2010)
Diesel Production at Refinery	0.06 kgCO$_2$/liter	NREL (2010)
Per Person	15 kgCO$_2$/day	UNSD (2015)

Table 14: GI Carbon Emission using P-LCA Model (in kgCO_2)

Construction Item	EF	Carbon Emission (kgCO_2)	
Materials	(kgCO_2/kg)	Case 2	Case 3
Stone Columns	0.005	757	2,206
Stone Bed	0.005	490	735
Construction Activity	(kgCO_2)		
Diesel used in Equipment (kgCO_2/liter)	2.68	2,866	4,547
Diesel Production at refinery (kgCO_2/liter)	0.06	62	99
Crew member (kg/day)	15.00	720	990
Transportation	(kgCO_2/liter)		
Tail Pipe Emission Factor	2.68	2,542	5,859
Diesel Production at refinery	0.06	55	127
Total		7,492	14,563

Table 15: P-LCA Model Carbon Emission Summary for each GI State (in kgCO_2)

Case	Material Production	Construction Activity	Diesel Production	Tail Pipe	Diesel Production	Total (kgCO_2)
1	0	0	0	0	0	0
2	1,247	3,586	62	2,542	55	7,492
3	2,942	5,537	99	5,859	127	14,563

Table 16: EIO Multipliers for each GI Item (CMU 2008)

Construction Item	EIO Multipliers (t-CO_2/Million$)	Corresponding NAICS[1] Sectors
Stone Aggregate	1073.4	212310: Stone mining and quarrying
Diesel	2042.0	324110: Petroleum Refineries

[1] North American Industry Classification System (NAICS) is a six-digit code that describe the economic levels: the first two digits indicates the most general business section, the third digit indicates the industry subsector, the fourth digit indicates the industry group, the fifth digit indicates the NAICS industry, and the sixth digit represents the national industry (i.e., U.S. Canadian or Mexican National specific sector). More information can be found at http://www.naics.com/info.htm.

Table 17: Hybrid Model Carbon Emission Summary for each GI State (kgCO_2)

Case	Material[1]	Construction Activity[2]	Diesel Prod. [1]	Tail Pipe[2]	Diesel Prod. [1]	Total Carbon Emission (kgCO_2)
1	0	0	0	0	0	0
2	1,491	3,586	1,413	2,542	1,254	10,285
3	3,517	5,537	2,241	5,859	2,888	20,043

[1]Material and Diesel Production emissions were computed using EIO-LCA model

[2]Tail Pipe Emissions and Construction Activity emissions were computed using P-LCA model

Table 18: Post-Event Repair – Input Parameter

Materials	Property	Case 1	Case 2
Level base, Grout injection	Factor for initial estimate of grout volume (C)	2	2
Re-grading & Resurfacing Pavement - Concrete	% of total hardscape area to be treated	30%	20%
	Depth of sidewalk (m)	0.1	0.1
Floor Finishes - Carpet	Normative Quantity (m^2)	90	90
	% of Normative Quantity to be treated	42%	20%
Exterior Doors	No. of damaged doors	1	1
	Door Area (m^2)	1.86	1.86
	Door Thickness (m)	0.045	0.045
Chimney	1.5m above roof to be repaired (Ea)	1	1
Construction Activity	Time	Case 1	Case 2
No. of days of work	Total no. of days	13	10
	Hours of operation per day	8	8
Use of Equipment – Installing grouting pipe, injecting grout	Total no. of days	4	3
	Installing Grouting Pipe (hrs)	10	8
	Injecting Grout (hours)	11	5
	Grout Injection rate (m^3/min)	0.05	0.05
Regrading & Resurfacing Paving	No. of days of work	3	2
	No. of hours of operation	4	4
Non-structural Components	No. of days of work	3	2
Mobilization of Equipment	No. of days of work	3	2
Labor per day	No. of crew members	6	6

% - assumed percentage

Table 19: Repair Items and the Corresponding Quantities for Case 1 and 2

Method	Construction Items	Unit	Quantity, Q	Unit	Quantity, Q_c
Case 1 & Case 2: Re-level Foundation, Compaction Grouting	Compaction Grouting- Grout	m^3	Footprint Area × Settlement × C[1]	kg	Q × Density
	Regrading Pavement - Concrete	m^2	%[2] × Hardscape Footprint Area	kg	Q × Depth[3] × Density
	Flooring – Carpet	m^2	%[2] x Normative Carpet Quantity	kg	Q × Density × Carpet Pile Height
	Exterior Doors	Ea	1	kg	Q x Volume of door x Density of door material
	Masonry Chimney	lump -sum	1	Ea	No. of bricks used
	Mobilization – Site Preparation & Tear Down	lump -sum	1	liter	Total Operation hours x FCR[4] of generator
	Diesel for m # of Equipment[5]	liter	Equipment_m × Operation Hours per Day_m × # of Days_m × FCR_m[4]	liter	Q
	# of crew members	Ea	Number of members working per day	Ea	Q
	Diesel for Transportation	liter	Vehicle_k x Number of trips_k x FEF_k[6] x distance travelled in a two way trip_k	liter	Q
Case 3: No Repair	-	-	-	-	-

[1] C = Factor assumed to estimate target volume of grout pumped into the ground

[2] % - Assumed percentage

[3] Depth for resurfacing pavement; assumed as 0.1m

[4] FCR = Fuel Consumption Rate (liter/hour)

[5] Includes equipment to install grouting pipe, grout injector, grader, and diesel generator

[6] Fuel Emission Factor of vehicle - Table 7

Table 20: Post-Event Repair Quantities (Q & Qc)

Repair Item	Quantity, Q			Quantity, Qc		
	Unit	Case 1	Case 2	Unit	Case 1	Case 2
Raw Materials						
Compaction Grouting – Grout	m^3	35	14	kg	75,446	30,179
Resurfacing Paving-Concrete	m^2	15	10	kg	3,621	2,414
Flooring – Carpet	m^2	38	18	kg	66	31
Exterior Doors	Ea	1	1	kg	45	45
Masonry Chimney	Ea	1	1	brick	248	248
Construction Activity						
Diesel to Install Grouting Pipe[1]	liter	95	76	liter	95	76
Diesel to Injector Grout[1]	liter	223	95	liter	223	95
Diesel for Resurfacing Paving[1]	liter	250	167	liter	250	167
Diesel to Repair Non-Structural Components[1]	liter	109	73	liter	109	73
Diesel for Mobilization [1]	liter	109	109	liter	109	109
Diesel for Electricity - Generator[1]	liter	472	363	liter	472	363
# of crew members	Ea	6	6	Ea	6	6
Transportation Diesel (Table 21)	liter	302	228	liter	302	228

[1] Diesel for corresponding equipment

Table 21: Diesel Required for Transportation

Vehicle	FEF [1] (kmpl)	Distance : 1 way trip[1] (km)	Vehicle Load Capacity [1]	Material Quantity	Case 1	Case 2	Case 3
Concrete Mixer Truck	2.59	48	13 m^3	Concrete (m^2)[2]	15	10	-
				# of trips[3]	1	1	-
				Diesel (liter)[4] =[a]	75	37	-
				Grout (ton)[2]	76	30	
				# of trips[3]	5	2	-
				Diesel (liter) [4] = [b]	112	75	-
Pick-up Truck	9.35	80	3 tonne	Non-structural Components (Ea.)[2]	3	3	-
				# of trips[3]	3	3	-
				Diesel (liter) [4] = [c]	52	52	-
Combination Truck – Equipment Transporter	2.51	80	-	Equipment[5]	1	1	-
				# of trips[3]	1	1	-
				Diesel (liter) [4] = [d]	64	64	-
				Total Diesel (liter) = [a]+[b]+[c]+[d]	303	228	-

[1] Vehicle Specification - Table 7

[2] Quantities of material shown in Table 20

[3] $\# \; of \; trips = Total \; Material \; Quantity / Vehicle \; Load \; Capacity$

[4] $Diesel = \# \; of \; trips \; \times distance \; traveled \; in \; a \; two \; way \; trip \div FEF$

[5] List of Equipment - Table 6

Table 22: Post-Event Repair: Material Cost and Total Cost including O&P

Repair Quantities	Cost including O&P Cost			Material Cost		
	Unit Cost	Case 1	Case 2	Unit Cost	Case 1	Case 2
Compaction Grouting - Grout	$ 1,107	$ 38,634	$ 15,454	$ 728	$25,417	$ 10,167
Regrading & Resurfacing Paving – Concrete	$ 50.17	$ 753	$ 502	$ 22.3	$ 334	$ 223
Flooring – Carpet	$ 24.65	$ 934	$ 445	$ 19.7	$ 746	$ 355
Exterior Doors	$ 144.4	$ 144	$ 144	$ 83.33	$ 83.33	$ 83.33
Chimney	$ 7,225	$7,225	$7,225	$ 6,502	$ 6,502	$ 6,502
Cost of Diesel used in Equipment[1]	$ 0.81	908	641	$0.65	726	513
Mobilization	$ 8,000	$ 8,000	$ 8,000	-	-	-
Installing Grouting Pipe and Injecting Grout – Equipment Rental Cost	$ 474	$ 1,896	$1,422	-	-	-
Grader – Equipment Rental Cost	$ 438	$ 1,314	$ 876	-	-	-
Equipment for Non-Structural Components – Rental Cost	$ 102	$ 306	$ 204	-	-	-
Generator for Electricity – Equipment Rental Cost	$ 102	$ 1,326	$ 1,020	-	-	-
# of crew members	$ 1,559	$ 20,267	$15,590	-	-	-
Transportation Diesel	$ 0.81	$ 224	$ 185	$0.65	$ 196	$ 148
Total Cost		$ 81,951	$ 51,707			

[1] Equipment include to install grouting pipe, grout injector, grader, diesel generator

Table 23: Summary of Costs for Post-Event Repair

Case	Material	Construction Activity	Transportation	Total Cost
1	$ 47,690	$ 34,016	$ 244	$ 81,951
2	$ 23,770	$ 27,753	$ 185	$ 51,707
3	0	0	0	0

Table 24: Post-Event Repair Carbon Emission using P-LCA Model (kgCO$_2$)

Construction Item	EF	Case 1	Case 2
Materials	(kgCO$_2$/kg)		
Compaction Grouting – Grout	0.213	16,070	6,428
Regrading & Resurfacing Paving - Concrete	0.13	471	314
Flooring – Carpet	3.89	255	121
Exterior Doors	0.81	36	36
Chimney	0.62	154	154
Construction Activity	(kgCO$_2$)		
Diesel used in Equipment (kgCO$_2$/liter)	2.68	3,006	2,123
Diesel Production at refinery (kgCO$_2$/liter)	0.06	65	46
# of crew members (kg/day)	15	1170	900
Transportation	(kgCO$_2$/liter)		
Tail Pipe Emission Factor	2.68	810	611
Diesel Production Emission Factor, at refinery	0.06	18	13
Total		22,054	10,747

Table 25: P-LCA Model Carbon Emission Summary for Post-Event Repair (kgCO$_2$)

Case	Material	Tail Pipe	Diesel Prod.[1]	Const. Act.	Diesel Prod. [1]	Total (kgCO$_2$)
1	16,986	810	18	4,176	65	22,054
2	7,053	611	13	3,023	46	10,747
3	-	-	-	-	-	-

[1]Diesel Prod. stands for Diesel Production.

Table 26: EIO Multipliers for Each Repair Item (CMU 2008)

Repair Item	EIO Multipliers (t-CO$_2$/Million$)	Corresponding NAICS[1] Sectors
Compaction Grouting- Grout	1196.2	327124: Clay Refractory Manufacturing
Regrading & Resurfacing Paving – Concrete	2650	327320: Ready-mix concrete manufacturing
Floor Finish – Carpet	979.6	314110: Carpet and Rug Mills
Exterior Door	505.6	321910: Wood windows and doors and millwork
Chimney – Masonry	1890.2	32712A: Brick, tile, and other structural clay product manufacturing
Diesel for Equipment and Transportation	2042	324110: Petroleum Refineries

Table 27: Hybrid Model Carbon Emission Summary for Post-Event Repair (kgCO$_2$)

Case	Material[1]	Construction Activity [2]	Diesel Production[1]	Tail Pipe[2]	Diesel Production[1]	Total (kgCO$_2$)
1	44,354	4,176	1,483	827	399	51,240
2	25,433	3,023	1,047	625	302	30,430
3	0	0	0	0	0	0

[1] Material and Diesel Production were computed using EIO-LCA model

[2] Tail Pipe and Construction Activity Emissions were computed using P-LCA model

Table 28: Parameters for the Settlement Log Normal Distribution (below, 0.03m is 0.1 ft)

Earthquake-Induced Settlement Event			Settlement Mode (m)			Settlement cov (δ)		
Events	Probability (a)	Probability (b)	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
E0	0.85	0.70	0.076	0.030	0.015	0.3	0.3	0.3
E1	0.10	0.20	0.106	0.061	0.023	0.3	0.3	0.3
E2	0.05	0.10	0.137	0.091	0.030	0.3	0.3	0.3

Table 29: Parameters for Normal Distribution of the Cost

Settlement Events		Mean (μ)	cov (δ)
Events	Value (m)		
S0	0.003	$ 0	0.2
S1	0.06	$ 51,707	0.2
S2	0.09	$ 59,624	0.2
S3	0.12	$ 71,894	0.2
S4	0.15	$ 81,951	0.2
S5	0.18	$ 92,058	0.2
S6	0.21	$ 102,139	0.2
S7	0.24	$ 111,968	0.2

Table 30: Parameters for Normal Distribution of the Carbon

Settlement Events		Mean (μ) (kgCO$_2$)	cov (δ)
Events	Value (m)		
S0	0.003	0	0.2
S1	0.06	10,747	0.2
S2	0.09	14,120	0.2
S3	0.12	18,072	0.2
S4	0.15	22,054	0.2
S5	0.18	25,824	0.2
S6	0.21	29,387	0.2
S7	0.24	33,214	0.2

Table 31: Summary of Total Cost

Case	New Building	Ground Improvement	Post-Event Repairs	Total
Case 1	$ 298,000	$ -	$ 81,951	$ 379,951
Case 2	$ 298,000	$ 31,592	$ 51,707	$ 381,299
Case 3	$ 298,000	$ 46,878	$ -	$ 344,878

Table 32: P-LCA & Hybrid-LCA - Total Carbon Emission for Each Case

Case	P-LCA CO_2 Emission ($kgCO_2$)				Hybrid CO_2 Emission ($kgCO_2$)			
	GI	Repair	GI + Repair	Project Total [1]	GI	Repair	GI + Repair	Project Total [1]
1	0	22,054	22,054	82,854	0	51,240	51,240	112,040
2	7,492	10,747	18,239	79,039	10,285	30,430	40,715	101,515
3	14,563	0	14,563	75,363	20,043	0	20,043	80,843

[1] Includes the initial carbon emissions of 60,800 $kgCO_2$ to build the house.

Table 33: P-LCA, Carbon Emission Summary

Case	Ground Improvement ($kgCO_2$)				Post-Earthquake Repairs ($kgCO_2$)			
	Material	Constr. [1]	Trans. [2]	Total	Material	Constr. [1]	Trans. [2]	Total
1	0	0	0	0	16,986	4,242	827	22,054
2	1,247	3,648	2,597	7,492	7,053	3,069	625	10,747
3	2,942	5,636	5,986	14,563	0	0	0	0

[1] Constr. is the Construction Activity carbon footprint which is the sum of the construction activity and diesel production carbon emissions in Table 15 and Table 25.

[2] Trans. is the Transportation carbon footprint which is the sum of the Tail Pipe and Diesel Production carbon emissions in Table 15 and Table 25.

Table 34: Hybrid, Carbon Emission Summary

Case	Ground Improvement ($kgCO_2$)				Post-Earthquake Repairs ($kgCO_2$)			
	Material	Constr. [1]	Trans. [2]	Total	Material	Constr. [1]	Trans. [2]	Total
1	0	0		0	44,354	5,659	1,227	51,240
2	1,491	4,999	3,796	10,285	25,433	4,071	926	30,430
3	3,517	7,778	8,747	20,043	0	0	0	0

[1] Constr. is the Construction Activity carbon footprint which is the sum of the construction activity and diesel production carbon emissions in Table 17 and Table 27.

[2] Trans. is the Transportation carbon footprint which is the sum of the Tail Pipe and Diesel Production carbon emissions in Table 17 and Table 27.

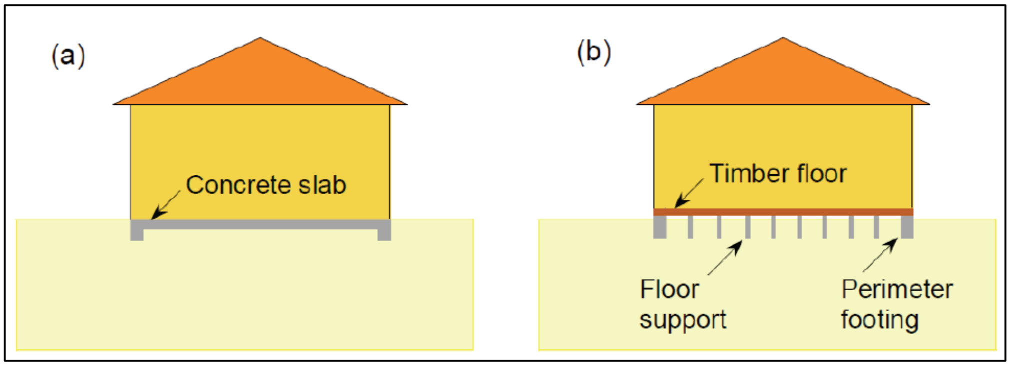


Figure 1: Prevalent house foundation types in Christchurch, New Zealand: (a) concrete slab, (b) perimeter footing (Cubrinovski et al. 2012)

Figure 2: Observed typical liquefaction damage to house foundations: (a) differential settlement resulting in tilt damage to house, (b) large crack in a concrete slab, (c) dishing of concrete slab on grade (Cubrinovski et al. 2012)

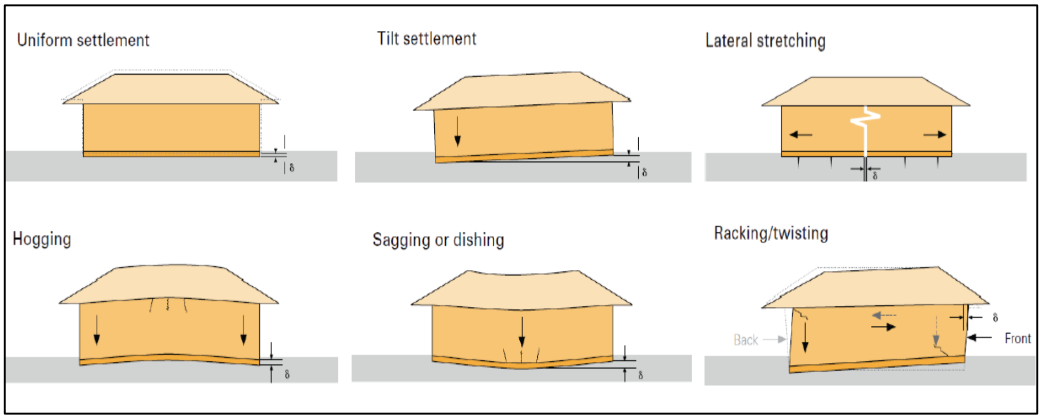
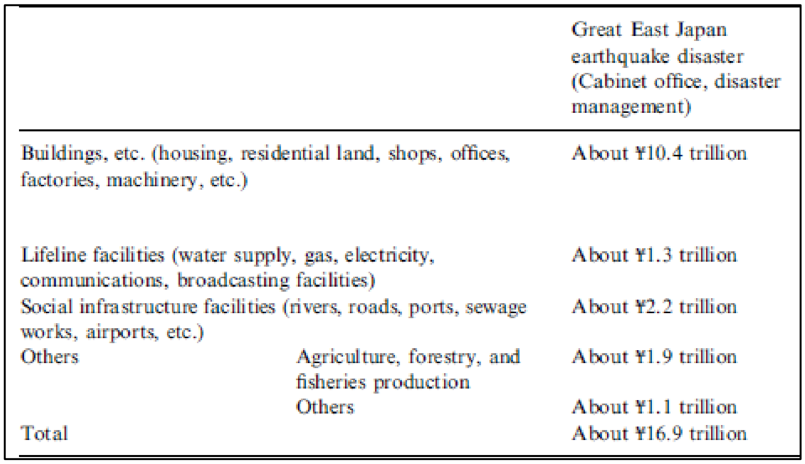


Figure 3: Schematic plot of typical damage patterns for house foundations (DBH 2011)

Figure 4: Structural damage due to liquefaction: (a) Tilting of a house, (b) Tilting of a house in Hinode, Japan, (c) fallen chimney bricks, (Ishihara 2011, Buchanan et al. 2011)

Figure 5: Large settlements and tilting of building due to liquefaction effect in Japan (Ashford et al. 2011)



		Great East Japan earthquake disaster (Cabinet office, disaster management)
Buildings, etc. (housing, residential land, shops, offices, factories, machinery, etc.)		About ¥10.4 trillion
Lifeline facilities (water supply, gas, electricity, communications, broadcasting facilities)		About ¥1.3 trillion
Social infrastructure facilities (rivers, roads, ports, sewage works, airports, etc.)		About ¥2.2 trillion
Others	Agriculture, forestry, and fisheries production	About ¥1.9 trillion
	Others	About ¥1.1 trillion
Total		About ¥16.9 trillion

Figure 6: Comparison of cost estimates of damage (Kazama and Noda 2012)

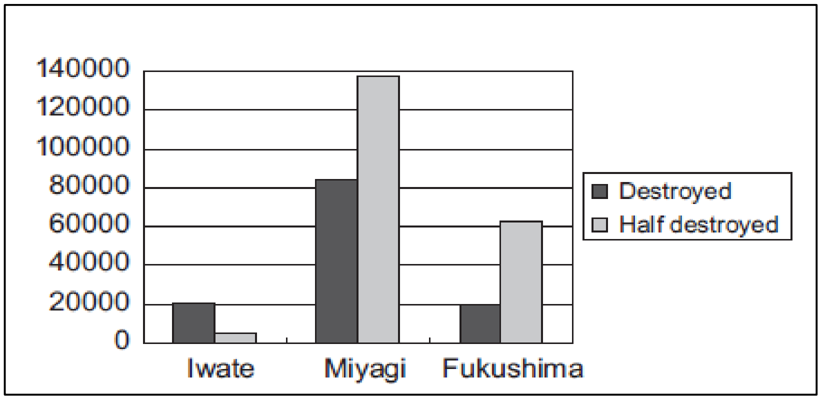


Figure 7: Number of damaged houses from different cities during the Great East Japan Earthquake in 2011 (Kazama and Noda 2012)

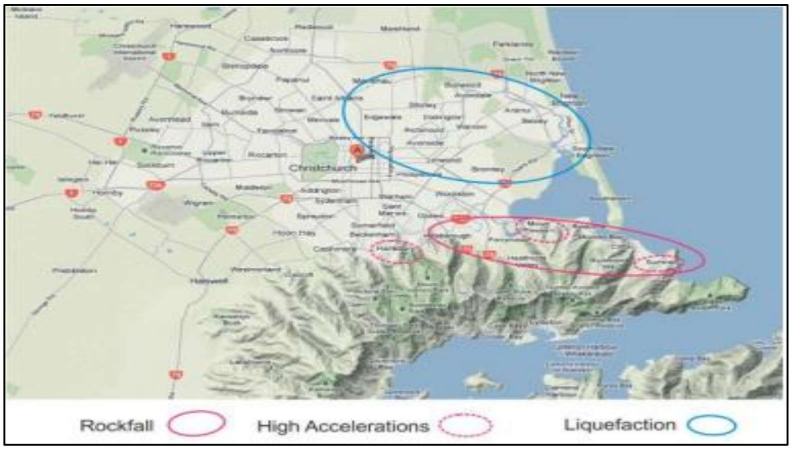


Figure 8: Approximate location of the worst types of damage during the 2011 Christchurch Earthquake (Buchanan et al. 2011)

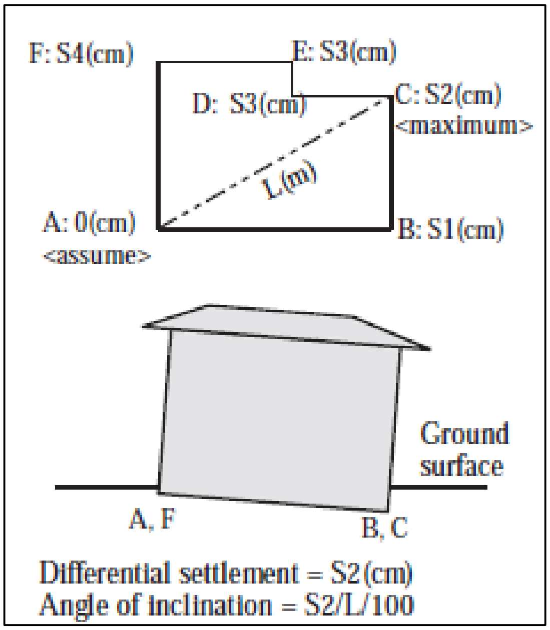


Figure 9: Definition of differential settlement and angle of inclination of houses (Yasuda 2010)

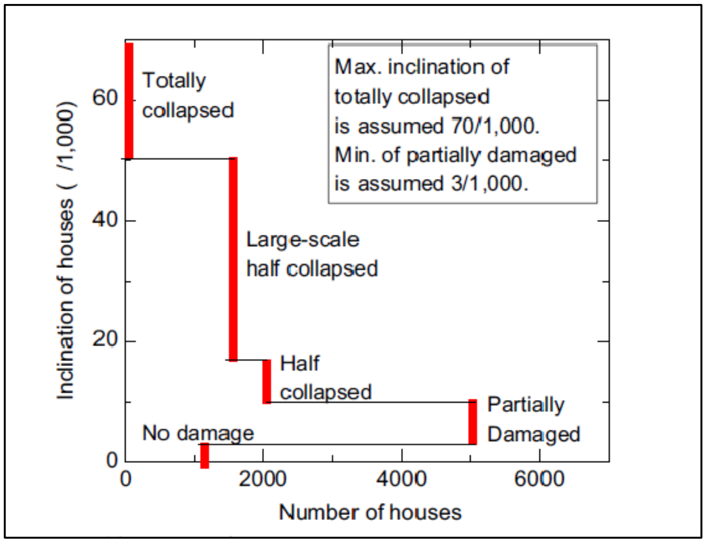
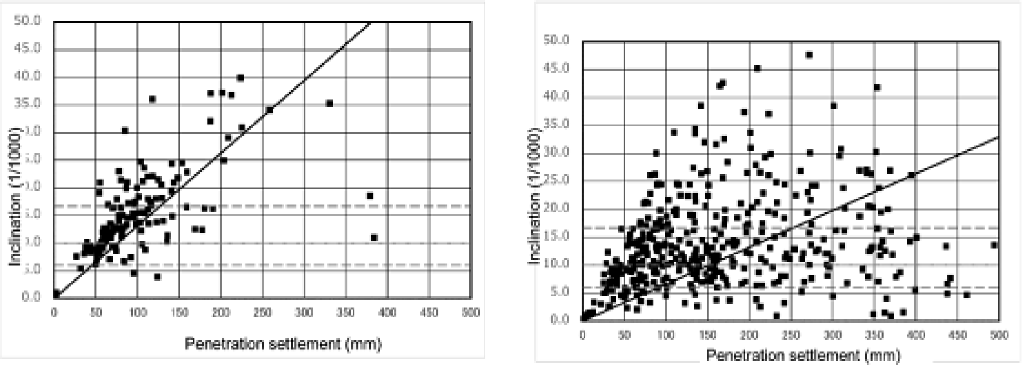


Figure 10: Frequency distribution of damaged houses due to liquefaction based on angle of inclination (Yasuda et al. 2012a)



(a) In Chiba and Narashino cities, where houses are clustered close together

(b) In Kamisu and Itako cities, where houses are scattered

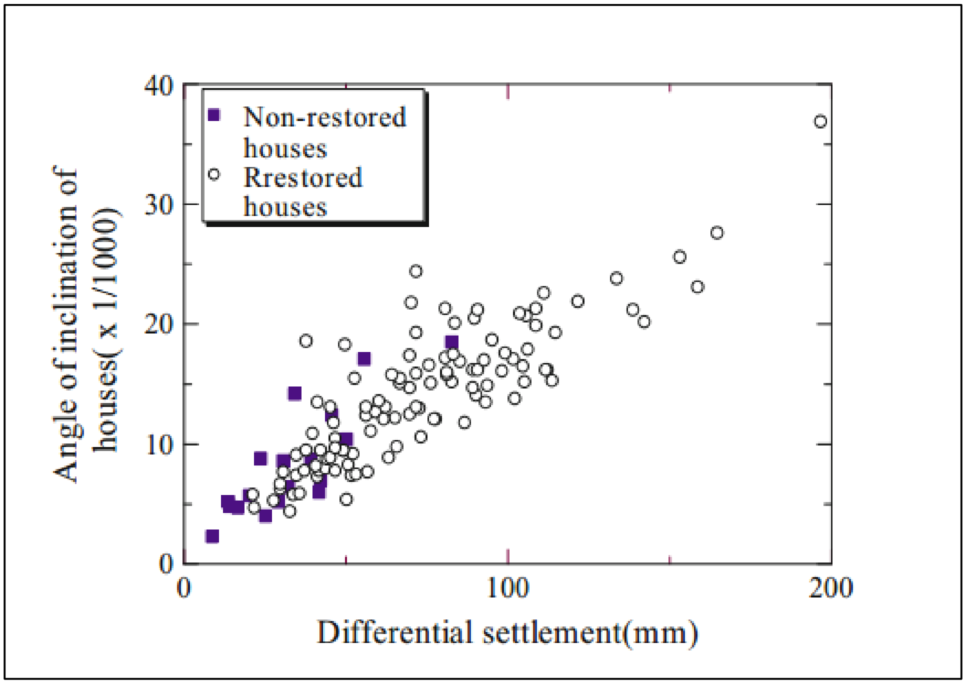


Figure 11: (a) Relation between angle of inclination and settlement in Chiba and Narashino, and their corresponding scatters of houses (Yasuda, 2014a), (b) Relation between angle of inclination and settlement in Kamisu and Itako, and their corresponding scatters of houses (Yasuda, 2014a), (c) Angle of inclination of restored (heavily tilted houses) and non-restored (slightly tilted houses that did not need restoration) houses in Japan (Yasuda 2014b)

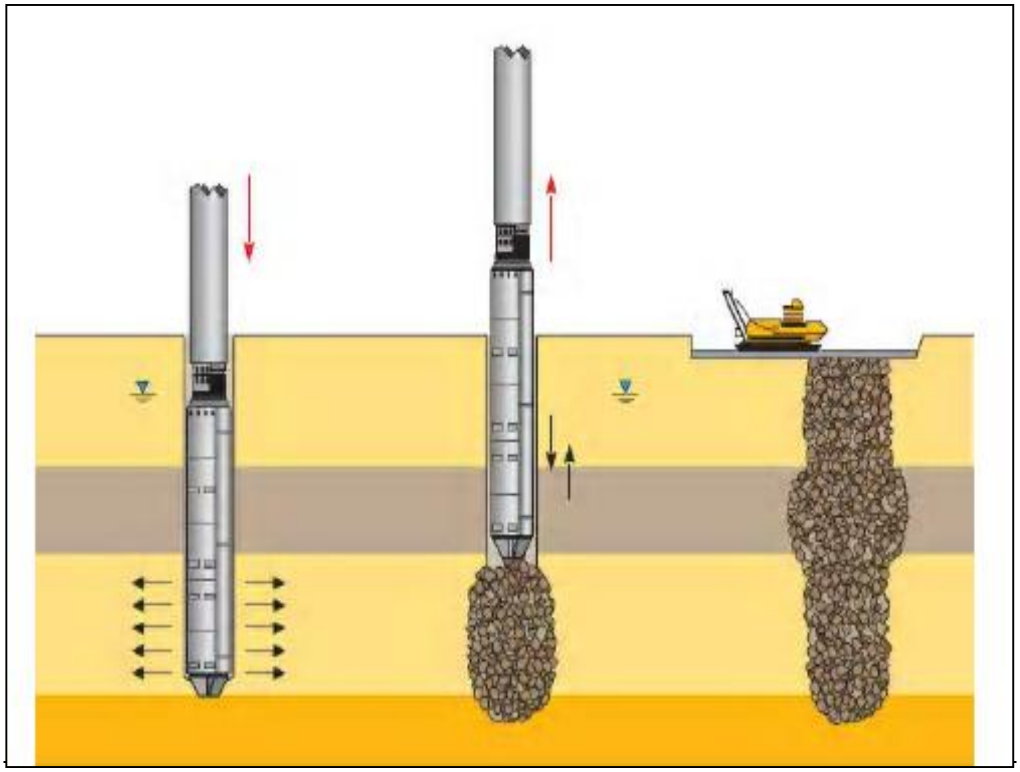


Figure 12: Schematic of stone column installation by dry bottom feed method (Chawla et al. 2010)

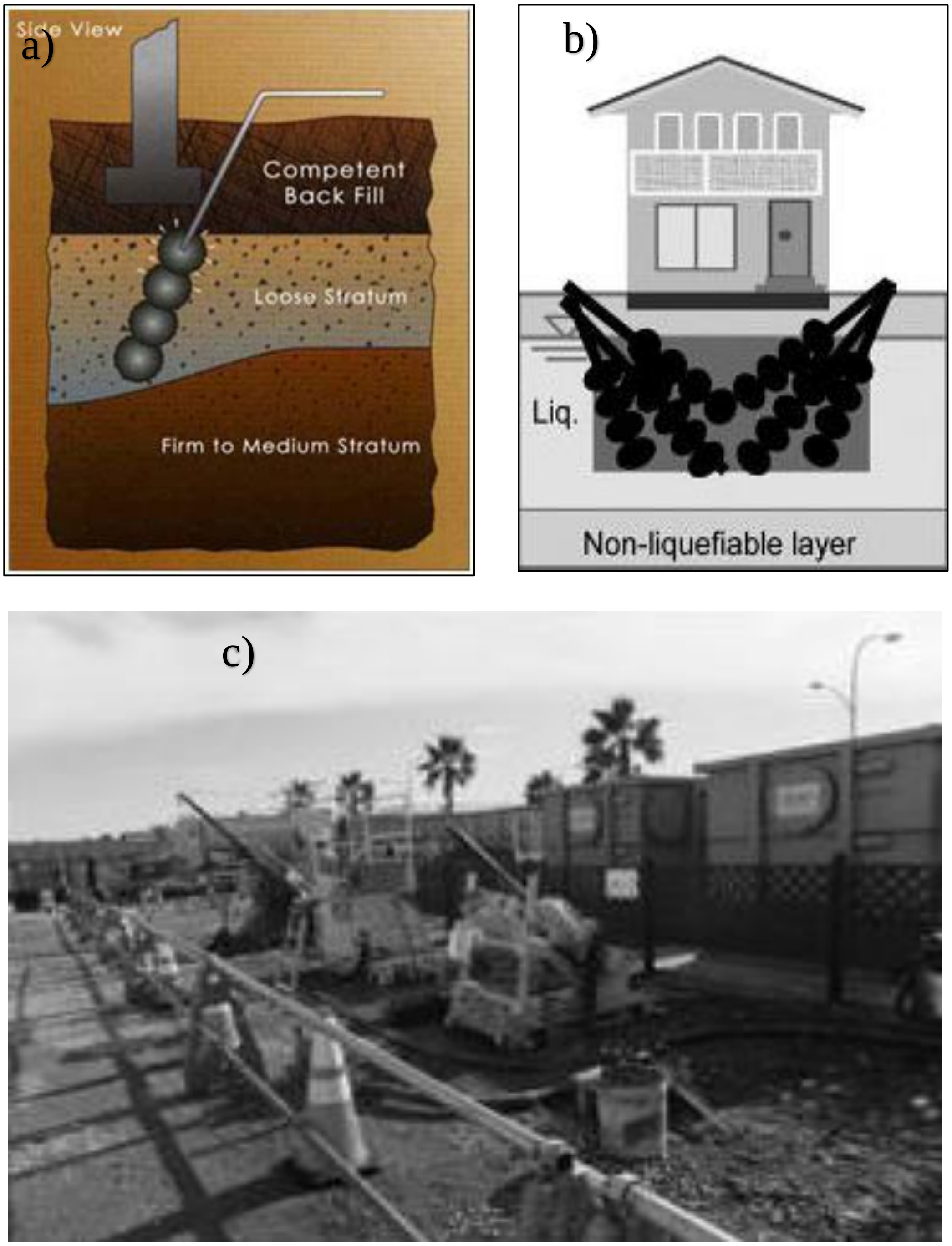
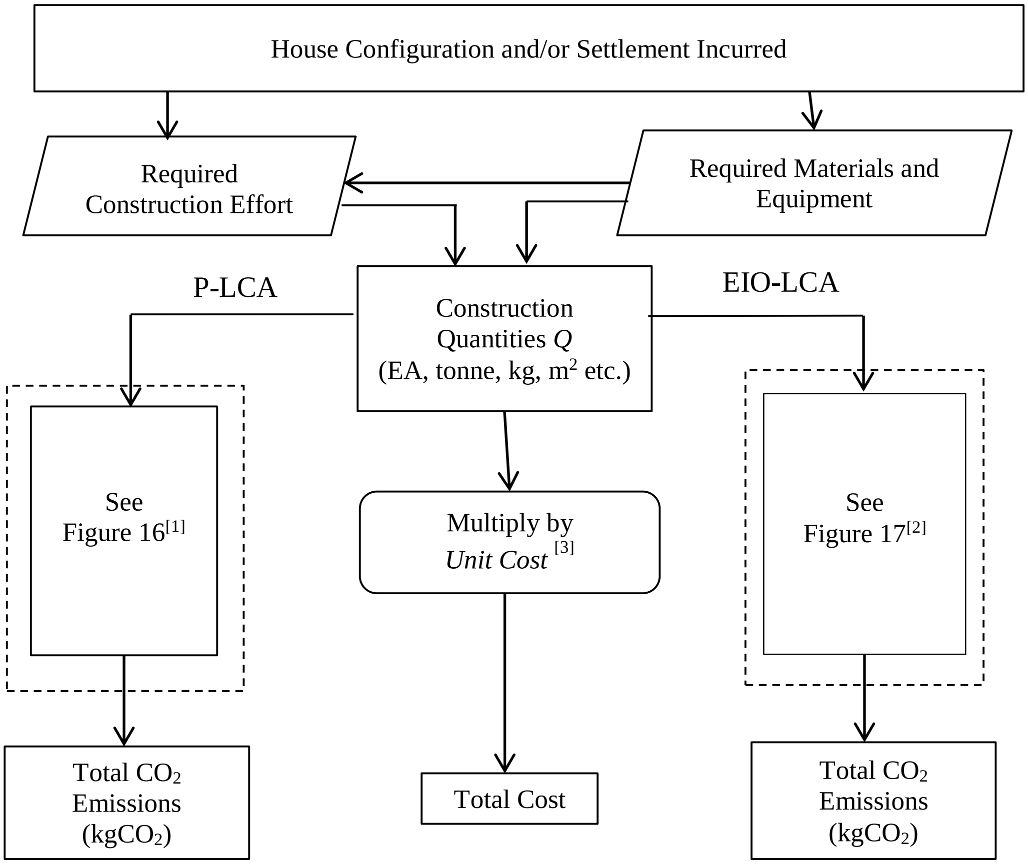


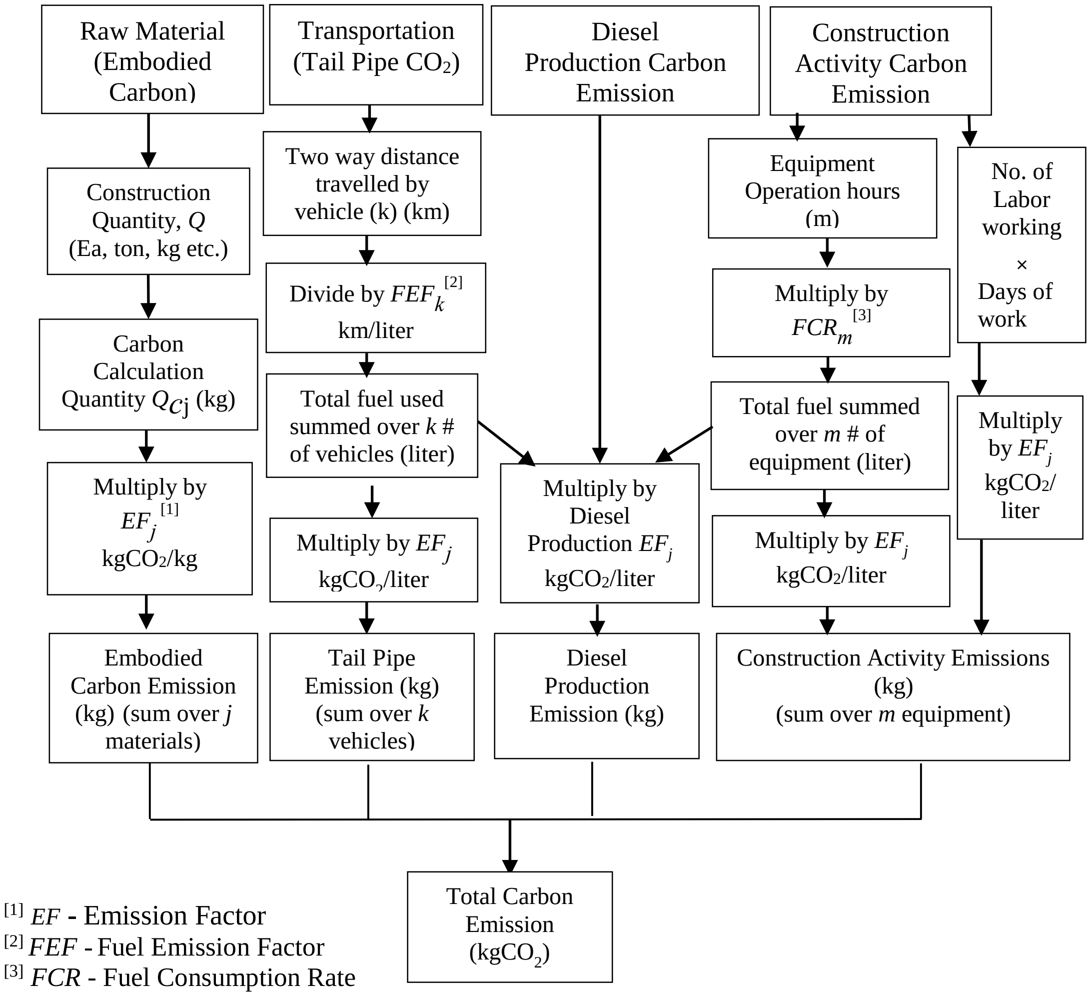
Figure 13: (a) Compaction grouting (Lincoln Company, LLC), (b) Compaction grouting method to re-level existing houses by drilling bores outside the house (Yasuda 2014a), (c) Equipment used for compaction grouting technique (Yasuda 2014a)

Figure 14: Grouting pipes installed for compaction grouting outside a private residence in Japan



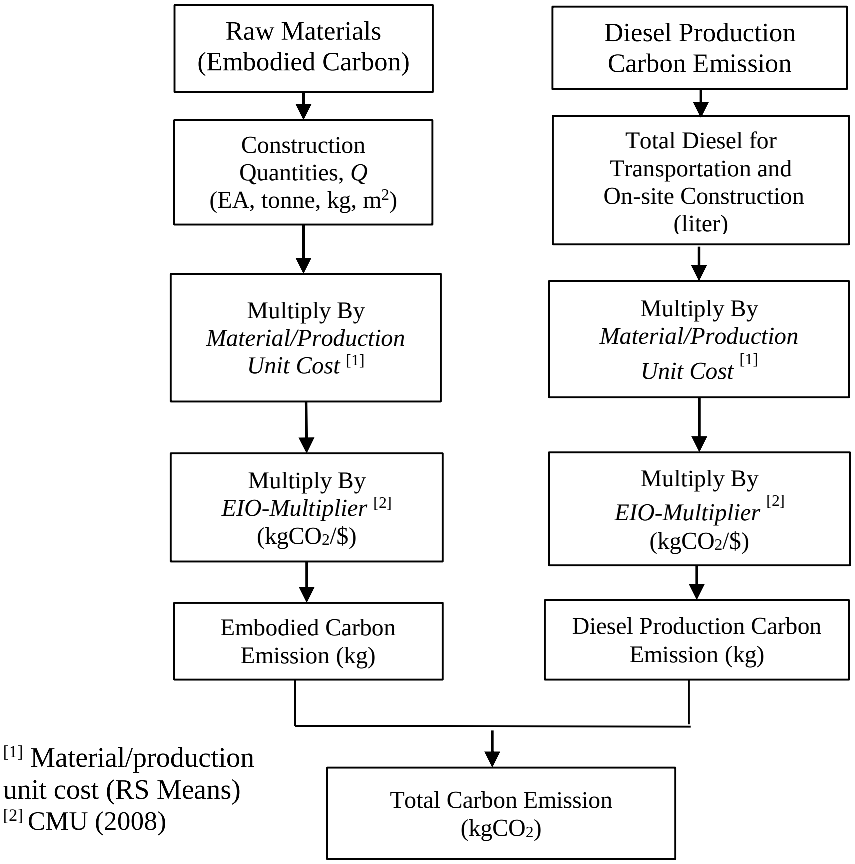
[1] For breakdown of process, see Figure 16
[2] For breakdown of process, see Figure 17
[3] Unit cost includes overhead and profit (RS Means)

Figure 15: Cost computation, P-LCA and EIO-LCA processes to compute carbon emissions



[1] *EF* - Emission Factor
[2] *FEF* - Fuel Emission Factor
[3] *FCR* - Fuel Consumption Rate

Figure 16: P-LCA approach for total carbon emission assessment



[1] Material/production unit cost (RS Means)
[2] CMU (2008)

Figure 17: EIO-LCA approach for total carbon emission assessment

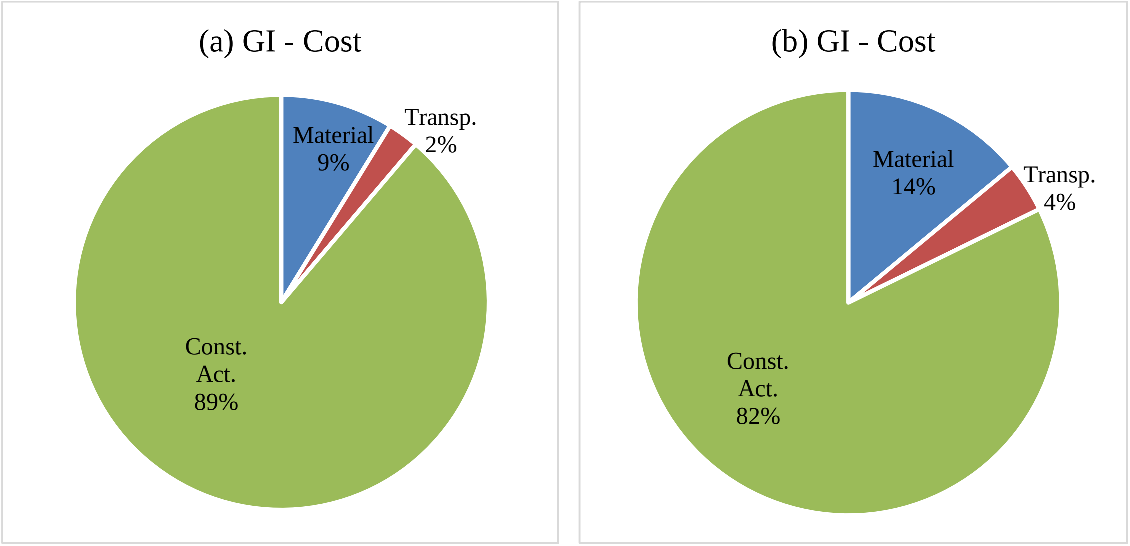
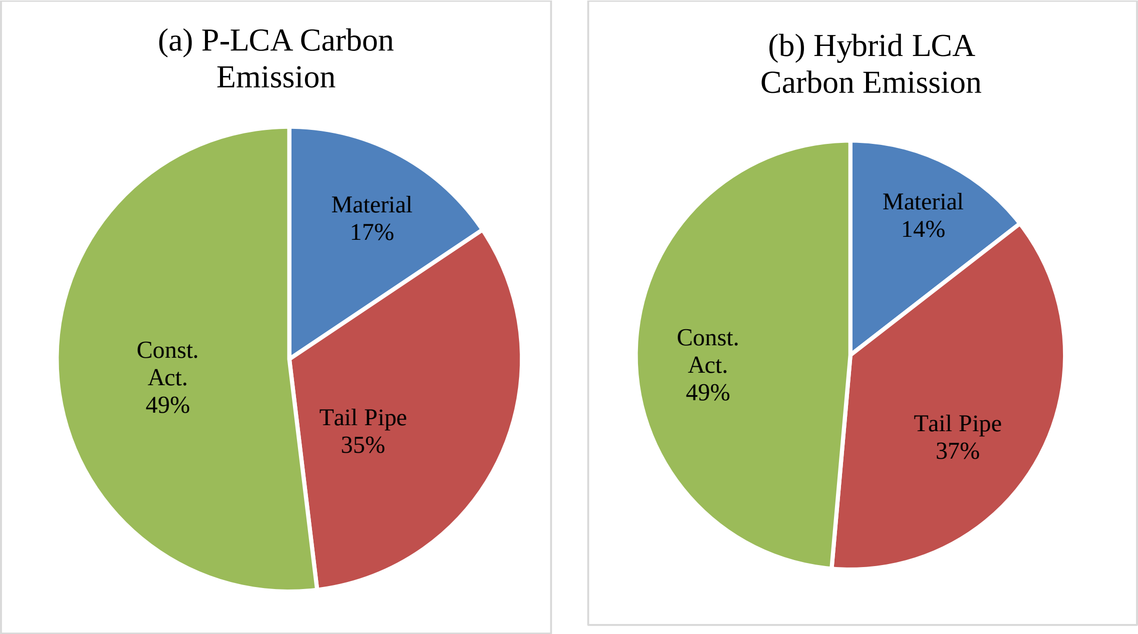


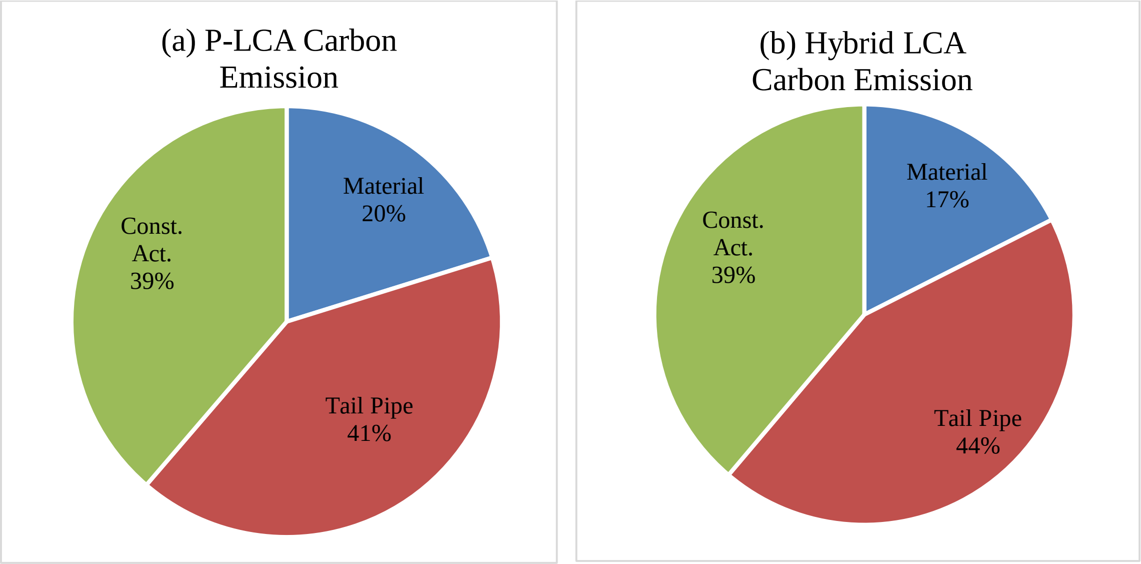
Figure 18: GI cost contribution from different phases of construction – (a) Case 2, (b) Case 3



(a) P-LCA Carbon Emission

(b) Hybrid LCA Carbon Emission

Figure 19: Case 2. GI carbon contribution from different phases of construction – (a) P-LCA, (b) Hybrid LCA



(a) P-LCA Carbon Emission

(b) Hybrid LCA Carbon Emission

Figure 20: Case 3. GI carbon contribution from different phases of construction – (a) P-LCA, (b) Hybrid LCA

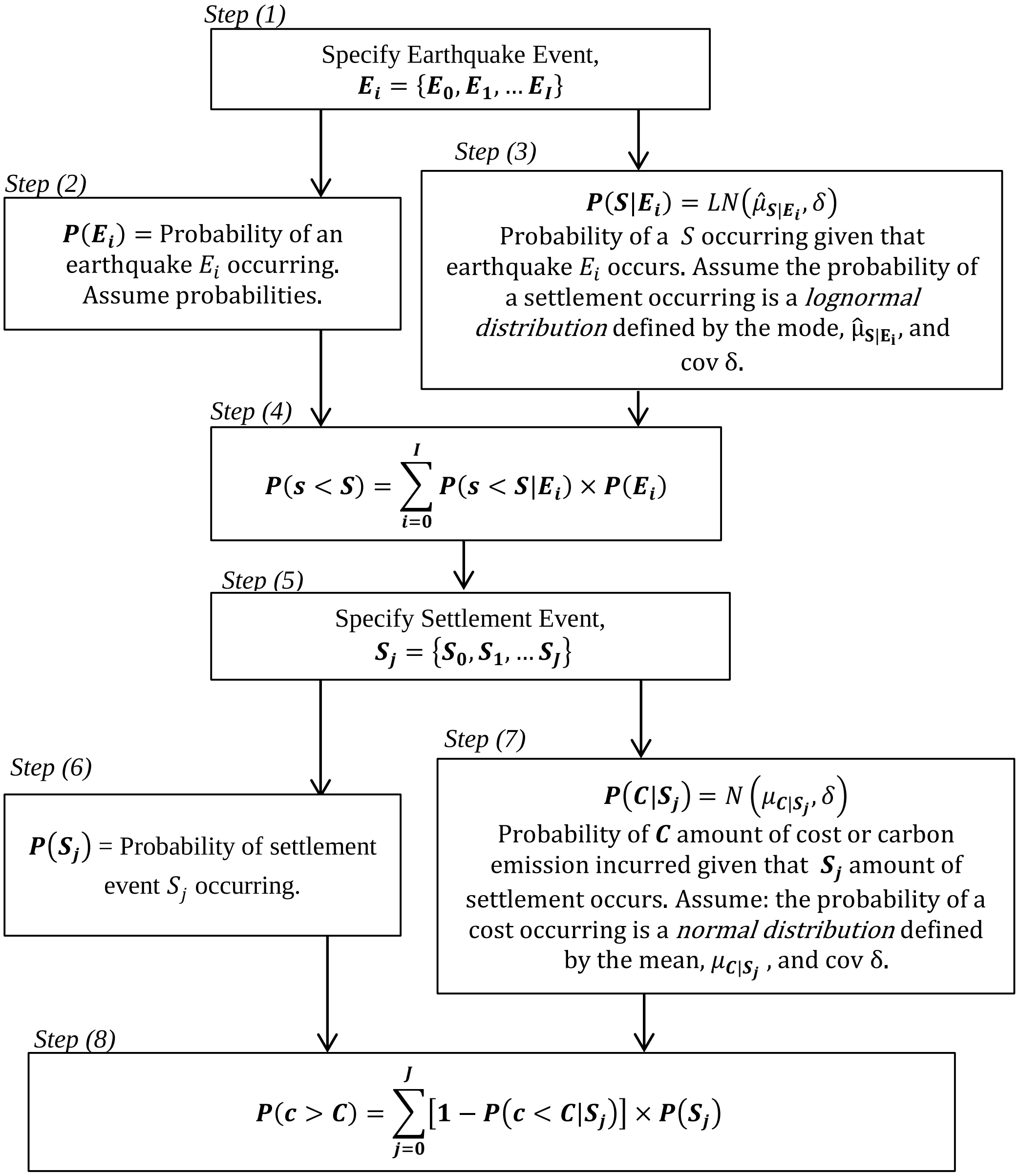


Figure 21: Flowchart for probabilistic framework

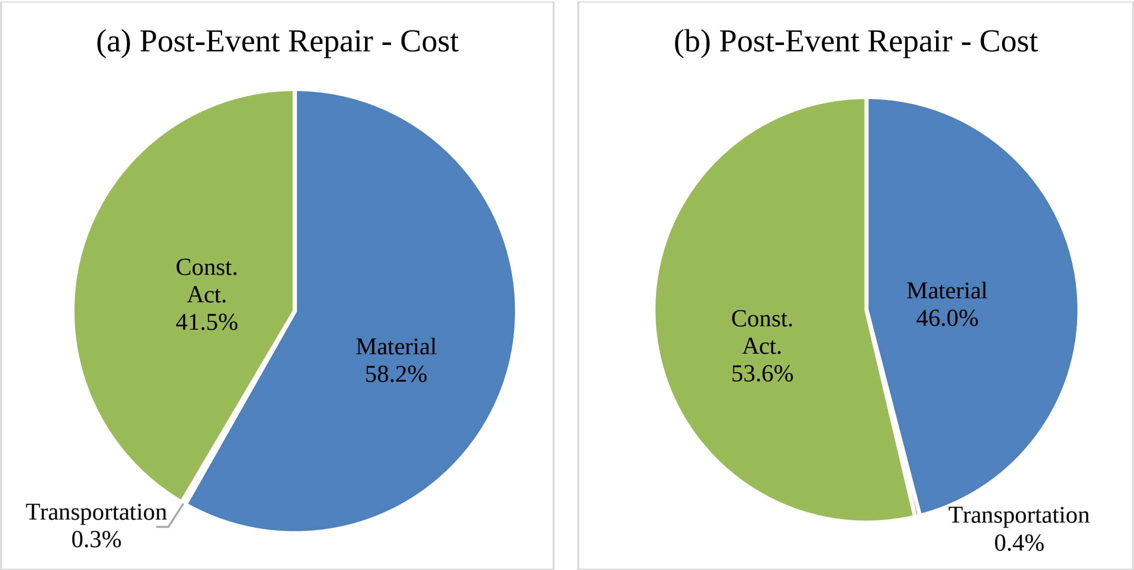


Figure 22: Post-event repair cost contribution from different phases of construction – (a) Case 1, (b) Case 2

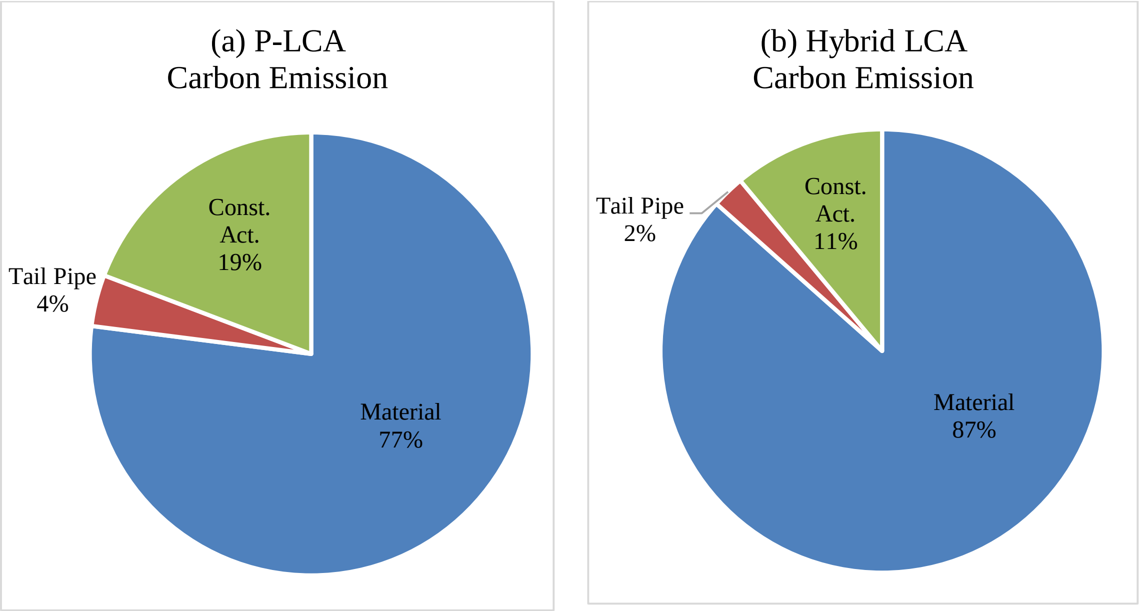


Figure 23: Case 1. Post-event repair carbon contribution from different phases of construction – (a) P-LCA, (b) Hybrid LCA

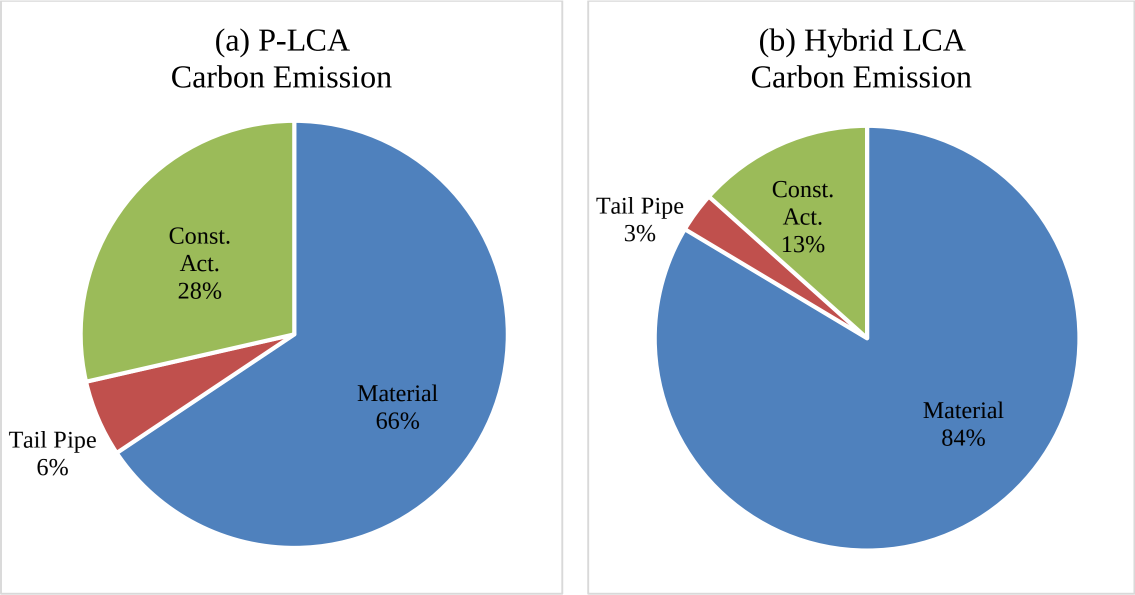


Figure 24: Case 2. Post-event repair carbon contribution from different phases of construction – (a) P-LCA, (b) Hybrid LCA

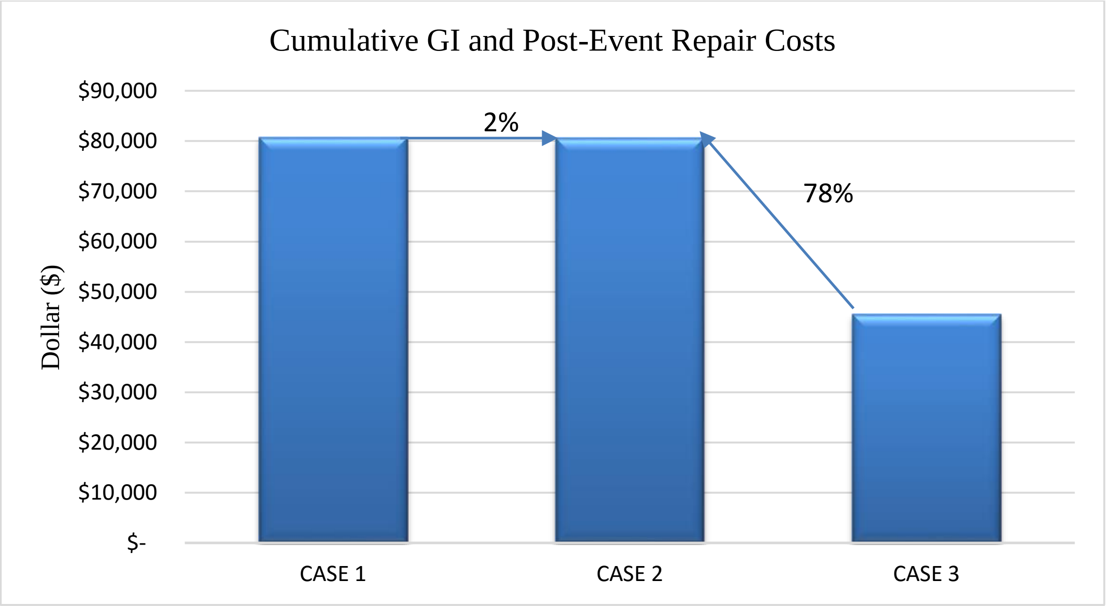


Figure 25: Cumulative GI and repair costs for the three cases

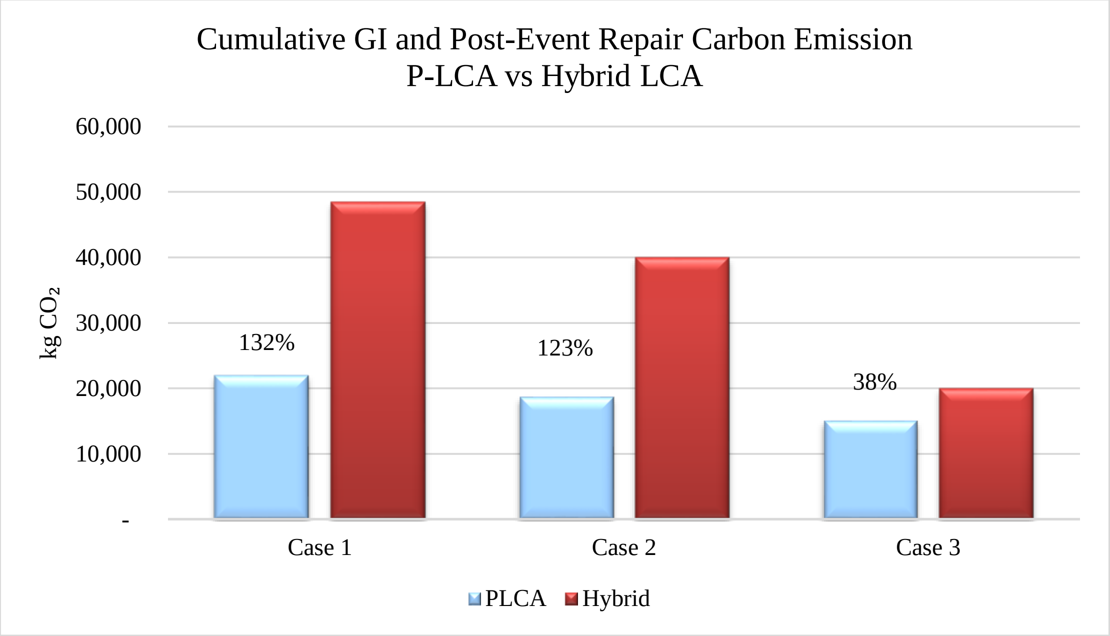
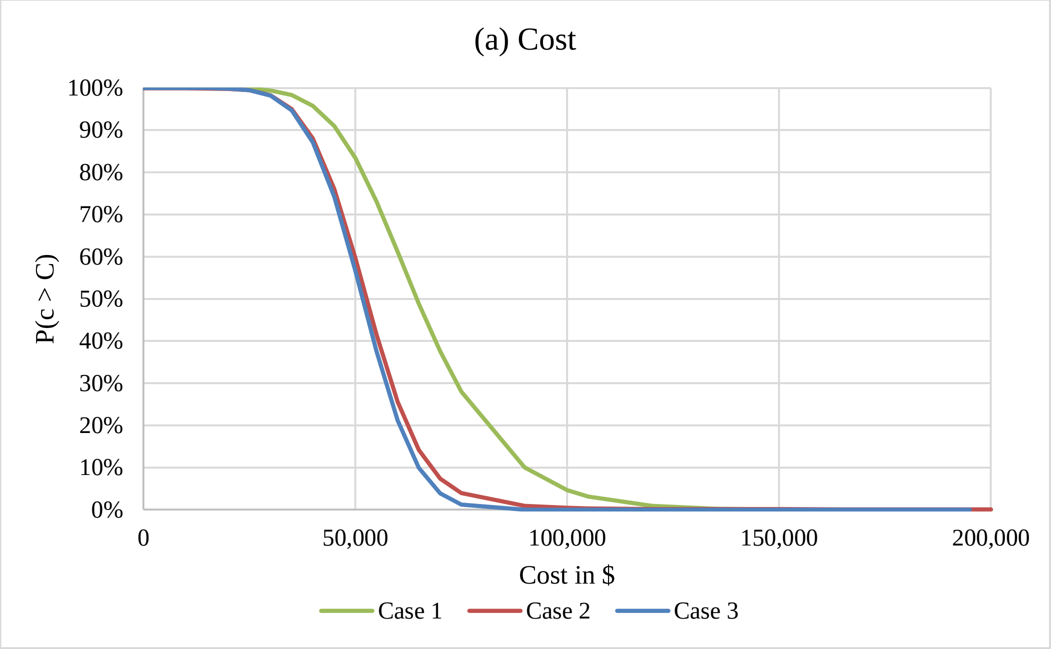


Figure 26: Carbon emission from GI + Repairs - P-LCA vs Hybrid LCA Model



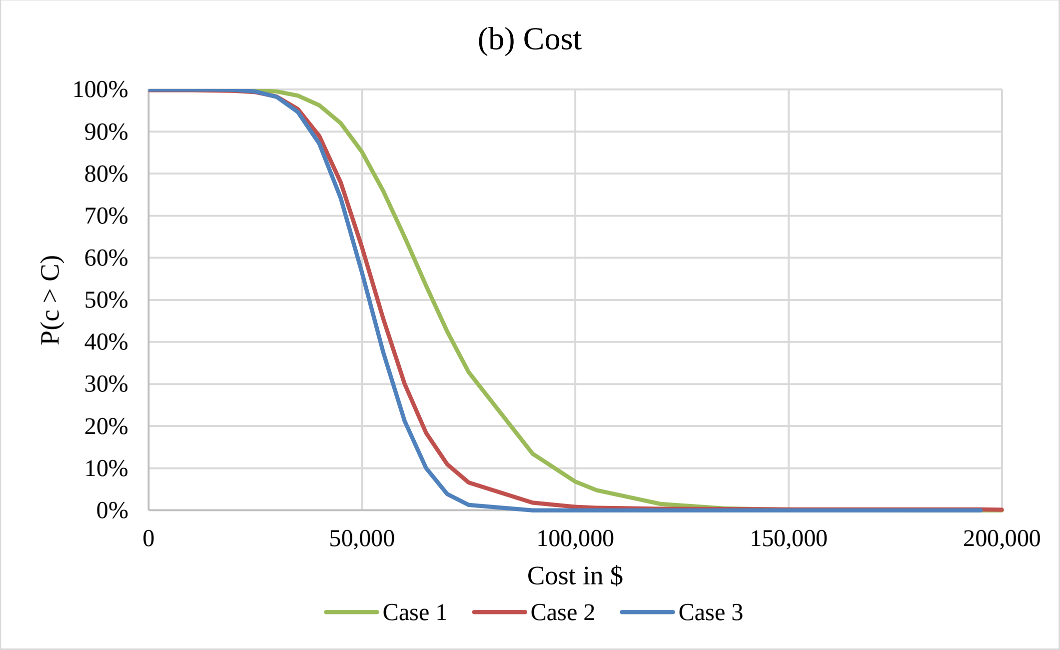
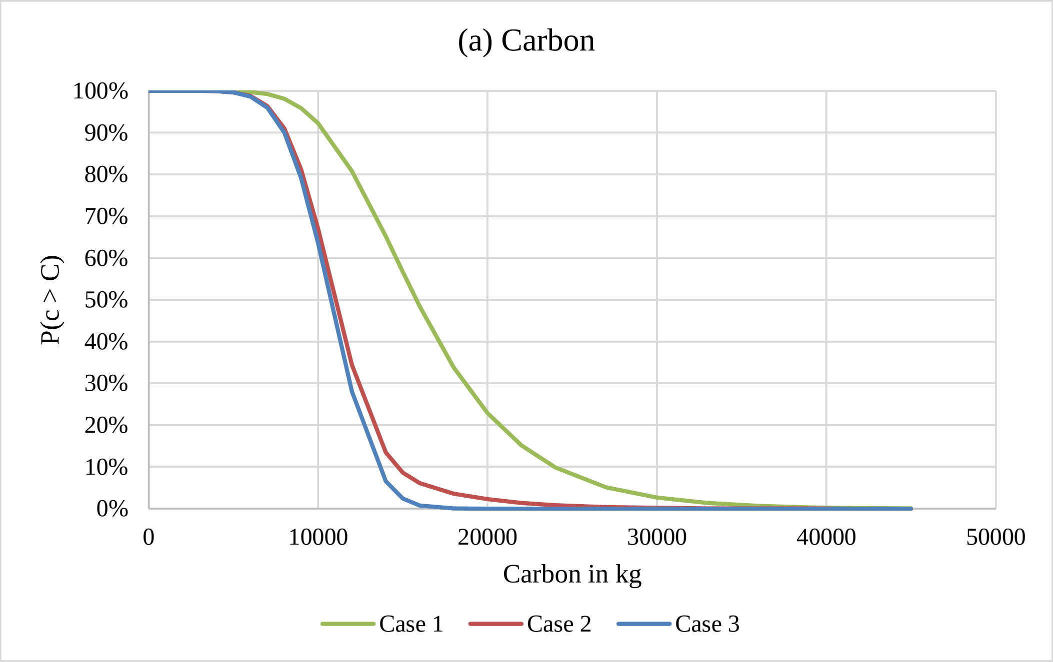


Figure 27: Probability of exceeding a repair cost (cov of 0.2 for settlement and 0.3 for cost and carbon): (a) for P(E) of 85%, 10% and 5% for small, moderate and large settlement events, and (b) for P(E) of 70%, 20% and 10% for small, moderate and large settlement events



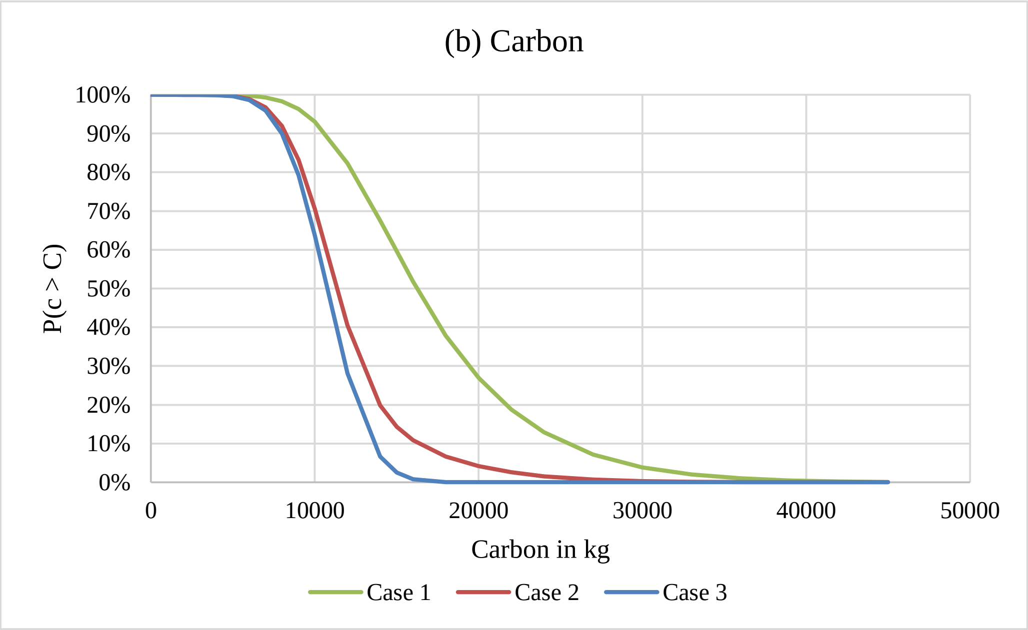
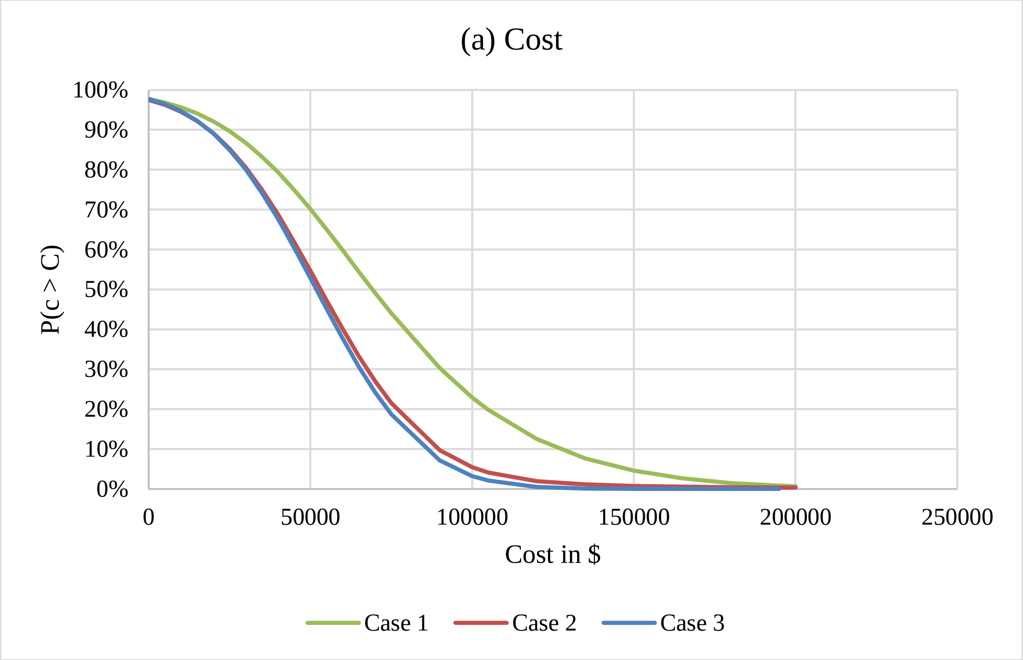


Figure 28: Probability of exceeding a repair carbon (cov of 0.2 for settlement and 0.3 for cost and carbon): (a) for P(E) of 85%, 10% and 5% for small, moderate and large settlement events, and (b) for P(E) of 70%, 20% and 10% for small, moderate and large settlement events



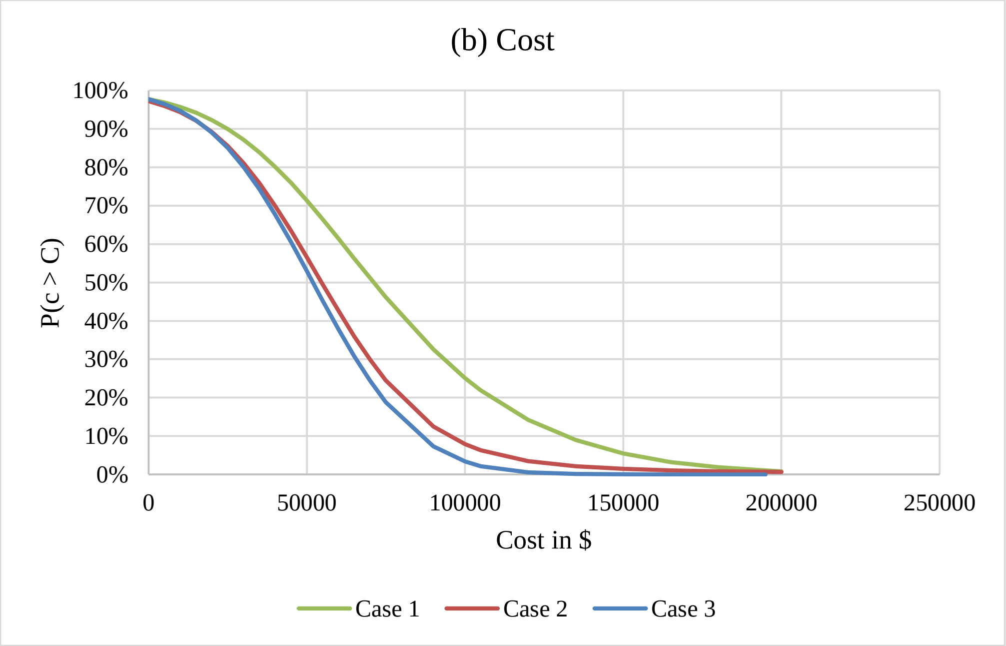
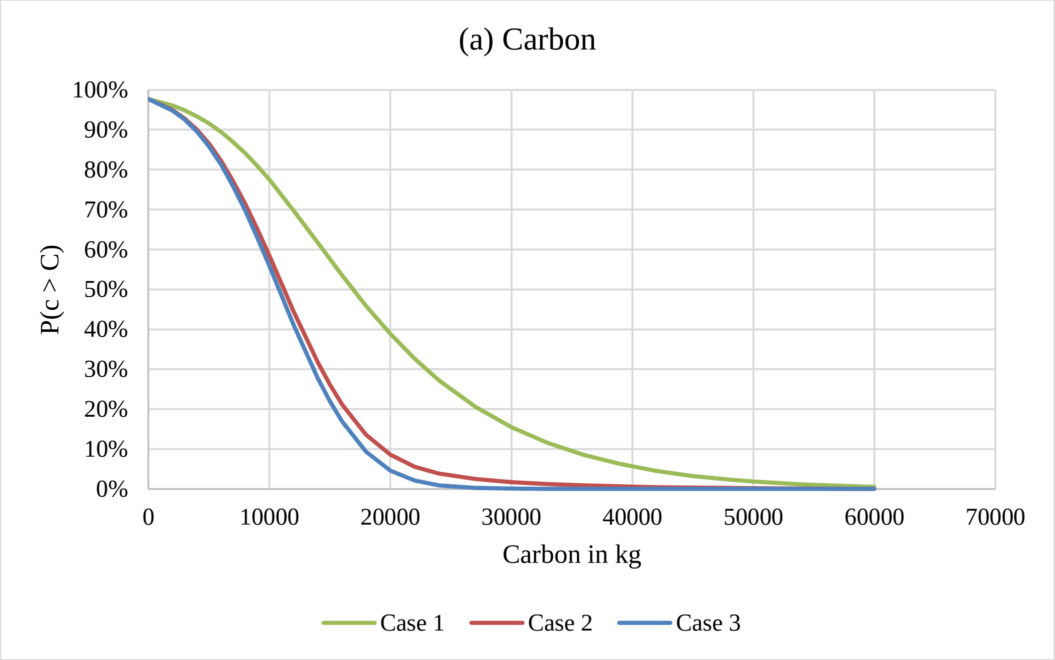


Figure 29: Probability of exceeding a repair cost (cov of 0.5 for settlement, cost and carbon): (a) for P(E) of 85%, 10% and 5% for small, moderate and large settlement events, and (b) for P(E) of 70%, 20% and 10% for small, moderate and large settlement events



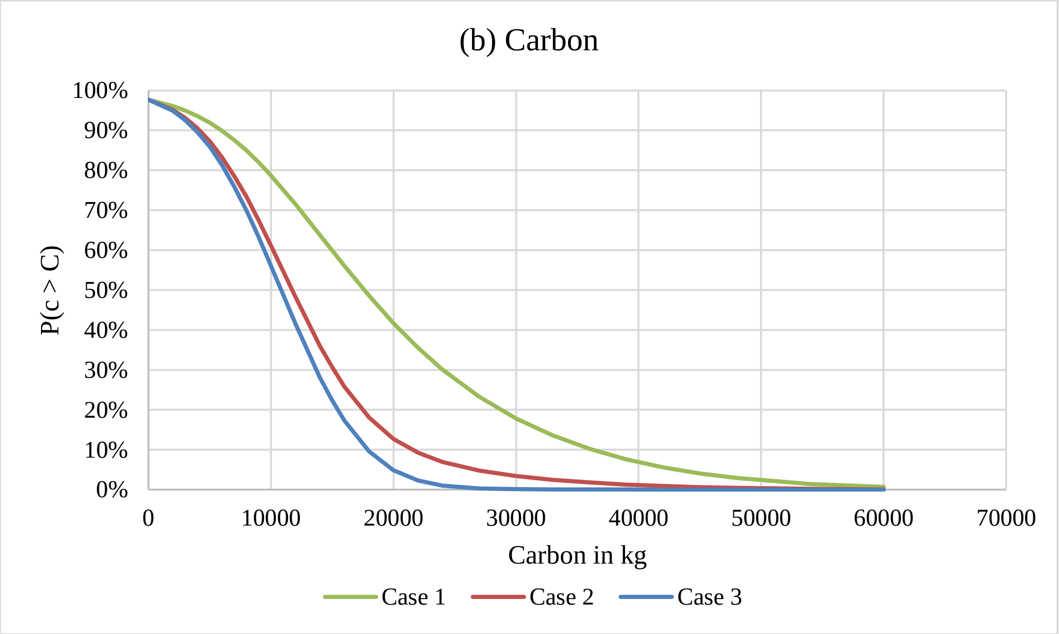


Figure 30: Probability of exceeding a repair carbon (cov of 0.5 for settlement, cost and carbon): (a) for P(E) of 85%, 10% and 5% for small, moderate and large settlement events, and (b) for P(E) of 70%, 20% and 10% for small, moderate and large settlement events