A Thesis

entitled

Life Cycle Assessment and Costing of Geosynthetics Versus Earthen Materials

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in Civil Engineering

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An Abstract of

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The purpose of this thesis is to determine the best outcome in a systems approach analyzing cost, emissions, and lifetime of traditional soil remediation with geosynthetic materials. The soil remediation systems will be analyzed by conducting a life cycle assessment (LCA) and a life cycle cost (LCC) analysis on the materials used within the system. This study will not include a life cycle impact assessment because this thesis is a preliminary LCA.

A retaining wall case study is an excellent lens for examining traditional materials and geosynthetics. The retaining wall was selected due to its relevance and frequency within geotechnical applications, and provides an avenue to evaluate the life cycle, cost effectiveness, and utility of geosynthetics. The four design alternatives include concrete gravity walls, mechanically stabilized earth walls, geotextile wrap-around walls, and gabion walls.

The LCI will be analyzed using a comprehensive publicly available database. As diverse as different materials are, geosynthetic properties including density, roll length, etc. will be

determined using required design parameters, considering the median values in order to represent an "average" product.

While traditional materials (i.e., soil and stone) tend to be the most massive element of the retaining wall and therefore contain a substantial amount of embodied carbon, the amount of embodied carbon or embodied energy within the geosynthetic is not insignificant. Three walls showed a greater contribution from the man-made materials toward the total embodied carbon. However, the greatest contribution toward embodied energy came from the man-made materials for both the gravity retaining wall and the geotextile wrap-around wall.

The LCC was performed to determine the true cost of construction of the retaining wall over its life cycle. In observing the results from the LCI as well as the total cost, it can be seen that the geotextile wrap-around wall outperforms the other wall alternatives in every category.

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Finally to the Lord my God. He made the ultimate sacrifice, and He has put so many things (not to mention the aforementioned people) in place for this to be possible. "'For I know the plans I have for you,' declares the Lord, 'plans to prosper you and not to harm you, plans to give you hope and a future.'" Jeremiah 29:11.

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List of Abbreviations

ACB..... Articulated concrete block

CCL ..... Compacted clay liner
CED ..... Cumulated energy demand
CO2 ..... Carbon dioxide
CO2e ..... Carbon dioxide equivalents
CSPE ..... Chlorosulfonated polyethylene

EPDM..... Ethylene propylene diene terpolymer

FPP ..... Flexible polypropylene
FRS ..... Fiber reinforced soil

GCL..... Geosynthetic clay liner

HDPE ..... High density polyethylene
HPTRM .. High performance turf reinforcement mat

ICE ..... Inventory of Carbon and Energy
ISI ..... Institute for Sustainable Infrastructure
ISO ..... International Organization for Standardization

LCA ..... Life cycle assessment
LCC ..... Life cycle cost
LCI..... Life cycle inventory
LCIA ..... Life cycle impact assessment
LDPE ..... Low density polyethylene
LEED..... Leadership in Energy and Environmental Design

MSE..... Mechanically stabilized earth

PE ..... Polyethylene
PET ..... Polyester
PP ..... Polypropylene

PVC..... Polyvinyl chloride

RCC..... Roller compacted concrete

S-LCA ..... Social life cycle assessment

USCS..... Unified Soil Classification System
USGBC... United States Green Building Council

VLDPE... Very low density polyethylene

1.0 Introduction

By performing a life cycle assessment (LCA) and a life cycle cost (LCC) to analyze the environmental and economic impacts of a product from "cradle-to-grave," a stakeholder might find that implementing geosynthetic materials into their design—retaining walls, for example—may not necessarily be more sustainable than using more traditional soil retaining methods. Historically, the primary materials used in geotechnical engineering include stone, sand, and clay. In Figure 1-1 it can be seen that these are the most produced materials, by weight, over the last century. Innovative materials, including geosynthetics, have been developed recently to improve separation, drainage, reinforcement, and filtration requirements which are often necessary for soil remediation. Recent construction trends, however, lean toward more sustainable design practices. Beyond standards and codes, sustainable design frameworks were developed to provide achievable milestones with sustainability being the primary goal. The popular sustainable design framework Leadership in Energy and Environmental Design (LEED) was developed by the United States Green Building Council (USGBC). Unfortunately, LEED is insufficient regarding overall environmental impact, the life of materials used, and the limited extent to which LEED may be applied. "Thus despite the substantial literature on sustainability, there appears to be rather few indicators specific to geotechnical engineering--or indeed more generally to the

construction phase of civil engineering works. Furthermore, there appears to be no specific guidelines for the geotechnical engineer at the design office or site level," (Jefferis, 2008). By performing an LCA and an LCC, a stakeholder will be well-equipped to choose the most economic-friendly solution with the least negative impact on the environment.

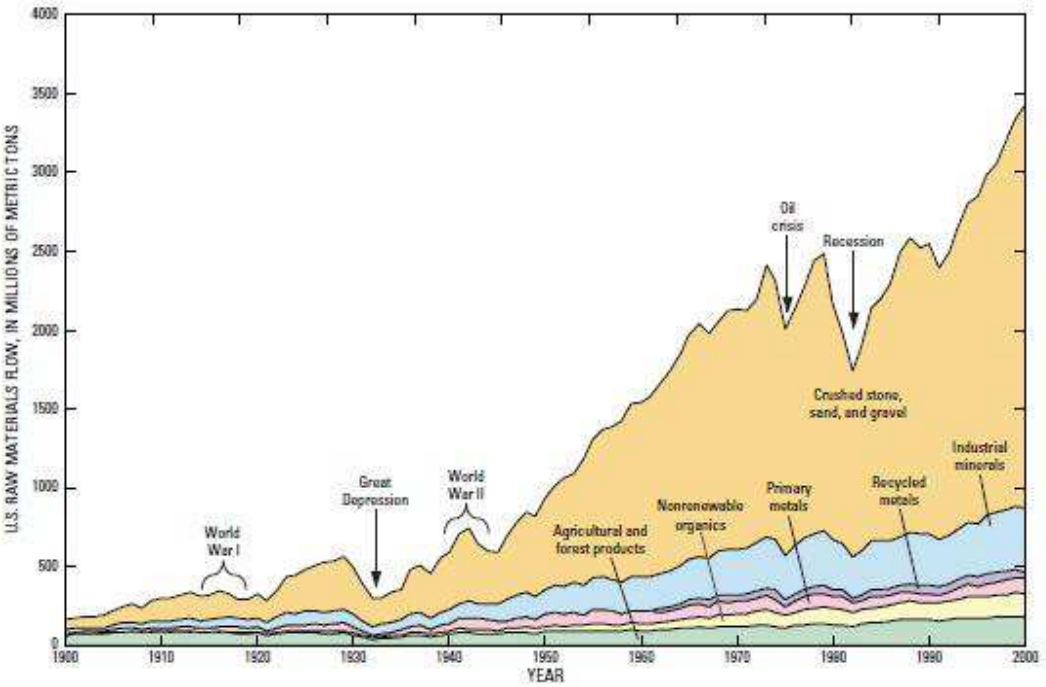

Figure 1-1. US Flow of raw materials by weight 1900-1998. (Wagner, 2002)

1.1 Geosynthetics: An Overview

It is difficult to perform an LCA on geosynthetics due to their petroleum-based nature. Firstly, these plastics are composed of polymers and mixes of polymers, the formulations of which are proprietary and impossible to trace without the consent of the manufacturers. Secondly, because petroleum (from which plastics and therefore geosynthetics are derived) is a limited natural resource, the production of geosynthetics is an unsustainable practice.

1.1.1 Geosynthetic Composition

Geosynthetics cover a broad range of petroleum-based materials comprised of thermoplastic polymers and thermoset polymers used to remediate soils for construction. Thermoplastics can be heated and remolded as necessary and maintain their integrity, whereas thermosets cannot. **Table 1.1** includes a brief overview of the two polymer types and their subsets.

Table 1.1. This table includes the two different types of polymers commonly used in geosynthetics and their subsets.

Thermoplastic	Thermoset
Semi-crystalline thermoplastic • high-density polyethylene (HDPE) • low-density polyethylene (LLDPE) • very low-density polyethylene (VLDPE) • flexible polypropylene (FPP)	Thermoset polymers • Nytrile • Butyl • ethylene propylene diene terpolymer (EPDM)
Semi-crystalline thermoplastic • high-density polyethylene (HDPE) • low-density polyethylene (LLDPE) • very low-density polyethylene (VLDPE) • flexible polypropylene (FPP)	
Thermoplastic elastomers • chloro-sulfinated polyethylene (CSPE)	
Thermoplastic polymers • polyethylene (PE) • polypropylene (PP) • polyvinyl chloride (PVC) • polyester • polyethylene terephthalate (PET)	

Geosynthetics with similar purposes and functions can be comprised of a variety of different polymers. Geotextiles, for example, can be comprised of PE, PP, PET, and/or PA (Koerner, 2005).

In addition to the basic composition of a geosynthetic, various additives to geosynthetics including carbon blacks, antioxidants, $CaCO_3$, metallic powders/flakes, silicate minerals (clay, talc, mica), silica minerals (quartz, diatomaceous earth, novaculite), metallic oxides (alumina, biocides), plasticizers, fillers, and colorants may be included in order to improve the properties (resilience, strength, etc.) of the geosynthetic.

Because geosynthetics can be comprised of so many different polymers, it is difficult to determine the exact composition of any given geosynthetic material without knowing the formulation of the material which is often proprietary to the manufacturers. Therefore it is nearly impossible to perform a LCA on these products and generic data must be obtained.

In order to compare and contrast geosynthetics in sustainability applications, it is necessary to categorize the geosynthetic based on function.

1.1.2 Geosynthetics Based on Function

By knowing the function of the geosynthetic, one can more easily compare two geosynthetics created for the same function and select the appropriate geosynthetic for design intention. Additionally, one can determine the most sustainable solution of the options available within the function. This is also helpful as new geosynthetic materials are invented, they can be categorized by function and thus analyzed with materials within the same category. The four functions of geosynthetics are separation, reinforcement, filtration, and drainage. Koerner (2005) summarizes the geosynthetics used in each application in

Table 1.2, below. These geosynthetics are broadly used in geotechnical design and are therefore prominent throughout research regarding sustainable attributes of geosynthetics.

Table 1.2. Identification of the usual primary function for each type of geosynthetic (adapted from Koerner, 2011).

Geosynthetic	Primary Function			
	Separation	Reinforcement	Filtration	Drainage
Geotextile	X	X	X	X
Geogrid		X		
Geonet				X
Geomembrane				X
Geosynthetic Clay Liner	X			
Geopipe				X
Geofoam	X			
Geocomposite	X	X	X	X

1.2 Sustainability Rating Systems, Standards, and Codes

Sustainability analyses are conducted through standards set by the ISO. Rating systems allow for a stakeholder to achieve marketable milestones for their project. Codes set the precedence for the safety and adequacy of construction while rating systems and standards allow stakeholders to achieve sustainable objectives. This section details the various rating systems, standards, and codes as they pertain to the sustainability of geotechnical design and geosynthetics.

1.2.1 Rating Systems

Civil engineers and architects use sustainability rating systems as frameworks for sustainable building design. Integration of these same concepts with geotechnical engineering would

better complete the disciplines involved in and necessary for construction projects. These rating systems are meant to expand sustainability beyond codes and standards in order to earn a "recognition label or distinction" (Sigmon, Owens, Meyers, Kennedy, & Worthen, 2011). Aditi Misra and Dipanjan Basu (2011) argued that a sustainability assessment framework for geotechnical engineering "can provide a complete assessment of a geotechnical project by balancing the social, economic and environmental aspects with the technical and technological aspects." This sustainability assessment framework is, in essence, what any rating system promotes. The triple bottom line of LEED and the purpose of Envision™ are defined by the same sustainability principles: social responsibility, economic prosperity, and the environment.

Leadership in Energy and Environmental Design (LEED)

Perhaps most familiar to stakeholders nationwide, the United States Green Building Council (USGBC) has developed Leadership in Energy and Environmental Design (LEED) in order to construct (or renovate) buildings that are more energy efficient and reduce the amount of emissions throughout the building's life cycle. The LEED certification process is a de facto LCA on every material and process used during the construction and maintenance of a building.

Unfortunately, the LEED rating system primarily applies to building construction, whereas the construction of a building may require considerable sustainable impact aside from the building itself. LEED does not easily account for the impacts of geotechnical engineering.

Geotechnical applications can account for seven or so credits and a project must accumulate at least 40 credits to become LEED certified and at least 80 credits to be rated platinum. Therefore, LEED does not adequately reflect geotechnical structures and must be supplemented to assess the sustainability of geotechnical structures in a comprehensive way.

Envision™

Several lesser-known initiatives have been created that are similar to LEED but serve different stakeholders. One such initiative is called Envision™. Whereas LEED applies primarily to the physical footprint of the building, Envision™ can be applied site-wide and beyond, with categories focused primarily on infrastructure. The categories outlined in the Envision™ Version 2.0 that can be applied to sustainable geotechnical engineering are listed in Table 1.3, below.

Table 1.3. Envision™ rating system credit identification numbers and titles that may be applied toward geotechnical engineering applications and geosynthetics.

ID No.	Credit Title
RA1.1	REDUCE NET EMBODIED ENERGY
RA1.2	SUPPORT SUSTAINABLE PROCUREMENT PRACTICES
RA1.3	USE RECYCLED MATERIALS
RA1.4	USE REGIONAL MATERIALS
RA1.5	DIVERT WASTE FROM LANDFILLS
RA1.6	REDUCE EXCAVATED MATERIALS TAKEN OFF SITE
RA1.7	PROVIDE FOR DECONSTRUCTION AND RECYCLING
NW3.3	RESTORE DISTURBED SOILS
CR1.1	REDUCE GREENHOUSE GAS EMISSIONS

Several additional rating systems are available for sustainable building practices depending on the stakeholders' intentions and needs.

1.2.2 Standards

The international standards for life cycle assessment and sustainability assessment from the International Organization for Standardization (ISO) and ASTM International (formerly known as the American Society for Testing and Materials or ASTM) are summarized in Table 1.4.

Table 1.4. International Standards for LCA and Sustainability Assessment (Calkins, 2009)

ISO 14010	Life-Cycle Assessment: General Principles and Practices
ISO 14041	Life-Cycle Assessment: Goal and Definition/Scope and Inventory Assessment
ISO 14042	Life-Cycle Assessment: Impact Assessment
ISO 14043	Life-Cycle Assessment: Improvement Assessment
ASTM E1991	Standard Guide for Environmental Life-Cycle Assessment (LCA) of Building Materials/Products
ASTM E2129	Standard Practice for Data Collection for Sustainability Assessment of Building Products
ASTM E2114	Standard Terminology for Sustainability Relative to the Performance of Buildings

1.3 Sustainability Assessment

James R. Mehelcic et al (2003) define sustainability as the use of natural resources such that the design of structures does not reduce the quality of life due to a reduction "in future economic opportunities or to adverse impacts on social conditions, human health and the environment." Throughout contemporary society the terms sustainable design and green building have become synonymous. They have become popular keywords meant to attract attention and increase the public's environmental awareness. This trend among many industries involves producing "greener" products or having the most sustainable practices. Sustainable construction practices are somewhat behind the trend, focusing primarily on the building itself at the center of construction with minimal regard to the site upon which the

building rests, the land which becomes the usable space surrounding the building. In order to assess the sustainability of a project, one must perform a life cycle assessment (LCA).

By performing an LCA and an LCC for site preparation in accordance with the standards set by the international Organization for Standardization (ISO), stakeholders will be well-equipped to choose the most economic-friendly materials and the most environmentally-friendly geotechnical design.

> "Life cycle assessment is a 'cradle-to-grave' approach for assessing industrial systems. […] LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection. The term 'life cycle' refers to the major activities in the course of the product's life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required to manufacture the product." (EPA 2006).

An LCA enables stakeholders to identify the "best product, process, or service with the least effect on human health and the environment." (EPA, 2006). Because stakeholders are varied, LCAs may be performed with the intent of private organizational use or for public needs.

The data for an LCA may be gathered from many sources which are specific to a product or facility. If specific data is limited or unavailable, the EPA (2006) argues that generic data may not represent industry-wide practices but may be used for a comparative study. Data that is

available to the public can then be compiled into a database or software such as BEES (NIST Building and Fire Research Laboratory), eiolca.net (Carnegie Mellon University), or the Environmental Impact Estimator (ATHENA™ Sustainable Materials Institute). Unfortunately many of these databases are limited in scope and materials as well as by location where data was obtained; therefore it is important to be selective when choosing a database from which data is to be gathered. (more on database selection in Chapter 4.0 Methodology).

As part of conducting an LCA, a life cycle inventory (LCI) quantifies the amount of pollution being emitted from the production, transportation, and life cycle of the product. "A life cycle inventory is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity. An inventory analysis produces a list containing the quantities of pollutants released to the environment and the amount of energy and material consumed. The results can be segregated by life cycle stage, media (air, water, and land), specific processes, or any combination thereof." (EPA, 2006)

Another consideration for choosing the material to best fulfill a purpose (i.e., construction) is the cost to the owner over the life span of the product, or the LCC. Life cycle costing involves analyzing the cost accrued during a product's production, installation, maintenance, removal, and disposal (or recycling).

In order to perform a thorough LCA and LCC, the geographic specificity and boundary conditions must also be taken into account.

1.3.1 Geographic Specificity and Life Cycle Assessment Boundaries

Life cycle assessment databases are limited by geographic location. According to EPA guidelines (2006), it is important to define a scope for LCA with regards to location ("geographic specificity"). The scope of interest can include regional, national, or international boundaries. For example, a database such as the Inventory of Carbon and Energy (ICE) from the University of Bath may have been formed in England but is used in many United States studies. Additionally, data from alternative countries for one type material can vary greatly due to environmental practices (EPA, 2006).

Within the scope for the LCA, boundary conditions must be imposed to consider direct and indirect influences. Depending on the size of the LCA and the breadth of materials used, the product or process under analysis could be composed of materials world-wide. Considering many geosynthetics originate from petroleum-based products, the analysis should consider imported oil, and therefore the international factor of "oilfield brines generated in the Middle East should be considered," (EPA, 2006).

While location is a physical boundary condition, analytical boundary conditions for LCAs consider a cradle-to-grave approach: analyzing the material from origination, manufacture, shipment, usable life, and ultimate disposal. Non-LCA sustainability analyses may limit

boundary conditions to a portion of the material's lifespan, depending on the scope of the analysis, explained below.

1.3.2 Sustainability and Construction: Materials or Process?

Are sustainability assessments within construction analyzing a *material* or a *process*? Graveline (2009) argues that construction materials are not independent but interdependent. One material undergoes several processes to be manufactured, and by default LCAs analyze those processes that are involved in making the material. Similarly, one structure (earthen or otherwise) requires several processes during its construction. The construction industry adds another level of difficulty to a sustainability analysis because structures consist of multiple components that are interdependent. For example, an LCA of a gravity retaining wall therefore consists of the materials and the process required to construct that wall—manufacturing the concrete, reinforcing steel, geocomposite, and plastic pipe; mining and importing stone and sand; as well as installation, maintenance, and end-of-life activities of the wall. The LCA of the structure requires an examination of all of the components within the system.

1.3.3 Methodologies

Several methodologies can be used to analyze the sustainability of a product or process including life cycle assessment, life cycle inventory, carbon energy demands, carbon footprint, carbon dioxide equivalents, etc. As previously stated, LCAs and LCIs are cradle-

to-grave analyses of a product or process in which the LCA qualifies the sustainability and LCIs quantify the pollutants. Carbon energy demands (CEDs) are a quantification of pollutants from cradle-to-factory gate. Carbon footprints quantify of pollutants produced from transporting the product from the factory to the site and during installation. A carbon dioxide equivalent (CO_2e) sums all pollution (carbon, nitrogen, methane, etc.) in terms of one equivalent carbon pollutant, and is often performed on the product from manufacture to installation or a portion thereof.

The availability of data is a major limitation when conducting a sustainability analysis. Many case studies are forced to use generic data due to the inaccessibility of data for products including geosynthetics that are "proprietary either by the manufacturer of the product, upstream suppliers or venders, or the LCA practitioner performing the study," (EPA, 2006). Graveline (2009) argues, "depending on the goals of […] a corporately funded LCA, a company may or not make the results public." He reasons that manufacturers who have conducted LCAs on their products "are concerned about confidentiality, misuse of data, and exposing the strengths or weaknesses of their manufacturing process." He concludes by noting that the LCA of the manufacturing process would likely be similar for similar products, and the "life expectancy" would be the most critical variable.

Therefore it might be most productive to initially use generic data for a product commonly used for a preliminary analysis; a more specific study can be performed to identify the specific alternative once the most cost-effective and most-sustainable preliminary option has been determined. In other words, the EPA (2006) suggests it's a good idea to do a broad

study in order to eliminate unsuitable materials and reduce wasted time analyzing unsuitable materials for sustainability.

Of the various methodologies available, an LCA can be initiated using the tools and databases that are available for common products and processes for a preliminary study. However, like with any current method, many of these tools are limited to the available data, particularly for geosynthetics.

1.3.4 Life Cycle Assessment Tools

The tools available to perform an LCA are varied by scope and resources. The available databases for analyzing the LCA of construction materials include the Building for Environmental and Economic Sustainability (BEES), the US Life-Cycle Inventory Database, the Athena Environmental Impact Estimator and EcoCalculator, and the Inventory of Carbon & Energy, each with limitations for use.

The National Institute of Standards and Technology (NIST) created the BEES software which offers analysis of 230 building products. Considering the veritable amount of building products in existence, the available quantity is diminutive. For example, one selection option includes "Parking Lot Paving," and the only product options from this group include: generic 100% portland cement, generic 15% fly ash cement, generic 20% fly ash cement, asphalt with GSB88 seal-bind maintenance, generic asphalt (traditional maintenance), anonymous IP cement concrete product, and Lafarge Alpena Type I cement. From this selection, other processes related to paving including subgrade soil remediation and subbase

construction are not represented, alternative pavement construction materials including fiber-reinforced concrete, for example, are not represented, and geosynthetics are completely absent from any of the available processes.

The National Renewable Energy Laboratory (NREL) US Life-Cycle Inventory Database includes data for the following sectors:

- Air Transportation
- Chemical Manufacturing
- Crop Production
- Fabricated Metal Product Manufacturing
- Forestry and Logging
- Mining (except Oil and Gas)
- Nonmetallic Mineral Product Mnf.
- Oil and Gas Extraction
- Petroleum and Coal Products Mnf.
- Primary Metal Manufacturing
- Rail Transportation
- Transit and Ground Passenger Trans.
- Transportation Equipment Manufacturing
- Truck Transportation
- Utilities
- Waste Management and Remediation Service
- Water Transportation
- Wood Product Manufacturing
- Biomass

These sector data could be a great start to any LCA, though like many databases, do not directly include geosynthetics. In order to use these databases for geosynthetics one must know the composition of the geosynthetic, which is proprietary.

The Athena Environmental Impact Estimator and EcoCalculator has even fewer options, only offering analyses of 150 building products and processes. The available building materials include those used to construct the physical building but not for the rest of the site (i.e., soil remediation and geotechnical applications). Unlike the BEES database, geosynthetics are offered but only as polypropylene (PP) and PVC material inputs as far as plastics are concerned.

The Sustainable Energy Research Team (SERT) at the University of Bath developed the Inventory of Carbon and Energy (ICE). In this UK study, SERT analyzed a number of research papers regarding the LCA from cradle-to-grave of construction projects and summarizes the resultant LCA information in tabular format for plastics, aggregates, asphalt, soil, stone, etc. The ICE database also provides information on data acquisition which is essential for analyzing the geographic specificity of a material.

Each of the aforementioned databases has deficiencies. The analysis may be supplemented by performing a sensitivity analysis.

1.3.5 Sensitivity Analysis

A sensitivity analysis on the components within the life cycle of a product can be performed in order to determine the most influential components of the product. By knowing what the most influential component is, materials and processes can be adjusted in order to create the most sustainable system from cradle to grave. The analysis can be applied to geosynthetics. It

can then be determined whether composition of the material, the location of where petroleum is mined that the plastic and thus the geosynthetic is comprised of relative to its manufacturing location (overall geographic specificity), and the processes used in the manufacture of the geosynthetic, can be analyzed. A sensitivity analysis can also address some of the proprietary aspects of an LCA of geosynthetics and determine whether the differences in processes between manufacturers are really influential in the overall LCA of the material.

2.0 Literature Review

As stated previously, a life cycle assessment must be performed in order to study the sustainability of geosynthetics and geotechnical applications. In order to address the rapidly developing industry of sustainable design with geosynthetics, the 24th Annual GRI Conference "Optimizing Sustainability Using Geosynthetics" was held in 2011. These Proceedings focused on several case studies, both local and international, and examined various methods to analyze the sustainability of geosynthetics. The goal of the conference was "to highlight research conducted internally as well as that of its members [focused on sustainability and to present a] clear-cut methodology of quantifying the differences insofar as carbon footprint between traditional and geosynthetic alternatives is concerned." (2011).

Fourteen of the twenty papers presented at the GRI Conference related directly to the sustainability assessment of geosynthetics within geotechnical applications and can be categorized according to the primary functions separation, reinforcement, filtration, and drainage. As stated in section 1.1, by dividing the current research by category, one can find an appropriate comparable study according to function in order to analyze a new geosynthetic.

As von Maubeuge, Heerten, and Egloffstein (2011) pointed out, establishing comparable LCAs requires the same scope, same technology, and same function. Figure 2-1 quantifies the geosynthetics within each function that were analyzed throughout the 14 papers presented at the conference. Within these 14 studies, 38 different geosynthetics and earthen materials were analyzed. The majority of the materials analyzed functioned as reinforcement, drainage, and/or filtration, with only five geosynthetics involving separation applications. From this it is apparent that the focus of geosynthetic sustainability is not distributed evenly across the four functions, and more focus should be applied toward geosynthetics involving separation, depending on the market demand for materials of that function.

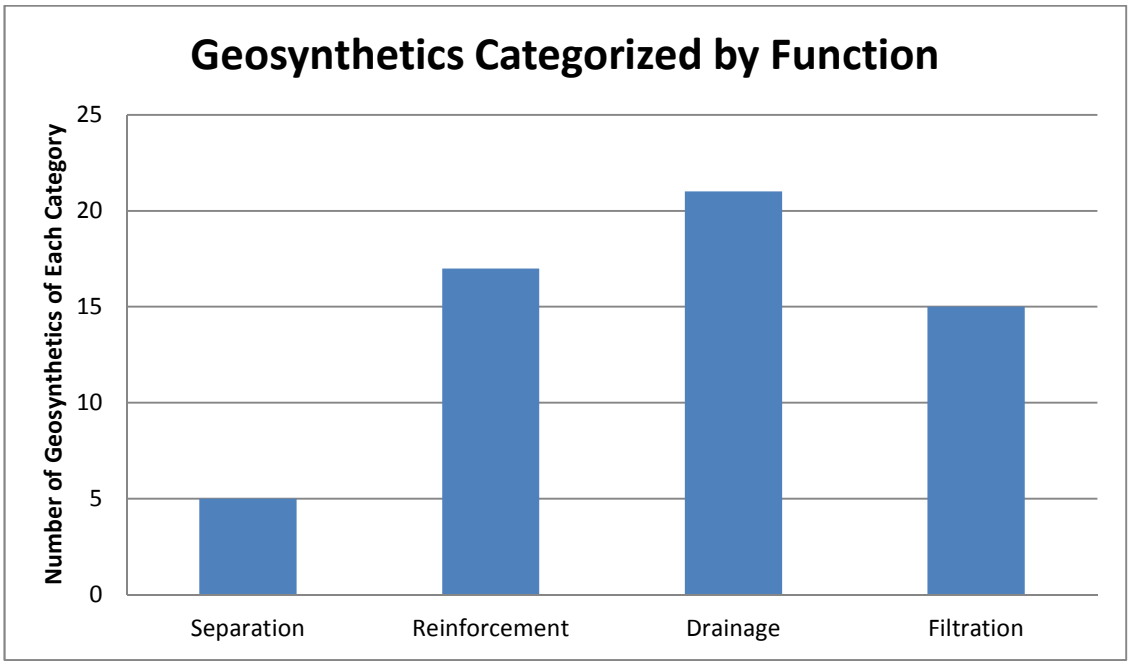

Figure 2-1. This chart shows the four primary functions—separation, reinforcement, drainage, and filtration—and quantifies the number of geosynthetics analyzed within each category for the 24th Annual GRI Conference Proceedings.

However, current research is very inconsistent within its methodology with regards to life cycle assessment—most perform simpler sustainability assessments such as carbon footprinting or embodied carbon analyses, for example. Additionally, the source of data generally appears to be from one solitary source which, although it may allow for consistency between studies, does not contribute to a study's specific needs geographically. Finally, these studies are limited by their boundary conditions such that a study may establish that it is performing a life cycle assessment, yet disregard the life of the geosynthetic after installation.

Sustainability analyses encompass several methodologies, and provide several avenues to observe geosynthetics in geotechnical design. In current research, while materials pertaining to the four primary applications of geosynthetics are represented, more focus should be applied toward geosynthetics which require the greatest market demand in order to analyze and therefore reduce the total impact of geosynthetics on the environment.

"Although researchers are starting to perceive that sustainability is an important new subject, the gap in knowledge, data, evaluation, technologies, strategies and policies in geotechnical engineering are still large." (Abreu, 2008).

While much research is yet to be performed to understand geosynthetics involvement in sustainability, the three inconsistencies included methodology, geography, and boundary conditions.

2.1 Problem 1: Methodological Consistency

While several studies claim to conduct an LCA, many do not represent a cradle-to-grave approach nor address an impact assessment that a true LCA requires in accordance with ISO 14040 *Environmental Management – Life Cycle Assessment – Principles and Framework* (2006). However, several barriers exist which do not allow for a complete LCA, including data availability as well as variability based on design. By utilizing the tools currently available, geosynthetics can be analyzed either broadly or narrowly, but not completely in terms of a true LCA.

The biggest problem among geosynthetic sustainability research is that the studies are increasingly varied by methodology and a consistent methodology is not utilized. As seen in Table 2.1, five studies use CED, six use carbon footprinting, five analyze CO_2 Emissions, two use LCC, and one uses LCA. Most papers within the conference focused on one of these sustainability assessment methods while few combined several. Only one of the 14 relevant studies within the conference presented a complete LCA on geosynthetics to present a cradle-to-grave approach and an impact assessment.

Table 2.1. This table summarizes the sustainability assessment methodology and boundary conditions utilized throughout the 24th Annual GRI Conference Proceedings.

Source	Methodology				
	LCA	**Carbon Footprint**	**CO_2 Emissions**	**CED**	**LCC**
Jones and Dixon (2011)				X	
Miner (2011)					X
Egloffstein, Heerten, and von Maubeuge (2011)				X	
Goodrum (2011)			X	X	X
Gregory (2011)			X		
von Maubeuge, Heerten, and Egloffstein (2011)			X	X	
Koerner (2011)			X		
Allen and Sprague (2011)				X	
Hsieh, Wu, Jang, Hsu, and Wu (2011)		X			
Filshill and Martin (2011)		X			
Hullings, Boudreau, and Edmunds (2011)			X		
Brown and Liew (2011)		X			
Athanassopoulos and Vamos (2011)	**X**	X			
Ramsey and Eichelberger (2011)		X			

2.2 Problem 2: Geographic Specificity

Another limitation of the work presented at the conference is data acquisition which primarily relied on the ICE database from the University of Bath (2008), regardless of the location of the study—both studies abroad and domestic utilized the same data. Unfortunately, no other database exists which is as complete or as inclusive for construction materials including geosynthetics. Relying on a sole source of data is problematic because sustainability analyses rely on geographic specificity—where do the materials originate and how far must they be shipped? By relying on this generic data produced from one country, these studies oftentimes gloss over the importance of origination, and justify the use of the generic database by implying that "figures for the United States would differ slightly; however, these figures can offer a useful snapshot comparison among plastic types" (Calkins, 2009), for example. Therefore this database can be useful as a first step to narrow down the type of geosynthetic to be used, and a more specific geosynthetic can be determined by conducting the full LCA.

One thing that many of these studies neglect to mention is the geographic location of the resources relative to the study's site. While Koerner's (2011) study considers the manufacture to installation life of a geosynthetic pipe application, geographical boundaries and transportation of the materials are neglected.

The only study that makes good use of this factor is Athanassopoulos and Vamos (2011) wherein the authors present a very clear visual (Figure 2-2) of emissions vs. distance to clay borrow source compared with emissions to transport the geosynthetic clay layer (GCL) at distances of 100 kilometers, 1,610 kilometers, or 3,000 kilometers. From their graph the reader can observe the exact distances from the clay borrow source at which it becomes more feasible to use a GCL alternative.

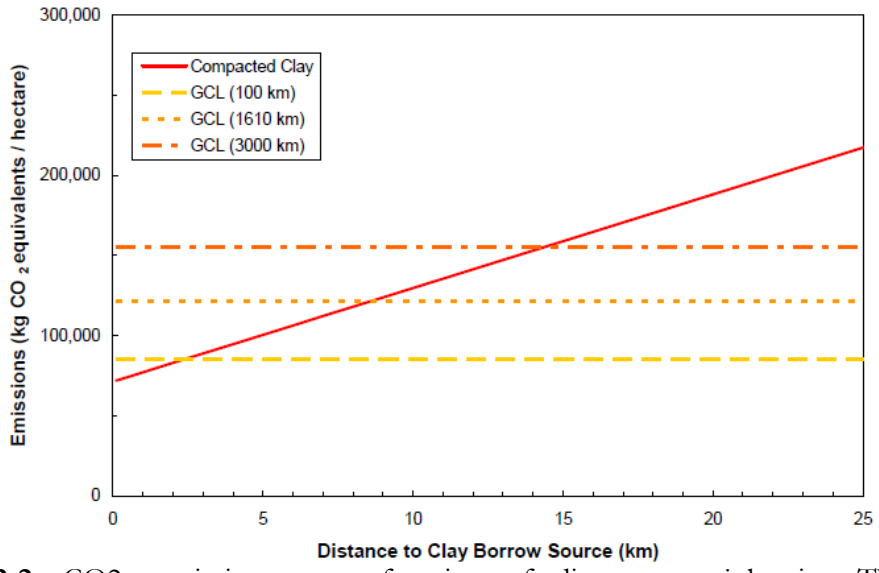

Figure 2-2. CO2e emissions as a function of distance to job site. This graph (Athanassopoulos and Vamos, 2011) shows the comparative CO2e emissions for using three different GCL alternatives or using a compacted clay liner.

2.3 Problem 3: Boundary Conditions

It is understood that an LCA is analyzed from cradle to grave. In most studies however, boundary conditions are limited by "cradle-to-factory gate," "cradle-to-installation," or solely installation of the system, neglecting the end of life consequences. While these applications have some relevance in research applications in order to examine a portion of the whole, they are not complete, and could neglect the most important part(s) of the life cycle. Graveline (2009) argues that "life expectancy" is a critical variable for comparing the LCA of similar materials. Additionally he remarks, "limiting the scope of the analysis to the production stage is not likely to provide meaningful information." Filshill and Martin (2011) remark "design life of each material must be accounted for […] to get a full account of the material used." As the European Commission (2004) found, "the environmental impact during use or after end-of-life can be even more important than the environmental impact of material production."

The most impactful study from the GRI Conference was the "Carbon Footprint Comparison of GCLs and Compacted Clay Liners" by Athanassopoulos and Vamos (2011) because their methodology utilized thorough, well-defined boundary conditions by conducting a carbon footprint analysis and examining organizational boundaries as well as operational boundaries. The project was limited by the assumption that "production and installation of each system involves emissions attributable to multiple organizations and processes [whereby] certain aspects of the [World Resources Institute] Protocol are not directly applicable or relevant." Because this study made use of measurable data, the carbon footprint analysis only covered cradle to installation, and could not predict disposal or

recycling consequences. Additionally, Athanassopoulos and Vamos (2011) showed the CO2e of different materials in graphic form, as seen in Figure 2-2, which aids in visualizing the best material choice based on distance to the borrow site and the resultant emissions.

The downfall of using a carbon footprint analysis is the boundary conditions which typically don't include the end result of the material—either disposal or recycling. Cradle-to-installation, the most thorough of the analyses within the conference which utilized carbon footprinting, were performed by Hsieh et al (2011), Filshill and Martin (2011), and Athanassopoulos and Vamos (2011). Alternatively, Brown and Liew (2011), only analyzed the carbon footprint of the mechanically stabilized earth (MSE) wall from manufacture to installation; not only do they neglect the carbon footprint of disposal/recycling, but they also neglect the required carbon footprint of obtaining the resources required to produce the materials in the MSE wall in the first place.

While Filshill and Martin (2011) examined the carbon footprint of different construction materials for underground water detention, their study failed to consider the structural strength of the systems. Systems must consider structural capacity of the materials, without which failure is imminent, at which point it does no good whether the system had more or less CED. This analysis may be more appropriate to aid in the selection of materials once a design has been settled upon, but should not necessarily dictate the design. While a CED analysis may be beneficial in differentiating between different materials, it does no good without first engineering the design, whereupon decisions can be made as to the appropriate materials for both the design and the sustainability.

A few studies concentrated on CO_2 emissions as a result of the transportation and installation phases of the project. One particular benefit was that while geosynthetics were transported long distances, they resulted in a reduction in material which ultimately led to lower emissions (Hullings et al, 2011). Ramsey and Eichelberger (2011) determined that actual fuel usage exceeded the theoretical usage by 50 percent, and reasoned that this didn't affect the total energy consumption and emissions because fuel usage accounts for less than 2 percent for the entire project.

Brown and Liew (2011) examined different exterior slope solutions for berms. By using geosynthetics, they were able to increase the slope of the berm from 3H:1V (3 lengths horizontal to 1 length vertical) to 1H:2V and therefore maximize the volume of usable space contained by the berms. Additionally, they found that using a geotextile berm results in a reduction in time and resources, arguing, "since carbon footprint is a measure of greenhouse emissions per unit of time, decreased construction time inherently leads to reduced carbon footprint." Ultimately, less select fill is required per square foot of area, and it can be concluded that this is the primary contributor to a reduced carbon footprint—not necessarily time.

Conversely, Hsieh et al (2011) found that the installation process emissions accounted for approximately 10% of that of the construction materials. In fact, in that study, it was the quantity of concrete or steel that contributed nearly 90% of the emissions from materials.

This correlates with Allen and Sprague's conclusions where massive materials contribute massive emissions.

The narrowest scope was analyzed by Ramsey and Eichelberger (2011) who only focus on the installation phase of the project for their carbon footprint analysis; granted their intent was only to improve a hypothetical analysis by including a more detailed approach and their approach only works as a small portion of the bigger picture. By so limiting the scope of the analysis, Ramsey and Eichelberger's contribution is of questionable usefulness for practitioners seeking to understand the bigger picture. Goodrum (2011) looked at both materials and delivery from an emissions standpoint, and concluded that geosynthetics improve both. However, they also admitted that research is ongoing.

CED determinations examine energy consumption and CO_2 emissions, and most studies utilize databases wherein the total energy consumption (or CO_2 emissions) can be estimated using a ratio of the amount of energy consumption (or CO_2 emissions) per mass of material. Allen and Sprague (2011) determined that the weight of the materials therefore defines and/or predetermines the outcome of a CED—the heavier the material, the greater the CED.

While a carbon footprint evaluation only measures the carbon output during shipment and installation, the CED quantifies the carbon footprint as well as the embodied carbon and energy within the material itself, and therefore provides a better picture of carbon output for the life of the material (refer to section 1.3.2 for further explanation). Like the carbon

footprint analyses, many of the CED analyses were limited to cradle-to-factory gate or cradle-to-installation, and neglect the maintenance to end-of-life carbon and energy outputs. By limiting the scope, the processes could be evaluated on a smaller scale. The papers that utilized CED were Jones and Dixon (2011), Egloffstein et al (2011), Goodrum (2011), von Maubeuge et al (2011), Allen and Sprague (2011), and Filshill and Martin (2011).

Egloffstein et al (2011) considered slopes supported using geosynthetics and retaining walls, and while their results generally coincided with those of Jones and Dixon, the results are site-, product-, and construction-specific. Similarly, in a separate study von Maubeuge et al (2011) compare two different construction projects (considering roadways and slope stability) with a similar methodology observing CED and installation costs only, and with similar unique results.

While many applications reduce emissions using geosynthetics, Jones and Dixon (2011) determined that since geocomposite walls required less volume than concrete blocks, additional required fill to compensate for volume led to an increase in embodied carbon for a retaining wall application. However, despite widespread geological boundary conditions, imported geosynthetic materials can still provide embodied carbon savings over traditional concrete materials. They also determined that waste may be minimized by incorporating it into design.

Although not part of the GRI Conference Proceedings, a report entitled "Sustainability in Geotechnical Engineering Internal Geotechnical Report 2011-2" by Misra and Basu (2011)

starts to analyze geotechnical engineering and sustainability, but ultimately performs analyses on materials as opposed to a total systems approach.

Several contradicting theories have been proposed about the end life of geosynthetics—while some argue for recycling, others point out that it's not a viable option. Most debate stems from the fact that not very many geotechnical structures have been demolished and so there is little data to support either argument. A typical argument for using geosynthetics is not only the intent of reducing the total amount of material required within a system but to ultimately be recycled at the end of the system's usable life, but much of this material may become wasted and dumped. In his article "Why is Sustainability Important in Geotechnical Engineering," Abreu (2008) makes several observations on key areas for research in sustainable geotechnical practices including "choosing, using, re-using and recycling materials during design, manufacture, construction and maintenance to reduce resource use and waste." Similarly, while Koerner (2011) focuses on CO_2 emissions, he argues that one major advantage of using geosynthetics is because they have "green benefits" including the ability of plastic materials to be recycled. By using a geosynthetic liner in pavement systems, Miner (2011) determined that investment in geosynthetics increases the lifespan of a system, although it makes milling and recycling a challenge. Unfortunately, geosynthetics are used in conjunction with earthen materials in most geotechnical systems and the practicality of removing and sorting the materials at the end of a system's usable life in order to recycle the plastic is questionable—most likely the materials will be dumped because they will have become intermixed, deteriorated, and useless to the next developer. Along these lines, Calkins (2009) states "With the exception of some HDPE products, most plastics are

disposed of in landfills or incinerators, as the recycling infrastructure for plastics faces challenges that limit the activity." The end result of the geosynthetic and the system, therefore, should be considered as the owner's responsibility, and both alternatives must be addressed in the LCA and LCC.

Perhaps reusing onsite soils is the only instance where recycling is a viable option, as demonstrated by Gregory (2011). In this instance, the geosynthetics were mixed with the soil to stabilize it for slope remediation. The alternative design option considered using imported engineered fill materials, which ultimately resulted in more than twice the emissions output than the geosynthetic-stabilized slope.

2.4 Lessons

As previously noted, current research reveals that several barriers exist which do not allow for a complete LCA, including data availability as well as variability based on design. By utilizing the tools currently available, geosynthetics can be analyzed either broadly or narrowly, but not completely in terms of a true LCA. The most effective study from the GRI Conference utilized thorough, well-defined boundary conditions by conducting a carbon footprint and examining organizational boundaries as well as operational boundaries.

3.0 Problem Statement

The purpose of this thesis is to develop and demonstrate a methodology to determine the best outcome in a systems approach analyzing cost, emissions, and lifetime of traditional soil remediation with geosynthetic materials. These soil remediation methods are often required to strengthen weak soils for structural purposes and to minimize erosion by expediting drainage from the site. The geosynthetic functions necessary for soil remediation can include separation, reinforcement, drainage, and filtration.

The soil remediation systems will be analyzed by conducting a life cycle assessment and a life cycle cost analysis on the materials used within the system. Following the methodology of the hypothetical case study analyzed in this report, a sustainable design based on minimizing emissions and cost while maximizing the usable life of the system for construction projects can be determined. Furthermore, as new geosynthetic materials are invented, they can be integrated into this analysis without significantly altering the methodology.

4.0 Methodology

This section outlines the LCA and LCC for natural and synthetic materials used in separation, reinforcement, drainage, and filtration applications.

According to the Environmental Protection Agency's (EPA's) *Life Cycle Assessment: Principles and Practice* (2006), the LCA process is divided into four parts: goal definition and scoping, inventory analysis, impact assessment, and interpretation. The goal of the LCA in this thesis is to find the best alternative of traditional soil remediation materials versus geosynthetics as a means to demonstrate an LCA methodology for geotechnical works. In order to best serve that goal, an initial case study will be established in Section 4.1.

Once the case study is defined with the required materials quantified, the inventory analysis may be performed. The inventory analysis will address materials required not only for construction, but will also consider wasted materials as well as address resources required for installation, maintenance, and demolition. In this way the entire life cycle of the case study can be observed.

The system boundaries under consideration for this study in accordance with the EPA's *Life Cycle Assessment: Principles and Practice* (2006) include raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management. The boundaries included in this system are considered to be cradle-to-grave. Shown in Figure 4-1 is an example of a cradle-to-grave system applicable towards a treatment project.

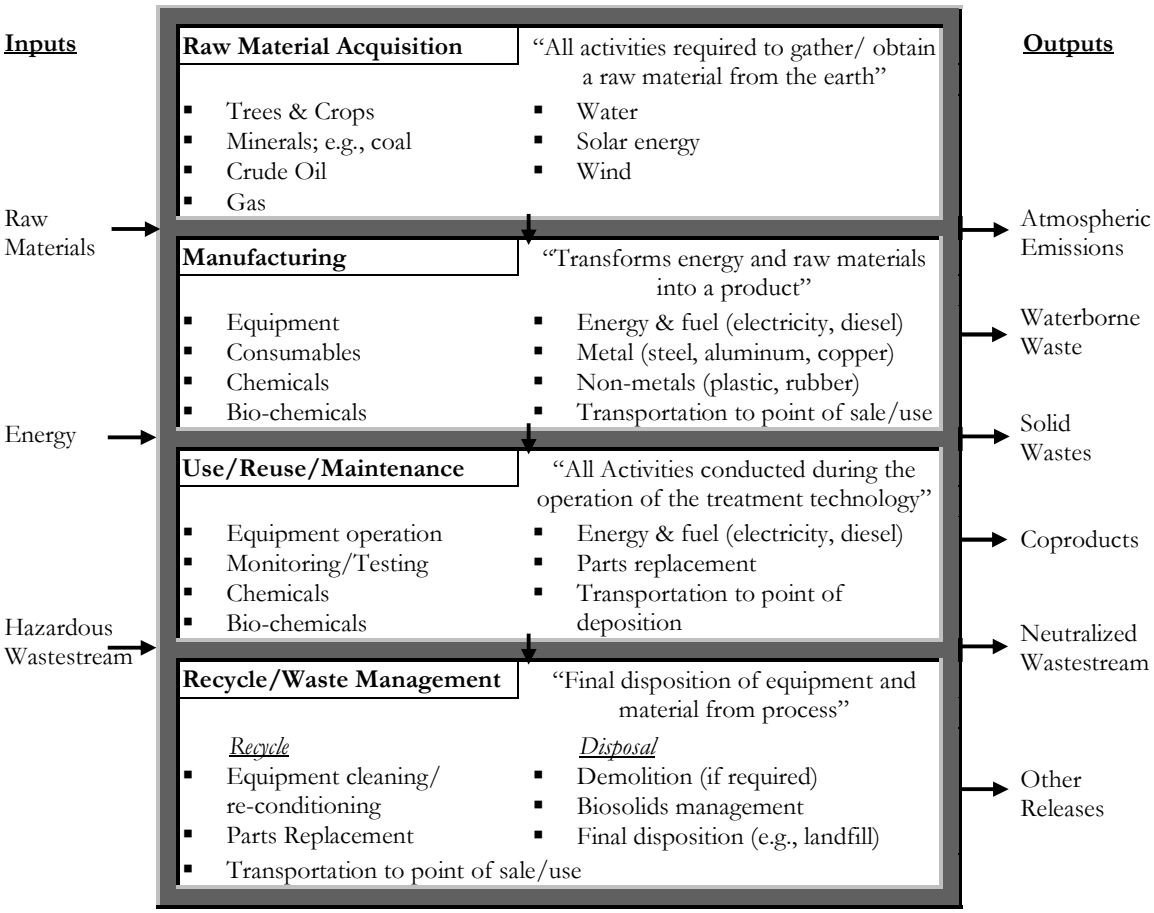

Figure 4-1. Sample life cycle stages for a treatment project. *Note*: Adapted from *Life Cycle Assessment: Principles and Practice,* Exhibit 2-1, by EPA, 2006.

This study will not focus on the third part of LCA: life cycle impact assessment (LCIA), which primarily considers ecological and human health effects. In order to perform an

LCIA, the quality of the data and results for the LCI must be sufficient for the goal and scope, the system boundaries must have been articulated and consistent in order to calculate indicator results for the LCIA, and there must be limited assumptions, averaging, aggregation, and allocation of the data to provide environmental relevance. An LCIA may be good to consider after a preliminary LCA, depending on the needs (fiscal, environmental, or otherwise) of the client or stakeholder. Because the methodology in this thesis may be considered a preliminary LCA, it does not include an LCIA which should be performed on a more project-specific case study with fewer variables.

Once required materials and resources are quantified, the LCC can be initiated using estimates required for construction, maintenance, and demolition. The cost can then be evaluated with regards to longevity as well as sustainability.

Now that the scope of the LCA has been defined, it is time to present the case study for which the most sustainable and cost effective case can be determined by performing the LCA and the LCC.

4.1 Hypothetical case study

The design of the hypothetical case study will help determine the best all-around design in terms of sustainability, cost, and function using a consistent methodology including LCA in conjunction with LCC, using specific geographical boundaries in order to address geographic specificity, and maintaining cradle-to-grave boundary conditions. This will be achieved by creating one general design scenario which requires soil remediation that can be adapted to

compare the effects of geosynthetics and earthen materials with regards to sustainability and cost, and performing the analysis using location and resources as variables.

A retaining wall case study is an excellent lens for examining traditional materials and geosynthetics. The retaining wall may require various geosynthetics including geogrid, geofabric, drainage pipe, potentially geofoam, and geonet. These geosynthetics can be categorized within the four functions (separation, reinforcement, drainage, and filtration) and are more easily exchangeable with conventional materials for the function they serve within a retaining wall problem. The benefit of using a retaining wall problem includes the ability to vary design options depending on soil conditions and pre-existing site conditions. Thus, it may be easier to transfer the analysis from site to site for the purpose of determining the effect of site location on LCA within this thesis, only.

The retaining wall was selected due to its relevance and frequency of occurance within geotechnical applications, and provides an adequate way to examine the life cycle, cost effectiveness, and utility of geosynthetics across the four functions within the system. For the purposes of this thesis, this design scenario includes a four-story building to be constructed atop an existing hill, at the base of which is an existing road. It is assumed that the building is set back from the wall such that surcharge pressures from the building do not act on the wall.

To maximize the use of the land and reduce land acquisition fees, the slope will be removed and a retaining wall will be constructed and backfilled, thus providing more space as

necessary for recreation or for parking, for example. The construction process of a gravity retaining wall is illustrated in Figure 4-2. From this general schematic, one can estimate the amount of in-situ soil to be excavated and recycled/reused as backfill material on-site; if the excavated material cannot be recycled it will be removed as waste and suitable backfill material will be imported.

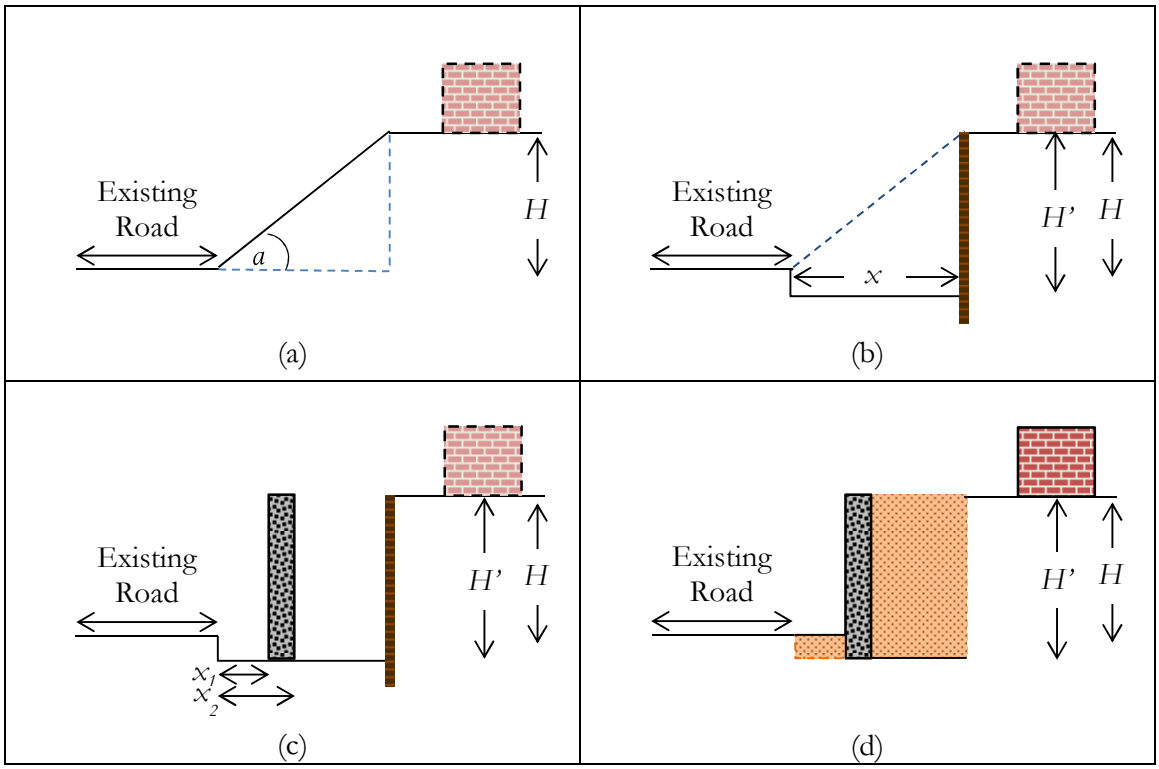

Figure 4-2. The retaining wall excavation illustrated in four stages: (a) prior to excavation, (b) excavation completed with temporary shoring, (c) wall constructed, and (d) temporary shoring removed and backfill placed.

This general design schematic will effectively translate across four design alternatives, discussed in the next paragraph. The variables are defined in Table 4.1.

Table 4.1. Variables and constants used within the case study design.

Symbol	Denotes	Equals
H	Height of initial slope	30 ft.
H'	Height of final retaining wall	35 ft. 4 in.
x	Distance from road to edge of excavation	90 ft.
x_1	Distance from road to outside of retaining wall	Varies
x_2	Distance from road to inside of retaining wall	Varies
a	Angle of initial slope	18.4°

This analysis will consider two primary in-situ soil types for ease of comparison. Typically soil strata are not uniform below the surface but for the performance of this analysis the in-situ soils will be either homogeneous sand or clay. For simplicity, the in-situ sand, as well as the imported sand, shall be comprised of a well-graded sand—Unified Soil Classification System (USCS) SW type. The in-situ clay shall be a low-plasticity (lean) clay—USCS CL type. The properties of in-situ soils and imported sand are estimated using common soil properties and are listed in Table 4.2. For the purpose of this analysis it is necessary to estimate these soil properties, although a full geotechnical subsurface investigation is necessary prior to any geotechnical design where this methodology is applied to a real site.

Table 4.2. Properties of soils in-situ (existing) and imported. Soil properties estimated using references from U.S. Army Corps of Engineers (1994) and Hough (1969).

Soil Type	Assumed Unit Weight, γ (pcf)	Assumed Effective Angle of Internal Friction, Φ' (deg.)	Assumed Cohesion, c (psf)
SW Well-Graded Sand (existing)	120	28	0
CL Low-Plasticity Clay (existing)	130	32	2,000
SW Well-Graded Sand (imported)	120	28	0

For this design scenario with an excavation greater than 20 feet in depth, shoring will be required according to standards set by the Occupational Safety and Health Administration (OSHA). However, it may not be the most cost-effective solution. For the purpose of this thesis, the shoring (or alternative bracing from lateral slopes for temporary excavation) will be considered requisite and uniform across the design scenarios, and its need will not be analyzed within the scope of this thesis. An LCA and LCC may be performed using the same process outlined here to help determine the best excavation alternatives from the available options.

4.1.1 Design Alternatives

The design alternatives as illustrated in Figure 4-3 include traditional cast-in-place concrete gravity walls, mechanically stabilized earth (MSE) walls, geotextile wrap-around walls, and gabion walls. By considering the various design alternatives, the overall system can be analyzed based on their contribution toward the life cycle of the system and the cost-effectiveness of the alternative geosynthetic or earthen solutions regarding separation, reinforcement, drainage, and filtration.

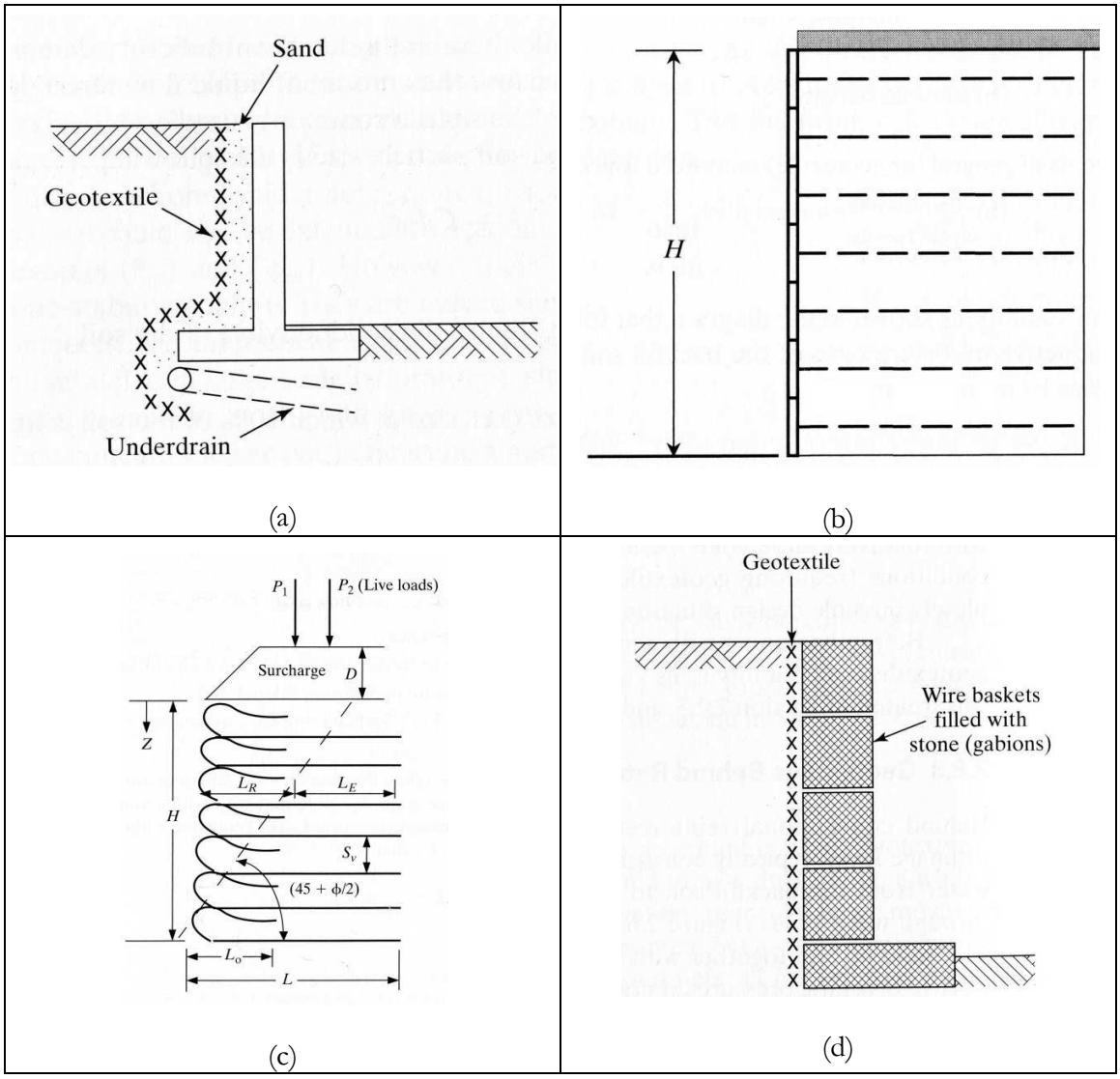

Figure 4-3. Retaining wall options using geosynthetics including (a) gravity retaining wall, (b) mechanically stabilized earth (MSE) wall, (c) geotextile wrap-around wall, and (d) gabion wall. *Note*: Adapted from *Designing with Geosynthetics*, fig. 2.62a, Example 3.10, fig. 2.45, & fig. 2.62d, by R. M. Koerner, 2005, Upper Saddle River, N.J.: Pearson/Prentice Hall.

Gravity Retaining Wall

The gravity retaining wall is the most conventional retaining wall. It is traditionally constructed out of concrete and reinforced with steel, with a toe and heel to aid in stability. The area behind the wall is backfilled with a granular material to allow for drainage, and an

underdrain is often included in the design to aid drainage and to reduce the hydrostatic pressure acting on the wall. Additional materials such as drain board, weep holes, and waterproofing materials may be utilized to further reduce the hydrostatic pressure. For the purposes of this thesis, the backfill material will consist of sand placed and compacted in 8-inch lifts over a drainage system consisting of an underdrain surrounded by pea gravel wrapped in a geofabric to aid in filtering fines. Any additional materials (drain board, weep holes, waterproofing, etc.) will not be considered for this study because it is expected that the concrete required for the gravity retaining wall will drive the LCA in this case, likely making it the least sustainable case. The gravity retaining wall will serve as a basis for comparison among the studies.

Mechanically Stabilized Earth Wall

The MSE wall is a widely popular design with its structural variability (stacked, angled, or vertical) and aesthetics (the façade can be curved, textured, etc.). Granular backfill material is compacted in lifts over uni-directional geogrid reinforcement which anchors the block wall in place via the weight of the soil above it and the tension within the geogrid anchoring the wall in place. For the purpose of this thesis and in order to keep the design more consistent across the four design scenarios, the MSE wall will be vertical and without curvature, and the facing will be synonymous with the concrete blocks which anchor the reinforcement.

Geotextile Wrap-Around Wall

The geotextile wrap-around wall is similar to the MSE wall utilizing compacted lifts of granular fill placed over a geotextile. To create the face of the wall, the geotextile is wrapped around the edge of the lift prior to the placement of the next lift. Once completed, the wall face may be treated with a bitumen or a cementitious coating (e.g. "shot-crete") in order to preserve the integrity of the geotextile and protect it from ultraviolet light or vandalism.

Gabion Wall

The gabion wall acts in the same way structurally as a gravity retaining wall but utilizes wire baskets filled with poorly-graded large stones. Unlike the other walls, these walls are considered "self-draining" due to the porous nature of the stones within wire baskets, and therefore drainage is not required behind the wall to reduce hydrostatic pressure. However, filter fabric is required to filter the finer particles from washing into the gabion baskets which would result in clogging and wall instability.

4.1.2 Materials for Construction

For each design alternative, the local and global stability requirements were analyzed for functionality. The quantity of required materials were then estimated and quantified for one foot of wall length for comparability, as shown in Table 4.3. Excavated materials are assumed to be used as fill material in the raising of the slope to meet new site grades.

Table 4.3. Excavation and fill requirements.

Wall Type	Soil Type	Required Excavation (cf/ft)	Additional Imported Sand Backfill/Fill Required (cf/ft)
Concrete Gravity Retaining Wall	Sand	215	1,555
	Clay	215	1,567
MSE Wall	Sand	96	1,535
	Clay	204	1,555
Wrap-Around Wall	Sand	48	1,587
	Clay	48	1,590
Gabion Wall	Sand	96	949
	Clay	96	955

Sand and clay soil quantities are fairly consistent between each of the wall types. However, with the MSE wall application, the required excavation of sand is significantly less than that of clay. However, it is comparable with the required excavation for gabion wall. The greater amount of clay excavation is due to a 30% increase in required reinforcement. This is largely due to the friction between a geogrid layer and clay layer is more than that of the geogrid and the sand (See Table 4.5), and it is therefore inversely related to the required length of installment. Therefore the required length of geogrid to prevent sliding is greater, and more excavation is required to accommodate the increased length of geogrid.

Additionally, it is notable that the quantity of required fill and backfill is much greater than that for excavation. This is due to the small wedge of material at the base of the existing slope for the length of excavation behind the wall is much smaller than the wedge of open space to backfill behind the wall as well as fill up to grades at the top of the wall.

The cost of construction including materials, labor, and equipment for each alternative were estimated using the widely used cost estimate book, *RSMeans Building and Construction Cost Data 2014* (R.S. Means Company, 2013). Required materials are presented in Table 4.4, below.

Table 4.4. Materials for each design alternative categorized by function.

Wall Type	Primary Function			
	Separation	Reinforcement	Filtration	Drainage
Concrete Gravity Retaining Wall	• Geofabric[1]	• Concrete • Reinforcing Steel • Sand Backfill	• Stone Backfill[1] • Geofabric[1]	• Drain Tile • Geofabric[1]
MSE Wall	• Geofabric[1]	• Wall Segments • Geogrid • Sand Backfill	• Stone Backfill[1] • Geofabric[1]	• Drain Tile • Geofabric[1]
Wrap-Around Wall	• Geofabric[1]	• Geofabric[2] • Sand Backfill • Shot-Crete	• Stone Backfill[1] • Geofabric[1]	• Drain Tile • Geofabric[1]
Gabion Wall	• Geofabric[2] • Gabion Basket • Filter Fabric[3]	• Gabion Basket • Stone Fill • Sand Backfill	• Filter Fabric[3]	• Gabion Basket • Stone Fill • Filter Fabric[3]

[1] In all cases, Stone Backfill and Geofabric in the Separation, Filtration, and Drainage columns refer to underdrain requirements.

[2] In the case of the Wrap-Around Wall, the geofabric is also required for reinforcement.

[3] In the case of the Gabion Wall, geofabric (referred to here as "filter fabric" due to its vertical alignment) is required as a separation layer between the sand backfill and the gabion baskets filled with stone.

Compaction is assumed to be using a vibratory or sheepsfoot roller, for ease of estimation, although alternative compaction efforts could be required for construction for wall stability. These, and additional assumptions, are summarized in Table 4.5, below. Waste, if any, was estimated based on available products (i.e., typical length of a roll of geofabric versus what was required by design) and included within each quantity takeoff.

Table 4.5. Assumptions for each design alternative.

Material Assumptions	Gravity Wall	MSE Wall	Geotextile Wrap-Around Wall	Gabion Wall
Backfill • Reuse all excavated material for site fill • Assume spread using dozer for cost estimate • Assume sand and clay have same LCI values	X	X	X	X
Compaction (Sheepsfoot) • Use in clay backfill applications only • Assume 4 passes for cost estimate	X	X	X	X
Compaction (Vibratory) • Use in sand backfill applications • Assume for all backfill applications to simplify LCA and LCC (alternative smaller equipment most likely used, though assumed similar life cycle and cost benefits/savings across the board) • Assume 4 passes for cost estimate	X	X	X	X
Concrete • Use 1:1.5:3 cement:sand:aggregate ratio for LCI estimate and strength requirements • Density = 2300 kg/m^3	X			
Drain Tile • Assume 6-in diameter perforated plastic tubing adequate for drainage requirements • PVC pipe • Minimum waterway wall thickness = 0.64 mm (from Table 7.5B, Koerner, 2005) • Density = 1380 kg/m^3	X	X	X	
Excavation • Assume excavation by track mounted front end loader for cost estimate • Assume sand and clay have same LCI values	X	X	X	X
Filter Fabric • Separation layer between stone-filled gabions and sand backfill • Polypropylene (PP) (polyethylene PET more typical, but usually coated - assume PP) • Density = 600 g/m^2				X
Gabion Baskets • Galvanized steel • Assume no PVC coating • 3 ft high typical • Density = 7800 kg/m^3				X
Geofabric for Underdrain • Polypropylene (PP) (polyethylene PET more typical, but usually coated - assume PP) • Average roll width = 17 ft; cut in half to line perimeter of drain trench with excess used as overlap • Average roll length = 328 ft • Assume placed by hand • Density = 600 g/m^2	X	X	X	

Table 4.5. Assumptions for each design alternative. (cont.)

Material Assumptions	Gravity Wall	MSE Wall	Geotextile Wrap-Around Wall	Gabion Wall
<u>Geogrid</u> • Polypropylene (PP) • Average Length = 50 m • Width varies by brand - assume 5 ft • Assume Biaxial (Design properties not readily available for more typical uniaxial geogrid) • Typical reinforcement spacing = 2 ft • Coverage ratio = 1.0 • Length-to-Height ratio = 0.80 • Typical interaction coefficient, C_i = 0.9 • Median Ultimate Tensile Strength T_{ult} = 2000 lb/ft • Soil-to-geogrid friction angle, δ_{fr} = 18.7° (sand), 21.3° (clay) • Include waste per roll in LCA and cost • Density = 250 g/m^2		X		
<u>Geotextile</u> • Polypropylene (PP) (LCI data unavailable for more typical polyethylene PET geofabric) • Average Density = 600 g/m^2 • Median Ultimate Tensile Strength T_{ult} = 1000 lb/in • Soil-to-geotextile friction angle, δ_{fr} = 24° • US Forest Service recommended overlap = 1 m • Cost estimating – use "heavy duty" 600 lb tensile strength geotextile • Density = 600 g/m^2			X	
<u>Reinforcing Steel</u> • Add RC30 requirements (C30/37 cylinder strength/cube strength in MPa; typical strong foundations) from LCI for reinforcing steel • Use steel bar & rod for LCI estimate • Density = 7800 kg/m^3	X			
<u>Shot-Crete</u> • Use cement (mortar) with a ratio of 1:4 cement:sand for LCI estimate • Estimate mass of water from mass of concrete less mass of mortar • Add LCI data for water to LCI data for mortar to estimate LCI for shot-crete • Density = 2100 kg/m^3			X	
<u>Stone Backfill for Underdrain</u> • Pea gravel • Uniform grade does not require compaction • Use stone gravel/chippings for LCI estimate • Density 1800 kg/m^3	X	X	X	
<u>Stone for Gabions</u> • Use limestone for LCI estimate • Density of limestone = 1631 kg/m^3				X

Table 4.5. Assumptions for each design alternative. (cont.)

Material Assumptions	Gravity Wall	MSE Wall	Geotextile Wrap-Around Wall	Gabion Wall
Wall Segments • "Straight Split" wall segments • Typical dimensions: 8" high x 18" wide x 12" deep • CMU blocks; concrete inherent • Use general concrete for LCI estimate • Density = 2100 g/m^3		X		

4.2 Life Cycle Assessment

Several components of the LCA will be examined in this study. Once the materials are quantified, an LCI will be performed on the materials and processes. Finally, each alternative will be examined through life cycle costing.

4.2.1 Life Cycle Inventory

The LCI will be analyzed using the most comprehensive available resource for these materials, the ICE from the University of Bath. As diverse as different materials are, geosynthetic properties including density, roll length, etc. will be determined using design parameters (i.e., tensile strength) and consider the median values in order to represent an "average" product. These will be found using GeosIndex (http://www.geosindex.com/) as well as commonly used product information sheets (i.e., material properties from gabion basket specifications from Maccaferri, 2013).

Limitations within the LCI will be addressed as follows.

Geographic Variability

The "geographic specificity" (EPA, 2006) should be based on several locations to the project area of interest. However, several variables including a large quantity of suppliers, as well as the distance of supplier and distance of manufacturer make sourcing materials an art form. The location of the site relative to the manufacturer of the materials for the design (concrete, geosynthetics, etc.), the quarries for required fill and backfill material, and the landfill for any waste material all affect the outcome of the LCA.

Although these variables cannot be estimated or quantified using broad assumptions, it may be more effective to first determine how these variables affect the outcome of the LCA by performing a sensitivity analysis.

Sensitivity Analysis

A sensitivity analysis will be performed in order to determine the most influential parameters within the LCA that drive the LCA. The input parameters observed for conducting the analysis are:

1. Impact (embodied energy or embodied carbon) of each material composition (e.g., geofabric composed of PET versus PP, etc.),
2. Impact of location of refinery to manufacturer,
3. Impact of location of manufacturer to supplier, and
4. Impact of location of supplier to site.

The first parameter will include several inputs, including PET, PP, etc. As many geosynthetics are created using different polymers, as discussed in Section 1.1, the alternative materials must be analyzed. The second, third, and fourth parameters will include inputs ranging from 1 mile to 1,000 miles. The impacts are dependent of each parameter variable and will determine the sensitivity index. Equation 1 was developed for this thesis to estimate the CED to transport materials.

$$\mathrm{CED}_m = c_m \sum_{i=1}^{n} \mathrm{CED}_i x_i G_i \qquad \text{(Equation 1)}$$

where,

CED_m = total carbon energy demand to transport material from factory gate to construction site (kg CO_2 per lineal foot of wall or MJ per lineal foot of wall)

c_m = quantity of material (units of material per wall unit)

i = mode of transport (i.e., 1 pertains to ship, 2 pertains to rail, 3 pertains to freight, 4 pertains to truck, etc.)

CED_i = carbon energy demand for fuel type (kg CO2 per gallon or MJ per gallon)

x_i = distance traveled to transport material (miles per unit)

G_i = f(fuel economy)

= f(mass, volume, area, drag)

≈ (average fuel economy)$^{-1}$ (gallons per mile)

4.2.2 Impact Assessment

The life cycle impact assessment (LCIA) is a necessary part of the LCA in order to understand the impacts to human and ecological health, as well as resource depletion. Using the EPA Bulletin EPA/600/R-06/060 "Life Cycle Assessment Principles and Practice" as a guide, Table 4.6 outlines the selected impact categories from the bulletin's Exhibit 4-1. Commonly Used Life Cycle Assessment Categories to be used within the context of this LCIA.

Table 4.6. Life cycle assessment impact categories.

Impact Category	Scale	Examples of LCI Data (i.e. classification)	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Additional Emissions [1]	Converts LCI data to carbon dioxide equivalents
Resource Depletion	Global Regional Local	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve

[1] It should be noted that additional emissions including Nitrogen Dioxide (NO_2), Methane (CH_4), Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), and Methyl Bromide (CH_3Br) may be included in a traditional LCIA, although the quantities for these are not readily available for the LCI portion of the LCA within the context of construction materials in general.

Because these impact categories are independent of one another, all LCI results can be applied toward each impact category. Each category can be subdivided and characterized into representative indicators of human and ecological health, as well as resource depletion. They are evaluated by multiplying the inventory data by the characterization factor in order to determine the impact indicator.

While this thesis is considered a preliminary study, the materials (if formulations and processes are defined) can be further evaluated for thoroughness using the EPA Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI).

The EPA tool TRACI contains data for nearly 4,000 compounds and their potential impacts. However, many of these compounds are only identifiable and quantifiable with consideration for definite boundary conditions including direct and indirect influences such as impacts from oilfield brines, importing oil, manufacturing the geosynthetic, etc. As previously stated, the production of geosynthetics is proprietary. Since this thesis serves as a preliminary study which utilizes generic data, the impact assessment cannot be performed.

The impact categories may be grouped to better facilitate the interpretation into emissions (air and water) or location (local, regional, or global) and understand their relative impacts.

It is anticipated that the impact assessment results alone provide sufficient information for analysis, such that weighting (a subjective valuation based on perceived importance or relevance) will not be relevant or valuable in the context of this paper.

4.3 Life Cycle Costing

An LCC will be performed in order to determine the economic costs of the retaining wall over its life cycle. The LCC can be broken down into subsets: cradle-to-factory gate, installation, maintenance, and end of life. The cost estimate for the materials and labor

during the construction phase can be performed using construction estimating techniques. Because the retaining walls are free standing structures, they do not require energy, water, or operational costs. Maintenance and repair costs would be minimal, and are assumed to be relatively consistent across the four design options. Similarly, property taxes would be comparable for the four walls, and are not considered applicable for this study. Little data is available for the end-phase of the wall structure. Therefore, the dominant cost element is the cost of construction.

The longevity of the wall is dependent upon the materials used in the wall. While concrete may have a lifespan of 50 years, geosynthetics may only be usable for 15 years. The benefit/cost ratio (BCR) will consider lifespan as well as the LCA compared to costs in the following ratio:

$$\mathrm{BCR} = \frac{\mathrm{Benefits}}{\mathrm{Cost}} \qquad \text{(Equation 2)}$$

where,

Benefits = expected longevity of wall (years)

Cost = quantifiable environmental or financial consequences such as CED (in terms of Embodied Energy (kg MJ) or Embodied Carbon (kg CO2)), or

= construction expense

5.0 Results and Discussion

Using the parameters outline in the previous chapter, each of the walls was designed using both geotechnical and structural elements. Materials were then quantified, and a life cycle inventory as well as cost estimates could be performed.

5.1 Life Cycle Assessment

The LCA process was divided into three components: cradle-to-factory gate, factory gate to installation, and installation to end of life. This was performed to analyze the LCA of each component of the life cycle individually, as well as to determine the best retaining wall alternative overall.

5.1.1 Cradle-to-Factory Gate

A life cycle inventory was performed on the materials required for each wall type, and the results are presented in Figures 5-1 and 5-2.

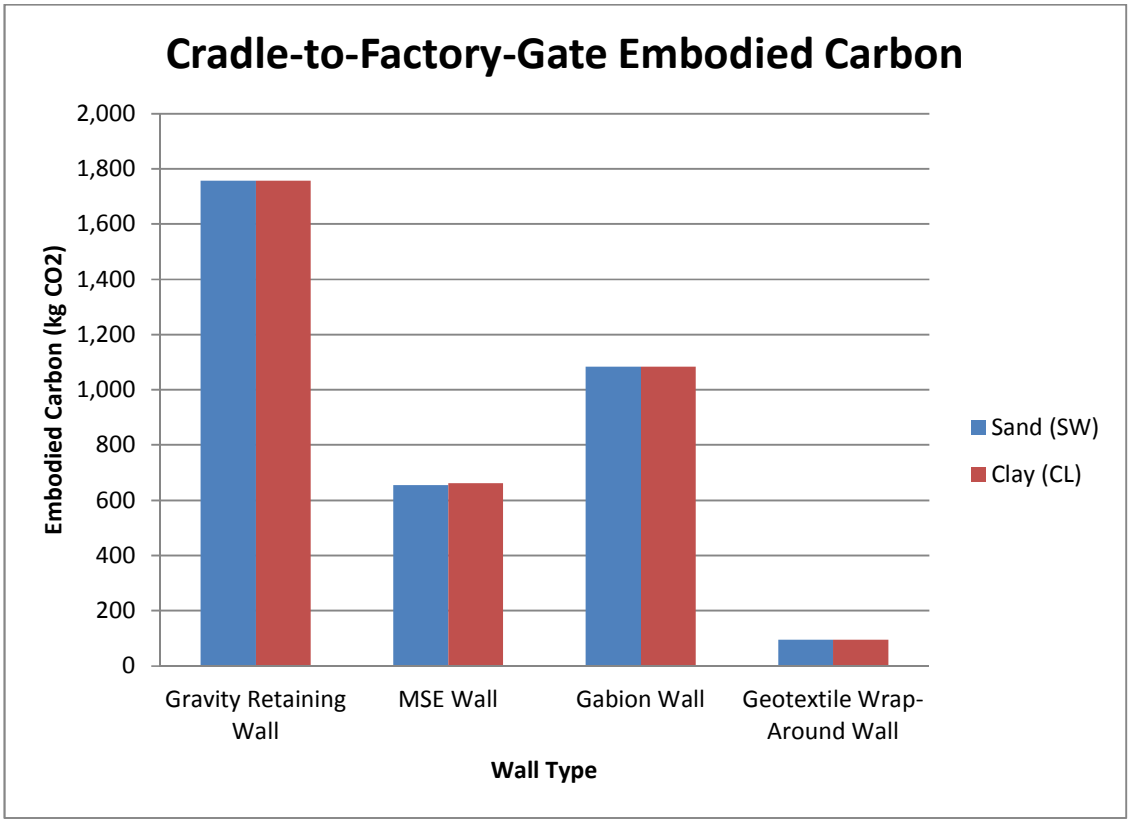

Figure 5-1. Comparison of embodied carbon from cradle to factory gate for each of the four wall types.

As seen in Figure 5-1, the gravity retaining wall contains the most embodied carbon, followed most closely by the gabion wall. These walls have the greatest mass of man-made elements compared to the alternatives. While traditional materials (soil as well as stone) have embodied carbon on the order of 10^{-2} to 10^{-3} CO_2/kg, man-made materials including cement, geosynthetics, and steel have embodied carbon on the order of 1 (or 10^{0}) CO_2/kg. That is, per unit mass, the man-made materials have up to 1,000 times more embodied carbon then that of soil and stone. While soil and stone tend to be the most massive element of the retaining wall and therefore contain a substantial amount of embodied carbon, the amount of embodied carbon within the geosynthetic is not insignificant. This explains why the

gravity retaining wall and gabion wall have the most embodied carbon, and why the geotextile wrap-around wall has the least embodied carbon.

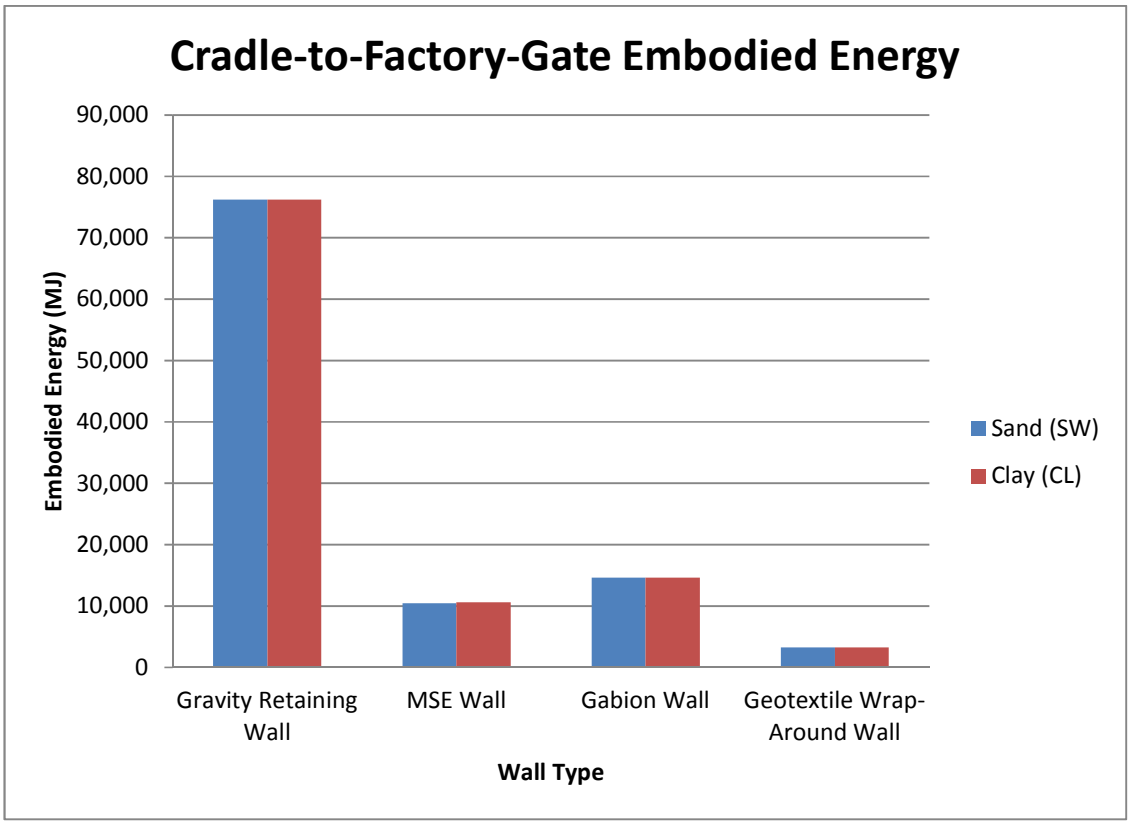

Figure 5-2. Comparison of Embodied Energy from cradle to factory gate for each of the four wall types.

Similar mass-driven results are seen with embodied energy. In Figure 5-2, the gravity retaining wall has nearly seven times the embodied energy as the MSE wall, five times that of the gabion wall, and *twenty-five* times that of the geotextile wrap-around wall. This is primarily due to the mass of the gravity retaining wall, and the amount of required man-made materials including concrete and reinforcing steel.

Life Cycle Contribution from Materials

To further understand the contribution from each material to the total cradle-to-factory gate CED for each wall type, the data was normalized by dividing the amount of CED from each individual material by the total CED for the entire wall unit. The graphs below display the contribution from each material toward total embodied carbon and embodied energy according to wall type.

From Figure 5-3, it can be seen that the concrete used in the gravity retaining wall design has the greatest contribution toward the total CED in terms of both embodied carbon and embodied energy. While the embodied carbon for concrete, reinforcing steel, and backfill are nearly equal, the embodied energy is most impacted by the use of concrete in this application. This graph also shows that the contributions from the geosynthetics (in this case, geofabric and drain tile) are minimal.

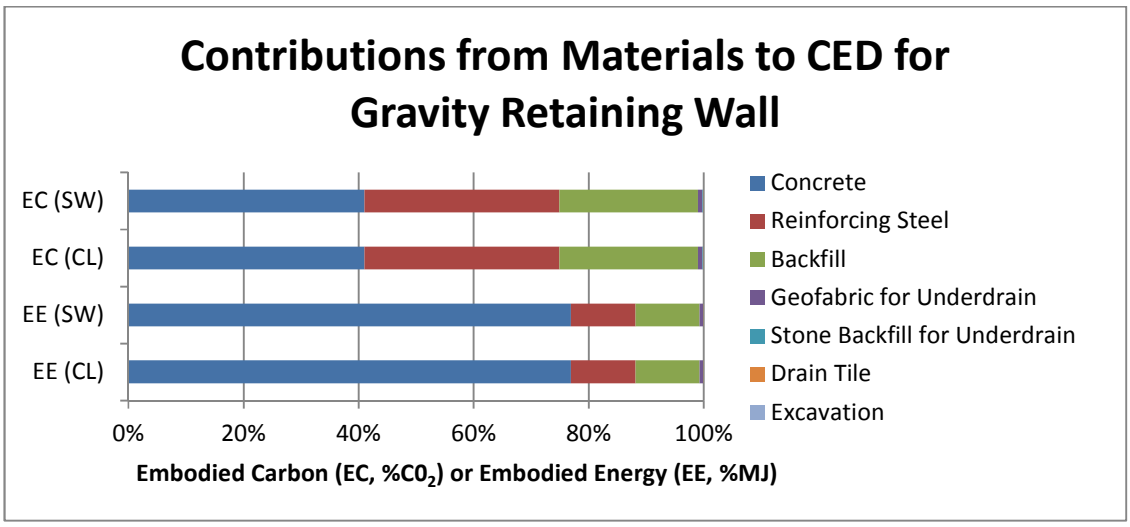

Figure 5-3. Contribution from each material used for a concrete gravity retaining wall toward total embodied carbon and embodied energy. Abbreviations "SW" and "CL" refer to sand or clay subgrade sites, respectively.

In the case of the MSE wall, the backfill is the greatest contributor both to the embodied carbon as well as the embodied energy for the wall, contributing more than 60 percent of the total CED as seen in Figure 5-4. The wall segments, formed from grout, are the second greatest contributor. The geosynthetics in this case are among the smallest contributors, although geogrid contributes 5 percent of the embodied carbon and 10 percent of the embodied energy.

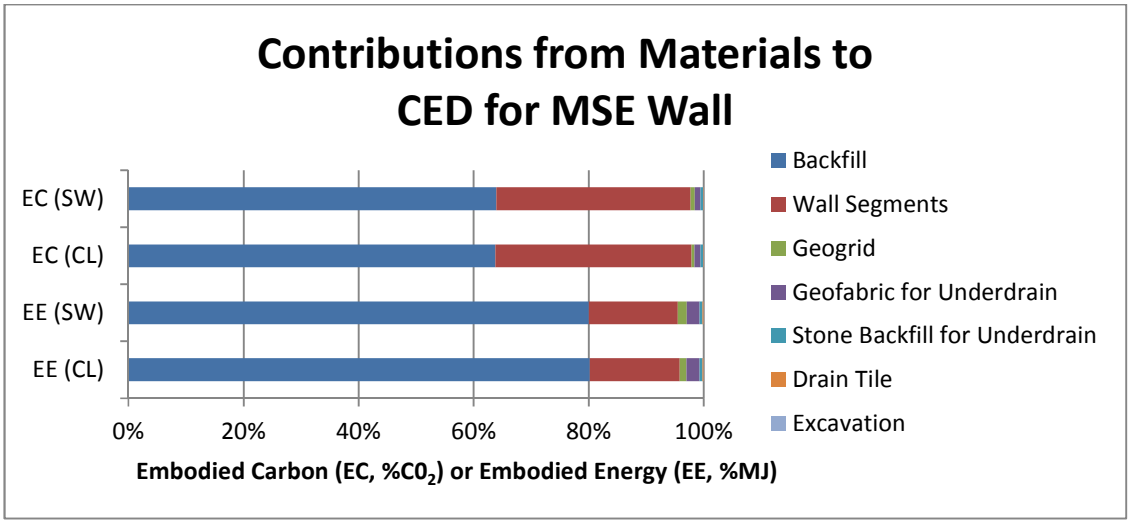

Figure 5-4. Contribution from each material used for a MSE wall toward total embodied carbon and embodied energy. Abbreviations "SW" and "CL" refer to sand or clay subgrade sites, respectively.

The gabion wall is a unique case in the comparison of man-made materials versus earthen materials. As seen in Figure 5-5, the greatest contributor to embodied carbon or embodied energy is not consistently from the same material. On the one hand, the stone for the gabions (an earthen material) contributes the most toward embodied energy. On the other, the gabion baskets (a man-made material made from galvanized steel) contribute the most

toward embodied carbon. These materials contribute the greatest mass for the wall. Like other earthen materials, the stone for the gabions contains embodied carbon on the order of 10^{-2} CO_2/kg and embodied energy on the order of 10^{-1} MJ/kg. Gabion baskets, on the other hand, have embodied carbon on the order of 10^{1} CO_2/kg and embodied energy on the order of 10^{0} MJ/kg. In terms of total mass, the stone amounts to 82 percent of the wall, and the gabion baskets amount to 0.4 percent of the wall. While the mass is significantly greater for the stones, the embodied carbon is three orders of magnitudes less than that of the gabion baskets, allowing the gabion baskets to contribute the most embodied carbon. The embodied energy, however is only one order of magnitude less, and with the mass of the stone, the stone just edges out the embodied energy of the of the gabion baskets.

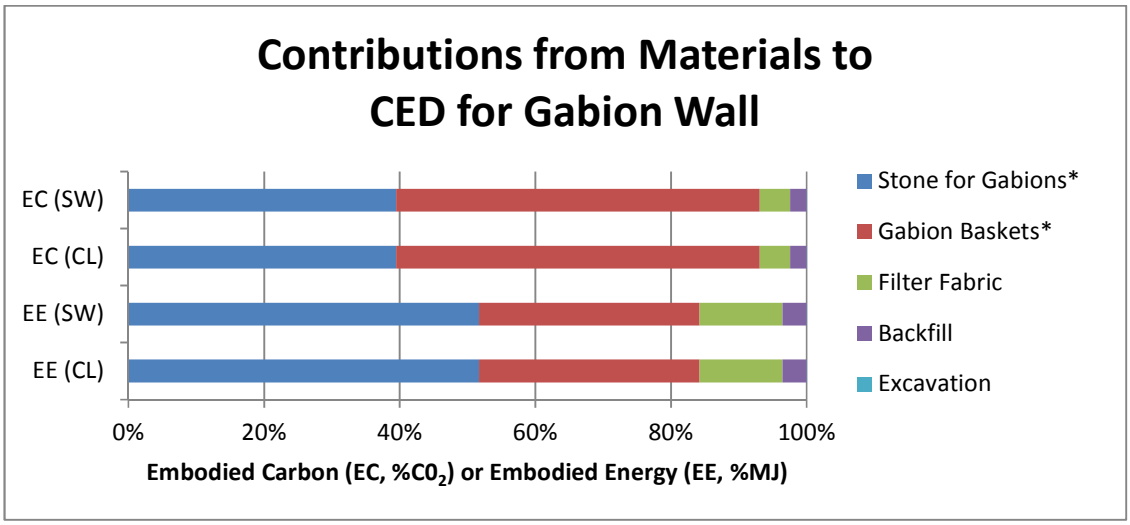

Figure 5-5. Contribution from each material used for a gabion wall toward total embodied carbon and embodied energy. Materials denoted with an asterisk (*) alternate as the greatest contributors to CED between embodied carbon and embodied energy. Abbreviations "SW" and "CL" refer to sand or clay subgrade sites, respectively.

In the case of the geotextile wrap-around wall, Figure 5-6 shows the geotextile is the largest contributor toward embodied carbon as well as embodied energy. It should be noted that this wall has the least embodied carbon and embodied energy of the four wall designs, and therefore the least impact from cradle-to-factory gate. While the geotextile is the largest contributor for this wall option, traditional materials such as the backfill materials contribute to 14% of the embodied carbon and 8% of the embodied energy. Interestingly, the geosynthetics and traditional materials alternate in their contributions toward embodied carbon and embodied energy, and including the contribution from the geotextile the geosynthetics are the largest contributor toward CED.

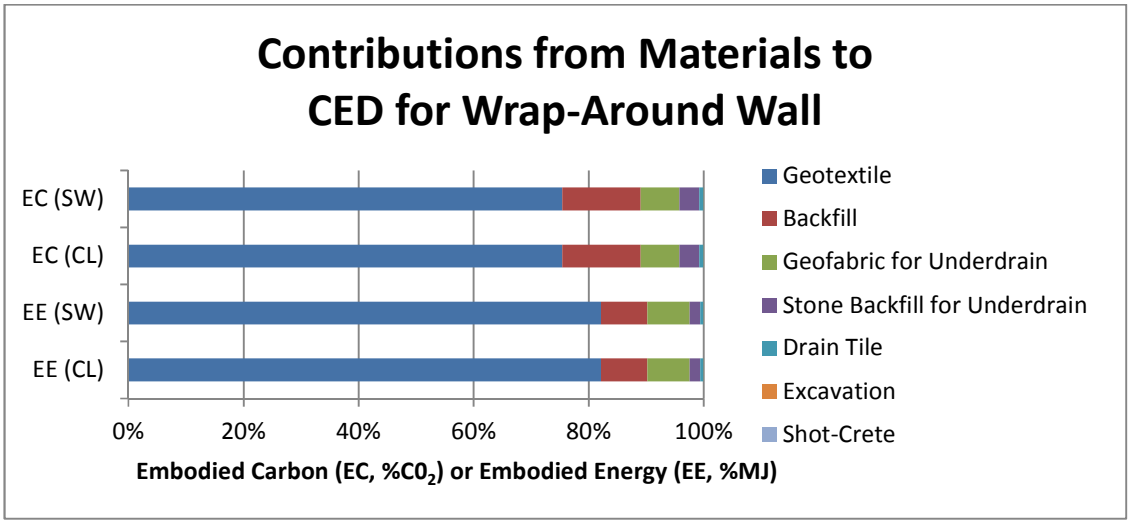

Figure 5-6. Contribution from each material used for a geotextile wrap-around wall toward total embodied carbon and embodied energy. Abbreviations "SW" and "CL" refer to sand or clay subgrade sites, respectively.

Now that the contributions from individual materials have been examined, the materials can be grouped into man-made and earthen materials for each wall type, from which it can be determined whether the man-made materials or the earthen materials are the greatest

contributors toward embodied carbon and embodied energy. It should be noted that varying clay or sand sites for the same wall type did not affect the percentage of contribution from each material. This can be seen in Figures 5-4 through 5-8 where the contributions for an SW site and a CL site nearly match. Therefore, to simplify the presentation of results, results for each wall type for SW sites are examined in Figure 5-7 below and, although not presented, results for CL (clay) sites would be comparable.

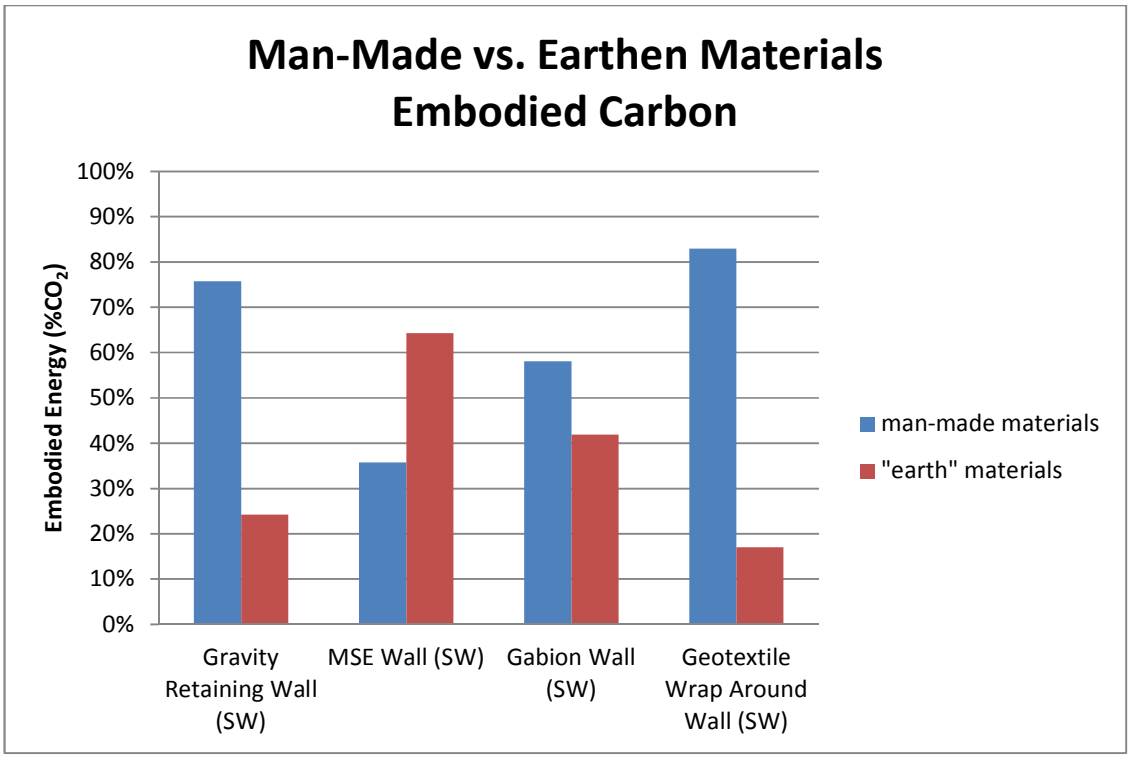

Figure 5-7. Contribution from man-made materials and earthen materials used for each wall type toward total embodied carbon. Abbreviation "SW" refers to sand subgrade sites.

Separating the man-made materials from the earthen materials shows how the collective group of materials contributes toward the LCA, and helps put into perspective the ramifications of using these materials in each wall design.

For the gravity retaining wall, from Figure 5-3 the embodied carbon was impacted nearly equally by concrete, reinforcing steel, and required backfill. By grouping the concrete and reinforcing steel into man-made materials along with geofabric for the underdrain as well as the drain tile, it can be seen in Figure 5-7 how these materials contribute the most toward embodied carbon.

For the MSE wall, from Figure 5-4 the embodied carbon was impacted most by the backfill. This is reflected in Figure 5-7 where the earthen materials contribute the most toward embodied carbon, including the excavation materials, backfill, and stone backfill for the underdrain.

The gabion wall has nearly equivalent contributions from man-made materials and earthen materials in Figure 5-7. The gabion baskets edged out the stone for the gabions, contributing the most toward embodied carbon in Figure 5-5. As discussed earlier, the embodied carbon per unit mass for the gabion stones is three orders of magnitude less than that of the gabion baskets. However, including the backfill with the stones as earthen materials, it can be seen that the earthen materials contribute the most toward embodied carbon for the gabion wall. As noted before, the gabion wall retains soil in the same way as a gravity retaining wall by using its mass to hold back the soil behind the wall. Both the concrete gravity retaining wall and the gabion wall, while massive, had the greatest contributions from the man-made materials.

Like the gravity retaining wall and the gabion wall, Figure 5-7 shows that the geotextile wrap-around wall receives the greatest contribution from man-made materials toward embodied carbon. As Figure 5-6 showed, the geotextile contributed nearly 80 percent of the wall's embodied carbon. While the geotextile is the only man-made material in the geotextile wrap-around wall, it is the single greatest contributor and therefore the man-made materials overwhelm the earthen materials in this wall type.

Three of the four wall types showed a greater contribution from the man-made materials toward the total embodied carbon. However, this is not the case for embodied energy as seen in Figure 5-8.

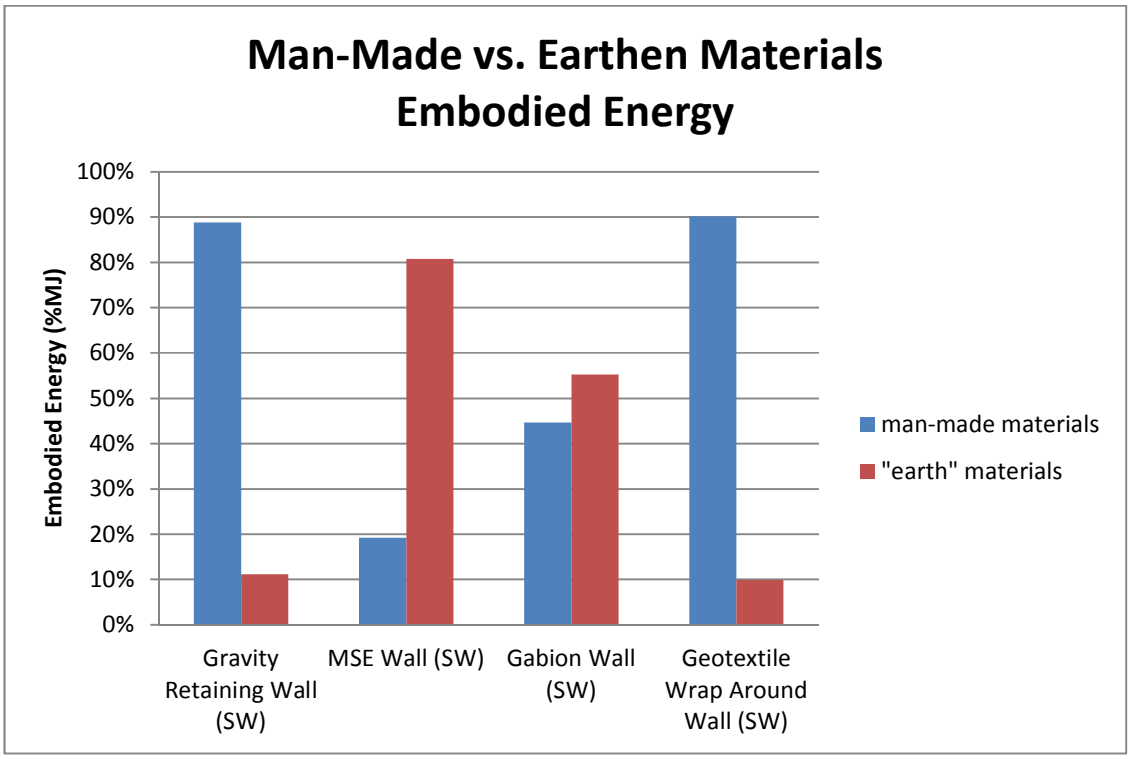

Figure 5-8. Contribution from man-made materials and earthen materials used for each wall type toward total embodied energy. Abbreviation "SW" refers to sand subgrade sites.

Figure 5-8 shows that the greatest contribution toward embodied energy comes from the man-made materials for both the gravity retaining wall and the geotextile wrap-around wall. Like the contributions toward embodied carbon, earthen materials dominate the contribution from embodied energy for the MSE wall. In the gabion wall, the earthen materials contribute more embodied energy than the man-made materials, but contributed less embodied carbon as seen in Figure 5-7.

The concrete contributed nearly 80 percent of the embodied energy in the gravity retaining wall as seen in Figure 5-3, and this is reflected in Figure 5-8.

For the MSE wall, the backfill contributed the most embodied energy in Figure 5-4. Again, this is reflected in Figure 5-8. Since the man-made materials including geogrid, wall segments, geofabric for the underdrain, as well as the drain tile only contributed ¼ of the embodied energy, it follows that these materials contribute the least toward embodied energy.

As in the comparison of individual materials in Figure 5-5, the man-made materials (most notably the gabion baskets) contributed the greatest amount of embodied carbon while the earthen materials (most notably the stone for the gabions) contributed the greatest amount of embodied energy. This is reflected in Figure 5-8 and, as discussed earlier in Figure 5-7. The mass of the earthen materials are the main cause of the greater contribution in embodied energy, as the amount of MJ per unit mass for each are separated by a fairly narrow margin of one order of magnitude between the stone and the gabion baskets.

While the percentage of contribution from geotextiles toward embodied energy and embodied carbon is greatest from the geotextile wrap-around wall, the quantity of geotextiles is low compared to that of the fill, and therefore the *total* embodied energy and embodied carbon is lowest of the four wall alternatives studied.

Life Cycle Contribution Based on Function

Since subdividing each wall type by each individual material as well as by earthen materials versus man-made materials showed the areas of contributions for CED, the contributions from man-made materials within any one wall type may be reduced further by substituting different materials based on the required function.

Each of the materials was assigned one or more functions as seen in Table 4.4. Then, like before, the contributions to CED based on function for each wall type was normalized to observe where the CED was most detrimental.

Table 5.1. Contributions toward embodied carbon and embodied energy for each design alternative categorized by function used for each wall type.

Material	Normalized Embodied Carbon (EC, CO2)				Normalized Embodied Energy (EE, MJ)			
	Gravity Retaining Wall (SW)	MSE Wall (SW)	Gabion Wall (SW)	Geotextile Wrap Around Wall (SW)	Gravity Retaining Wall (SW)	MSE Wall (SW)	Gabion Wall (SW)	Geotextile Wrap Around Wall (SW)
Separation	1%	1%	58%	86%	1%	3%	45%	91%
Reinforcement	99%	98%	96%	89%	99%	97%	88%	90%
Filtration	1%	1%	4%	86%	1%	3%	12%	91%
Drainage	1%	2%	98%	11%	1%	3%	96%	10%

Because several of the materials had multiple functions, as can be seen in Table 5.1 the materials cannot be normalized by function to determine their contributions toward total CED for the wall. Take the geofabric for the underdrain as an example. It functions as a separation material as well as a filtration material between the stone for the underdrain and the backfill materials, and it also acts as a part of the drainage system for the wall. It doesn't contribute to each function separately – it's not 30% separation, 40% filtration, and 20% drainage. It serves multiple functions at one time. Because it contributes to multiple functions, it cannot simply be "swapped out" by another material (i.e. sand). Therefore in this case, to reduce its CED one must reduce the CED of the material selected rather than choosing a traditional material.

To reduce the amount of embodied carbon and embodied energy in a gravity wall, one must first consider changing the materials used in the wall. By trading the concrete for gabion baskets filled with stone, for example, the embodied carbon and embodied energy are effectively reduced. On the other hand, to design a concrete gravity retaining wall to perform as well as a gabion wall in drainage, additional materials such as drain board or a geocomposite (identified in Table 1.2) would be required to eliminate the hydrostatic head behind the wall.

The best way to swap materials for function is to change the type of material. From the overview of geosynthetics in Section 1.1, the types of plastics available in the construction of geosynthetics are numerous, and new polymers continue to be created. This thesis acts as a broad study, and from here the specific materials used in each wall application can be fine-

tuned to minimize emissions. This may include trading the polypropylene (PP) geotextile used in this study for a polyethylene (PET) with a carbon black coating for durability; this would require more data for the LCI, however, which is not available at the time of the preparation of this thesis.

By changing one material in each wall, the data can once again be normalized as before, and the contributions from each material to the whole of the wall can be observed. Additionally, the overall embodied carbon and embodied energy may increase or reduce. By changing multiple materials, perhaps one with greater embodied carbon than its predecessor but works better with other materials with lower embodied carbon, it may produce a wall with ultimately less embodied carbon overall. These adjustments are crucial to minimize emissions that result from wall construction.

The original purpose of subdividing each material by function was to see where each geosynthetic material might be swapped out based on their function with an earthen material that might perform better in an LCA, and vice versa. From Table 5.1, it can be seen that each wall type has the greatest contribution from materials that are used in a reinforcement application. This is because by design the retaining wall is used to reinforce the soil behind it. Second to the contributions from materials acting as reinforcement are the contributions for materials acting as drainage for the gabion wall. The gabion wall is a special purpose wall, and by design it allows for drainage through the wall itself. Because each of the materials in this case study act in multiple functions, they are not easily interchangeable.

5.1.2 Factory Gate to Installation

While the previous section focused on the materials, this section will focus on the multiple processes required for construction and their impact on the overall sustainability of the wall applications. As discussed in Section 1.3.2 construction materials are not independent but interdependent, and the construction of a wall includes both the materials and the process required to construct the wall. The LCA of the structure requires an examination of all of the components within the system.

Life Cycle Contribution from Processes

While it's relatively easy to track the required man-hours to assemble these walls, it is nearly impossible to estimate the type of equipment used and construction methods without making gross generalizations and assumptions which may or may not adversely affect the outcome of the LCA. Simply put, there are many alternatives when it comes to construction including the size of equipment used, the amount of equipment required, idling of trucks and equipment during construction, etc. Therefore, taking an all-things-equal approach, one can make observations regarding the energy required by grouping the methods (and therefore the required equipment) and the amount of man-hours. The two charts below, one each for a sand site (Figure 5-9) and a clay site (Figure 5-10), summarize the amount of equipment time required for these activities, measured in man-hours. It should be noted that the amount of equipment time required for excavation and backfill are considerably less than that of other installation requirements, and were scaled using a logarithmic scale for visibility on the charts.

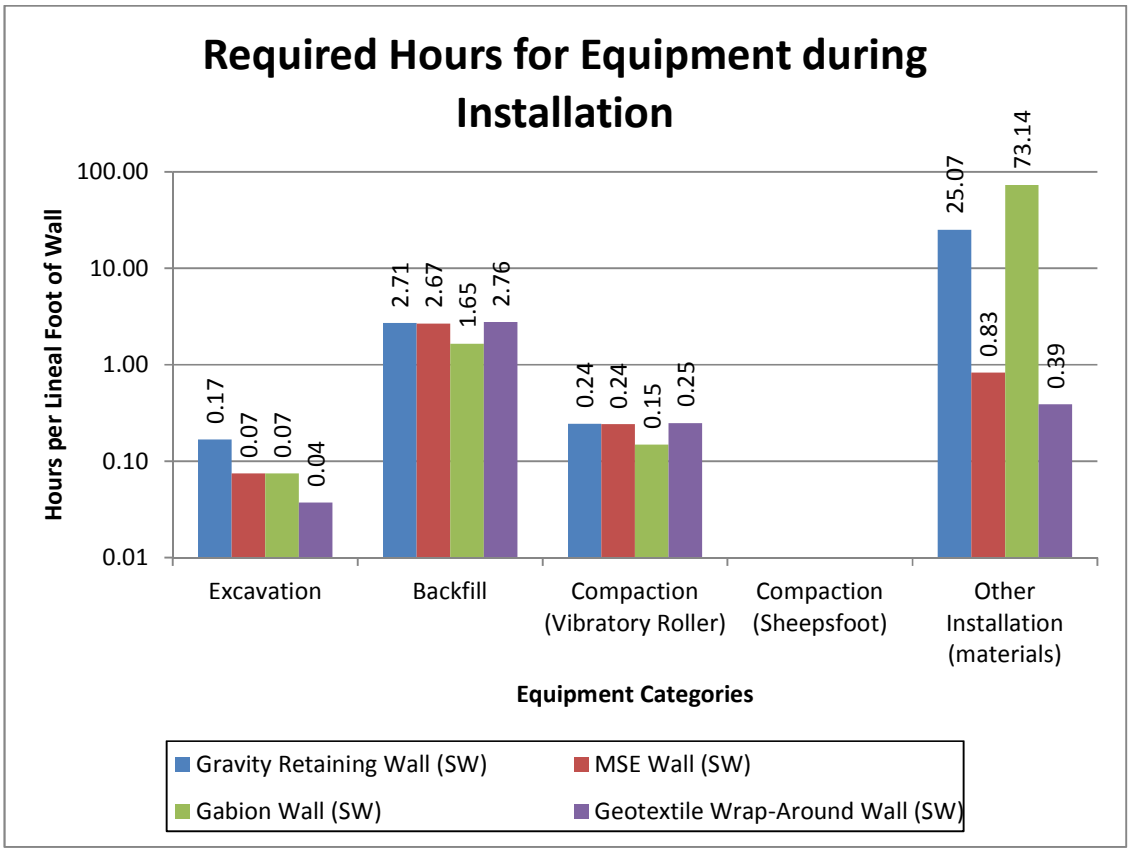

Figure 5-9. Required hours for equipment during installation for each of the four wall types bearing in native sand (SW) soils.

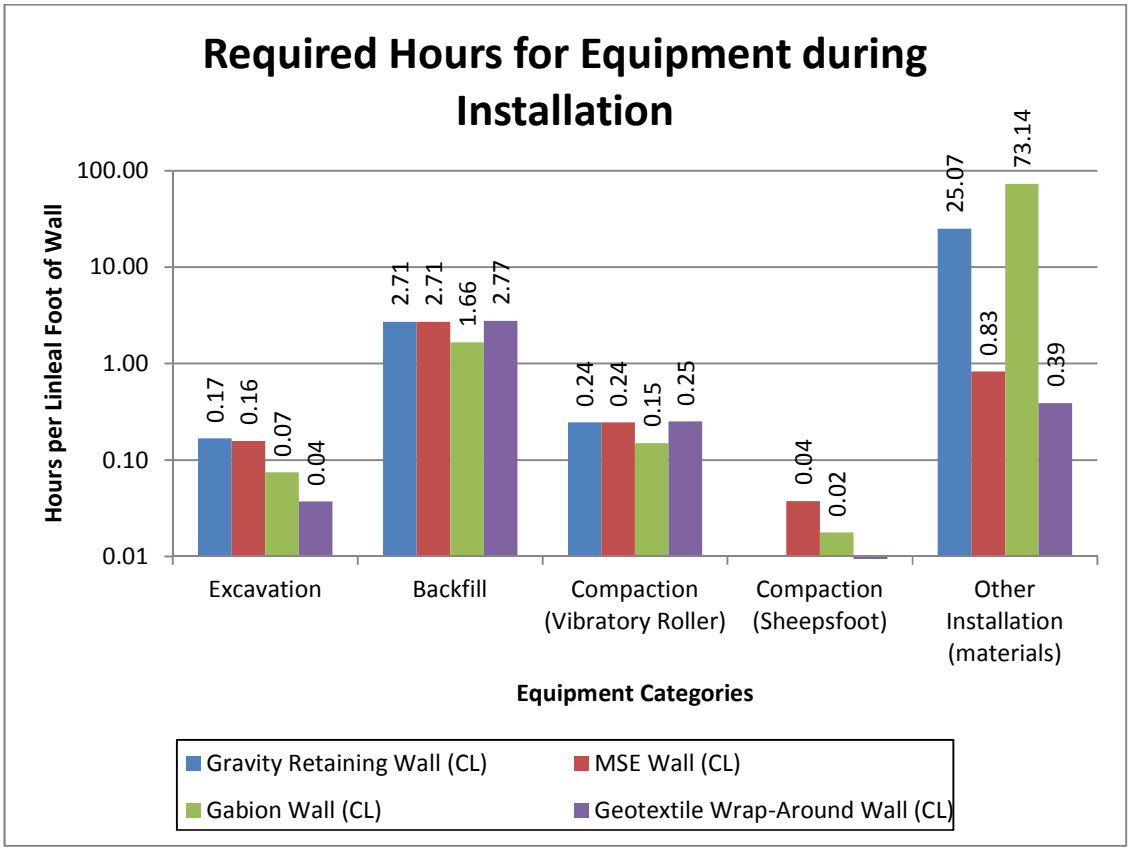

Figure 5-10. Required hours for equipment during installation for each of the four wall types bearing in native clay (CL) soils.

The required number of hours in each category is comparable between the sand site and the clay site. The most notable difference is the required compaction using a sheepsfoot roller is greater at a clay site, whereas at a sand site a sheepsfoot roller is not required at all.

The amount of time required for excavation changes somewhat for each type of wall. This is due to the change in the amount of materials required for wall installation. Due to local stability requirements, the geotextile wrap-around wall requires the least amount of "real estate." However, due to global stability requirements, the MSE wall requires slightly longer

geogrid embedment depth at the clay site compared with the sand site, and therefore mirrors the required space for a gravity wall at the clay site.

The time contribution for backfill (and, therefore related compaction) between each alternative is comparable. The elements of the gabion wall require a lot of space for internal stability, and therefore the amount of backfill (and compaction required) and the amount of time backfilling this type of wall is slightly less.

The time contribution for other installation methods vary since "other installation" is an umbrella category referring to assembling the materials required for each wall. The gravity wall requires placing the reinforcing steel, forming, and pouring concrete. While concrete takes time to cure, this can be accomplished without sacrificing man-hours. The MSE wall requires placement of blocks and reinforcement. The gabion wall requires assembling and filling multiple massive gabion baskets, the most time consuming of any task. The wrap-around wall requires the least time for assembly with simple geotextile placement *during* backfill activities. While the wrap-around wall and the MSE wall are similar in this respect, the extra material for the MSE wall (the blocks) delays the construction process.

While a similar approach is used in MSE wall design, the same quantity of geogrid is required for both sand and clay sites due to wasted materials. The calculated required length of geogrid for sand was 24 feet whereas for clay was 35 feet. Adding a cover depth of 18 inches between MSE blocks increases the lengths to 25.5 feet and 36.5 feet. Unfortunately, the smallest roll of geogrid is 50 meters (164 feet) which effectively results in 11 feet of waste

per roll for the SW MSE wall and 18 feet of waste per roll for CL MSE wall. Therefore, the 5 rolls of geogrid must be ordered for the SW MSE wall and 7 rolls of geogrid must be ordered for the CL MSE wall.

Sensitivity Analysis

Based on $\mathrm{CED}_m = c_m \sum_{i=1}^{n} \mathrm{CED}_i x_i G_i$ (Equation 1), the equation has no unique solution. If, for example, n=4 transportation nodes, and given boundary conditions including $\sum_{i=1}^{n} x_i \leq 500$ miles (per LEED guidelines), CED_i can be estimated based on published data, G_i can be estimated based on published data from the EPA (including resources such as EPA430-K-08-004, "Direct Emissions from Mobile Combustion Sources," updated most recently in May 2008), and C_m can be estimated based on wall requirements, five unknowns (x_1, x_2, x_3, x_4, and CED_m) cannot be solved given two equations (Equation 1 as well as $\lim_{x_i \to 0} \mathrm{CED}_m = 0$).

5.1.3 Installation to End of Life

It is anticipated that traditional retaining walls do not require additional energy input to maintain, and therefore do not output energy other than their embodied energy, which was discussed in the cradle-to-factory gate section. This is provided that good construction techniques were utilized during installation, and that natural disasters or vandalism do not inhibit the wall's performance. These factors are typically unique to individual walls (though perhaps not uncommon for MSE walls due to installation and drainage design issues), and

are therefore considered unique and rare occurrences which are not included within the scope of this paper.

5.2 Life Cycle Cost

The life cycle cost (LCC) was performed to determine the true cost of construction of the retaining wall over its life cycle.

The total financial cost for each wall was determined using traditional construction costing estimates from cradle-to-factory gate. As mentioned in Section 5.1.2, equipment requirements (distance traveled, idle time, etc.) were too varied to account for factory gate-to-installation, and must be determined from actual conditions for the specific site being analyzed. This follows from the study performed by Boyd and Eichelberger (2011) where actual fuel usage was 50% greater than estimated. Furthermore, Hsieh et al (2011) concluded, "the installation process emitted only about 10% carbon dioxide compared to that associated with the construction materials." Additionally, too little data exists to accurately estimate the cost of maintenance over the lifespan, the length of the lifespan, and the demolition costs of the wall.

Based on construction costing estimates, the total cost for wall materials are shown in Figure 5-11, below.

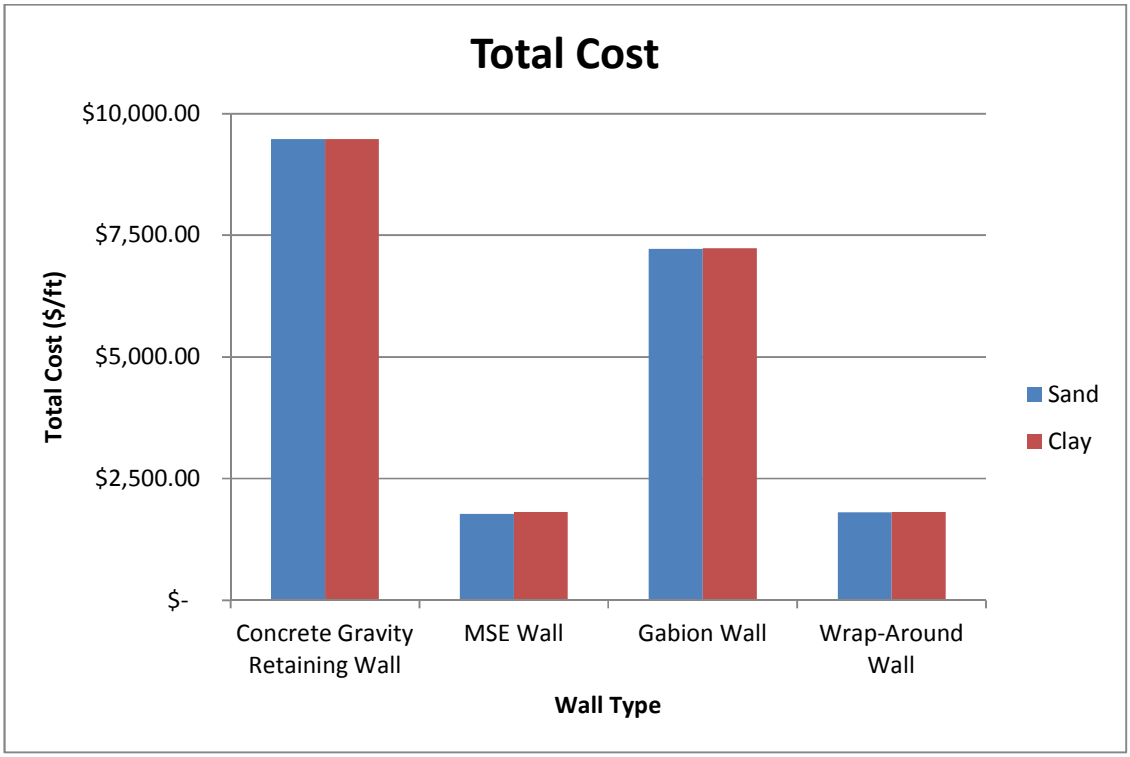

Figure 5-11. Total cost for materials for each wall type.

The concrete gravity retaining wall is the most expensive wall, followed by the gabion wall. The geotextile wrap-around wall and the MSE wall have very similar costs associated with the materials required for construction.

The costs associated with the wall include both environmental and financial consequences. To put these consequences in perspective, the costs were compared with the benefits which include the expected life of the structure. While most retaining wall structures are designed for an expected life of 75 years, little data exists for the actual life of these structures. It would be a difficult and painstaking process to determine the lifespan of a wall based on case studies, and would require efforts to aggregate data based on material, local, or global failures, as well as to date existing structures that have not yet failed or have been replaced.

It's possible that retaining walls constructed over 75 years ago have outlasted their expected lifespan. Additionally, since geosynthetics have only been utilized in soil stabilization since the 1920s (Koerner, 2005), retaining walls utilizing modern petroleum-based geosynthetics have not likely been around for 75 years.

Without data for the expected lifespan of these walls, the benefit/cost ratio (BCR) cannot be determined outright. However, a benchmark can be set from which the walls can be compared. In observing the results from the CED study as well as the total construction expense, it can be seen that the geotextile wrap-around wall outperforms the other wall alternatives in each category.

If the geotextile wrap-around wall had an expected lifespan of 75 years, how many years would it require for the other design alternatives to have the same BCR as the wrap-around wall? Simply put,

$$\text{BCR} = \frac{\text{Benefits}_i}{\text{Cost}_i} = \frac{\text{Benefits}_{wrap-around\ wall}}{\text{Cost}_{wrap-around\ wall}} \qquad \text{(Equation 3)}$$

$$\frac{\text{Benefits}_\text{i}}{\text{Cost}_\text{i}} = \frac{75\ \text{years}}{\text{Cost}_{\text{wrap-around wall}}} \qquad \text{(Equation 4)}$$

$$\text{Benefits}_i = 75\ \text{years}\frac{\text{Cost}_i}{\text{Cost}_{wrap-around\ wall}} \qquad \text{(Equation 5)}$$

where,

$Benefits_i$ = expected longevity of wall type *i* (years)

$Cost_i$ = CED (in terms of Embodied Energy (kg MJ) or Embodied Carbon (kg CO2)) of wall type *i*, or

= financial expense of construction of wall type *i*

i = indicator for wall type (i.e., concrete gravity wall, MSE wall, gabion wall, or wrap-around wall)

Equation 5 determines the amount of usable lifetime required for wall type *i* have the same BCR as the geotextile wrap-around wall. Comparatively, the results are presented in Figure 5-12.

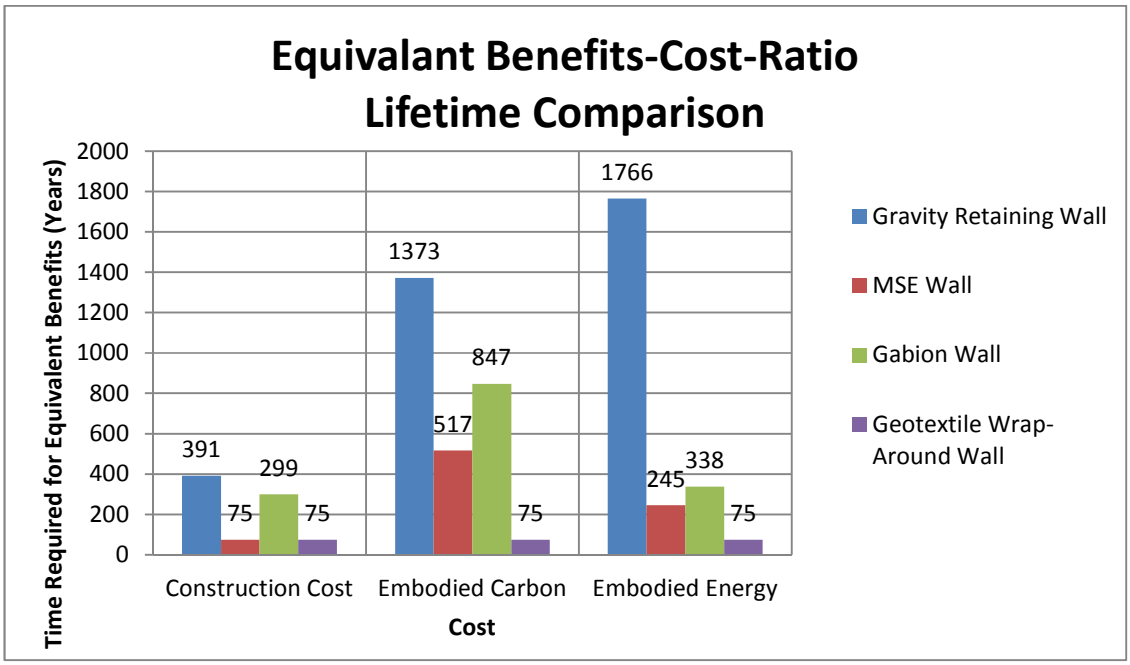

Figure 5-12. Time required for each wall type to have the same BCR as the geotextile wrap-around wall.

By comparing each alternative's relative financial cost, embodied carbon, and embodied energy to that of a geotextile wrap-around wall, it can be seen that while financially they may be comparable, equivalent embodied carbon or embodied energy outputs over the lifespan of the alternative would require the alternative to last well beyond the 75-year design life with respect to the same output for the geotextile wrap-around wall. Based on finances alone, the MSE would have a comparable lifespan as the geotextile wrap-around wall, and the gravity retaining wall and gabion wall were estimated to require a life of nearly 400 years and 300 years, respectively, to have the same BCR as the other alternatives. Similarly, to have the same BCR in terms of embodied carbon or embodied energy, the concrete wall would have to have a life of nearly 1,370 years and 1,770 years, respectively, and the MSE and gabion walls would need to last between 240 to 850 years.

Based on the extensive required lifespans of each wall alternative compared with that of the wrap-around wall for the cradle-to-factory gate and installation (cost only) phases, the cost for the installation (embodied carbon and embodied energy), maintenance, and end-of-life phases would need to be huge to reduce the required lifespan of the walls for an equivalent BCR to the wrap-around wall.

6.0 Discussion, Conclusion, and Recommendations

By performing a life cycle assessment (LCA) and a life cycle cost (LCC) to analyze the environmental and economic impacts of a product from "cradle-to-grave," this thesis has shown that implementing geosynthetics into a retaining walls design, for example, is more sustainable than using more traditional soil retaining methods.

6.1 Summary of Findings

The purpose of this thesis was to determine the best outcome in a systems approach analyzing cost, emissions, and lifetime of traditional soil remediation with geosynthetic materials. Following the methodology of the hypothetical case study analyzed in this thesis, a sustainable design based on minimizing emissions and cost while maximizing the usable life of the system for construction projects can be determined.

Once the retaining wall case study was defined with the required materials quantified, the inventory analysis could be performed. The inventory analysis addressed materials required not only for construction, but also considered wasted materials as well as addressed resources required for installation, maintenance, and demolition. The system boundaries under consideration for this study in accordance with the EPA's

Life Cycle Assessment: Principles and Practice (2006) included raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management.

The retaining wall was selected due to its relevance and frequency within geotechnical applications, and provides an adequate way to examine the life cycle, cost effectiveness, and utility of geosynthetics across the four functions within the system. The design alternatives included traditional cast-in-place concrete gravity walls, mechanically stabilized earth (MSE) walls, geotextile wrap-around walls, and gabion walls. Once the materials were quantified, an LCI was performed on the materials and processes. Finally, each alternative was examined through life cycle costing using a benefits-cost-ratio.

While soil and stone tend to be the most massive element of the retaining wall and therefore contain a substantial amount of embodied carbon, the amount of embodied carbon or embodied energy within the geosynthetic is not insignificant. This was evident in the gabion wall example. In terms of total mass, the stone amounted to 82 percent of the wall, and the gabion baskets amounted to 0.4 percent of the wall. While the mass was significantly greater for the stones, the embodied carbon was three orders of magnitudes less than that of the gabion baskets, allowing the gabion baskets to contribute the most embodied carbon. The embodied energy, however was only one order of magnitude less, and considering the mass of the stone, the stone just edged out the embodied energy of the of the gabion baskets.

To further understand the contribution from each material to the total cradle-to-factory gate CED for each wall type, the data was normalized. Three of the four wall types showed a

greater contribution from the man-made materials toward the total embodied carbon. However, this was not the case for embodied energy—the greatest contribution toward embodied energy came from the man-made materials for both the gravity retaining wall and the geotextile wrap-around wall. The concrete used in the gravity retaining wall design had the greatest contribution toward the total CED in terms of both embodied carbon and embodied energy. In the case of the MSE wall, the backfill was the greatest contributor both to the embodied carbon as well as the embodied energy for the wall, contributing more than 60 percent of the total CED. The gabion wall was a unique case in the comparison of man-made materials versus earthen materials—the greatest contributor to embodied carbon or embodied energy is not consistently from the same material. On the one hand, the stone for the gabions (an earthen material) contributes the most toward embodied energy. On the other, the gabion baskets (a man-made material made from galvanized steel) contribute the most toward embodied carbon. In the case of the geotextile wrap-around wall, the geotextile was the largest contributor toward embodied carbon as well as embodied energy. Separating the man-made materials from the earthen materials showed how the collective group of materials contributed toward the LCA. The man-made materials contributed the greatest amount of embodied carbon while the earthen materials contributed the greatest amount of embodied energy.

The life cycle cost (LCC) was performed to determine the true cost of construction of the retaining wall over its life cycle. The total financial cost for each wall was determined using traditional construction costing estimates from cradle-to-factory gate. As mentioned in Section 5.1.2, equipment requirements (distance traveled, idle time, etc.) were too varied to

account for factory gate-to-installation. Additionally, too little data exists to accurately estimate the cost of maintenance over the lifespan, the length of the lifespan, and the demolition costs of the wall. The concrete gravity retaining wall is the most expensive wall, followed by the gabion wall. The geotextile wrap-around wall and the MSE wall have very similar costs associated with the materials required for construction.

In observing the results from the CED study as well as the total construction expense, it can be seen that the geotextile wrap-around wall outperforms the other wall alternatives in each category. A comparable benefits-to-cost ratio was determined assuming the geotextile wrap-around wall had a typical expected lifespan of 75 years. Based on finances alone, the MSE would have a comparable lifespan as the geotextile wrap-around wall, and the gravity retaining wall and gabion wall were estimated to require a life of nearly 400 years and 300 years, respectively, to have the same BCR as the other alternatives. Similarly, to have the same BCR in terms of embodied carbon or embodied energy, the concrete wall would have to have a life of nearly 1,370 years and 1,770 years, respectively, and the MSE and gabion walls would need to last between 240 to 850 years.

Based on the extensive required lifespans of each wall alternative compared with that of the wrap-around wall for the cradle-to-factory gate and installation (cost only) phases, the cost for the installation (embodied carbon and embodied energy), maintenance, and end-of-life phases would need to be huge to reduce the required lifespan of the walls for an equivalent BCR to the wrap-around wall.

6.2 Discussion and Conclusion

The majority of the materials analyzed functioned as reinforcement, drainage, and/or filtration, with only five geosynthetics involving separation applications. From the 2011 GRI conference, it was apparent that the focus of geosynthetic sustainability is not distributed evenly across the four functions, and more focus should be applied toward geosynthetics involving separation, depending on the market demand for materials of that function. Additionally, the source of data generally appeared to be from one solitary source which may allow for consistency between studies does not contribute to a study's specific needs geographically. Boundary conditions were limited by "cradle-to-factory gate," "cradle-to-installation," or solely installation of the system, neglecting the end of life consequences. While these applications have some relevance in research applications in order to examine a portion of the whole, they are not complete, and could neglect the most important part(s) of the life cycle. Additional work should focus on these portions of the life cycle.

Several assumptions were made in selecting the materials for each wall design. The first assumption was four roller passes were required for all backfill compaction efforts – this is not reasonable for general use as many different types of compaction equipment are available and may work better in small spaces including that behind a wall, though assumed similar life cycle and cost benefits/savings across the board. Additionally, more or fewer than four passes may be required, depending on efficiency of the equipment. The second overarching assumption was based on the need to simplify the composition for several geosynthetics based on availability of data for the composition of the geosynthetic as well as the availability of data for carbon/energy analyses.

Unfortunately, using generic data may not represent industry-wide practices but was used for this comparative study. As such, to evaluate the amount of embodied carbon and embodied energy in a gravity wall, one must first consider changing the materials used in the wall. The best way to swap materials for function is to change the type of material. By changing one material in each wall, the data can once again be normalized as before, and the contributions from each material to the whole of the wall can be observed. Additionally, the overall embodied carbon and embodied energy may increase or reduce. By changing multiple materials, perhaps one with greater embodied carbon than its predecessor but works better with other materials with lower embodied carbon, it may produce a wall with ultimately less embodied carbon overall. These adjustments are crucial to minimize emissions that result from wall construction. However, this study was limited by data availability for geosynthetics, and many LCI databases do not directly include geosynthetics, and was therefore performed as a comparative study using publicly available resources.

The original purpose of subdividing each material by function was to see where each geosynthetic material might be swapped out based on their function with an earthen material that might perform better in an LCA, and vice versa. Unfortunately, too little data exists to accurately estimate the cost of maintenance over the lifespan, the length of the lifespan, and the demolition costs of the wall. The costs associated with the wall include both environmental and financial consequences. Without data for the expected lifespan of these walls, the benefit/cost ratio (BCR) could not be determined outright.

It is anticipated that traditional retaining walls do not require additional energy input to maintain, and therefore do not output energy other than their embodied energy, which was discussed in the cradle-to-factory gate section. Since this thesis serves as a preliminary study which utilizes generic data, the impact assessment cannot be performed It would be a difficult and painstaking process to determine the lifespan of a wall based on case studies, and would require efforts to aggregate data based on material, local, or global failures, as well as to date existing structures that have not yet failed or have been replaced.

Several contradicting theories have been made about the end life of geosynthetics—while some argue for recycling, others point out that it's not a viable option. Most debate stems from the fact that not very many geotechnical structures have been demolished and so there is little data to support either argument. A typical argument for using geosynthetics is not only the intent of reducing the total amount of material required within a system but to ultimately be recycled at the end of the system's usable life, but much of this material may become wasted and dumped.

Because this thesis may be considered a preliminary LCA, it does not require an LCIA which should be performed on a more project-specific case study with fewer variables.

The purpose of this thesis was to develop and demonstrate a methodology to determine the best outcome in a systems approach analyzing cost, emissions, and lifetime of traditional soil remediation with geosynthetic materials. This was accomplished by determining the cost and emissions for the cradle-to-factory gate phase, the cost and equivalent man-hours required

for the installation phase, and the equivalent lifespan considering cost and emissions for four retaining wall alternatives. In general, the use of geosynthetics resulted in a more sustainable and cost-effective wall design.

While portions of an LCA were not included in this study, the overarching conclusion determined that a geotextile-wrap around retaining wall outperformed the other retaining wall options on every level, despite being incomplete. It should be recognized that while the MSE wall and the wrap-around wall require nearly equal costs and time for construction, the MSE wall is the more frequently used in real-world applications likely due to the appearance of the façade. If, however, the need for more sustainable construction becomes the deciding factor, a stakeholder may overlook façade in favor of the wrap-around wall. Additionally, if processes for transportation and installation were predictable and indicative of the output of emissions, if maintenance and end-of-life activities were dependent on the material composition of the wall, and if retaining walls lasted up to 1,800 years, perhaps the results of this discussion would vary.

6.3 Recommendations for Future Work

Current research is very inconsistent within its methodology with regards to life cycle assessment—most perform simpler sustainability assessments such as carbon footprinting or embodied carbon analyses, for example. Additionally, the source of data generally appears to be from one solitary source which, although it may allow for consistency between studies, does not contribute to a study's specific needs geographically. Finally, these studies are

limited by their boundary conditions such that a study may establish that it is performing a life cycle assessment, yet disregard the life of the geosynthetic after installation.

However, several barriers exist which do not allow for a complete LCA, including data availability as well as variability based on design. By utilizing the tools currently available, geosynthetics can be analyzed either broadly or narrowly, but not completely in terms of a true LCA.

While geotextiles are considered proprietary, database resources including the ICE from the University of Bath should be kept up to date and re-evaluated frequently in order to best estimate the sustainability of materials currently in production. At the time of preparing this thesis, this widely used resource was most recently updated in 2011. Should such resources remain stagnant, they will become obsolete in the developing world of geotextiles.

Additional work should be performed to analyze the effect of transportation of materials from factory-gate to installation depending on fuel economy, quantity or weight of materials, and mode of transportation, as discussed in the sensitivity analysis portion of this thesis. The results of such an analysis could help determine the most sustainable material chosen for the function within the wall (separation, reinforcement, filtration, and drainage), and therefore improve the overall sustainability of the wall.

Work should also be considered to collect data for the typical lifespan of a wall, and segregate the data based on end of life due to global/local stability failures and material failures. If a retaining wall has not yet failed, maintenance needs to be documented, and its lifespan recorded and/or projected before its end-of-life. Finally, end-of-life activities pertaining to recycling or reuse of materials should be documented to better predict the likelihood for more sustainable end-of-life procedures.

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