MATERIAL QUANTITIES OF FOUNDATION SYSTEMS IN BUILDING STRUCTURES

by

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B.Sc. in Civil and Environmental Engineering
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Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of

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ABSTRACT

There are three major areas in which buildings consume energy: (1) energy consumption from operational processes, such as heating and electricity, (2) energy from building material production and supply, and (3) energy from design and construction processes. In recent years, improved operational energy efficiency has shifted the framework for quantifying a building's energy consumption to a total life-cycle approach, which includes energy consumed in the design and construction phases, also known as the embodied energy. Researchers and industry professionals are in the early stages of developing methods and metrics to quantify embodied energy of buildings, particularly focused on building superstructure. To date, no extensive studies have been performed on the material quantities of foundation systems in building structures or their environmental impact. This thesis answers the key question: "How much do foundation systems contribute to the overall material quantities of buildings, and do foundation systems significantly contribute to the overall embodied energy?"

Two methods are used to address these questions. First, an analysis was performed on a survey of building materials using a database of embodied energy recently developed at MIT. The database contains information on material quantities of foundation systems from 200 actual buildings. Second, a case study was analyzed in an attempt to evaluate gaps in the database.

Ultimately this thesis is intended to provide preliminary benchmarks for material quantities and embodied energy of foundation systems in buildings. The findings in this study show that foundation systems contribute approximately 25% to a building's total weight and contribute nearly the same percent to the building's overall embodied energy. In addition it provides architects, engineers, contractors, and building owners with information related to the sustainability of building structures.

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1.0 INTRODUCTION

1.1 Motivation

"Reduce, Reuse, Recycle" is known to most as the slogan of environmental sustainability since its popularization in April 1970 during the inauguration of Earth Day (Lewis, 1985). What many people don't know is that "Reduce, Reuse, Recycle" is more than a slogan, it's a hierarchy. Reducing consumptions of resources is the utmost important practice in building a more sustainable society. With increasing concerns about rising CO_2 emissions and their environmental impacts, society is becoming pressed to find any and all areas where CO_2 and other greenhouse gases can be reduced. With buildings accounting for 46.7% of all CO_2 emissions in United States, it is an obvious sector to explore opportunities for CO_2 emission reduction (Danson, 2013).

Life-cycle assessment (LCA) is a powerful tool for evaluating CO_2 emissions from buildings because it identifies the resource flows and environmental impacts at every stage of a building's life (Horne, 2009). Using this approach, the emission sources of buildings are most easily analyzed if they are split into categories. Three logical subdivisions of emission sources in buildings are (1) operation processes, such as heating and electricity consumption, (2) emissions from building material production and supply, and (3) emissions from construction processes. In recent decades, substantial efforts have been made in the operational efficiency of buildings, which has significantly lowered the level of operational CO_2 emissions from buildings. By 2008, 37 states and territories in the U.S. had commercial codes which put restrictions on buildings' operational energy consumption (Building Technology Program, 2008). The reduction of operational emissions of buildings has shifted the importance to the material and construction phase emissions (often referred to as the "embodied carbon" of a structure), particularly in short-lifespan buildings. More recently, there has been an uptick in research related to embodied carbon from building materials, but universal design tools and rating systems are still in an early-development stage.

The need for reducing greenhouse gas emissions has never been higher. According to the United States Environmental Protection Agency in 2014, the U.S. emitted more greenhouse gas then every country but China totaling 6,873 million metric tons of CO_2 which accounted for approximately 15.6% of global greenhouse gas emissions (United States EPA, February, 2016). With more evidence linking greenhouse gas emissions to adverse effects of our Earth, such as global warming, increased volatility of weather patterns, and rising ocean levels, reduction of CO_2 should be considered wherever possible. With this in mind, designers of buildings should consider the effects their designs have on carbon emissions. Until now, no extensive studies have been performed on the material quantities of foundation systems in building structures or their environmental impact. The design of foundation systems is just one aspect of many in the construction industry where carbon emission reductions should be considered.

The success of this thesis will not be measured in obtaining accurate and defensible values for material quantities and embodied carbon of foundation systems. It aims to give designers a high-level intuition on the impacts of design decisions for foundation systems. If nothing else, the goal of this thesis is to continue the dialogue between architects, engineers, contractors, and owners, about the sustainability of buildings, so that they ask themselves, "can we do better?"

1.2 Problem Statement

The amount of publically available information on foundation system's material quantities is thin. The aim of this thesis is to build literacy on the material quantities in foundation systems of buildings and their environmental impact. Material quantities of foundation systems is a relatively defensible metric to analysis, as they can be easily measured in units of mass, weight or volume; however, quantifying a foundation system's environmental impact is less concrete. Typically applications of LCA in buildings use a metric called embodied energy to quantify the environmental impacts. Embodied energy is energy consumed by all processes associated with the mining, processing, transportation, construction, and demolition of the building's materials (Horne, 2009). Although this is useful in evaluating environmental impact in terms of energy consumption, it does not accurately quantify the level of CO_2 or other greenhouse gas emissions. The same amount of embodied energy can emit different intensities of greenhouse gases depending on the energy source and the material's manufacturing processes (De Wolf, 2014). In an effort to more accurately account for emissions of CO_2 and other greenhouse gases, leaders in building material manufacturing have introduced the concept of embodied carbon (EC), which considers the greenhouse gases emitted from building materials.

Using the above mentioned metrics and framework, this thesis will address the following questions:

1.) How much do foundation systems contribute to the overall material quantities, EE, and EC of a building? Are there benchmarks that designers can use to evaluate their designs?
2.) Do foundation systems significantly contribute to the overall EE/EC of a building structure?
3.) What buildings have the most efficient foundation systems? Are there techniques that buildings designers could implement to reduce material quantities of foundation systems?

It should be noted that this thesis is being completed in conjunction with MIT's Database of Material Quantity Outputs (deQo) spearheaded by Catherine De Wolf (De Wolf, 2014). As such, the contributions of this thesis are meant to supplement the ongoing work at MIT's Building Technology Lab and the deQo. Specifically the deQo aims to "define the challenges and opportunities in obtaining the material quantities and estimating the embodied carbon" of foundation systems.

1.3 Definition of concepts

In order to make a fair, unbiased assessment of foundation systems' material quantities and their embodied carbon contributions, clearly defined assumptions and boundaries need to be established. There are two areas where boundaries and assumptions need to be defined, (1) boundaries for interpreting material quantities of foundations, and (2) boundaries for EE/EC calculations. The following sections describe the assumptions and the boundaries used in this thesis.

1.3.1 Boundaries and assumptions for interpreting material quantities

Design and construction of foundation systems is an involved process. Foundation system design takes into consideration three main factors, (1) the magnitude and orientation of load exerted by the structure, (2) the underlying geology on which the structure stands, and (3) a project-specific allowable settlement. To perform a complete and fair comparison between individual projects, all three factors should be considered. Currently there are no tools or frameworks to assess material quantities of foundation system in this context, and publically available project-specific information on the three factors of foundation design is sparse. The creation of the deQo provides a new opportunity to begin studying the material quantities of foundation systems in a broad context. The database contains information on material quantities for a wide array of building types. From the database, many interpretations of material quantities in foundation systems can be made. However, currently the database does not contain information on project-specific geology or allowable settlement. Due to these limitations, interpretations of the material quantities from the database should be considered an average for all geologic settings and settlement.

In addition, material quantities of foundation systems in this thesis only consider structural materials. Structural materials consist of unnatural manufactured products such as concrete, rebar, and steel that are primarily used to support the building. Most foundation systems also involve the use of earth materials, such as soil, and other materials, such as waterproofing membranes, these products were not considered in this thesis due to the lack of available information. Only structural materials, which consist of concrete and steel were evaluated regarding quantities.

1.3.2 Boundaries and assumptions for EE/EC calculations

The design community lacks a consensus on an appropriate method for calculating EE/EC coefficients of materials. There are multiple organizations that provide EE/EC coefficients that allow for an easy conversion from a material quantity to its equivalent EE/ EC. The most widely accepted coefficients are those of the Inventory of Carbon and Energy (ICE) developed by the University of Bath. To remain consistent with the coefficients used in the deQo, calculations of EE/EC in this report also utilize the ICE coefficients shown in Table 1-1 below.

Table 1-1: *Embodied Energy (EE) and Embodied Carbon (EC) coefficients (Hammond & Jones, 2008)*

Material		Embodied Energy Coefficients (EEC)	Embodied Carbon Coefficients (ECC)
	Unit:	mJ/kg	Kg COe_2/kg
Concrete	Normal Strength Concrete[1]	0.95	0.130
	Mid-Strength Concrete[2]	1.11	0.159
	High Strength Concrete[3]	1.39	0.206
Steel	Steel Reinforcing[4]	0.26	0.180
	General Steel	25.7	1.77
	Predominately Recycled Steel[5]	13.6	1.77
Aggregate	General Aggregate	0.1	0.005

The boundary conditions related to the calculation of the EE/EC coefficients are explained in detail in the ICE database; however, some boundary conditions should be noted for the context of this thesis. Firstly, the EE/EC coefficients are considered a partial-product life cycle assessment from the manufacturer (cradle) to the factory gate, known as the "cradle-to-gate" boundary condition. This method accounts for all energy (in primary form) until it leaves the factory gate (Hammond & Jones, 2008). Based on ICE's assessment, this approach is meaningful for high-energy materials, such as concrete and steel, because impacts from the missing transportation and energy source data are considered to be negligible. Second, the coefficients convert material mass (kg) into equivalent millijoules (mJ) of embodied energy and kilograms of COe_2 (kg COe_2), where kg COe_2 represents the

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[1] Normal Strength Concrete: <4,000 psi compressive strength

[2] Mid-Strength Concrete: 4,001-5,999 psi compressive strength

[3] High Strength Concrete: >6,000 psi compressive strength

[4] Steel reinforcing coefficients are for every 25kg of steel/m^3 of concrete

[5] Predominately Recycled Steel: >50% recycled content

mass of all greenhouse gases in terms of equivalent kg CO_2. Lastly, the ICE uses the recycled content approach for recycled metals. This method should not be confused with the substitution method, which is cited by many metal manufactures. Unlike the substitution method, the recycled content approach credits the use of recycled materials in the product rather than crediting its recyclability. For instance, in the case of steel shown in Table 1-1, the "predominately recycled steel" represents incoming steel to the project that has a recycled content of 50% or more.

1.4 Organization of thesis

The following sections aim to answer the questions summarized in the problem statement; however, the results presented in this thesis are equivocal without context. Section 2 provides background information on foundation design for readers who are unfamiliar with the practice. Additionally, Section 2.0 includes a literature review of work others have performed related to the environmental impacts of foundation systems.

Section 3.0 describes the methodology used to determine benchmarks for the material quantities of foundation systems. It will describe the deQo analysis and present a case study, both of which are used to create foundation system benchmarks.

Section 4.0 and 5.0 present the results. The results are shown in three different categories. First, in Section 4.0, overall results are presented from the database. Then filtered database results are presented by market sector and building type. In Section 5.0, the case study is described in detail, followed by the results, which relate the results in Section 4.0 to a particular geology.

Lastly, the conclusion will summarize and interpret the results, and discuss how they can be used. Additionally the conclusion will describe the future work to be completed in the field, and highlight the opportunities that exist.

2.0 CURRENT STATE OF PRACTICE

2.1 Foundation systems and ground-structure interaction

All permanent building structures are, in some way, supported by the surrounding or underlying earth. The foundation systems, which transmit the loads from the structure to the ground, are designed to distribute the loads to the ground in a manner that meets the objectives of the structure it supports. Depending on the structure and the geologic conditions surrounding the structure, there are many foundation systems that are commonly used in practice. Design of foundation systems can vary widely not only based the local geology and structural demands, but also due to regional design practices, and individual project constraints. However, foundation systems are generally classified in two categories (1) shallow foundations, and (2) deep foundations. Foundation contractors and engineers often differ on terminology and definitions of the foundation systems. The following sections provide brief overviews of the basic concepts of foundation design using widely accepted terminology and definitions.

2.1.1 Shallow foundations

Shallow foundations, otherwise known as bases, footings, spread footings, and mats, are systems that take concentrated loads (typically from vertical columns) and spread them laterally so that stresses and strains below the foundation do not exceed strength limitations or deformation requirements. Figure 2-1 below shows a typical isolated shallow foundation cross-section with a column load, defined as P.

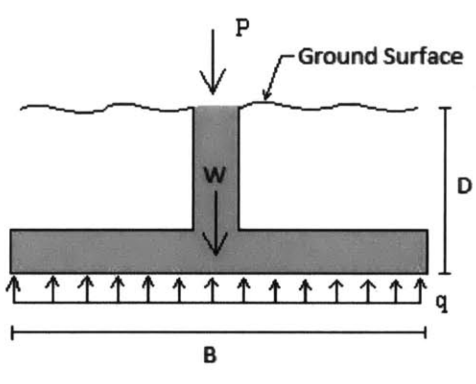

Figure 2-1: *Typical shallow foundations cross-section*

The distributed stress q is calculated by $q = (P + W)/B$, where P (in units of force/length) is the vertical column load, and W (in units of force/length) is the self-weight of the foundation material.

In simplified terms, foundation design consists of determining an allowable soil bearing pressure and the required dimension of B so that q is at a safe stress level and limits settlement to an acceptable amount.

In general foundation engineering practice, shallow foundations are defined by the embedment depth, or the ratio of D/B as shown in Figure 2-2. Typically, shallow foundations are defined by $D/B \leq 1$, but occasionally can be greater (Bowles, 1988).

2.1.2 Deep foundations

Similar to shallow foundations, deep foundations distribute concentrated loads to the underlying ground. However, unlike shallow foundations, they generally distribute the load vertically and laterally. They are typically used when soil near the ground surface is insufficient to support shallow foundations. Deep foundations are most commonly referred to as piers, caissons, or piles and can either be drilled or driven. Figure 2-2 shows a typical deep foundation cross-section with a column load of P.

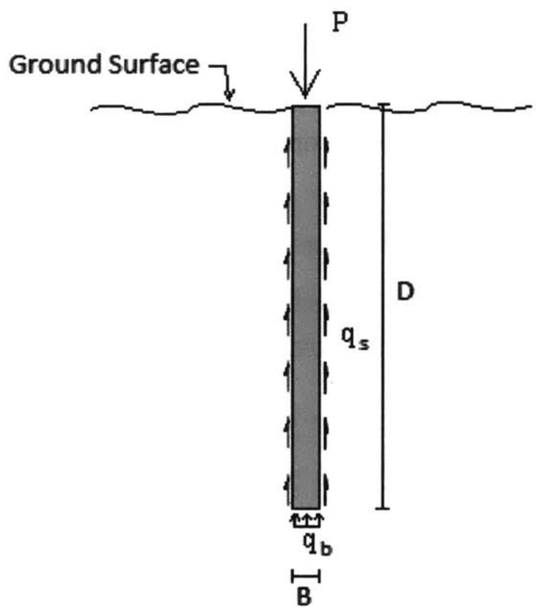

Figure 2-2: *Typical deep foundation cross-section*

The distributed stresses q_s and q_b are induced by the column load, P (in units of force). Determining allowable q_s and q_b is much more complicated than with shallow foundation, however the same basic principles apply. Pile geometry (D and B) is designed so that q_s and q_b are at a safe stress level and limits settlement to an acceptable amount. Typically deep foundations geometry consists of foundation systems where $D/B \geq 4$, but more typically the embedment ratio is much greater than four (Bowles, 1988).

2.1.3 Ground improvement methods

Ground improvement is the practice of changing the physical properties of soil so that shallow foundations for structures can be used rather than deep foundations. There are a many ground improvement techniques used on "soft" ground. The different techniques largely depend on the type of ground and the desired result. It should be noted that ground improvement techniques result in the use of materials that are rarely considered part of the structural system.

2.2 Literature review

Research related to the material quantities, and the embodied carbon, of foundation systems is scant. Although many contractors, construction estimators, engineers, and building developers have a sense of material quantities for foundation systems given a building schematic and site conditions, there is a lack of publically available data. The following sections provide a summary of the available publications related to the material quantities and embodied carbon of foundation systems.

2.2.1 Ground Improvements for a Sustainable World

At the 2008 American Society of Civil Engineers' GeoCongress, a group from Menard, a design-build geotechnical specialty contractor, published three case studies comparing the embodied carbon of traditional foundation systems to ground improvement methods. In essence, ground improvement techniques increase the soil's allowable bearing capacity, rather than changing the foundation systems in order to achieve a sufficiently distributed stress [q] (Spaulding, Masse, & LaBrozzi, 2008).

In their paper, the authors evaluate three sites where ground improvement technologies were proposed after an initial traditional foundation design was complete. Using initial design concepts and their experience in foundation construction, the authors were able to calculate estimated carbon emissions from the alternative foundation system and compare the results to the carbon emissions data they collected during ground improvement construction. They considered both emissions from material production and supply, defined as direct emissions, and emissions from foundation installation, such as equipment operations, defined as indirect emissions. By making some assumptions about construction techniques, they were able to approximate the direct and indirect embodied carbon. Exact calculations for the embodied carbon of the foundations were not included in the study; however, the authors describe the calculations as using "recognized carbon emission...values for both direct and indirect emissions." Each case study includes a description of the aspects that were included in the carbon emissions calculation. Generally, they included the carbon emissions from material quantities (direct) and emissions from the construction equipment (indirect). No other sources of carbon emissions were used in the study (Spaulding, Masse, & LaBrozzi, 2008).

Results of the three case studies showed that use of ground improvement technology significantly reduces the carbon emissions at the foundation construction stages. Based on their calculation, embodied carbon was decreased by 200% to 1,450% by using ground improvement technology. Although this only represents three specific sites out of the thousands of new buildings that are constructed every year, it demonstrates that altering the foundation systems can produce significantly different carbon emissions (Spaulding, Masse, & LaBrozzi, 2008).

2.2.2 Environmental emissions at foundation construction stage of buildings – Two case studies

This paper uses two case studies to develop a model to estimate and compare CO_2 emissions at the foundation construction stage of buildings. The authors' objective of the paper is to estimate and compare the different sources of CO_2 emissions during the foundation construction phase of buildings. Similar to *Ground Improvements for a Sustainable World,* the case study considers embodied carbon of materials, transportation, and equipment usage. Both of the cases presented in the study were high-rise residential buildings; however, one was constructed with a raft foundation (shallow foundation system) and one was constructed on pile foundations (deep foundation system). The same contractors were employed for both of the case study projects so that construction performance and management could be assumed equal; however the construction methods and material quantities vary drastically between the two projects. The materials used for both cases were primarily concrete and steel reinforcing. Other materials used in the projects such as earth materials and formwork were not considered in the calculation (Sandanayake, Zhang, & Setunge, 2015).

Based on the results of the paper, emissions from materials govern the overall embodied carbon of foundation systems. Both cases demonstrated that materials accounted for 66-67% of the carbon emissions and equipment usage and transportation accounted for approximately 18-19% and 14-16% respectively, as shown in Figure 2-3 (Sandanayake, Zhang, & Setunge, 2015).

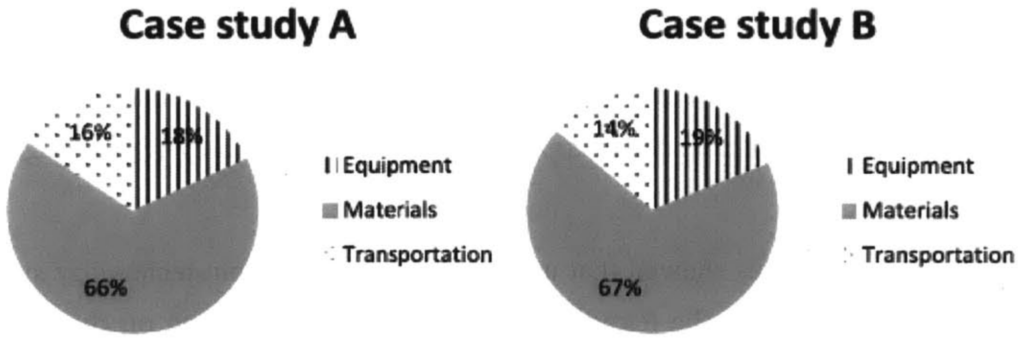

Figure 2-3: *Greenhouse gas emission distribution for both case studies (Sandanayake, Zhang, & Setunge, 2015)*

This paper demonstrates that focus on the material quantities of foundation systems is an effective tool in reducing the total embodied carbon. In addition, it shows that reducing material quantities of foundations also reduces the emissions from the equipment usage and transportation stages of foundation construction. CO_2 emissions from foundation materials in Case Study A and Case Study B were reported as 1,058 metric tons and 662 metric tons, respectively. Comparing the two case studies, Case Study B emitted approximately 37% less CO_2 from materials when compared to Case Study A. Similar CO_2 emission reduction values were reported between Case Studies A and B for equipment usage and transportation, and were reported as a 36% reduction for equipment usage, and 46% reduction for transportation. This demonstrates that reducing material quantities of foundation systems is related to the CO_2 emissions from foundation construction processes (Sandanayake, Zhang, & Setunge, 2015).

3.0 METHODOLOGY

This thesis uses two approaches to understand the material quantities of foundation systems. First, a statistical analysis is performed on a sample of 200 buildings from the deQo. The second part of this thesis attempts to relate the effect of geology on the material quantities of foundation systems. Detailed descriptions of the two methods are discussed below.

3.1 deQo analysis of existing buildings' foundation systems

3.1.1 Description of database

The deQo is a collaborative collection of building information for construction projects from around the world. The database provides a platform for architects, engineers, and other stakeholders to share information about their designs, so that a wide-reaching comparison of material quantities and embodied carbon of buildings can be performed. The data are compiled from Building Information Models (BIM) from several leading international architectural and structural engineering firms. The database relies on voluntary input from the industry and sets universal rules for boundary conditions to allow one to make meaningful comparison and statistical analyses of buildings (De Wolf, 2014).

Although the deQo is still in the early stages of development, it contains information on hundreds of buildings constructed from 2011 to 2015. For the analyses of foundation systems, projects with detailed information about a building's substructure were needed. At the time of this writing, the database contained approximately 200 buildings with information on substructure including data on material type and quantities of foundation systems that were either under construction or completed and in-use. Some of the projects in the database were reported to be in the "design" phase. These projects were not included in the analysis because of the uncertainty related to design changes affecting the material quantities. These 200 hundred projects were used in the analysis, and consisted of a wide variety of buildings from many market sectors and from regions around the world.

3.1.2 Interpretation of the data

The building sample used in this analysis has its advantages and disadvantages. One advantage is that the sample of buildings is diverse. The data analyzed contain information on buildings of different shapes and sizes, found around the world, with presumably different underlying geology, and across a wide array of market sectors, which typically dictate the allowable settlement. This diversity creates meaningful statistical averages and limits the impact of biases. However, without having data on geology, and allowable settlement, systematic differences in geology and allowable settlement cannot be addressed. For instance, if a disproportionate number of the projects analyzed were constructed on geologic settings that are advantageous for foundation systems, the calculated average material quantity of the foundations in the database would not be representative.

One bias that is known is the size of the projects. Small projects, such as single-family homes, were not represented in the sample. This is due to the size of the firms that contribute to the deQo database. To date, the contributing firms are large international structural engineering organizations, which tend to work primarily on large scale projects.

Understanding the variation in the data is not only important for interpreting the data, but for comparisons to benchmarks. When comparing a building's foundation material quantity to the benchmark, interpretation is needed for projects with atypical geology or allowable settlement. In an attempt to portray the differences between individual projects, the analyses use box-and-whisker and scatter plots to facilitate the visualization of the ranges, outliers, minima and maxima, and trends. Additionally the projects were sorted into many categories and analyzed separately, so that systematic differences between buildings have a reduced effect. Figure 3-1 depicts box-and-whisker plots with their graphic definitions and the configuration of the displayed values.

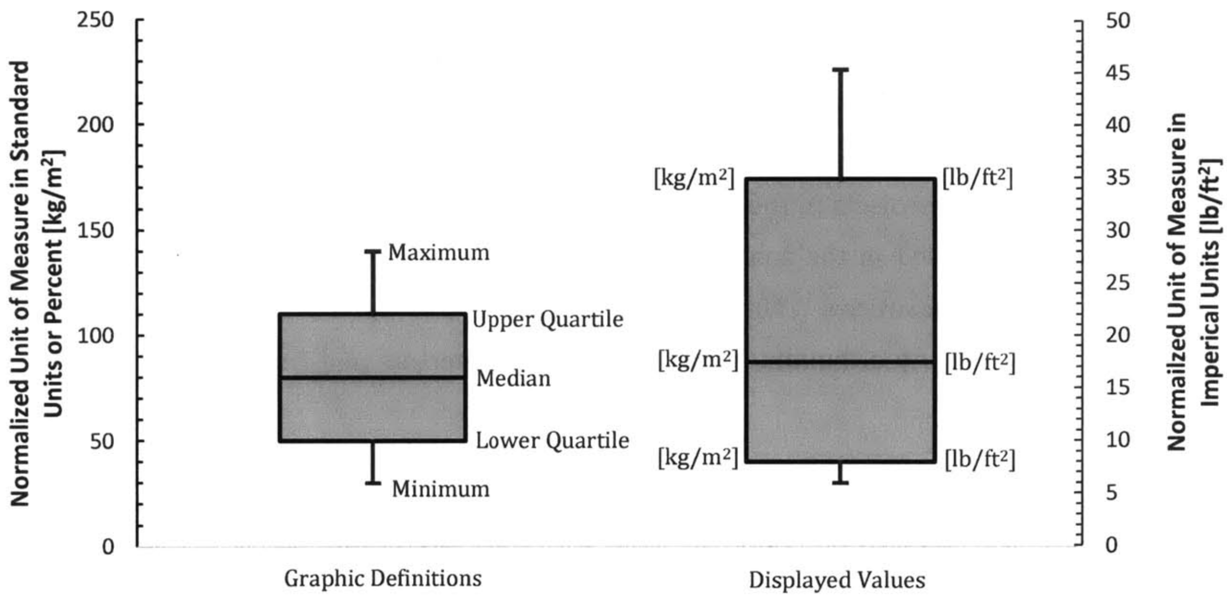

Figure 3-1: *Box-and-whisker plot graphic definitions and displayed values*

3.1.3 Description of calculations

In order to make meaningful comparisons between material quantities of foundation systems, the individual project needs to be normalized by a functional unit[6]. There are many functional units that could be used to describe a building's use, such as gross floor area (GFA[7]), or number of people it holds. This thesis normalizes material quantities of the buildings by their GFA. However, since the foundation system is one portion of the entire building system, it is also important to understand what percent of a building's material is utilized in the foundation system.

The predominant material used for building foundations is reinforced concrete; however, there were several projects that utilize foundation elements such as steel piles. No other materials besides concrete and steel were listed in the database for foundation elements. If foundation systems contained multiple components with different materials they were listed as separate line items (i.e. foundation walls, steel piles, caissons etc.). Each line item described the raw material, its use, and the quantity of the material. To normalize foundation material (NFM), the sum of the raw material quantity for reinforcing bars (RB), concrete (C), and steel (S) for each foundation component was considered and calculated as follows:

$$NFM\left[\frac{kg}{m^2}\right] = \frac{\sum RB\,[kg] + \sum C\,[kg] + \sum S\,[kg]}{GFA\,[m^2]}$$

In order to calculate an accurate percentage of the EE/EC contribution from the foundation system, the same method for calculating EE/EC that was utilized for the total building EE/EC values reported in the deQo needs to be applied. EE/EC values in the deQo were calculated using the ICE coefficients for the entire building. Using the coefficients in Table 1-1, the following equation was used to calculate EC/EE values in accordance with the ICE guidelines:

$$EE\,[mJ] = \sum C_i\,[kg] * (\,EEC_i[\frac{mJ}{kg}] + EEC_r[\frac{mJ}{kg}] * \frac{RB\left[\frac{kg}{m^3\ of\ concrete}\right]}{25\left[\frac{kg}{m^3\ of\ concrete}\right]}) + \sum S_i * EEC_s$$

Where: C_i = Raw material quantity of concrete for each concrete strength i (in units of kg)

RB = Raw material quantity of steel reinforcing (in units of $\frac{\text{kg}}{\text{m}^3\text{ of concrete}}$)

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[6] Functional Unit: A unit of measure which characterizes the quantity of a building's potential utilization.

[7] Gross Floor Area: Total floor area inside the building envelope.

S_i = Raw material quantity of steel with recycled content i (in units of kg)

$EECc_i$ = Embodied Energy Coefficient corresponding to the concrete strength (in units of $\frac{\text{mJ}}{\text{kg}}$)

EEC_r = Embodied Energy Coefficient for reinforcing (in units of $\frac{\text{mJ}}{\text{kg}}$)

$EECs_s$ = Embodied Energy Coefficient for Steel (in units of $\frac{\text{mJ}}{\text{kg}}$)

The same procedure was used for embodied carbon calculation by replacing the *EEC* coefficients with *ECC* (in units of $\frac{\text{kg of CO}_2}{\text{kg}}$).

3.2 Case study comparing materials quantities based on geology

As previously discussed, the underlying geology plays a major role in the material quantity of foundation systems. Since the deQo currently does not contain information related to the underlying geology of projects, a case study was selected as an attempt to understand the role geology has on the material quantity of foundation systems. In order to make a fair estimation of foundation quantities for different geologies, other variables need to be held constant. Originally this approach attempted to study the foundation systems of two identical buildings located on different geologies; however, finding two identical buildings located on different geologic settings proved to be a difficult task. Instead one long-span building was selected where the underlying geology varied significantly from one side of the building to the other. The case study, which is further described in Section 5.0, consists of a building, that is nearly identical along its length, and has varying underlying geology. This approach evaluated material quantities of the foundation system for this long-span building and compared the materials quantities to the underlying geology. The aim of this case study is to develop a relationship between geology and material quantities of foundation systems.

4.0 SURVEY OF EXISTING BUILDINGS' FOUNDATION SYSTEMS

The following sections summarize the results of the data analyzed from the deQo. The results are intended to lead to the benchmarks of material quantities in foundation systems. In addition, the results of the embodied energy and the embodied carbon are also presented to provide insight on the environmental impacts of foundation systems, and to understand the opportunities that foundation systems have in reducing CO_2 emissions.

The results are presented in metrics that architects, engineers, and contractors of foundation systems can use to make meaningful comparisons with their individual projects. First, data are displayed for all buildings in the survey. This is intended to provide the broadest benchmark of how foundations systems perform across the built environment. Second, the data are divided by market sector, so that buildings constructed with similar uses can be compared. This analysis was performed in an attempt to eliminate biases that may arise from different performance standards across market sectors. For example, educational buildings may generally have lower allowable settlement limit than buildings in other market sectors, so it would appropriate to have a specific benchmark for educational buildings so that an "apples-to-apples" comparison can be made. Third, the data were analyzed by building form. Building form was defined by the number of stories and the superstructure system (i.e. steel or concrete).

4.1 Results for all buildings surveyed

The results for all 200 buildings surveyed are presented in two forms. First, the data are displayed by the percent contribution of foundation system to the buildings' total weight, EE and EC, shown in Figure 4-1 below.

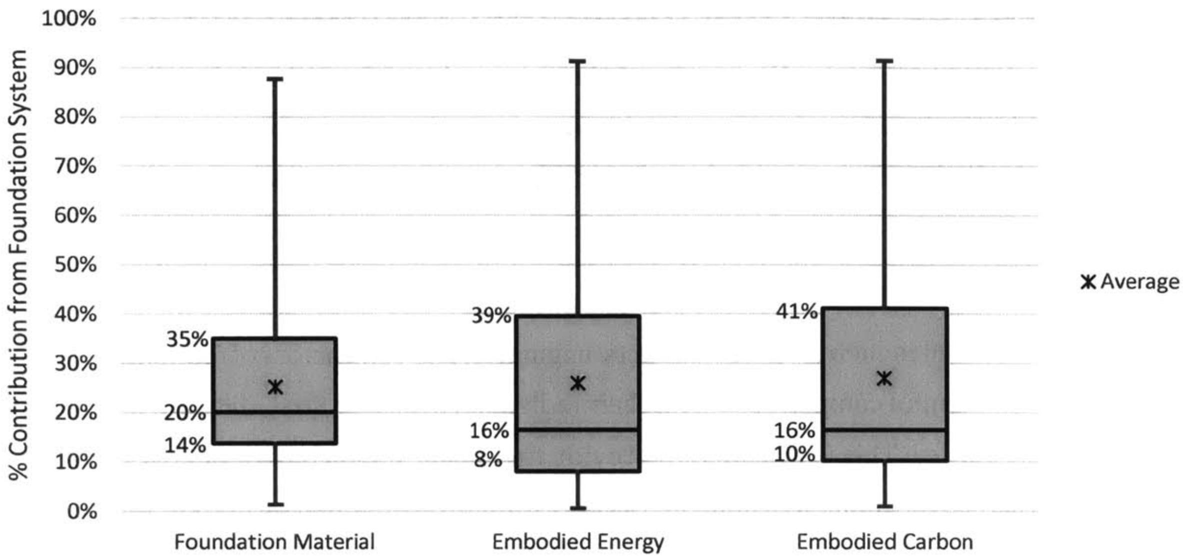


Figure 4-1: *Percent foundation material contributes to total building weight, EE, and EC for all buildings surveyed*

Based on the survey, the average foundation systems is 25.4% of a building's total weight. Average embodied energy and embodied carbon contributions from the foundation systems are 26.2% and 27.3% respectively, and values for the median, lower and upper quartiles are displayed to the left of the box plots. As illustrated in Figure 4-1, scatter in the data is large, with the percent of foundation material ranging from 1.8% to 87.7%; however, if outliers are removed from the data, the scatter reduces significantly. Ninety percent of the buildings surveyed have foundation systems that contribute between 7% and 48% to the total building weight.

Table 4-1 shows standard statistical values for material quantities of foundation systems for all buildings surveyed, normalized by GFA. Similar to Figure 4-1, scatter for normalized values is also large. The numbers below represent the statistical values for all buildings with outliers removed (90% building survey).

Table 4-1: *Standard statistical values for Normalized Foundation Material (NFM), Embodied Energy (NEE) and Carbon (NEC) for all buildings surveyed*

	NFM (kg/m^2)	NEE (mJ/m^2)	NEC ($KgCOe_2/m^2$)	NFM (lb/ft^2)	NEE (mJ/ft^2)	NEC ($lbCOe_2/ft^2$)
Average	292.0	1,406.0	170.3	59.9	130.7	15.8
Min	40.0	77.4	9.5	8.2	7.2	0.9
Median	219.2	550.4	76.6	44.9	51.2	7.1
Max	935.3	10,056.5	918.2	191.7	934.6	85.3

4.2 Results by market sector

The projects in the deQo were divided into market sectors. Classification of an individual project into a market sector was based on two primary criteria: (1) the project's intended use, and (2) the entity responsible for developing the project. Determining the market-sector classification for the individual projects was relatively clear for the majority of projects; however, there were a few projects where the market-sector classification was more ambiguous. For instance, an office building would, quite clearly, be classified as a commercial building, but a university dormitory is not as easily classified into a market sector. A university dormitory could arguable be classified in the residential market sector due to its use as a housing facility; however, the entity, that develops it is an educational institution, so it could also fit the definition for an educational building. For cases where the developing entity and the project's use were in conflict, priority was given to the developing entity. As such, in the case of the university dormitory example, the project was classified in the education market sector. Table 4-2 lists the market sectors analyzed and gives descriptions of typical buildings classified within the sector.

Table 4-2: *List of market sectors and description of typical buildings*

Market Sector	Description
Commercial	Office/retail buildings
Data Centers	Communication and computer server housing facilities
Education	Administrative, classroom, research, and student-activity university/college buildings, and primary and secondary educational buildings
Healthcare	Hospitals, urgent care centers, and health centers
Hospitality	Hotels, recreation and visitor centers
Residential	Condominium and apartment buildings

Additionally, there were some projects that did not fit into market sectors listed in Table 4-2. For instance, sports and entertainment facilities have unique uses that warrant a separate market sector category. If a market sector had less than 10 projects in the database, it was not included in this thesis because it was deemed not statistically relevant.

Figure 4-2 illustrates the percent contribution of the foundation systems to the building totals by market sector. The market sectors are shown on the horizontal axis, and the associated sample sizes are displayed in brackets.

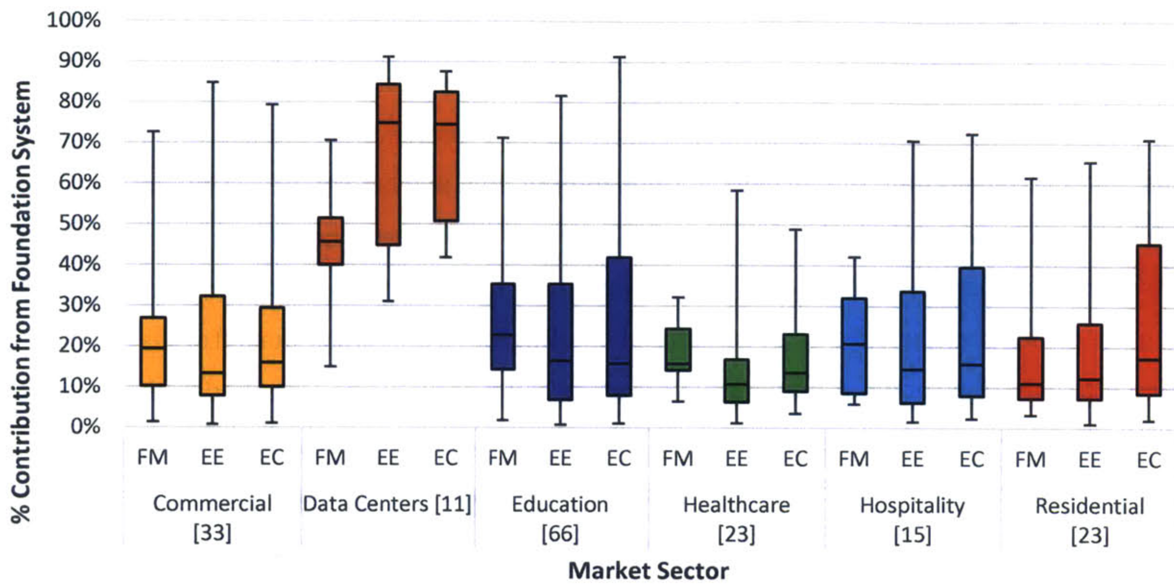


Figure 4-2: *Percent contribution of foundation system weight (FM), EE, and EC compared to building total by market sector*

A similar market-sector graphical representation is shown in Figure 4-3 but shows the NFM. This chart is not only useful as a benchmarking tool, but also could be used as a way to approximate foundation material for proposed projects. Values for the median, and lower and upper quartiles are displayed in kg/m², to the left of the box plots, and in lb/ft² to the right.

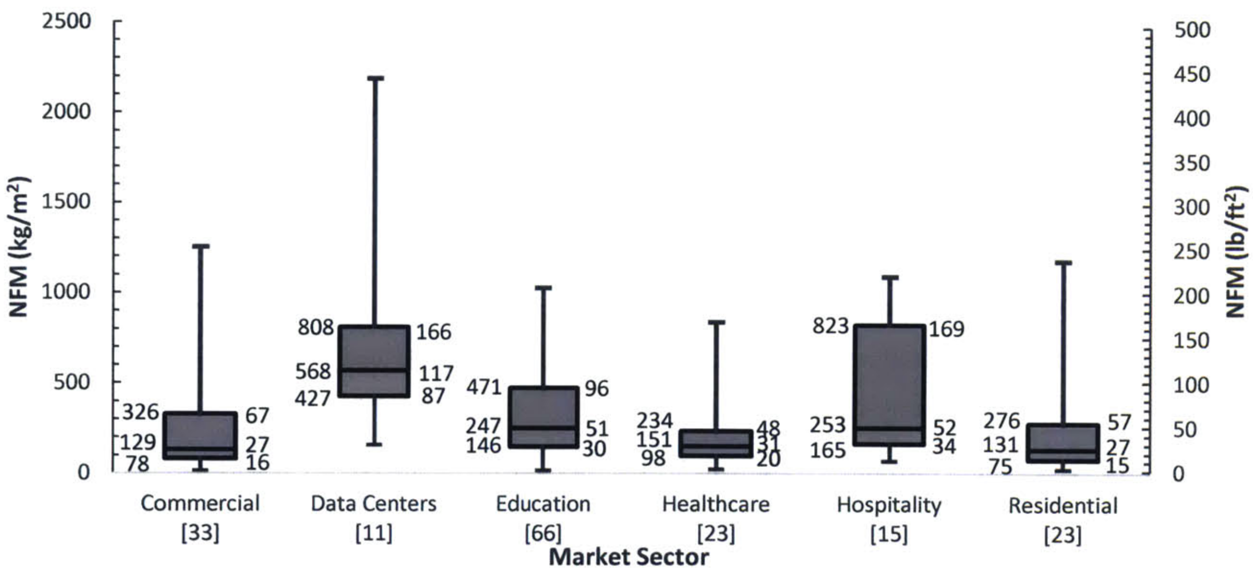


Figure 4-3: *Normalized Foundation Material (NFM) weight by market sector*

4.3 Results by building structural form

Another useful way to organize the data is by the structural systems or by the number of structural stories. Structural systems are defined as the primary material used for the superstructure. There are three categories listed in the database for structural systems: (1) concrete, (2) steel, and (3) composite, where composite systems utilize both concrete and steel as primary members in the superstructure. Figure 4-4 and Figure 4-5 illustrate the percent contribution of the foundation systems to the buildings' total weight, EE and EC, and the NFM by structural system. The structural systems are shown on the horizontal axis, and the associated sample sizes are displayed in the brackets. Values for the median, and lower and upper quartiles for percent and kg/m² are displayed to the left of the box plots, and lb/ft² are displayed to the right.

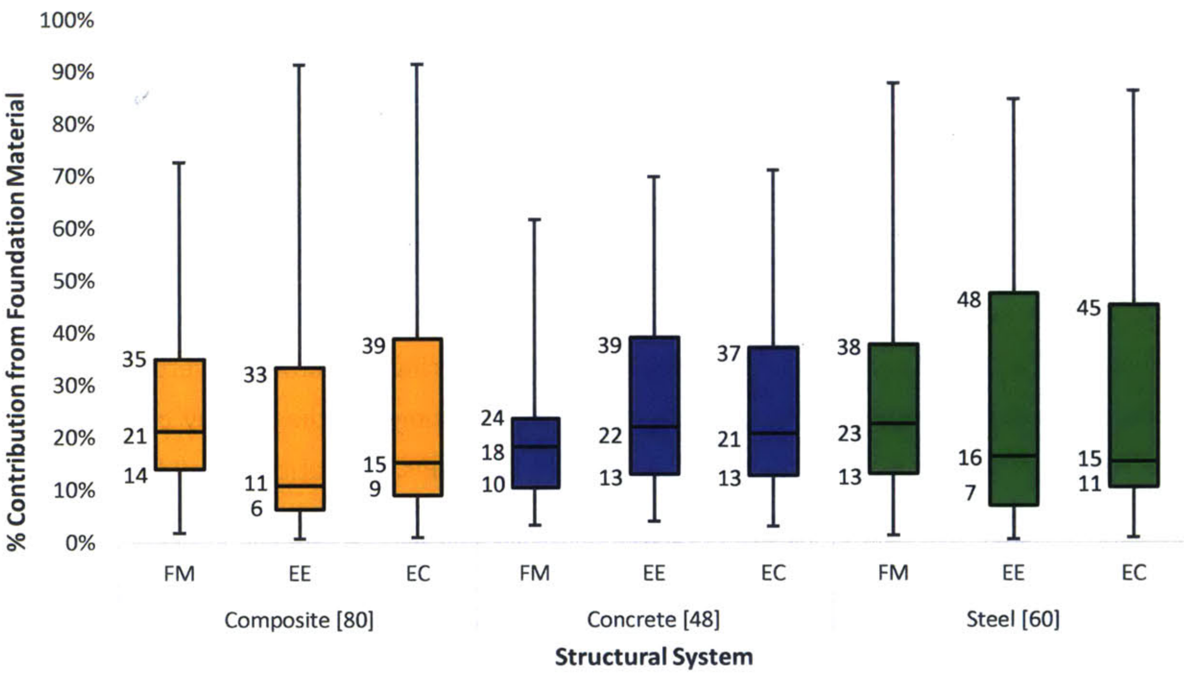


Figure 4-4: *Percent contribution of foundation material weight, EE, and EC compared to building total by structural system*

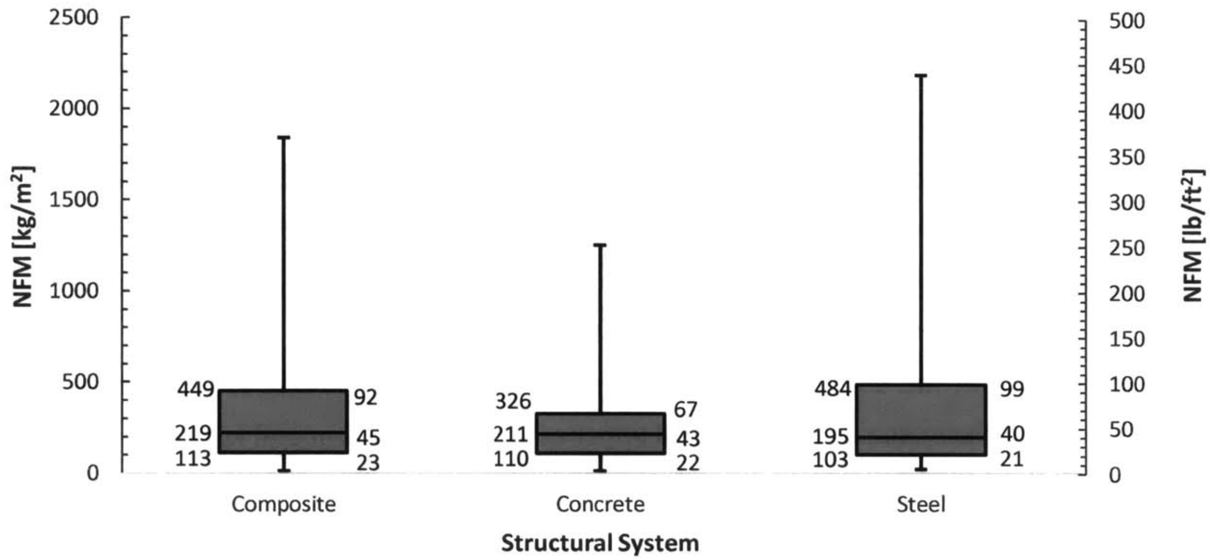


Figure 4-5: *Normalized Foundation Material (NFM) weight by Structural System*

Figure 4-2 through Figure 4-5 are included in attempt to reduce systematic errors caused by project-specific foundation design criteria, such as allowable settlement. Although there is no known correlation between a building's market sector and its design criteria, it is a logical argument. For instance, a university laboratory, with sensitive equipment, require more stringent allowable settlement than a typical commercial buildings. With more stringent allowable settlement, more foundation material is needed to reduce settlement. This is shown in the data by comparing the average NFM for commercial buildings to educational buildings. Educational buildings have on average 69 lb/ft^2 of foundation material, whereas commercial buildings have on average 54 lb/ft^2.

Another interesting way to display the data is by the number of structural stories. Based on the data, the number of structural stories plays a significant role in the design of foundation systems of buildings. Figure 4-6 shows individual project foundation weight as a percent of the total building weight versus the number of building stories.

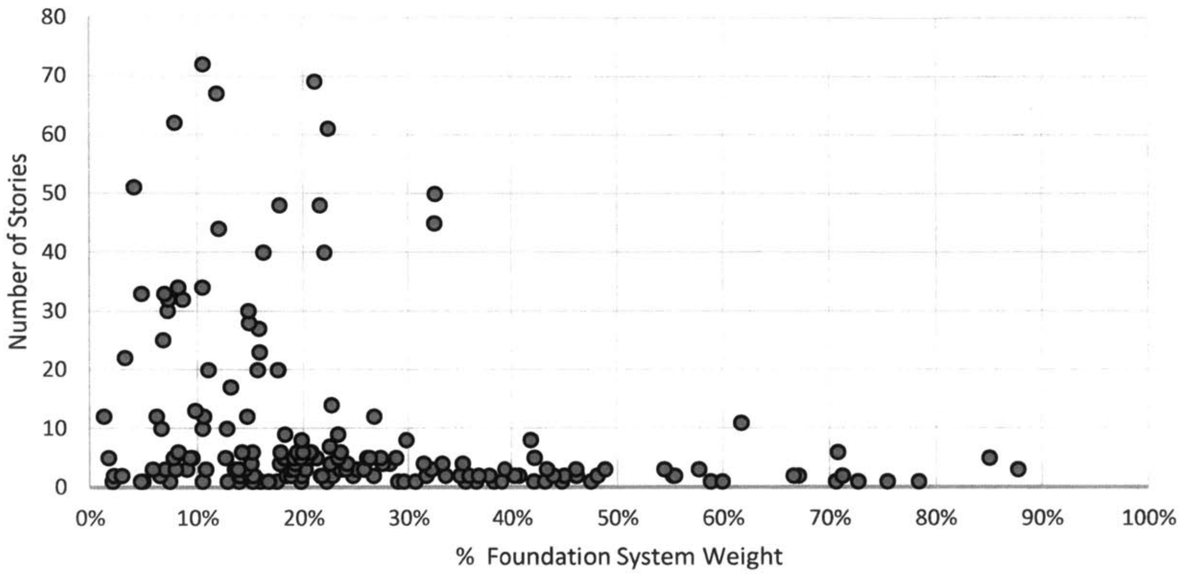


Figure 4-6: *Percent weight of foundation system versus number of structural stories*

As displayed in Figure 4-6, there is dense cluster of data points along the horizontal axis. This is because a majority of the buildings in the database are less than 10 stories resulting in large scatter for all buildings, with no discernable trend. In the current building market, it is very rare to see buildings taller than 10 stories outside the commercial and residential sectors. By filtering the data to only show commercial and residential buildings, trends start to become more evident. Figure 4-7 shows a scatter plot of the percent foundation weight compared to total building weight of commercial and residential buildings versus the number of structural stories with an exponential regression line.

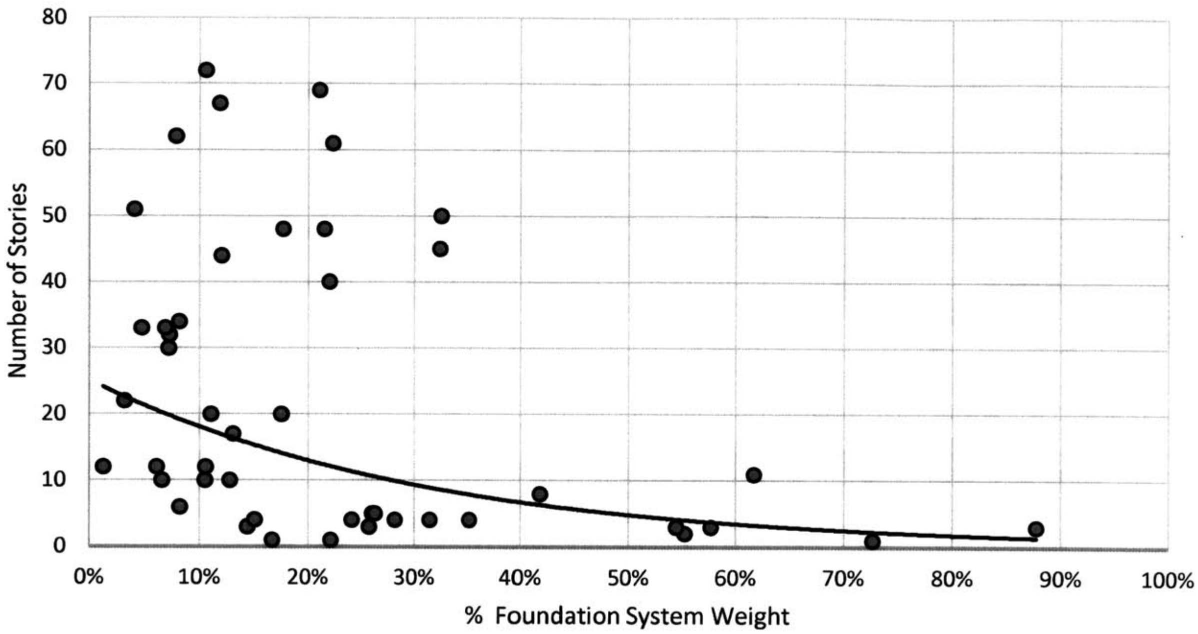


***Figure 4-7:** Percent weight of foundation system for commercial and residential buildings versus number of structural stories*

5.0 CASE STUDY RESULTS

This section presents a case study in an attempt to relate geology to material quantities of foundation systems as discussed in Section 3.2. More specifically the results are intended to provide an explanation of the variability and scatter in the deQo analyses in Section 4.0. First, the project site is described to provide basic architectural and geologic information. Second, the foundation solutions are discussed, followed by the results of the material quantities of the foundation systems by underlying geology.

5.1 Description of case study

The selected case study consists of a residential apartment complex in the greater Boston area. At the request of the project owner, the project name and location was redacted from this thesis in order to maintain confidentiality. As such the project is hereafter referred to more generally as "the apartment complex" or "the project." This project was selected because it consists of a uniform long residential building over varying geology. In addition, the apartment complex has an attached parking garage, which also spans varying geologies. Since the building loads of the residential building and the parking garage differ, multiple analyses were performed for the project.

The apartment complex was developed by a single owner, who utilized the same contractors, engineers, and architects across the site. The project involved the construction of a 4-level, wood-framed residential apartment building and a 4-level, above-ground concrete parking garage. Structural loads (dead load plus live load) for the garage columns range from 220-1,000 kips. Garage shear walls are expected to apply a total load of 28 kips/ft along exterior walls and 47 kips/ft along the central shear wall. The residential building is supported by bearing walls with total structural loads (dead load plus live load) of 4.8 kips/ft for interior walls and 5.6 kips/ft for exterior walls. The project-specific allowable settlement was set at 1.5 inches for total settlement and 0.75 inch for differential settlement. The structural loads and the allowable settlements are summarized in Table 5-1, and Figure 5-1 shows the approximate building layout.

Table 5-1: *Case study - Summary of loads and allowable settlements*

Building Type	Structural Loads			Allowable Settlements	
	Column Load (kips)	Interior Wall Load (kips/ft.)	Exterior wall Load (kips/ft.)	Total (in.)	Differential (in.)
Residential	-	5.6	4.8	1.5	0.75
Parking Garage	220-1,000	47	28	1.5	0.75

As shown in Figure 5-1, the apartment complex was constructed on a site approximately 582 ft. by 332 ft. in size. Topography at the site generally slopes gently downward from north to south with a localized steeper slope at the northern boundary. Elevation (El.) at the site ranges from El. 43 ft in the north to El. 30 ft in the south. Approximate ground elevation for the two buildings is shown on Figure 5-2 and Figure 5-3.

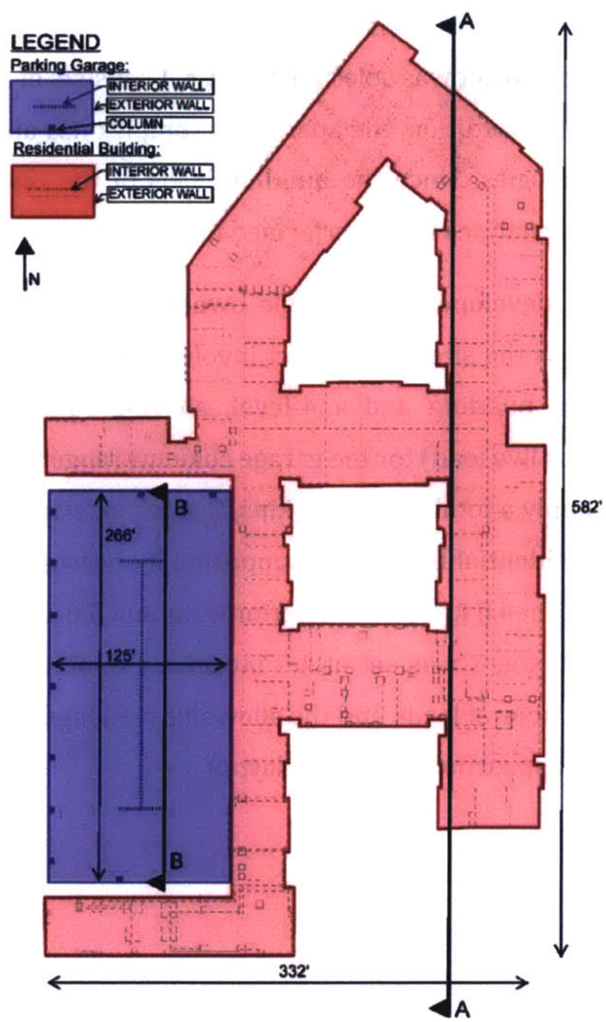


Figure 5-1: *Case study - Building layout*

With respect to the local geology, the subsurface conditions vary most dramatically from north to south. Based on soil explorations performed at the site, glacial till deposits are found as shallow as six feet below ground surface (bgs) at the northern site boundary, whereas at the southern site boundary, glacial till was not encountered until approximately 30 ft. bgs. The glacial till primarily consists of very dense sand and gravel with varying amount of silt and clay. Above the glacial till, granular fluvial deposits were encountered in the soil explorations, varying in thickness from approximately 2 ft. to 25 ft. The fluvial deposits consist primarily of fine to coarse, medium dense sand, with some gravel, and trace amounts of silt. Above the fluvial deposits, pockets of material containing over 5% organic matter were encountered and were classified as either buried subsoil, peat, or organic silt. The soil explorations also indicated urban fill extending from the ground surface to between 3 ft. and 8 ft. bgs. Bedrock at the site was not encountered in any of the borings and was not taken into consideration as part of the foundation deign. Figure 5-2 and Figure 5-3 below show soil profiles along cross-section A-A and B-B.

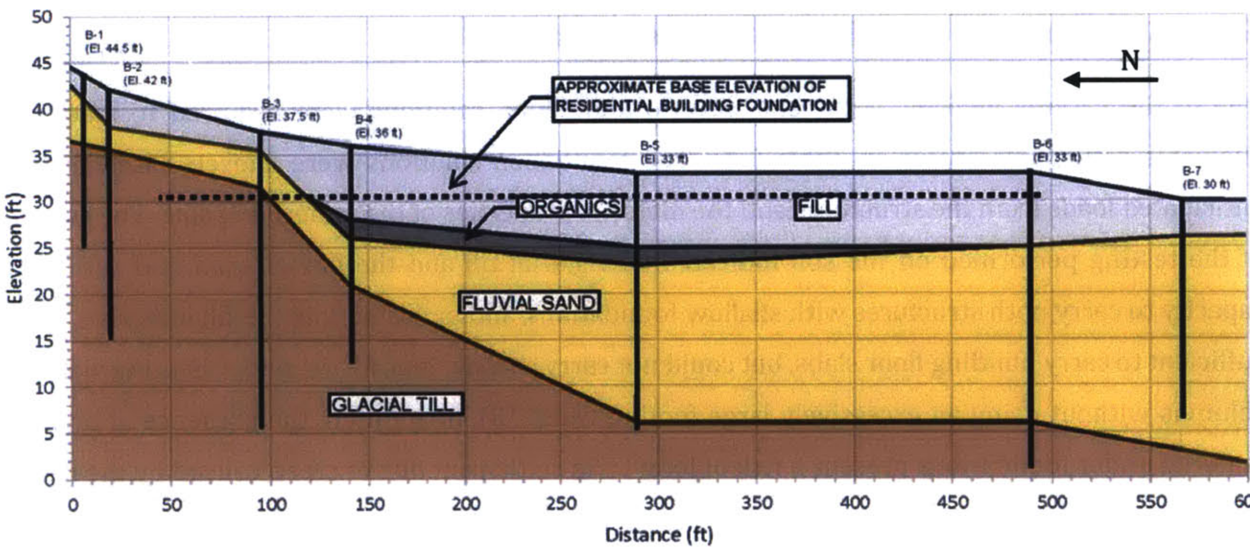


Figure 5-2: *Case study – Residential building soil profile (cross section A-A in Figure 5-1)*

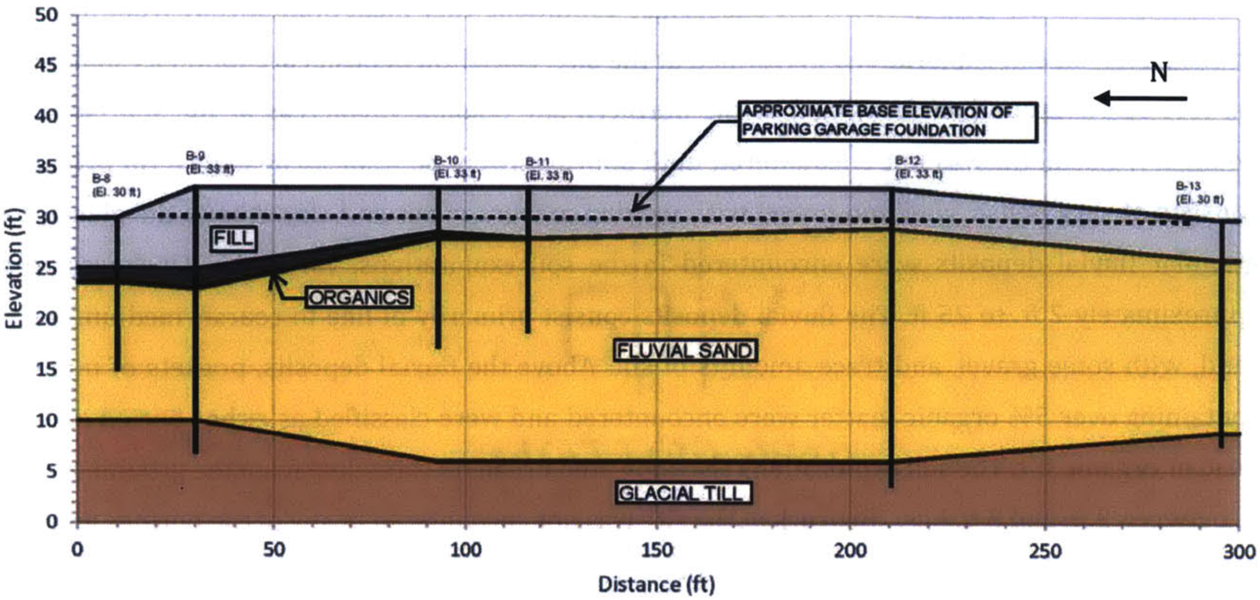


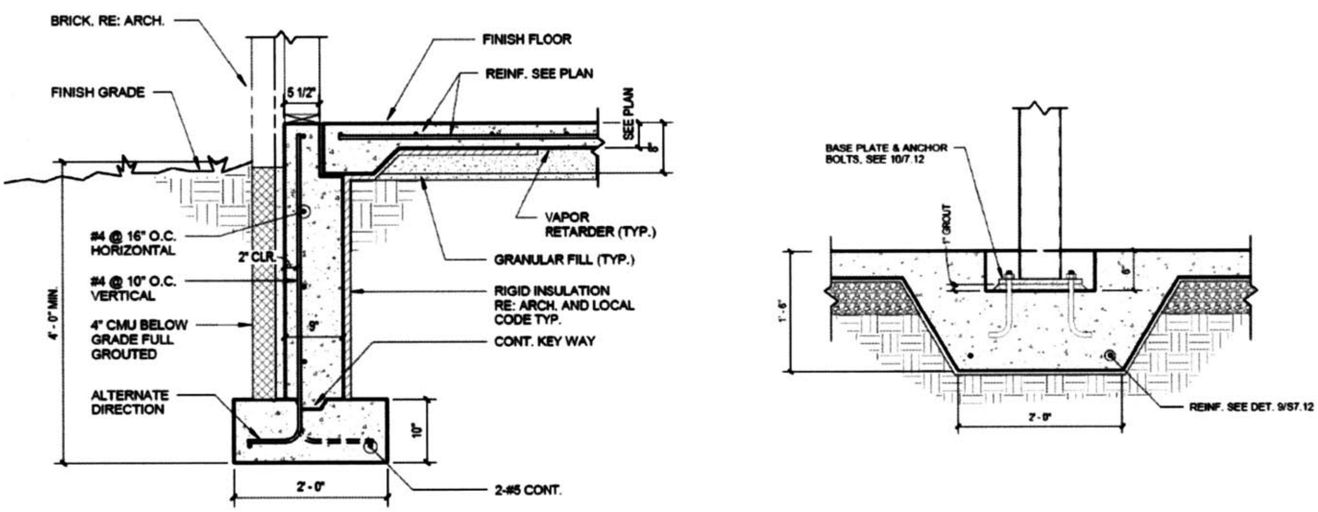
***Figure 5-3:** Case study – Parking garage soil profile (cross section B-B in Figure 5-1)*

5.2 Case Study - foundation system solutions

Due to the varying geology at the site, several foundation solutions were required to meet the allowable settlement shown in Table 5-1. The foundation solutions were chosen based on the anticipated loads from the structures and the material properties of the underlying soil. The results of the testing performed on the soil indicated that glacial till and the fluvial sand had sufficient capacity to carry both structures with shallow foundations, and indicated that the fill materials were sufficient to carry building floor slabs, but could not carry shallow foundation under bearing walls or columns without using an excessively large footing width (B). In addition, the presence of organic material under foundations present a risk of long-term settlement due to creep caused by the decay of organic matter. As such, areas where organic material was encountered below the building footprint required either ground improvement or deep foundations for footings and floor slabs. Based on the results of soil testing, the design team implemented foundation solutions for footings with a base elevation of El. 33 ft. Subsequently, both the apartment building and the parking garage were segregated into subdivisions based on the underlying soil conditions. The foundation solutions for the apartment building consisted of either shallow foundations bearing on the natural glacial till or the fluvial sand or shallow foundations bearing on fill material after aggregate piers were installed as a ground-improvement measure to increase fill stiffness. Since the parking garage had much larger loads compared to the apartment building, a more robust foundation system was required to achieve the settlement limits. As such, foundation solutions for the parking garage consisted of grouted piers that effectively act as deep foundations. Table 5-2 summarizes the foundation solutions, and Figure 5-4 through Figure 5-6 show typical foundation sections. The locations where the foundation solutions were utilized are shown on Figure 5-7.

***Table 5-2:** Case study – Summary of foundation solutions*

Building Subdivision	Foundation Solution
1	Shallow continuous spread footings and floor slab bearing on glacial till
2	Shallow continuous spread footings and floor slab bearing on aggregate piers installed in fluvial sand
3	Floor slabs bearing on fill and shallow continuous footings bearing on aggregate piers installed in fluvial sand
4	Shear walls, columns, and floor slab bearing on grouted piers installed in fluvial sand
5	Floor slabs bearing on fill with shear walls and columns bearing on grouted piers installed in fluvial sand



Section at Exterior Bearing Wall

Section at Interior Bearing Wall

***Figure 5-4:** Case study – Typical residential building foundation sections at interior and exterior bearing walls (Building subdivision 1 - 3)*

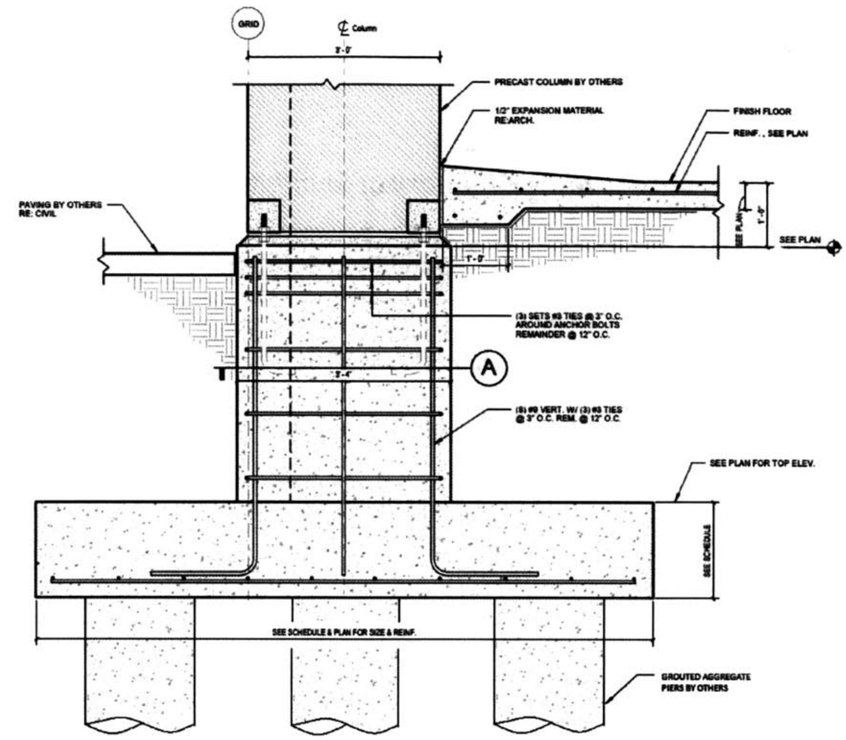
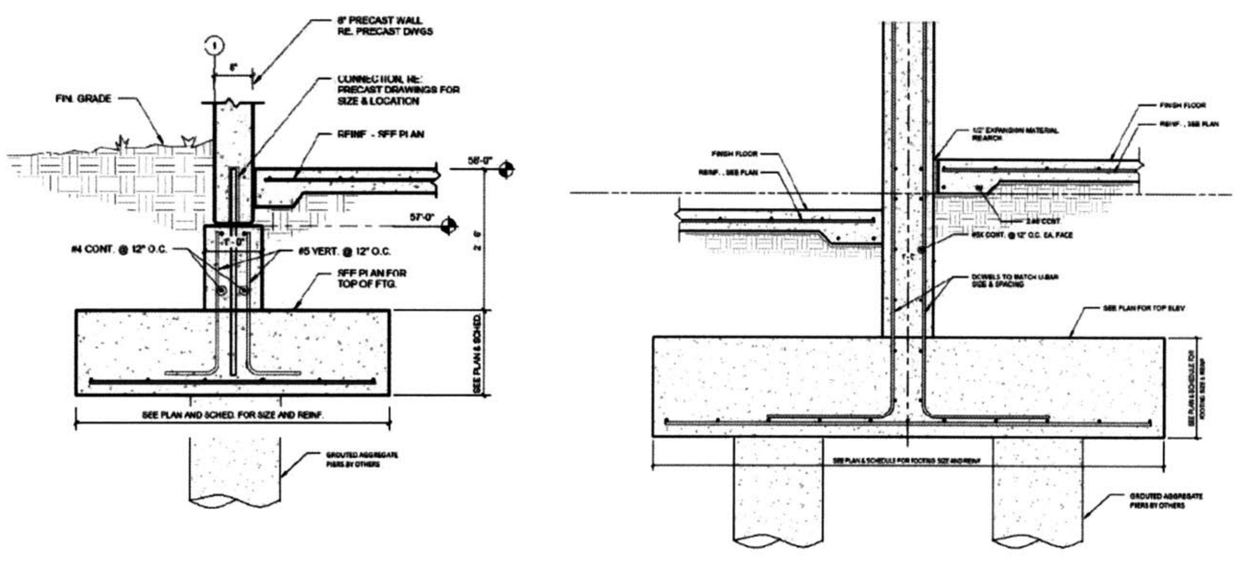


***Figure 5-5:** Case study – Typical parking garage foundation section at vertical columns (Building subdivision 4 and 5)*



Exterior Section at Bearing Wall

Interior Section at Bearing Wall

***Figure 5-6:** Case study – Typical parking garage foundation section at interior and exterior walls (Building subdivision 4 and 5)*

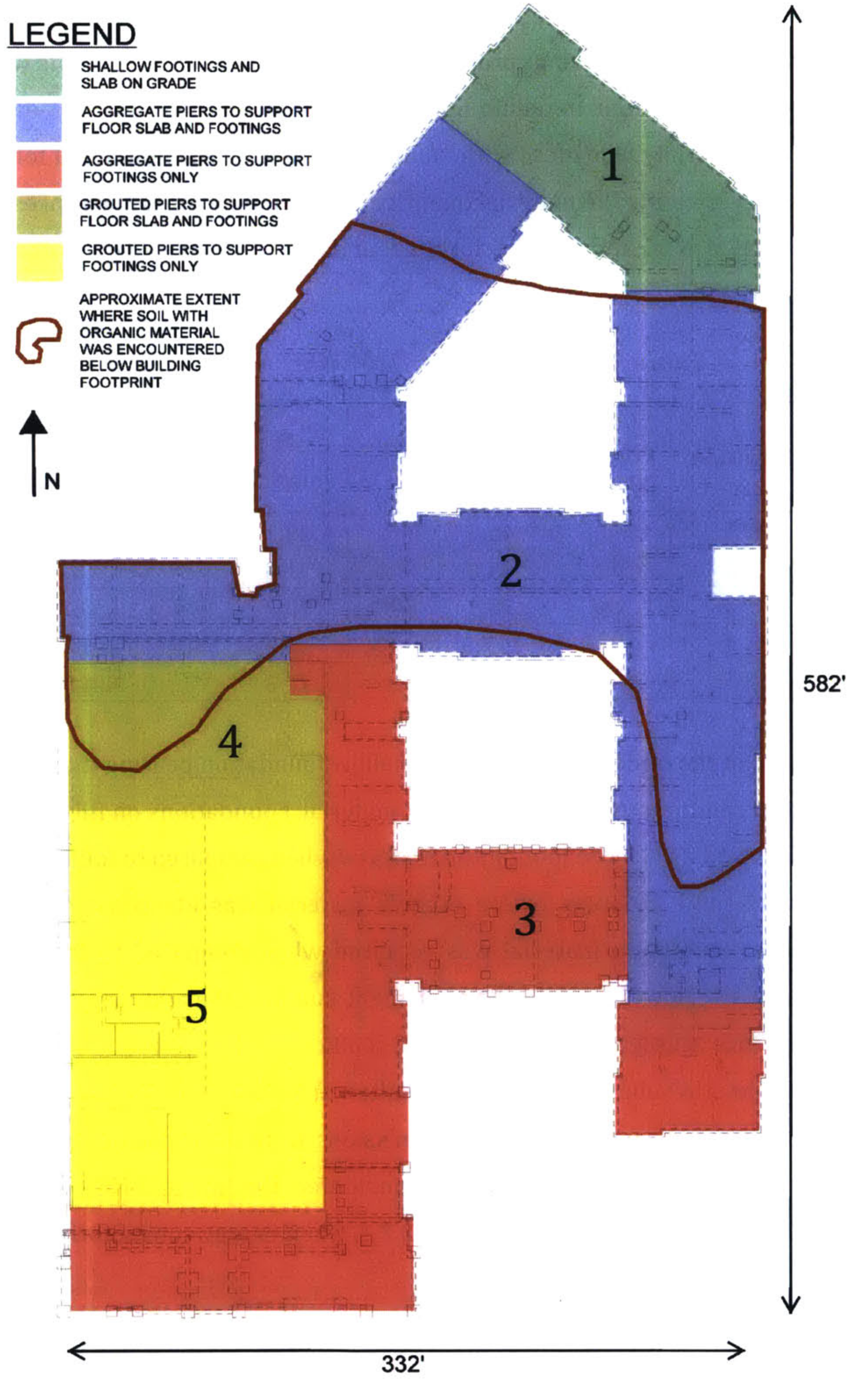


Figure 5-7: *Case study – Building foundation system solution subdivision*

5.3 Case study - Foundation system material quantities

Using the structural foundation drawings provided for the project, material take offs were performed on the foundation system in order to obtain quantities. A representative area for each subdivision was chosen, and the material quantities for the foundation system were summed for that area. The NFM was calculated by dividing the material quantity by the GFA (4 times the representative area). Table 5-3 shows the NFM, NEE, and the NEC, for the foundation systems and the percent increase (Δ) for each of the subdivisions.

Table 5-3: *Case study – NFM, NEE, NEC results*

Building Subdivision		Building Pressure (kips/ft²)	NFM		NEE		NEC	
			(lb/ft²)	Δ[8] (%)	(mJ/ft²)	Δ[8] (%)	(lbCOe₂/ft²)	Δ[8] (%)
Apartment Building	1	0.5	46.6	-	20.1	-	6.1	-
	2		65.0	40%	21.0	4%	6.2	2%
	3		58.1	24%	20.7	3%	6.1	1%
Parking Garage	4	3.8	117.3	16%	86.2	10%	14.2	19%
	5		101.2	-	77.3	-	11.5	-

As expected, the area of the building that utilized shallow foundation bearing directly on the glacial till or the fluvial sand required the least foundation material. Foundations on fill with no underlying organic material required 24% more foundation material when compared to foundations bearing on the glacial till/fluvial sand. In areas where organic material was identified below the building footprint, 40% more foundation material was required when compared to foundations bearing directly on the glacial till/fluvial sand. In the apartment building, the additional material consisted solely of aggregate. Since aggregate has lower EE/EC coefficients than steel and concrete, the ground improvement performed in subdivision 2 and 3 resulted in a negligible increase of NEE and NEC. It should be reiterated that the energy, and carbon emissions, from the construction process were not included in this calculation. If these aspects were considered, the NEE and NEC values would likely be much higher. However, as discussed in Section 2.2.1, when energy consumption is considered as

[8] Δ: Represents the percent increase of NFM, NEE, and NEC between building subdivisions. The lowest NFM, NEE, and NEC for the apartment building and parking garage were used as the reference points for the calculations.

part of the EE/EC calculation for ground improvement methods the values are still less than if traditional deep foundations were used.

For the parking garage, deep foundations were required for all footings due to the relatively high loads when compared to the loads of the apartment building. In addition, a portion of the floor slab was located over organic material, so additional deep foundations were installed to support the floor slab. This resulted in approximately 16% more material than the areas of the parking garage where the floor slab did not require additional support.

Comparing the apartment building to the parking garage structure, a relationship between the building load and material quantities of the foundation system can be made. Building pressure, in Table 5-3, represents the entire load of the building divided by the square footage of the building footprint (not the GFA). For this particular case study, the parking garage applied approximately 760% more pressure to the bearing soil when compared to the apartment building. This additional load resulted in an average increase of 92% in the NFM for the parking garage compared to the apartment building. Also, on average the EE was nearly quadrupled and the EC was more than doubled.

6.0 CONCLUSION

6.1 Discussion of results

The result presented in Section 4.0 and 5.0 provide meaningful answers to the three questions this thesis aims to answer: (1) are there benchmarks that designers can use to evaluate the material quantities in foundation designs, (2) do foundation materials significantly contribute to the embodied energy and embodied carbon of a buildings, and (3) what types of buildings most efficiently utilize their foundations? A detailed discussion of the results and how they relate to each of these questions is provided in the following sections.

6.1.1 Foundation system material quantity benchmarks

Using a sample of 200 buildings from the deQo, foundation material in buildings was found to contribute approximately 20-25% (median-average) to a building's total weight. This is a significant preliminary benchmark for approximating the material required to support buildings; however, understanding the context of this benchmark is important. The 20-25% average is for multiple building types, on different geologies, with different design criteria (i.e. allowable settlement limits); and the actual percentage will vary depending on the project. As such, when comparing specific projects to the benchmarks, the variations should be considered. For instance, residential buildings should be compared to a residential benchmark, steel-framed buildings should be compared to the steel-superstructure benchmark, and so on... These results are provided in more detail in Section 4.0.

The role geology plays in the quantity of foundation material was addressed by evaluating a case study. Based on the results from the case study, NFM for the lightly loaded residential building was 46.6 lb/ft^2 for foundations constructed on dense glacial till, and 65.0 lb/ft^2 for foundations construction over softer organic material. This range corresponds to the scatter observed in the deQo data. The average and median NFM values calculated for all buildings in the deQo were 44.9 lb/ft^2 and 59.9 lb/ft^2, respectively. Comparing these two ranges, the distribution of NFM in the deQo analyses can be related to the effects geology has on foundation system material quantities. This indicates that geology needs to be considered when benchmarking foundation material quantities for building structures.

In summary, this thesis provides benchmarks for foundation system material quantities. With no known site-specific information, a good approximation for the material quantities of a foundation system is 20-25%. This is ideal for a case in which an architect develops a concept without specific buildings details, but has a rough estimate on the building weight. If more building information is known, a more accurate approximation can be made by using the figures in Section 4.0. For projects with known site geology, reasonable approximations can be made by using values 20-40% higher for buildings on relatively "soft" ground and, conversely, values 20-40% lower for hard ground as demonstrated in the case study.

6.1.2 Contribution of the foundation system to EE and EC of buildings

Foundation systems contribute to a building's overall embodied carbon and embodied energy at approximately the same proportion as they contribute to a building's overall weight. This demonstrates that improving foundation design to include less materials has the potential to significantly reduce the overall embodied energy and carbon of buildings. In addition, this thesis presents alternatives in foundation design that utilize low-energy materials. The use of aggregate piers in the case study showed that use of ground improvement, from a material standpoint, reduces the EE/EC. This is congruent to the work of Spaulding, Masse, and LaBrozzi, 2008, which shows ground improvement techniques lead to less embodied carbon in foundation systems.

6.1.3 Buildings that most efficiently utilize their foundations

There are certain types of buildings that better utilize their foundation system; structural height has a significant effect on the performance of a building's foundation system. Based on the data, taller buildings tend to utilize their foundation materials more efficiently. This is a meaningful statistic because it indicates that the biggest opportunity for CO_2 emission reduction is in improving foundation design in low-rise buildings.

6.2 Future research

Foundation systems are just one area in the built environment that needs continued research related to embodied energy and embodied carbon. Generally, strategies for incorporating EE/EC considerations in conceptual design are needed across all design sectors. This cannot be achieved until designers have tools to evaluate the embodied energy and carbon impacts of design decisions, and these tools cannot be developed until there are sufficient data to support them.

As mentioned, this thesis is intended to provide preliminary benchmarks for material quantities in foundation systems and their environmental impact. In order to move from preliminary to more concrete benchmarks, two main actions need to occur. First, more data on actual projects are needed. With more data the development of benchmarks will become more accurate and more specific.

Second, different types of data need be collected. Information on the project geology and allowable settlement should be included with data collected from actual buildings. As shown in this thesis, geology is crucial to understanding the benchmarks. Ultimately, better data create the potential for a deeper understanding of the material quantities in foundation systems, their performance, and their environmental impact. Once this is better understood, tools for designers can more easily be developed, resulting in more efficient foundation designs.

More research is also needed on the type of materials used in foundation systems. The use of aggregate in ground improvement has been shown in this thesis, and in the work of others, to be an effective way to reduce CO_2 emissions from foundation systems; however, research related to use of other materials that were not discussed in this thesis needs to be considered. For instance, fly ash and slag are commonly used as substitutes for cement in concrete. These substitution materials impact the EE/EC of concrete, and therefore the EE/EC of foundations. More research is needed on the use of these materials in concrete to quantify their impact on the EE/EC of foundation systems.

When wider research is performed on the material quantities of foundation systems, along with the total material quantities of buildings, follow-up actions need to be developed. In order to sustain success in constructing buildings with low embodied energy and carbon, real estate developers have to have incentives to use low EE/EC practices. This thesis lays the groundwork for material accounting in foundation systems, but more importantly, it opens opportunities for architects and engineers to expand their knowledge on sustainable design.

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