Foundation Settlements of English Cathedrals

by

Zoe Temco

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

Masters of Engineering in Civil Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2017

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Abstract

In this thesis, the structural and geotechnical components that contribute to the settlement of English cathedrals are analyzed. The stress at the base of tower and nave piers was found and compared to the allowable bearing capacity. The expected settlement range of each cathedral's tower and nave piers was calculated by analyzing the site's soil conditions. The average settlement expected for a central tower pier not founded on bedrock is between 14 and 21 cm, which is greater than the average expected settlement of a nave pier, 7cm. An average differential settlement between the nave and tower piers expected is between 7 and 14 cm, which can contribute to cracking in the masonry or even structural failures. Less differential settlement will occur in areas with firmer soil than with deep clay.

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Thesis Supervisor: Herbert Einstein
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1. Introduction

The aim of this thesis is to understand the connection between soil conditions and the stability of the central tower of English cathedrals and to predict and analyze the settlement of several English cathedrals. The foundations are arguably one of a cathedral's most important components, but they are seldom studied. In this thesis a possible shape and size for a typical tower foundation will be considered. This will be done by assuming a constant shape (a truncated pyramid) and analyzing the tower stresses and settlement at the foundation base. This thesis will also address how medieval builders may have dealt with a variety of soil conditions. Foundation systems during the 11^{th} century were mostly just large masonry masses.

This thesis will also study the settlement of English cathedrals. For a given cathedral, the settlement of a tower pier and the settlement of a nave pier will be calculated, and the approximate difference between them will be analyzed. In order to calculate the settlement, the weight of each component of the cathedral is needed. The weight is found by calculating the volume of each structural component, such as a pier, and multiplying it by the unit weight of stone, to estimate the weight. Three methods are then used to calculate the settlement. The estimated settlements are related to soil conditions. Ultimately, a general statement will be made regarding tower settlements and subsurface conditions.

1.1. Background

Although cathedrals are among the most fascinating buildings, they are not often studied in terms of structural and geotechnical engineering, but more often in regard to architectural history. English cathedrals are intriguing because of their age and complexity. Built during the medieval era, very few contemporary drawings and writings on the construction of the cathedrals exist. It is important to understand the structural components of cathedrals because English cathedrals have been analyzed from the perspective of architects and art historians for centuries. Materials, craftsmen, and politics contributed to the structure of each cathedral. Even though the construction of most English cathedrals began during the last quarter of the 11^{th} century, the structural integrity of the cathedrals varies greatly.

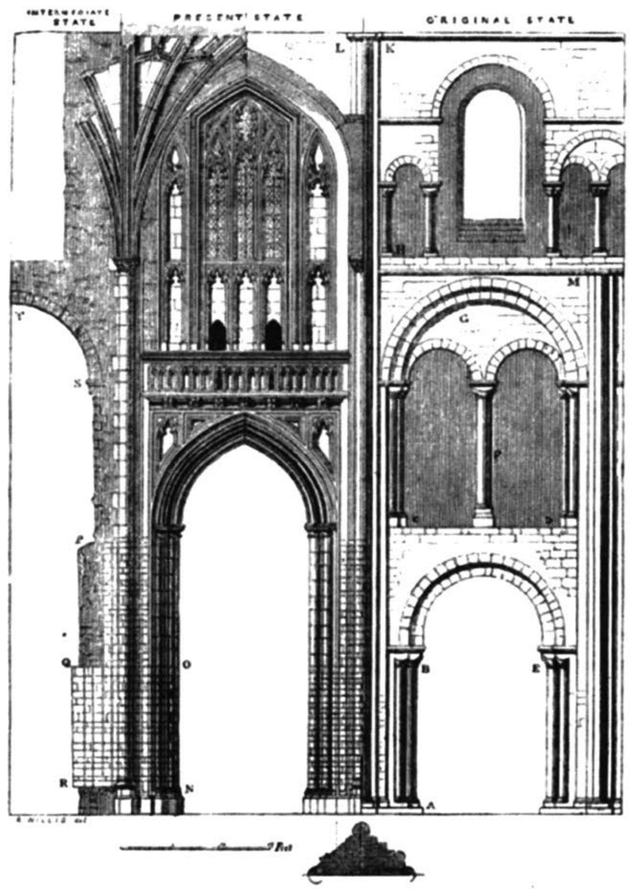
There are 62 cathedrals in England, marking the center of many metropolitan areas and displaying a unique cultural and structural history (Pevsner and Metcalf, 1985a). Figure 1 shows a map of the major cathedrals, not including those in London. The cathedrals circled will be discussed in this thesis. The Romans first inhabited many of the sites of current cathedrals. They built fortresses, homes, Christian religious sites, and towns. The remains of which can still be seen today. The foundations of a Roman fortress are still visible at York Minster Cathedral (Dowrick and Beckmann, 1971). Some cathedrals also have Saxon remains dating from the seventh century. In some cases the materials from the Saxon structures were used to build later structures on the site.

Figure 1: A map of the major English Cathedrals

The Norman Conquest of England in 1066 created a dramatic shift in the building and style of religious buildings. As art historian Priscilla Metcalf notes, "In the first thirty years after the Norman Conquest, i.e. before 1100, major building or rebuilding was energetically begun… structural design was empirical: Winchester's new tower promptly fell in 1107; Durham's pioneering rib-vaults over the choir had to be rebuilt in the 13th century (but the original aisle vaults remain)" (Pevsner and Metcalf, 1985a). Many of the central towers were built during this period as well. Norman artwork also left a legacy in the stained glass still remaining in most cathedrals. Figure 2 shows Peterborough Cathedral, which has a typical central tower. Central towers like this one are the focus of this thesis.

Figure 2: Peterborough Cathedral, which has a typical central tower

The Norman building style only had a century to become predominant before being influenced by the Romanesque style, and soon, the Gothic style, which arrived from France. Norman architecture refers to the Norman arches and relatively smaller windows as seen on the right side of Figure 3. Many cathedrals were rebuilt and retrofitted to utilize components of the style, and during the 13th century Early English style became popular, defined by its pointed arches and spires, again influencing the architecture of the Norman cathedrals. While the skeleton of most of the cathedrals was Norman, components, such as the nave bays at Winchester, were altered to reflect the times. Winchester Cathedral was changed to reflect the current style as shown on the left side of Figure 3. Like the nave at Winchester, windows and arches were replaced throughout the cathedrals. At Ely, the north transept has a



ELEVATION OF TWO BAYS OF THE NAVE, SHOWING ITS TRANSFORMATION.
(From Willis's "Architectural History of Winchester Cathedral," 1846.

Figure 3: The difference in styles at Winchester Cathedral

mixture of Norman and Gothic windows. Gothic windows let in much more light. Similarly, central towers were often updated. Peterborough Cathedral's tower is supported by two Norman style arches and two Gothic style pointed arches. Possibilities for the difference include that money ran out during construction, or a master mason or builder in charge of the project died. Figure 4 shows the two types of arches at Peterborough Cathedral.

Figure 4: The difference in styles in Peterborough's tower

As the cathedrals were updated, technological advances were used to help reach the new heights. Flying buttresses were first introduced to England during the 12th century (Pevsner and Metcalf, 1985a). The buttresses were also used to support the Norman central towers. Sir Nikolaus Pevsner, a revered scholar of the history of architecture, remarked, "The architecture of England between 1250 and 1350 was, although the English do not know it, the most forward, the more important, and the most inspired in Europe" (Pevsner and Metcalf, 1985a). The structural aspects of the architecture are important to study, especially to understand how the work was done with preindustrial tools.

English cathedrals are easily recognizable by their central, or crossing tower. For centuries these towers were the tallest structures in the country, and at times, the world. They are feats of structural and geotechnical engineering. While today they stand high above their town, many towers collapsed and were rebuilt. Norwich Cathedral and St Albans Cathedral are the only two surviving Norman towers. The rest were built or rebuilt in the 13^{th}-15^{th} centuries.

The need for repair or rebuilding stems from two causes: structural problems and geotechnical problems. Structural issues include poor masonry, weak mortar, or crooked lines. Geotechnical issues include insufficient foundation size and inadequate soil conditions. The aim of this thesis is to understand the connection between the soil conditions and stability of the crossing tower for each cathedral.

1.2. Literature Review

This section reviews the key literature relating to the settlement of cathedrals and other unreinforced masonry structures. Very little has been published regarding the structural and geotechnical aspects of cathedrals. Jacques Heyman's *The Stone Skeleton* explains the analysis of masonry structures (Heyman, 1997). Jean Kerisel's Rankine Lecture (1975) "Old structures in relation to soil conditions" details the foundations and settlement of historic structures, such as cathedrals (Kerisel, 1975). Kerisel explains why understanding the whole masonry structure, not just the foundations, is important.

The most helpful text in researching this thesis is the paper "Archaeology and engineering: the foundations of Amiens Cathedral" by Bonde et al. This paper addresses the bearing stress of a portion of Amiens Cathedral and studies the adequacy of the cathedral's gothic foundations (Bonde et al, 1997). This thesis plans to expand on this paper using similar methodology to understand the Norman foundations of English Cathedrals. First, the foundations are idealized as smooth, stepped, truncated pyramids, as shown in Figure 5. Then, the weight of the structure carried by the pier and the weight of the pier and foundation are added together. This final weight is divided by the area of the base of the foundation to find the bearing pressure. The bearing pressure is then compared to the allowable bearing capacity for a given soil. This thesis will expand upon this to calculate the settlement of the tower and nave piers for each cathedral.

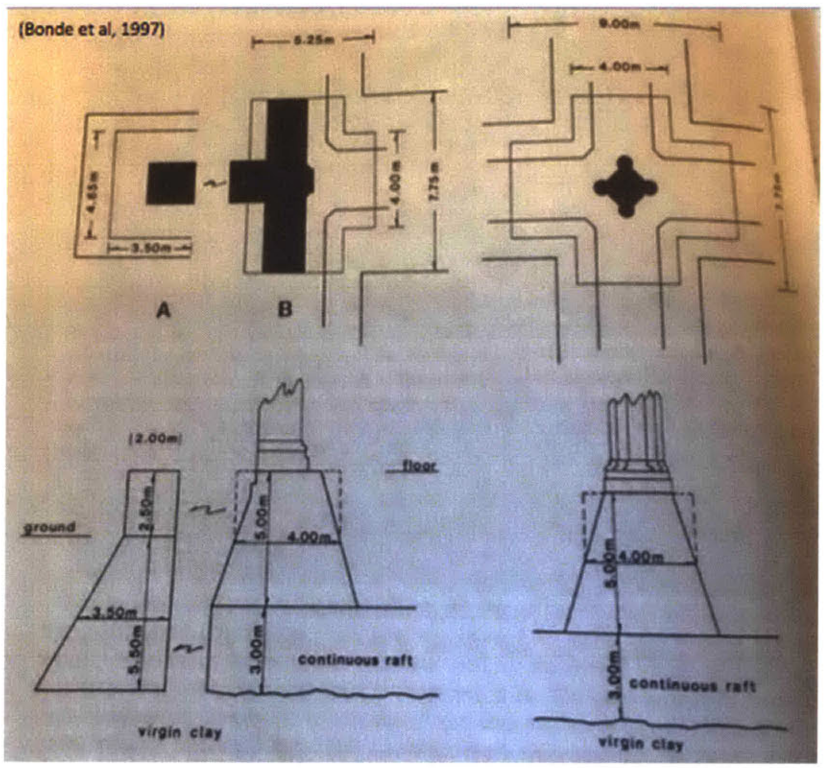


Figure 5: Representation of Gothic cathedral foundations (Bonde et al, 1997)

Architectural Technology up to the Scientific Revolution expands on the previously mentioned paper and explains the foundations of medieval structures and building techniques (Mark, 1995). Mark covers timber, masonry, and hybrid foundations. Very few other texts pay close attention to the structural components of cathedrals, unless they are highlighting a problem. The differential settlement of the central tower at York Minster Cathedral, threatening the integrity of the structure, showed that a structural and geotechnical study of cathedrals was important in order to preserve them for future centuries. The "York Minster structural restoration" engineering report illustrates the need for careful engineering analysis of structures previously studied from an architectural history perspective (Dowrick and Beckmann, 1971). The archaeological photos and recordings from the restoration are helpful in understanding how a foundation deforms under a tower load and what this can mean for the stability of the structure.

The Bell's Cathedrals series (1897-1908) published by George Bell & Sons in the late 19th and early 20th centuries provides floor plans, dimensions, and architectural descriptions of each cathedral, including the materials used. The series does not have the same art history focus as other architectural texts, but explains the building's history. These have been very useful in understanding the structures and finding the dimensions.

Although there are many texts on cathedrals, their history, architecture, and archaeology, there is very little literature on the foundations and geotechnical conditions of English Cathedrals.

From a geotechnical engineering perspective, there are many papers and textbooks that cover settlement, most of which focus on more complex methods of calculation (such as plasticity), than used in this thesis. Elasticity is studied as the method of settlement in this thesis because the soil information, such as permeability, is not available from the borings acquired from the British Geological Survey. While all textbooks include a section on calculating the settlement of a structure, they do not all provide a limit on allowable settlement. Skempton and McDonald (1956) propose limiting values of settlement depending on if the soil is clay or sand, and the allowable maximum angular distortion based on data. Bjerrum (1963) recommends the limit of angular distortion for various structures, including the danger of structural damage to most buildings as 1/150. Many other papers also provide allowable distortions, settlements, and ways to calculate them. The International Building Code (2015) states: "The settlement of a single deep foundation element or group thereof shall be estimated based on approved methods of analysis. The predicted settlement shall cause neither harmful distortion of, nor instability in, the structure, nor cause any element to be loaded beyond its capacity" (International Building Code, 2015). Here the challenge is deciding what the allowable distortion for a tall, unreinforced masonry structure is, and how the differential settlement within a cathedral relates to this amount. This section provided an overview of the problems to be addressed in this thesis, a background on cathedrals, and a literature review of related works. The following chapter will address the structural analysis structural assumptions considered in this thesis.

As demonstrated by the literature review, the geotechnical aspects of cathedrals are rarely studied. This thesis aims to estimate the settlement of the foundations of six English cathedrals. The difference between the tower and nave piers will be analyzed by considering both the structural and geotechnical aspects of cathedrals. The following chapter focuses on the structural analysis of cathedral piers.

2. Structural Analysis

Many central, or crossing, towers collapsed when they were first built, and many faced collapse later, such as Chichester Cathedral's central tower, which collapsed in 1861, and York Minster's tower, which was heavily repaired in the 1960s. There are two major reasons for collapse: structural problems and geotechnical problems. This chapter will focus on the structural issues that central towers face and explain the calculations finding the stress in each tower pier. Geotechnical considerations will be addressed in Chapter 5.

This thesis will focus on the following cathedrals and abbeys: Peterborough Cathedral, Durham Cathedral, Winchester Cathedral, St Albans Cathedral, Selby Abbey, and Ely Cathedral. The scope of this paper has been narrowed to only six cathedrals to encompass cathedrals with varying soil conditions.

2.1 Background

Cathedrals are large masonry structures. Masonry works through compression and does not carry tensile loads well. Masonry's natural state is cracked, so it cannot always be stated that masonry cracked due to settlement (Heyman, 1997). However, in some cases, settlement can contribute to cracking. In England, almost all the stone used in cathedrals is limestone from local quarries. Limestone was used to build the cathedrals because it is a common rock in England that is soft enough to be cut into blocks with medieval tools and has a high enough compressive strength to support a tower.

One reason for structural distress is a weakness between masonry layers. This can be caused by inadequate mortar or gaps between stones. Cracks can propagate between limestone blocks through the mortar as shown in Figure 6. It is less common for the limestone itself to crack, however, this has occurred at Winchester Cathedral, as shown in Figure 7.

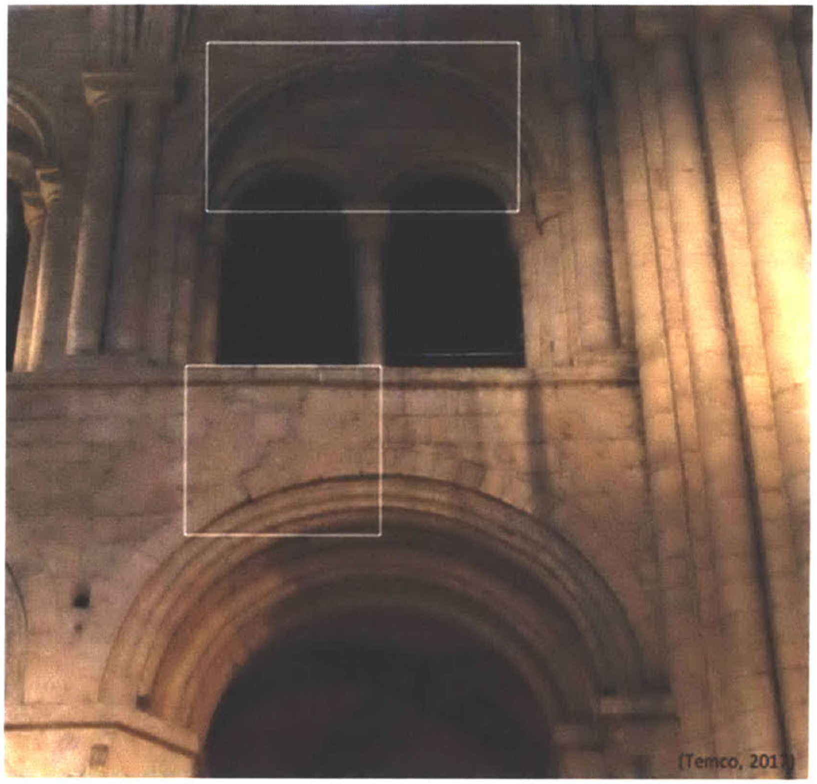


Figure 6: Crack between stones at Durham cathedral

Figure 7: Cracked stone at Winchester Cathedral

Another reason for structural failure is structural instability caused by differential settlement. Differential settlement occurs when one component of a cathedral settles by a different amount than another. Often two tower piers will settle differentially due to a difference in underlying soil conditions or foundations. For example, York Minster Cathedral was built over a Roman fortress, reusing some Roman foundations. These older foundations were inadequate to support the large cathedral and caused differential settlement to occur. The differential settlement can be seen in Figure 8, where there is a large crack in the foundation and the settlement is easily visible.

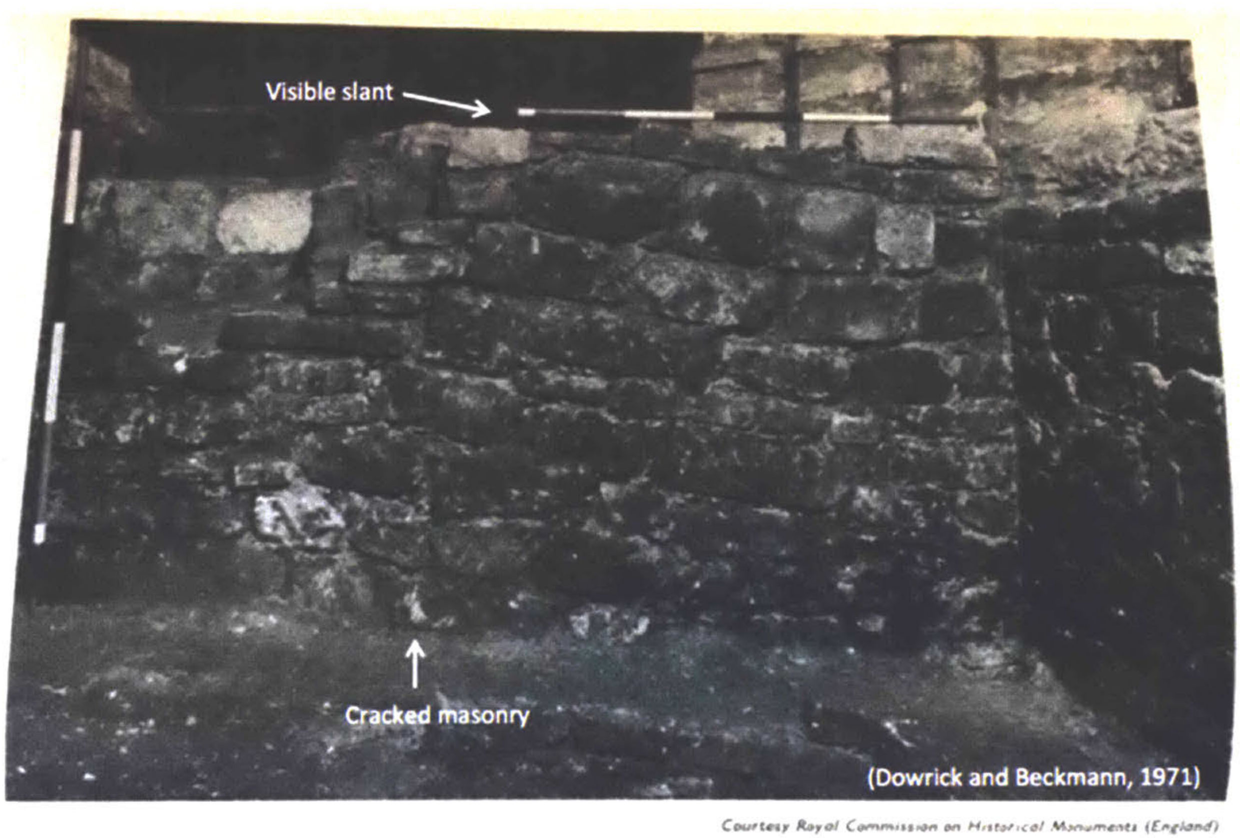


Figure 8: York Minster Roman Foundation

To estimate the settlement at the base of a tower pier, the stress due to the weight of the tower at the base of the pier needs to be calculated.

2.2 Assumptions

Many simplifying assumptions were made when finding the volume and weight of each cathedral's central tower. The dimensions for each cathedral can be found in Appendix A. Some general assumptions were made for each cathedral. Gothic arches were approximated as triangles and Norman arches were treated as ellipses to simplify the calculation of the volume of the structures as shown in Figure 9. A constant tower wall thickness of 1.52m was assumed for each cathedral and a thickness of 0.61m was assumed for each nave arch. Tower piers were considered as rectangular to simplify calculations. Figure 10 shows a plan view of the assumed tower and nave dimensions. Figure 11 shows the difference in size of Peterborough Cathedral's nave and tower piers.

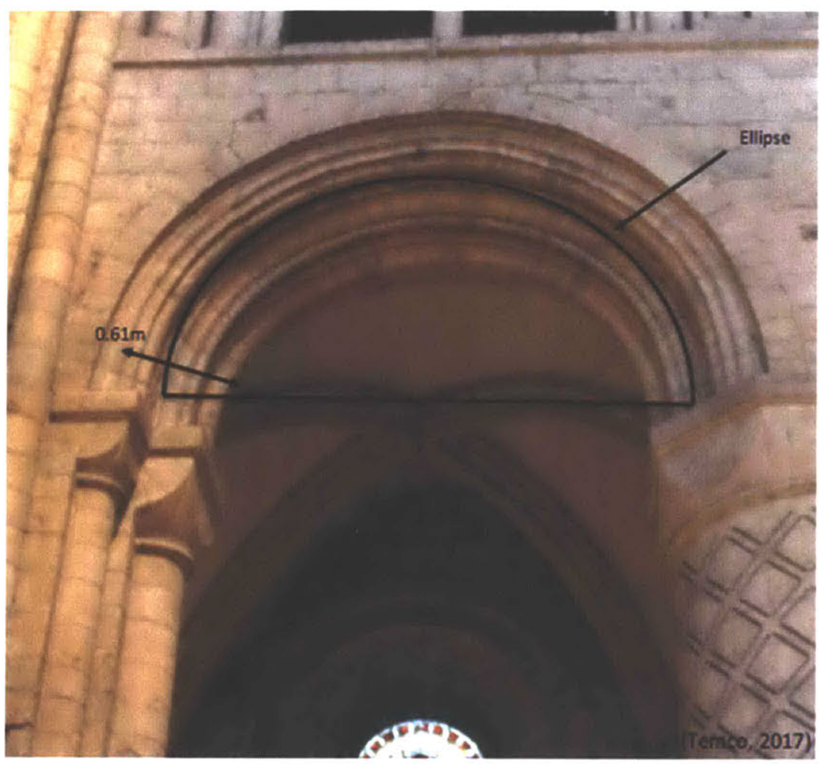


Figure 9: Example Norman arch with dimensions

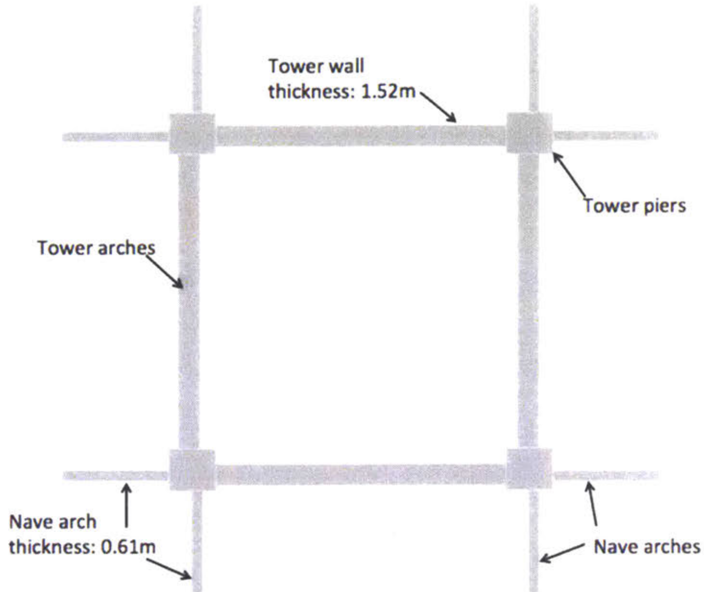
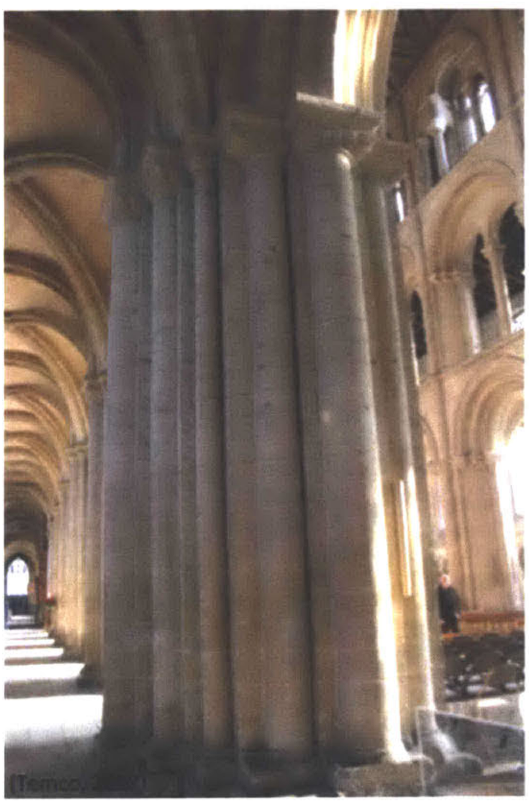
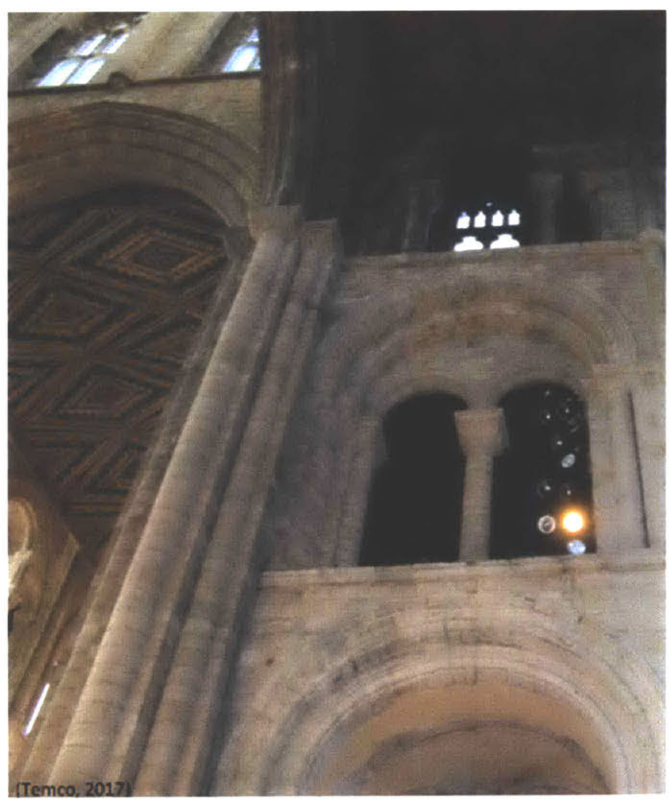


Figure 10: Plan view of tower assumptions (not to scale)





(a) Nave Pier (b) Tower Pier

Figure 11: Peterborough Piers (a) Nave and (b) Tower

2.3 Methodology of calculating the stress at the base of a pier

Peterborough Cathedral will be used as an example to demonstrate the procedure followed to calculate the settlement at the base of a pier. The area considered is any part of the structure whose load is carried by the tower piers considering the tributary area. First, the dimensions of the cathedral were recorded. Peterborough Cathedral was built using geometric rules, which made finding the dimensions easier than in other cathedrals. The simplified geometry is shown in Figure 12 (Stallard, 1994).

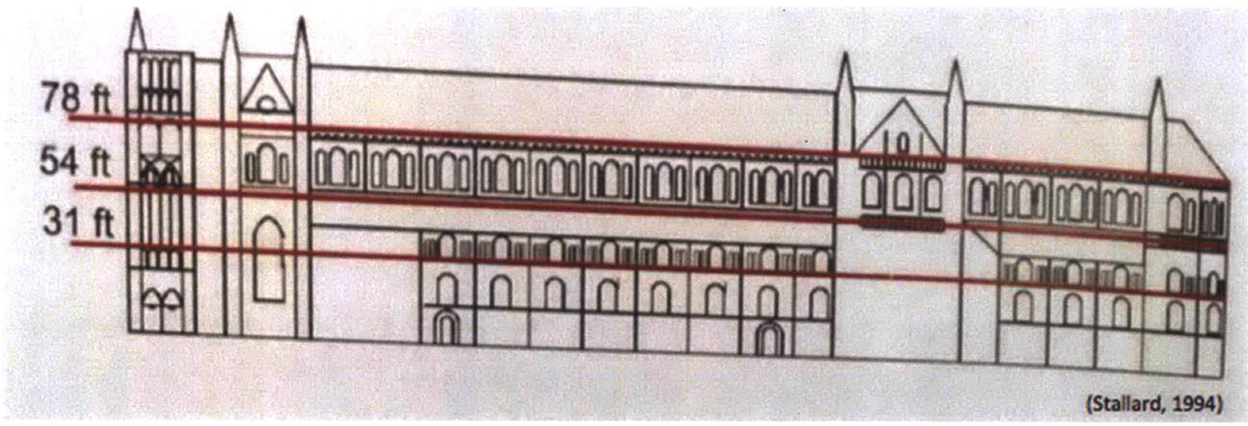


Figure 12: Peterborough Cathedral geometry

Next, the volume of each component was calculated. In the case of arches, the solid volume was found and then the open space under the arch was subtracted. The volume of each component, such as a wall of the tower, was multiplied by the amount within the tower, in this case four. The volume of each material, stone, timber, and copper roofing, was then added up separately. These volumes were multiplied by the density of each material. The mass of material was then multiplied by the gravitational constant to find the weight of the central tower, including the piers, in kN. The stress at the bottom of each pier at floor level was found by dividing the tower by the number of piers, four at Peterborough Cathedral, and then dividing the weight carried by each pier by the surface area of each pier at the floor level. The floor plan and tributary area are shown in Figure 13.

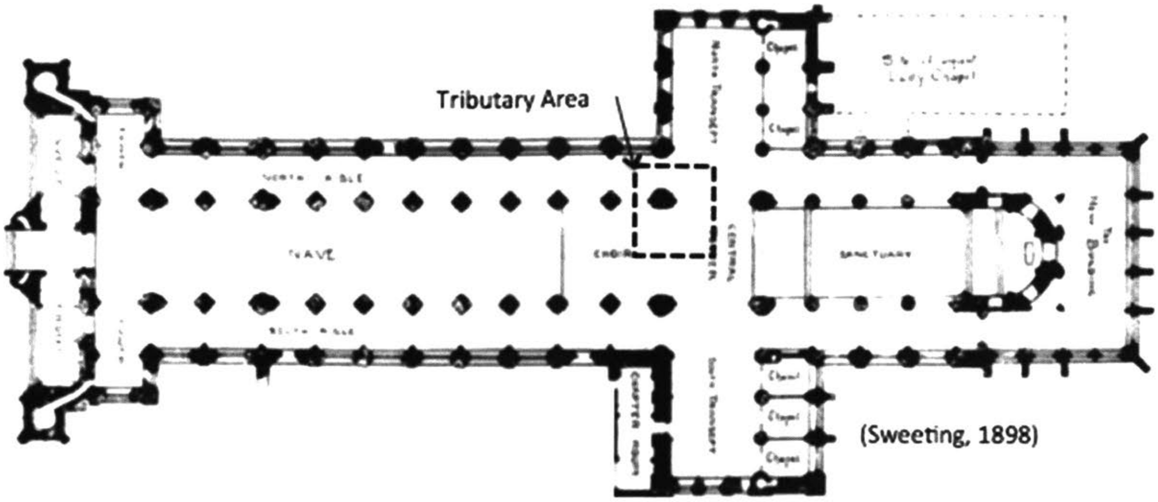


Figure 13: Peterborough Cathedral floor plan and tributary area

This research considers the foundations of cathedrals, so the stress required is the stress of the pier on the soil. Because the exact size of the foundations of the tower piers is unknown at Peterborough, a minimum stress and a maximum stress are calculated. The maximum stress is calculated by adding the weight of the pier to the weight of the foundation, assuming the foundation has the same base area as the pier, and dividing the sum by the pier area. The minimum stress is calculated by adding the weight of the pier to the largest possible foundation, assuming it is a smooth footing, and then dividing the load it by the new, larger area. The larger foundation is idealized as a truncated square pyramid, or a smooth stepped footing, for ease of calculation, as shown in Figure 14. The larger bottom area is a function of depth in this thesis, where the depth of the foundation is added to each dimension of the pier, such that a pier that is 3mx3m with a foundation depth of 1.3m has a final bearing area of 4.3mx4.3m, as demonstrated in Figure 15. Figure 16 shows a cross section taken from an 1898 excavation of the cathedral by J.T. Irvine, showing the shape of the stepped footings at Peterborough Cathedral, which are considered to be smooth for ease of calculation in this thesis. Figure 17 explains the stresses for a tower pier at Peterborough Cathedral. Additional information can be found in Appendix A.

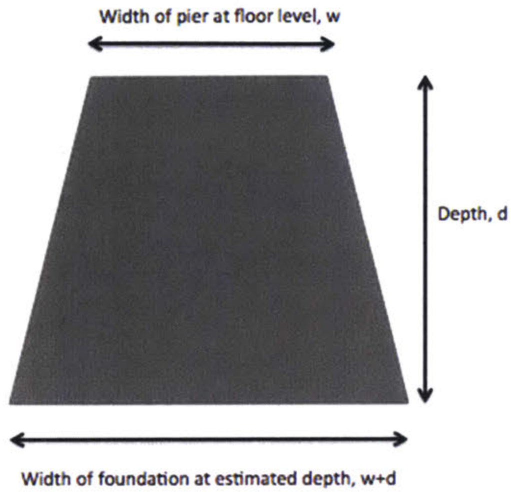


Figure 14: Idealized Smooth Footing (Not to scale)

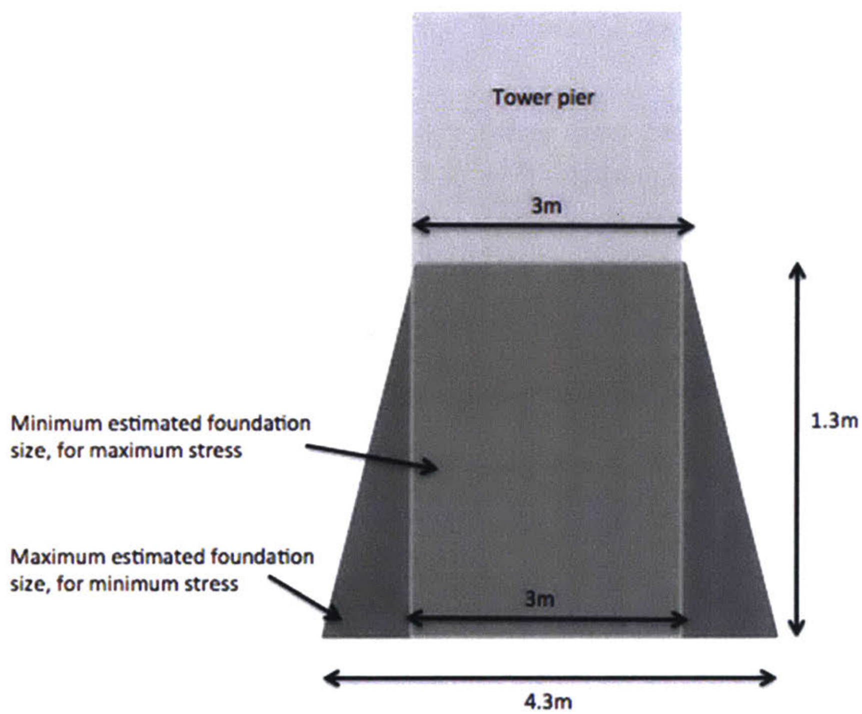


Figure 15: Peterborough Cathedral's estimated foundation dimensions (Not to scale)

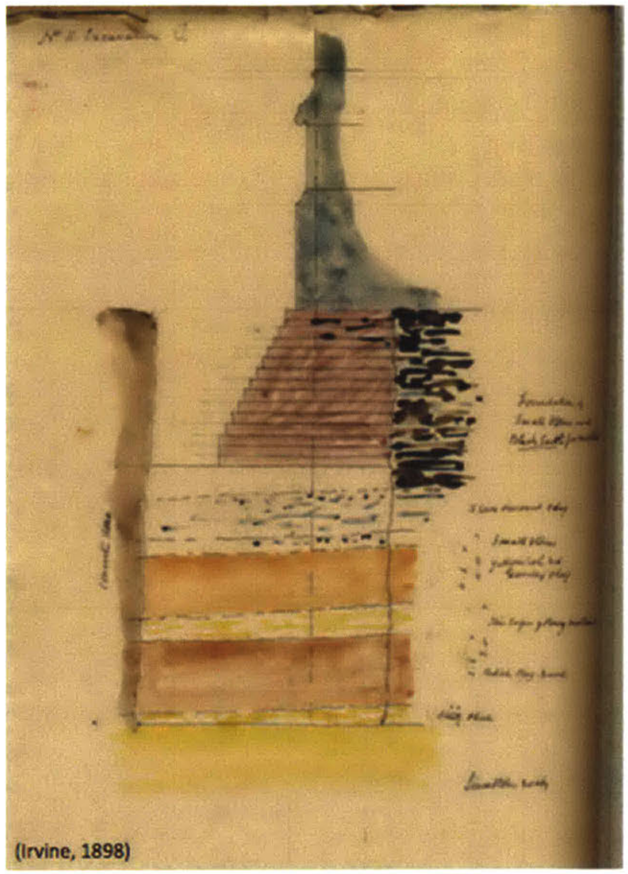


Figure 16: Irvine excavation and cross section

Pier total (kN)	1700
Pier base area (m^2)	9.29
Stress in pier at floor level (kN/m^2)	1830
Foundation depth (m)	1.3
Foundation base area (m^2)	18.9
Added foundation volume (m^3)	19.4
Added foundation weight (kN)	457
Weight at depth (kN)	17500
Max stress at depth (kN/m^2)	1860
Min stress at depth (kN/m^2)	925

Figure 17: Peterborough Cathedral values to compute stresses

Table 1 is a list of results, and for each cathedral tabulates the foundation depth, the maximum and minimum stresses, and the tower height. The same procedure as outlined above was followed for each cathedral. The tower height is included because it is the largest factor affecting the stresses at the base of each pier. The height of Ely Cathedral's Norman Tower was estimated to be the same as Peterborough's Tower. This is because they were built around the same time and as they are closely located, they were built very similarly.

Table 1: Summary of stresses at base of pier

Cathedral	Foundation Depth (m)	Minimum Stress (kN/m^2)	Maximum Stress (kN/m^2)	Tower Height (m)
Peterborough Cathedral	1.3	925	1863	45.72
Durham Cathedral	2.3	768	2048	66.45
Winchester Cathedral	4.6	383	1406	45.72
St. Albans Cathedral	5.3	326	1135	43.89
Selby Abbey	3.0	442	2437	39.62
Ely Cathedral Norman	4.0	374	1309	45.72
Ely Cathedral Octagon	1.7	429	1006	52.00

This chapter focused on the structural analysis of the cathedrals and the stresses in each pier. The following chapter will cover the geotechnical considerations and calculate the settlement for each pier.

3. Geotechnical Considerations

The previous chapter considered the structural components of cathedral towers and naves. This section will cover the geotechnical considerations corresponding to the central tower and nave of an English cathedral, as well as calculate the expected settlement.

3.1. Assumptions

Several assumptions were made regarding the soil conditions of each cathedral. First, elastic theory was used to calculate settlements. Each soil layer is considered to be continuous and have equal depth at all points under the cathedral. The modulus of elasticity was estimated and the same values were used consistently throughout this thesis. These values can be found in Table 2. Similarly, the allowable bearing capacity of soil layers is found in Table 3, adapted from Mark, 1995. The soil conditions were retrieved from the British Geological Survey (BGS) site and the borings used were made available by the BGS. These borings are available in Appendix C.

Table 2: Soil Moduli of Elasticity

	E (MPa)			
Soil Description	Loose	Medium	Dense	
Gravels/ sands well graded	55	120	240	
Sand, uniform	20	40	65	
Sand/ gravel silty	9.5	16	25	
Soil Description	Soft	Medium	Stiff	Hard
Silts with slight plasticity	5.25	12.5	27.5	60
silts with low plasticity	3.75	8	20	45
Clays low medium plasticity	2.75	6.5	19	50
clays high plasticity	2.175	5.5	13.5	26
Organic silts		2.75		
Organic clays		2.25		
Peat*				50
Rock Description				
Chalk	960			
Limestone	1500			
Sandstone	1500			

* Described as "hard," "impervious," and "compressed" (Henderson and Crook, 1984)

Table 3: Allowable Bearing Capacity (Mark, 1995)

Subsoil	metric tons/m^2	kN/m^2
Massive rock (trap rock)	1000	9800
Foliated rock (slate)	400	3900
Sedimentary rock (sandstone)	150	1500
Compacted gravel, sand gravel mixtures	130	1300
Loose gravel; Compact coarse sand; Stiff clay	40	400
Loose coarse sand or sand gravel; Compact fine sand	30	300
Loose, fine sand; Medium stiff clay	20	200
Soft clay	10	100

3.2. Methodology

The stress at the base of the cathedral piers was estimated in the previous chapter. This chapter focuses on calculating the settlement of these piers. To calculate the settlement, three methods were used: the stress bulb approach, the rigid plate load method, and the uniform plate load method. These three methods range from least conservative, estimating smaller settlements (stress bulb approach) to more conservative, estimating larger settlements (uniform plate load method).

All three methods rely on the Modulus of Elasticity of soil. The assumptions made regarding the stiffness of each soil type were described in the previous section and the values are shown in Table 2. Two different values for the Modulus of Elasticity were considered in the settlement calculations. The first value is the average modulus over the depth of influence, assumed to be $\frac{\sqrt{2}}{2}B$, where B is the width of the base of the foundation. E_{avg} is calculated by the formula $E_{avg} = \frac{E_1 t_1 + E_2 t_2 + \cdots}{t_1 + t_2 + \cdots}$, where t_n is the layer thickness and E_n is the corresponding modulus. This formula lets the cathedrals with bedrock near the surface have a higher modulus. The second modulus considered is just the top bearing layer of soil, denoted by E_{top}. This modulus leads to greater settlements. The three methods used to calculate settlement follow below.

Stress bulb approach: The stress bulb is defined by the depth of influence, $t = \frac{\sqrt{2}}{2}B$. To calculate the settlement, the formula $\delta = \frac{Pt}{AE}$ is used, where P is the force (kN) at the base of the foundation, t (m) as the depth of ground deformed, A (m) is the area at the base of the foundation, and E (MPa) is the Modulus of Elasticity estimated by the two different approaches mentioned above. δ (m) is the estimated settlement. These calculations were repeated for all of the cathedrals towers and piers. The settlement was calculated for each cathedral for the maximum settlement (from the maximum load) and the minimum settlement (from the minimum load). This method was repeated for E_{avg} and E_{top}. Figure 18 shows a typical cross section with soil strata and depth of influence.

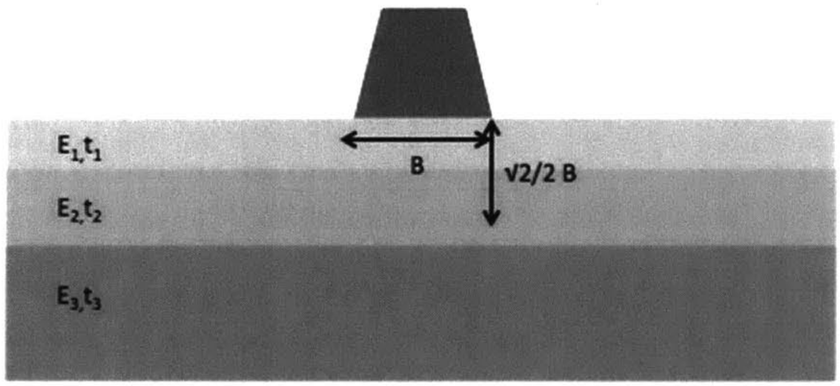


Figure 18: Typical soil cross section and depth of influence

Rigid plate approach: The foundation is assumed to be rectangular so a circle with the same area as the rectangular footing was found. The equivalent radius, a (m), was then calculated. The formula for a rigid plate is $\delta = \frac{P}{2aE}(1 - \nu^2)$, where a (m) is the equivalent radius and ν is Poisson's ratio, assumed to be 0.2. This method was repeated for E_{avg} and E_{top}.

Uniform plate approach: This method yields the highest average settlements. The deformation is found by the formula $\delta = \frac{2P}{\pi a E}(1 - \nu^2)$. This method was repeated for E_{avg} and E_{top}.

3.3. Soil Conditions and Interpretations

Each cathedral has different soil conditions. Soil layers are idealized to be simply clay or simply rock. Soil information was found on the British Geological Survey website and soil borings were retrieved from the site. The borings used for soil cross sections are those closest to the cathedral. The history of structures on the site that collapsed due to inadequate soil conditions is important to study because it may shed light on why medieval builders chose to build how they did.

3.3.1 Peterborough Cathedral

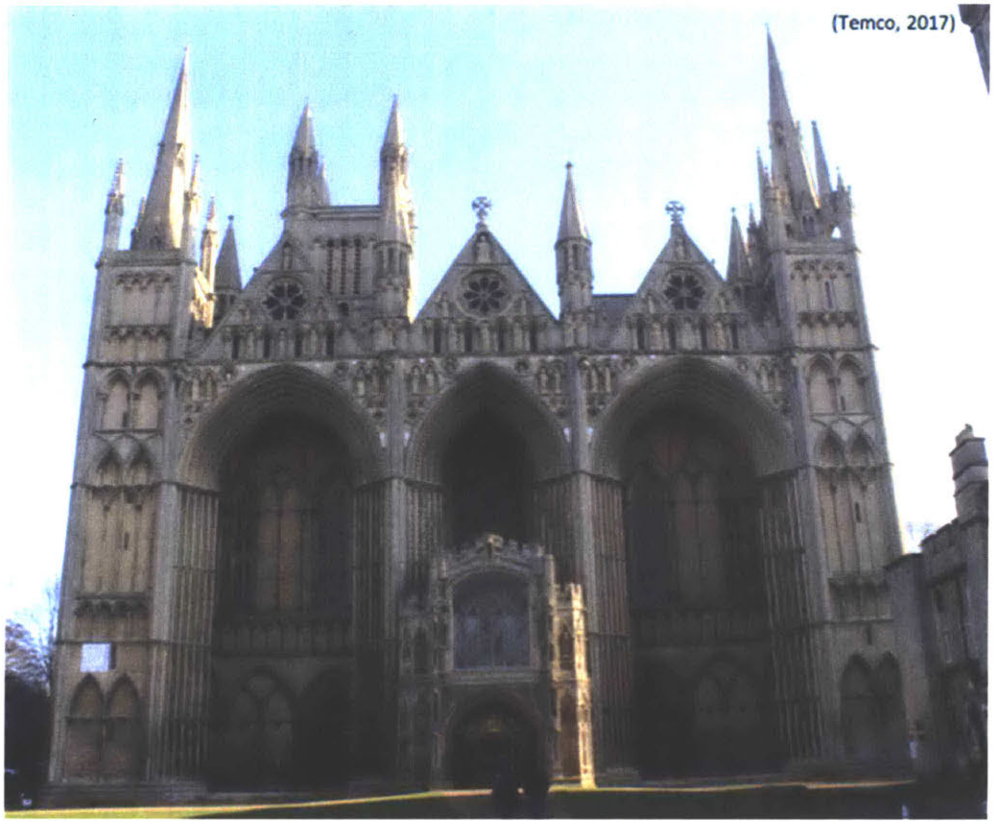


Figure 19: Peterborough Cathedral

Peterborough is located in Cambridgeshire, England, about 75 miles north of London and near the River Nene, as shown in Figure 20. The first monastery on the site was founded in 655 A.D. The Vikings destroyed the settlement in 870, and it was rebuilt as a Benedictine Abbey between 960 and 970. A fire destroyed the abbey in 1116, and the current cathedral was rebuilt between 1118 and 1238 (Peterborough Pocket Guide). The central tower was built from 1155-1177, but was taken down because of impeding collapse ("Peterborough Cathedral"). During the 14th century the Norman tower was rebuilt in the Early English style with pointed arches.

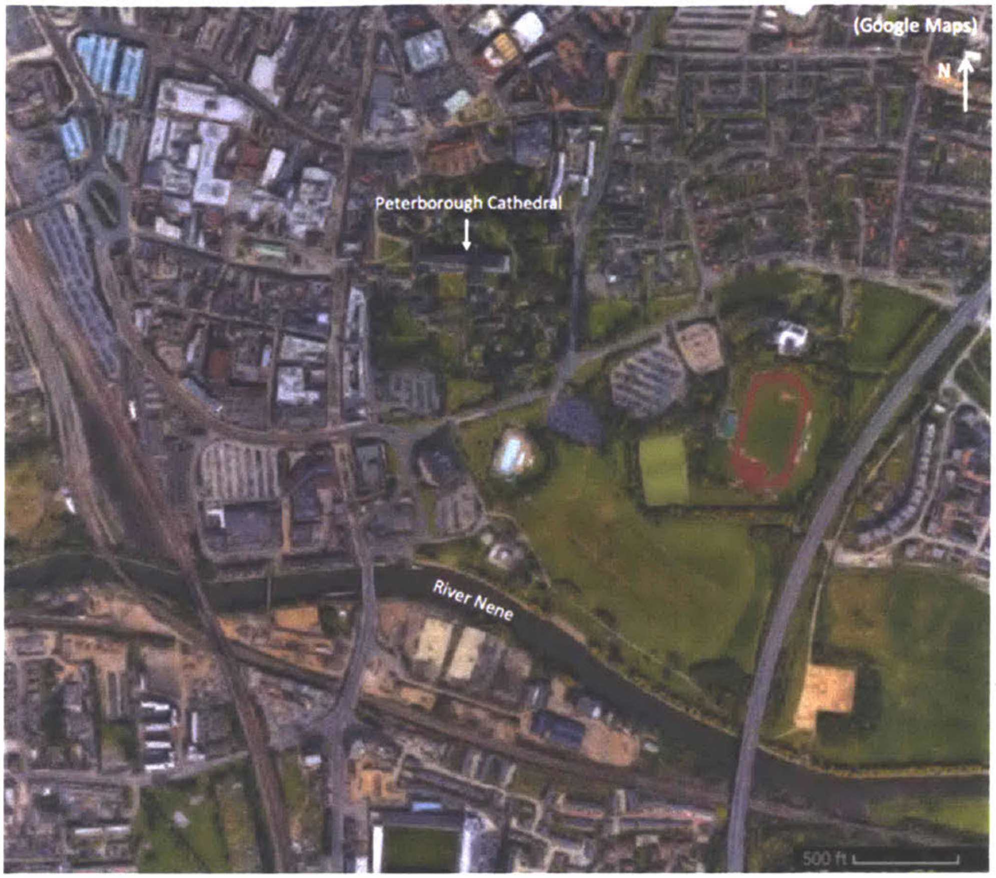


Figure 20: Peterborough Cathedral location aerial view

In 1883 architect J.L. Pearson condemned the tower as unsafe and the area beneath it was no longer used. Figure 21 shows the extent of the damage in a photo taken before 1883.

Figure 21: Cracks in Peterborough Cathedral's tower

Planks of wood and iron bands were used to support the central piers. Large cracks can be seen above the arches. Sir Gilbert Scott, a well-known restoration architect, was hired to work on the cathedral. The Building News and Engineering Journal published in article on Peterborough Cathedral in 1893 saying,

> "Considerable evidence of settlement is not so distinctly marked. The foundations at this point do not seem faulty, for the pier from the ground-line to the organ-gallery level shows no actual settlement. Above this level the compression increases upwards, showing that the failure of the column is chiefly due to the crushing of the rubble core. The north aisle of the choir, long in a sadly decrepit and sinking state, had to be shored with timber, while the foundations throughout the cathedral were of the most faulty description. The site itself is a bad one, owing to its extremely water-logged nature" ("Peterborough Cathedral").

Foundations are not always the main cause of collapse. This article shows that although many cathedrals collapsed due to inadequate foundations, or in the case of Peterborough Cathedral's tower, had already been removed once because of foundation problems, the foundation is not always the cause of collapse. To complete the restoration of the tower in the 1880's, the portion of the tower above the arches was removed stone by stone and reconstructed the same way as before.

Cambridgeshire is relatively flat, and Peterborough is on the edge of the Fens. Until the Fens were drained during the 17th century, Peterborough and the surrounding areas often flooded. The water table during the 12th century was vastly different than the water levels in the area today. The water table was much higher. The top layer of soil consists of sandy alluvial deposits, underlain by Bilsworth clay, a stiff clay or mudstone, which is underlain by Bilsworth limestone. J.T. Irvine's drawings from the 1890's show that the foundations of the choir go to a depth of 1.3m and are resting on the clay as previously shown in Figure 16 and as expanded upon in Figure 22. The limestone is about 2m below the clay. Figure 23 is a geologic map of the surrounding area.

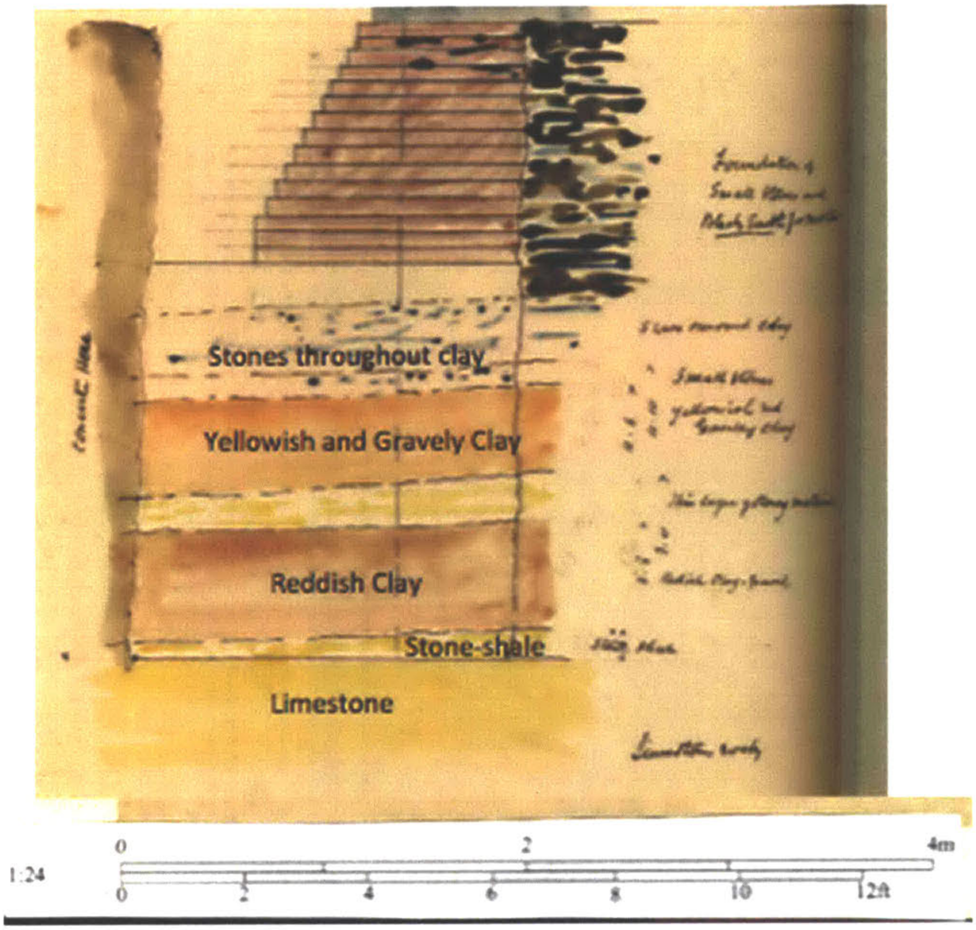


Figure 22: Peterborough Cathedral geologic cross section

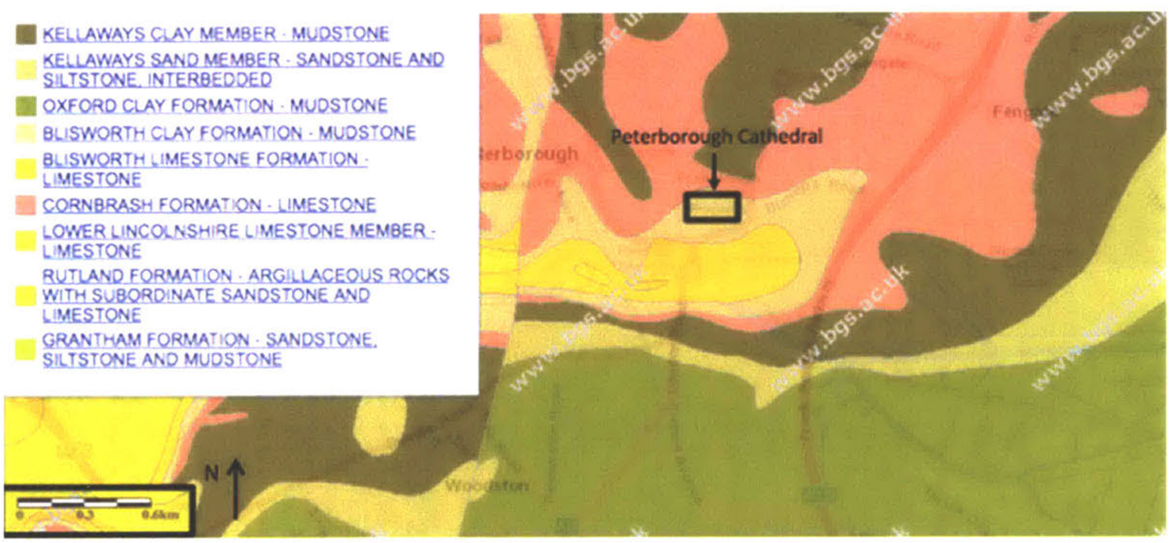


Figure 23: Geology of Peterborough and surrounding area

The foundations are truncated pyramids, as shown in Figures 22. However, these foundations are idealized as pyramids to facilitate the calculations of bearing area and weight, as shown in Figure 15. The estimated foundations size is the top bound of a range, assuming the foundation's actual area ranges from as small as the pier to as large as each side of the pier plus the foundation's depth.

The calculated values for Peterborough Cathedral are summarized in Table 4. The complete calculations can be found in Appendix A. The estimated differential settlement between the tower and the nave when considering E as just from the top layer is 16.5 cm, showing how the two components of the cathedral move with respect to each other considering differences in pier and foundations size.

Table 4: Peterborough Cathedral calculated values

	Peterborough Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Elastic Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	390	17484	17311	0.013	0.015	0.020	0.016
	Top E	19			0.181	0.217	0.277	0.225
Nave	Average E	19	2438	2327	0.051	0.058	0.074	0.061
	Top E	19			0.048	0.058	0.074	0.060

The difference in the two settlements calculated for the tower is because of the difference in E. For this thesis, limestone is assumed to be 1.9m from the surface. When the averaged E is found considering the bulb of influence, E_{avg} significantly increases due to the comparatively high stiffness of the limestone compared to the stiffness of the clay. The two values for the nave are very similar because the bulb of influence under a nave foundation is smaller because the nave pier is smaller than the tower pier.

3.3.2 Durham Cathedral

Figure 24: Durham Cathedral

Durham Cathedral is located in County Durham, about 250 miles north of London. Durham has been inhabited for about four thousand years. The River Wear cuts through the town, forming the peninsula that the cathedral and other medieval buildings were built on, as shown in Figure 25. The cathedral is visible from every part of the town, perched above the river. The present cathedral was begun in 1093. "Durham Cathedral is the only cathedral in England to retain almost all of its Norman craftsmanship, and one of few to preserve the unity and integrity of its original design. The nave, quire and transepts are all Norman and the nave boasts what is believed to be the world's first structural pointed arch" ("Durham Cathedral", 2017). The tower was struck by lightning twice during the 15th century, and the top stage of the tower was finished in 1488. At 250 feet in height, Durham's central tower is one of the highest in England. As Pevsner remarks, Sir Gilbert Scott and the clerk of the works, E.R. Robson, "restored [the tower] in (1858-61), thickening the facing and heightening the battlements" (Pevsner and Metcalf, 1985a).

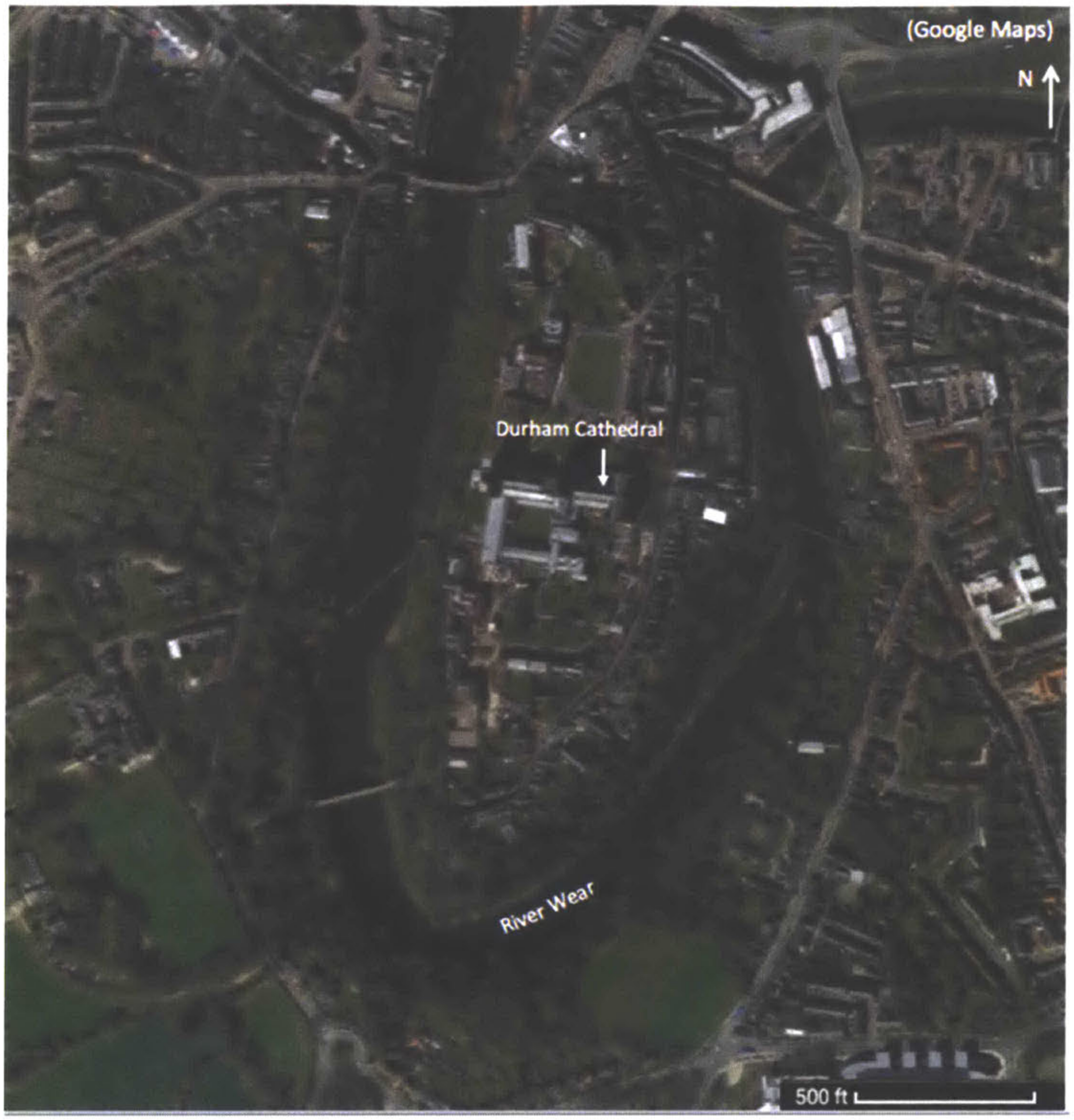


Figure 25: Durham Cathedral aerial view

In 1153 a medieval writer commented, regarding an eastern extension, "[Bishop Hugh de Puiset] began to build a new work at the east end of the church. Columns and bases of marble were brought in from overseas…after great sums had been spent on workmen and the walls had risen to scarcely any height, at last it fell into ruin, and it became clear that is was not acceptable to God and his servant St. Cuthbert. So, leaving that work, he began another at the west"

(Salzman, 1952). A cathedral archaeologist, Stuart Harrison, interpreted this move from the east side to the west side as related to the site's soil conditions. In his article, "Observations on the Architecture of the Galilee Chapel," Harrison states,

> "The cause of failure in the eastern design is readily apparent in the nature of the geology of the ground beneath the cathedral. At the west end the bedrock is relatively close to the surface but progressively drops towards the east until in the area of the Nine Alters Chapel it is around 4m below ground level. It seems clear because of the large floor area covered by the pier bases the architects skimped the foundations which must have started to sink. They cannot have realised that with such a small pier base, supporting a large arcade, the point loading was very large" (Harrison, 1994).

This can be interpreted that the builders did not think they needed large foundations due to the large size of the floor. However, the floor does not take the loads from the piers. Foundations are needed to spread this load. Figure 26 shows a plan view of the cathedral along with the assumed bedrock depth for this thesis.

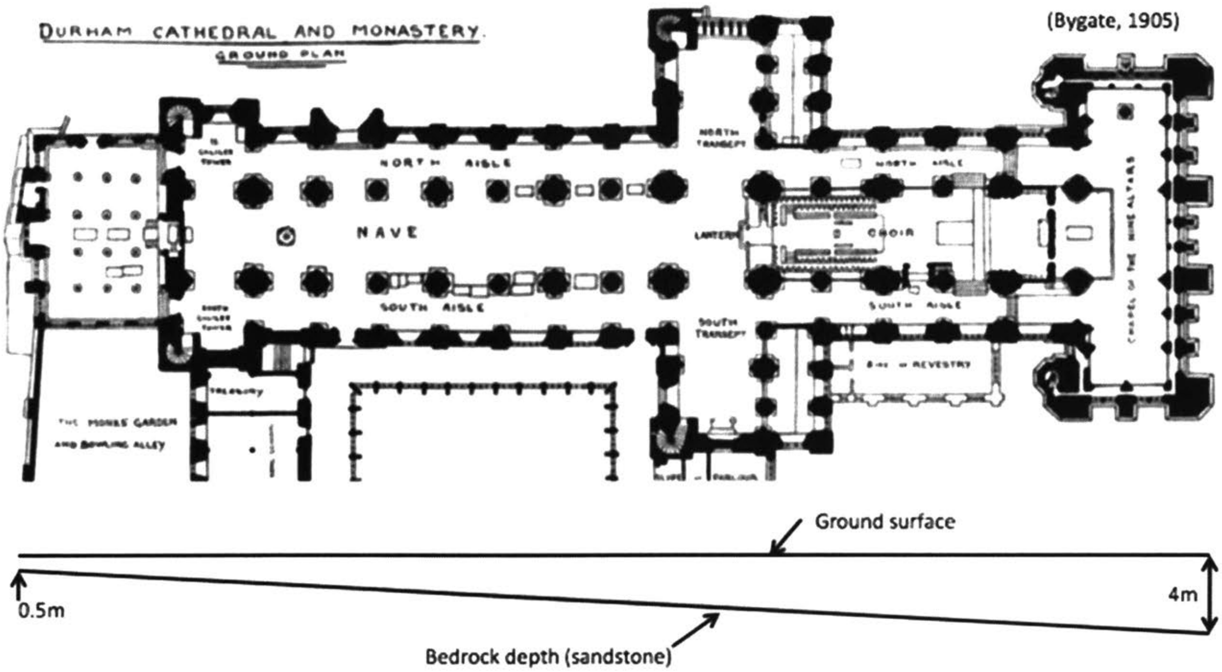


Figure 26: Durham Cathedral plan view

The bedrock under Durham Cathedral is sandstone as shown in Figure 26. Sand and gravel deposits, sometimes with a trace of clay, overlay the sandstone. The sandstone is assumed to be 0.5m below the surface of the west end of the cathedral, and 4m below the surface at the east end. The sandstone depth beneath the tower was interpolated from those two values and is assumed to be 2.3m below the surface, as shown in Figure 26. A depth of 2.3m is reasonable for medieval builders to have constructed foundations. Figure 27 shows the bedrock in Durham and the surrounding area.

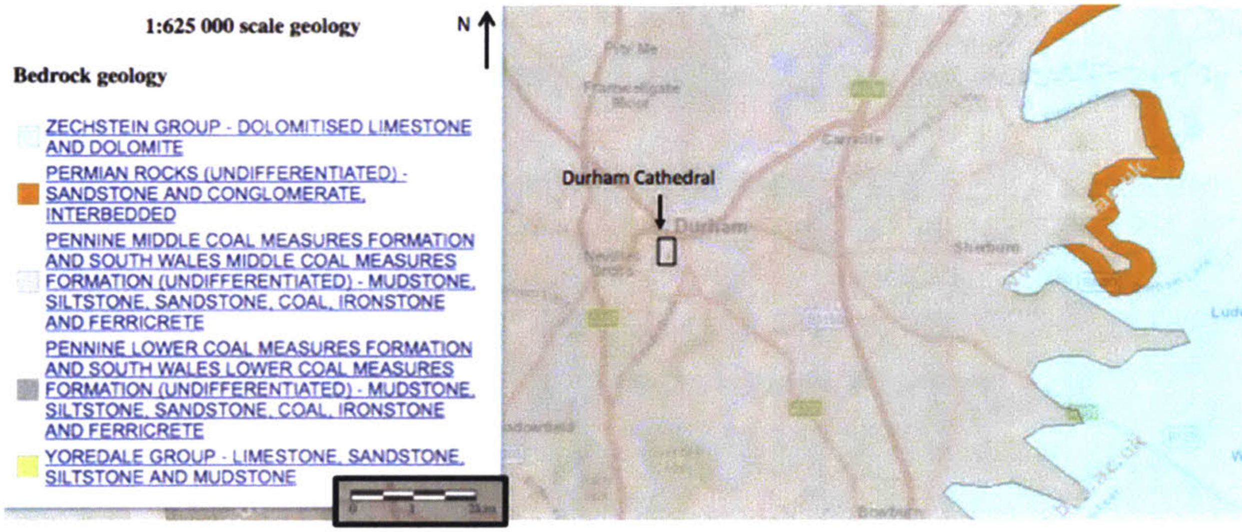


Figure 27: Durham and area geologic map

The foundations are assumed to be stepped foundations and are idealized as pyramids to facilitate the calculations of bearing area and weight as shown previously. The dimensions are shown in Figure 28. Durham's location on bedrock near the surface is unique to the cathedrals studied in this thesis. It is one of the reasons why the central tower could be constructed so tall without collapsing.

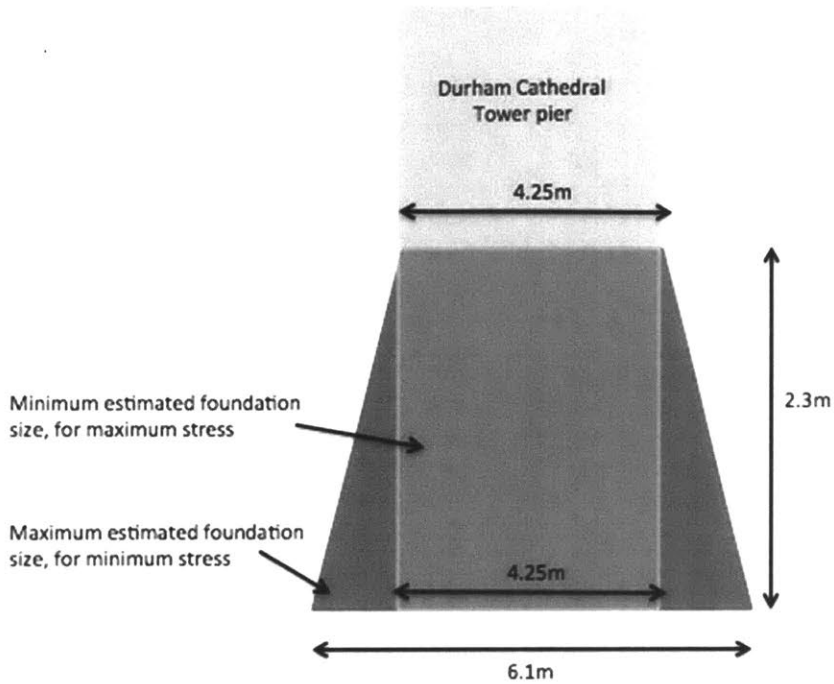


Figure 28: Durham Cathedral estimated foundation size (Not to scale)

For Durham Cathedral, the calculated values are shown in Table 5. The estimated differential settlement between the tower and the nave is 0.2 cm, showing how bedrock near the surface is beneficial because a cathedral can bear on the bedrock without much settlement.

Table 5: Durham Cathedral calculated values

	Durham Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Elastic Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	1500	28520	27760	0.003	0.003	0.004	0.003
	Top E	1500			0.003	0.003	0.004	0.003
Nave	Average E	1500	4417	4076	0.001	0.001	0.001	0.001
	Top E	1500			0.001	0.001	0.001	0.001

3.3.3 Winchester Cathedral

Figure 29: Winchester Cathedral

Winchester Cathedral is located in Hampshire County. It is about 60 miles south west of London. Winchester was first settled during the Iron Age, and then during the Roman period. It was constantly inhabited during the Dark Ages, during which the Old Minster was built. In 871 Alfred the Great declared Winchester as his capital ("Winchester, Ancient Capital of England"). The Normans began a cathedral on the site of the old minster in 1079. Figure 30 shows the orientation of the old minster and the north west side of the current cathedral.

Figure 30: Orientation of the old minster along the current cathedral

The groundwater and soil conditions of Winchester Cathedral contribute to the unique state of the crypt and the repairs done on the choir foundations in the early 20th century. When the crypt was first built the floor was at a depth greater than it is now. It flooded regularly as the ground water table rose each winter. The water level in the crypt is shown in Figure 31. As John Crook remarks his book with Ian Henderson, *The Winchester Diver*, become of the yearly flood, "the floor level of the Crypt was artificially raised, at some date before the fifteenth century, by half-filling it with earth: this was cleared again in the late nineteenth century… the level of the Crypt floor would seem to indicate a rise in the winter water-table since the end of the eleventh century…. The water table seems to be higher now than when the cathedral was first built" (Crook and Henderson, 1984).

Figure 31: Winchester Cathedral Crypt

The cathedral needed a lot of repairs during the end of the 19th century, and the foundations of the choir were underpinned during a huge project from 1905-1912. A diver was used because of the height of the water table. The soil conditions that the cathedral is built on likely contributed to the need for repairs. The cathedral was built on Marly Clay, underlain by peat, which is underlain by a thin layer of silt, followed by gravel and then chalk below, as shown in Figure 32 (Henderson and Crook, 1984).

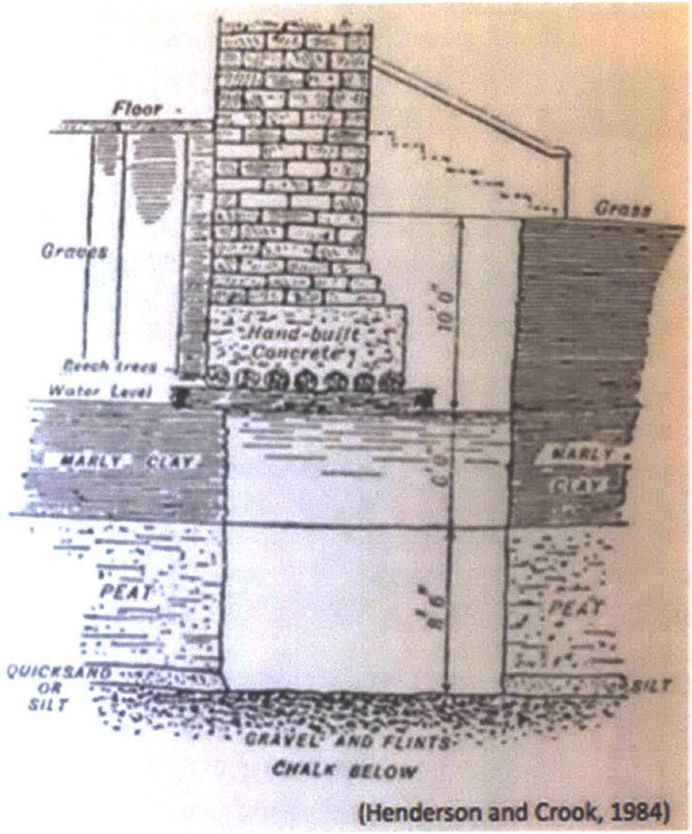
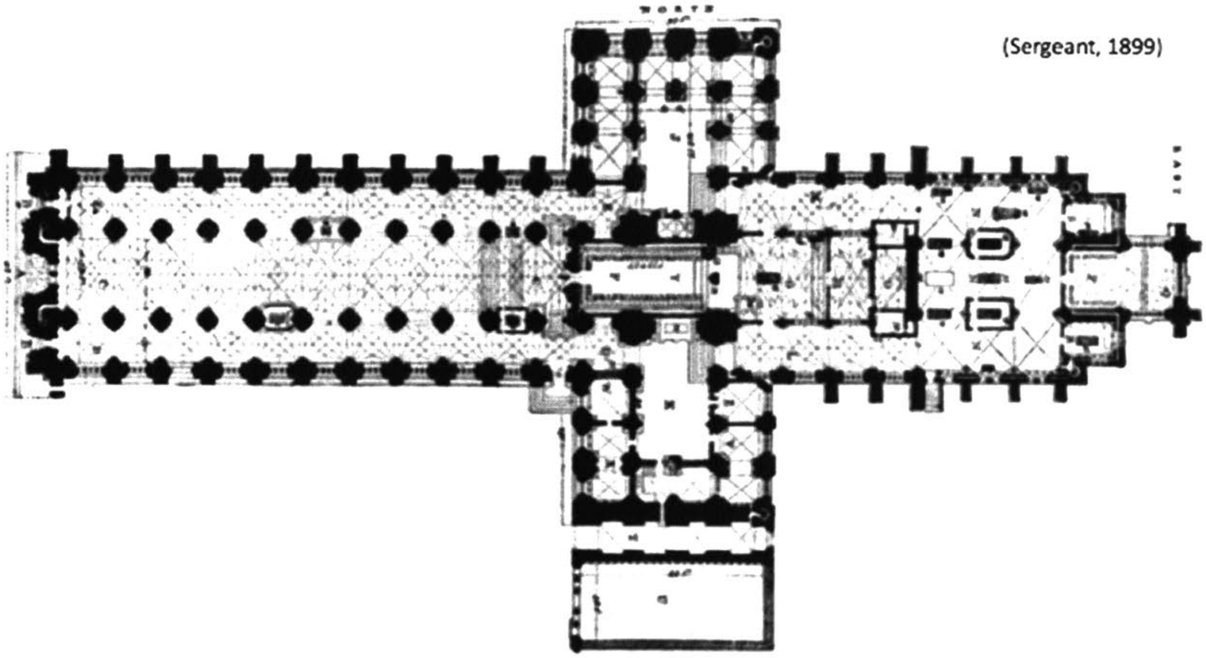


Figure 32: Winchester soil profile

The original tower collapsed in 1107. This is possibly due to inadequate foundations along with a change in the water table. For this thesis, it is assumed that the foundations of the central tower go to the same depth as those of the choir, and rest on Marly Clay at a depth of 4.6m. A plan view of the cathedral is shown in Figure 33.



(Sergeant, 1899)

Figure 33: Winchester Cathedral plan

The foundations are assumed to have the dimensions shown in Figure 34. Winchester is a unique case to study because so much work was done on the cathedral about a century ago. Additionally, cracks are still visible and are still being monitored in the choir.

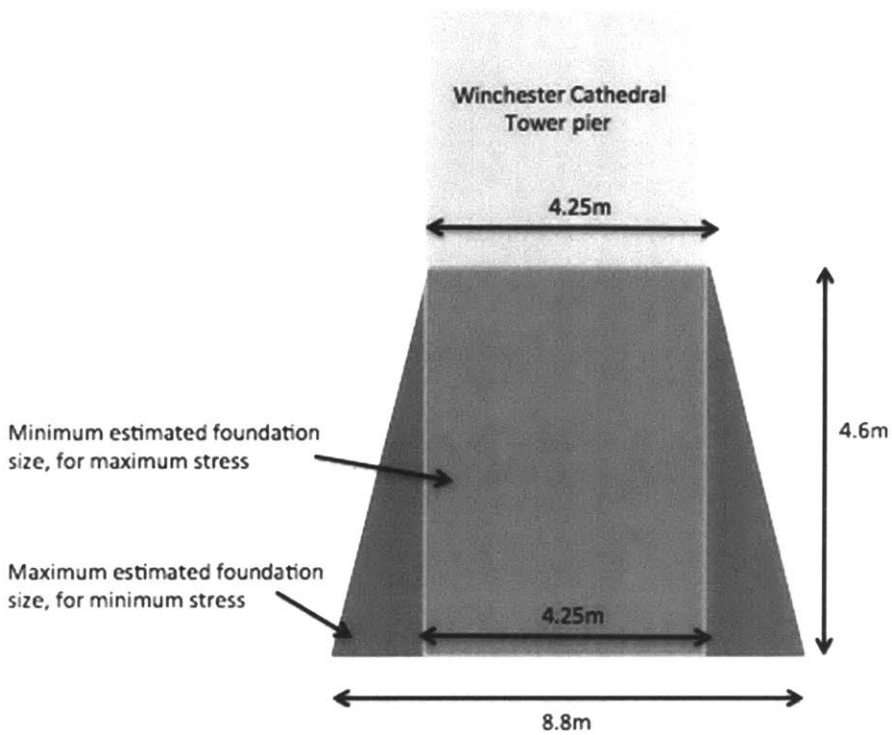


Figure 34: Winchester Cathedral estimated foundation dimensions (Not to scale)

For Winchester Cathedral, the calculated values are shown in Table 6. Similar to Peterborough Cathedral, there is a large difference in the average estimated settlement between the two E values used. This is because Winchester's soil strata vary, and the soil is not only Marly Clay, as E_{top} consdiers. In this situation, the actual settlement will be closer to the E_{avg} value than the E_{top} value because of the many other relevant soil layers.

Table 6: Winchester Cathedral calculated values

	Winchester Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Elastic Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	139	29944	25598	0.077	0.092	0.118	0.096
	Top E	19			0.223	0.210	0.268	0.234
Nave	Average E	22	4959	1974	0.046	0.053	0.068	0.056
	Top E	19			0.049	0.061	0.078	0.063

3.3.4 St Albans Cathedral

Figure 35: St Albans Cathedral

St Albans Cathedral is located in Hertfordshire, England, about 19 miles north of London. St Albans was a very important Roman town. Construction of the present cathedral started in 1077. St Albans Cathedral is unique in the study of the geotechnical conditions of crossing towers because "it is the only 11th century crossing tower in a major church still standing in its original form" (Mitchell, 2006). In 1870 Sir Gilbert Scott led the repairs when it was discovered that the northeastern corner of the tower was weakened, possibly during the dissolution of the monasteries during the 16th century (Scott, 1977). From an architectural perspective, as Pevsner remarks, "St Alban's crossing tower is sturdy and seems squatter than it is, because of its uncommon bulk… Inside, we are never allowed to forget the overpowering weight of the walls. The Norman piers and arches seem cut into them, of materials so hard that no pier, no shaft becomes a being with an individual life" (Pevsner and Metcalf, 1985b). The tower piers are shown in Figure 36.

Figure 36: St Albans Central Tower Piers

St Albans is located on the northern edge of the London Basin. The cathedral is likely underlain by some sand and gravel, possibly from river deposits. From local borings, there is stiff brown clay with chalk overlaying chalk. It is assumed that the tower foundations rest on the chalk, which is about 5m below ground surface. Figure 37 is a geologic map.

Figure 37: St Albans Geologic Map

The dimensions of the assumed foundations are shown in Figure 35.

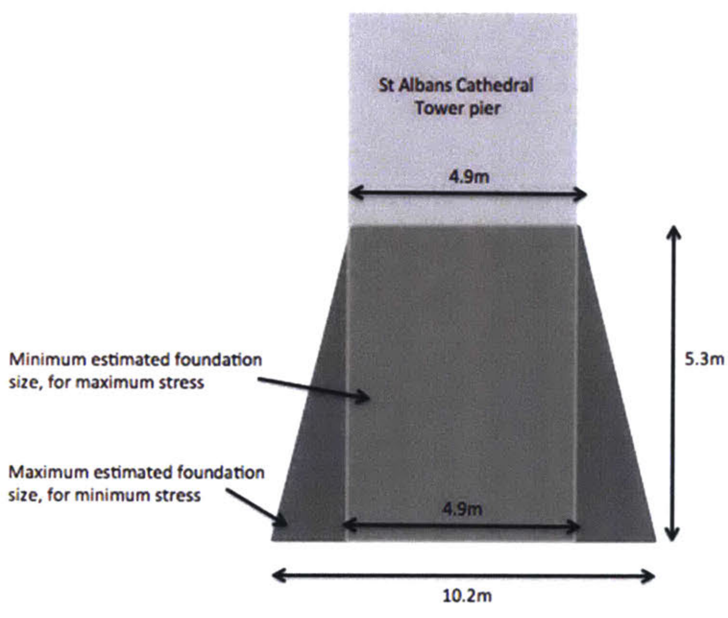


Figure 38: St Albans Cathedral estimated foundation size (Not to scale)

For St Albans Cathedral, the calculated values are shown in Table 7. The estimated differential settlement between the tower and the nave is 0.2 cm, showing how good soil and rock conditions, such as chalk, and larger piers, can lead to limited structural movement. The values are the same for the Average E and the Top E cases because there is only one soil stratum considered, chalk.

Table 7: St Albans Cathedral calculated values

	St. Albans Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Elastic Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	960	33721	26998	0.003	0.004	0.005	0.004
	Top E	960			0.003	0.004	0.005	0.004
Nave	Average E	960	8502	3591	0.001	0.002	0.002	0.002
	Top E	960			0.001	0.002	0.002	0.002

3.3.5 Selby Abbey

Figure 39: Selby Abbey

Selby is located in North Yorkshire, England, along the River Ouse, about 175 miles north of London, as shown in Figure 40. Selby's origins date from a Viking settlement along the river. The Abbey was founded in 1069. A stone building on the current site was begun in 1097. Most of the original abbey still stands today.

Figure 40: Selby Abbey Aerial View

Structurally, the most interesting aspect of Selby Abbey is the deformation present in the nave arches adjacent to the tower. The tower was built after the nave and settled dramatically before the upper portion collapsed in 1690. A new tower was soon built, and the abbey employed Sir Gilbert Scott in the 1870s for additional repairs. In a letter from his son, J. Oldrid Scott, to William Herbert Scott (believed to be unrelated), as published in, "The Story of Selby Abbey: From Rise to Restoration," J. Oldrid Scott comments, "The poor design of the tower is quite out of harmony with this beautiful building and it is in such a dilapidated condition that some steps are necessary even for security. The tower has from the very first suffered from the subsidence caused by the subsoil and foundations being unequal to the weight placed on them, and the arches abutting the tower began to settle at a very early date" (Scott, 1899).

Figure 41 shows a floor plan and the timeline of the construction of Selby Abbey. The tower piers date back to the 12th century, although the two eastern piers have been repaired more recently. The piers that show the deformation are the 12th century piers. The pier on the north side of the nave is shown in Figure 42.

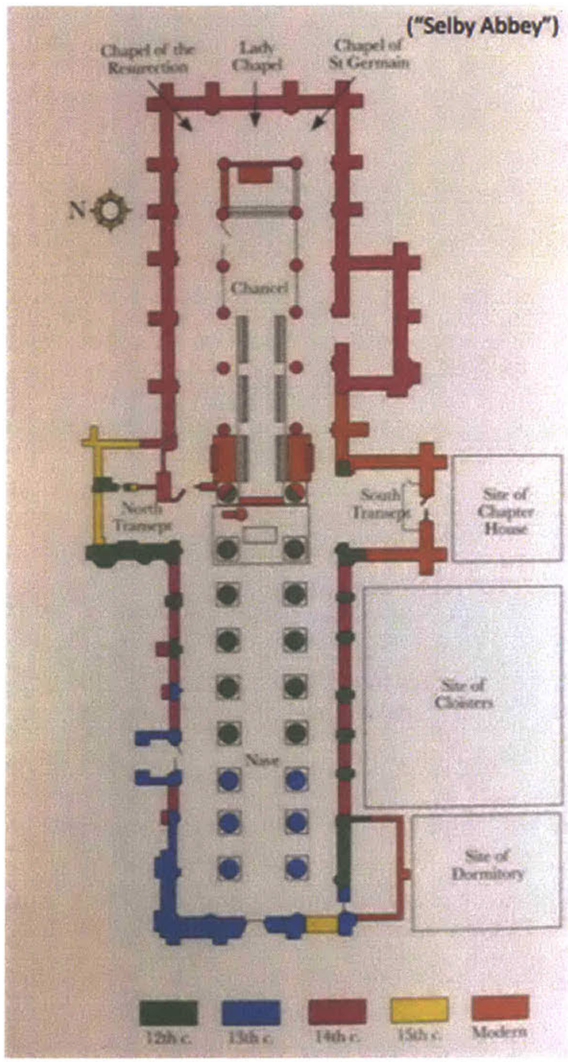


Figure 41: Floor plan and construction timeline of Selby Abbey

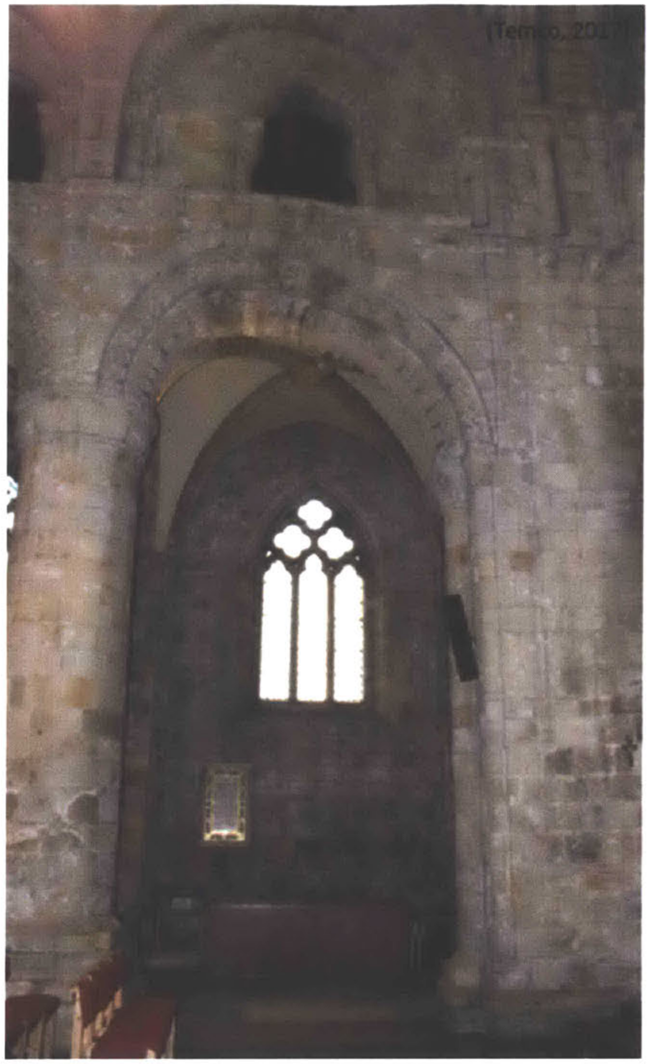


Figure 42: Selby Abbey pier and arch

The settlement is likely because the foundations were inadequate. The cathedral is not founded on rock but on a soft to firm brown silty laminated clay, which compresses, allowing a large amount of settlement to occur. Because the clay is laminated, changes in the water table could affect the strength of the bearing strata. Sandstone is below the clay, but as deep as 20m, and out of the range of the depth of influence. It is possible that the foundations were built on short timber piles, 1m-2m in length, which was common when the soil was not good quality and timber was accessible. The possibility of timber piles is not considered in this thesis. Depending on the water table, some of the timber may have rotted and are no longer supporting the foundation. It is also difficult to know, without excavation, if there are timber piles, and their dimensions, depth, and capacity. The estimated foundations size range is shown in Figure 43.

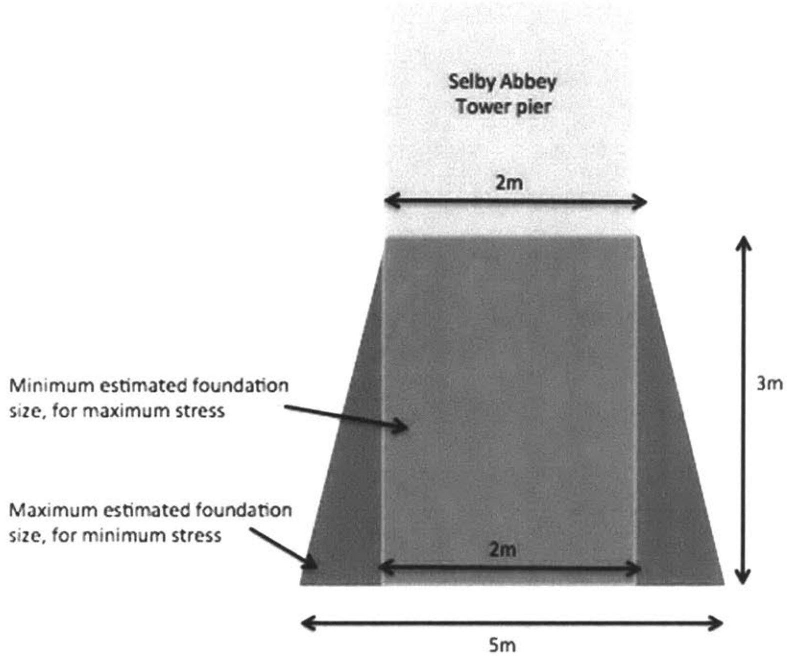


Figure 43: Selby Abbey estimated foundation size (Not to scale)

For Selby Abbey, the calculated values are shown in Table 8. The estimated differential settlement between the tower and the nave is 20.1cm. This difference was shown in Figure 42. The visibility of the differential settlement in Selby Abbey provides a greater understanding to the structural stability of cathedrals. The E used does not affect the calculations because only one soil stratum is considered, clay.

Table 8: Selby Abbey calculated values

	Selby Abbey	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Elastic Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	12.75	11229	10162	0.200	0.240	0.306	0.249
	Top E	12.75			0.200	0.240	0.306	0.249
Nave	Average E	12.75	1352	1241	0.039	0.047	0.059	0.048
	Top E	12.75			0.039	0.047	0.059	0.048

3.3.6. Ely Cathedral

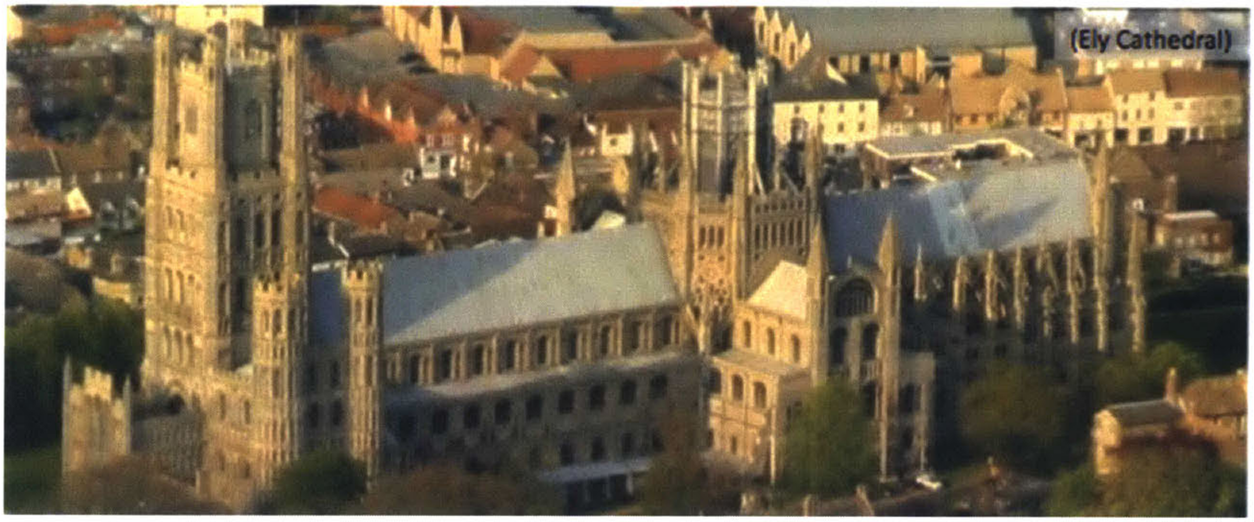


Figure 44: Ely Cathedral

Ely is located in Cambridgeshire, England, about 80 miles northeast of London and 25 miles southeast of Peterborough. Because of the proximity to Peterborough, Ely Cathedral and Peterborough Cathedral have many similarities. The first monastery on the site was founded by Etheldreda, a Saxon Princess, in 673. The site was continually occupied and the construction began on the current cathedral in the 1080s. The site is shown in Figure 45.

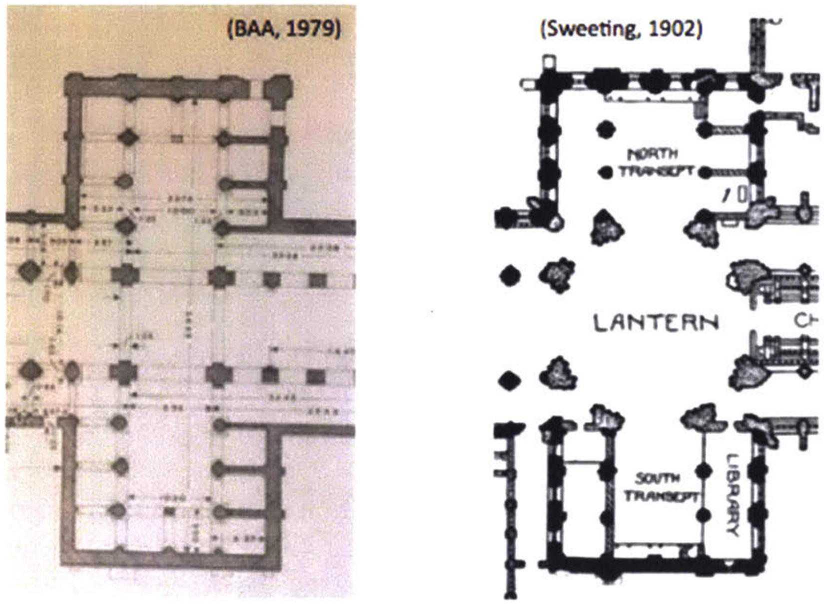
Figure 45: Ely Cathedral Aerial View

Ely is located in the Fens, marshland in eastern England. Ely itself is 39 m above sea level so it did not flood as often as the surrounding marshland. “The "Isle of Ely" is so called because it was only accessible by boat until the waterlogged Fens were drained in the 17th century. Still susceptible to flooding today, it was these watery surrounds that gave Ely its original name the ‘Isle of Eels’, a translation of the Anglo Saxon word ‘Eilig’” (Historic UK).

Ely Cathedral is built using Barnack Limestone, which was floated in on barges from the nearby town. This is the same stone used to construct Peterborough Cathedral. The original cathedral had a Norman crossing tower, similar to Peterborough's tower. The tower collapsed in 1322 and was replaced with the Octagon Tower that it is now famous for, as shown in Figure 47. This thesis considers both the Norman Tower and the Octagon Tower. The geology of the site played a role in the move from a typical crossing tower to an octagon tower during the rebuilding because the collapsed tower and ground underneath was unusable due to the failed preexisting foundations. Text translated from the fall and construction and published in Salzman's Building England Down to 1540 shows the process of rebuilding the tower.

> "After the fall of the central tower at Ely in 1322, Alan the Sacrist 'spent great labour and much money in removing from the cathedral the fallen stones and beams.... Finally he measured out in eight divisions, with the art of an architect, the place where he thought to build the new tower; and he set the workmen to dig and search for the foundations of the eight stone columns whereupon the whole building should be supported... until at last he found solid and secure ground. Then, when these eight places had been carefully dug out and firmly founded with stones and sand, at last he began those eight columns" (Salzman, 1952)

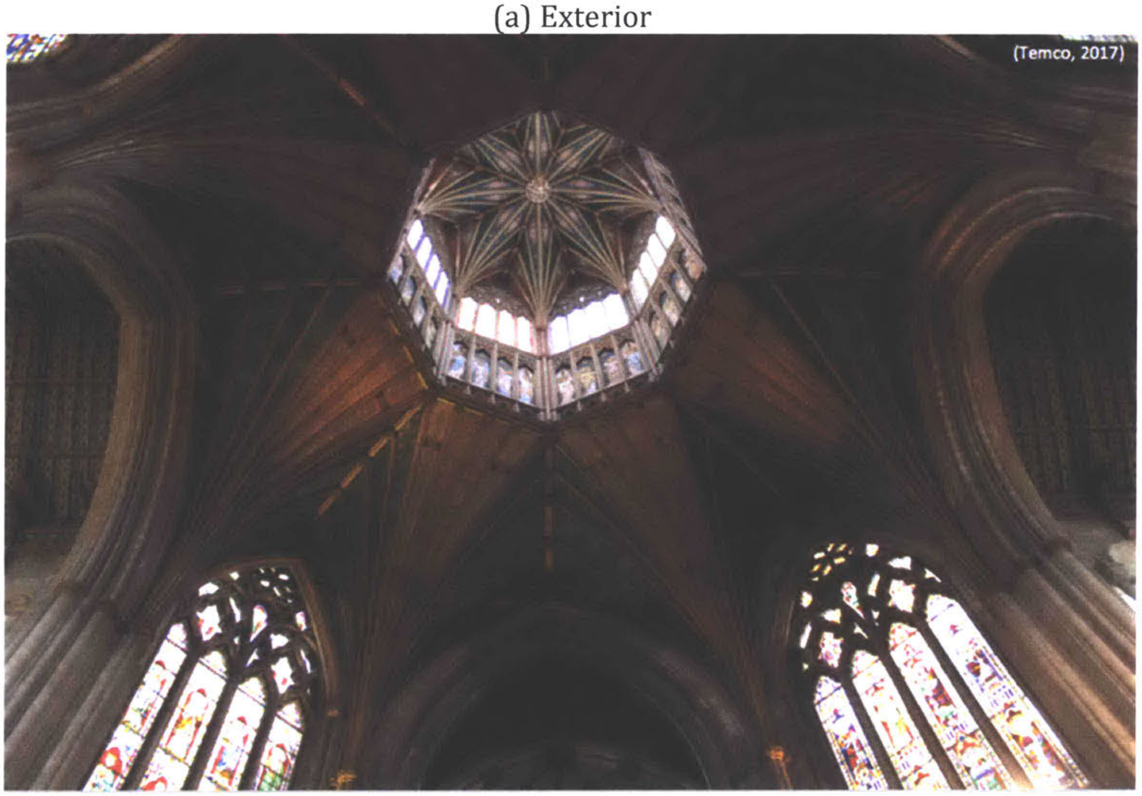
The plan view of the original Norman cathedral tower and the new Octagon tower are shown in Figure 46. The Norman plan has four tower piers (Figure 46a), while the eight tower piers in the Octagon plan (Figure 46b) are visible, as they are not in the center but in a ring around the crossing.



(a) Norman pier plan (b) Octagon pier plan

Figure 46: Ely Cathedral Tower Pier placement

(a) Exterior



(b) Interior

Figure 47: Ely Octagon

Ely is underlain by about 3m of sand with stiff clay underneath. Sandstone is the bedrock. The Norman foundations are estimated to have been about 4m deep for the tower and 1.7m deep for the nave. 4m is chosen because it is possible that the Norman foundations were dug into the stiff clay. The foundation depth of the nave is estimated to be 1.7m because that is the depth of a nearby passage constructed around the same time. The foundation depth of the Octagon is also estimated to be 1.7m deep because excavating any deeper would require supporting the existing nave, choir, and transept. Figure 48 shows a geologic map.

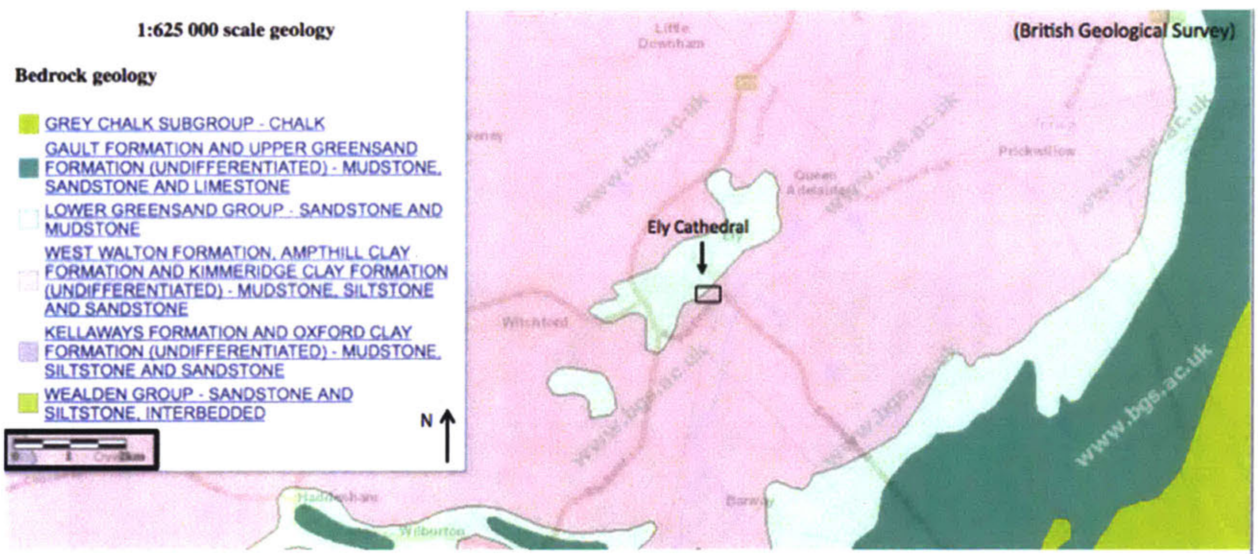


Figure 48: Ely Geologic Map

The depth of the foundations and estimated foundation shape and size range for the Norman tower is shown in Figure 49 and the foundation for the Octagon tower is shown in Figure 50.

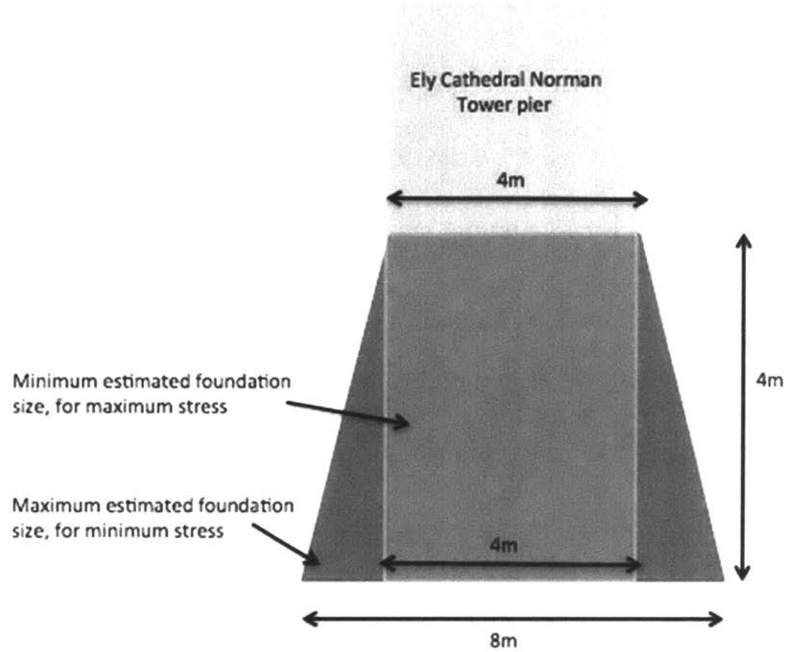


Figure 49: Ely Norman Cathedral estimated foundation size (Not to scale)

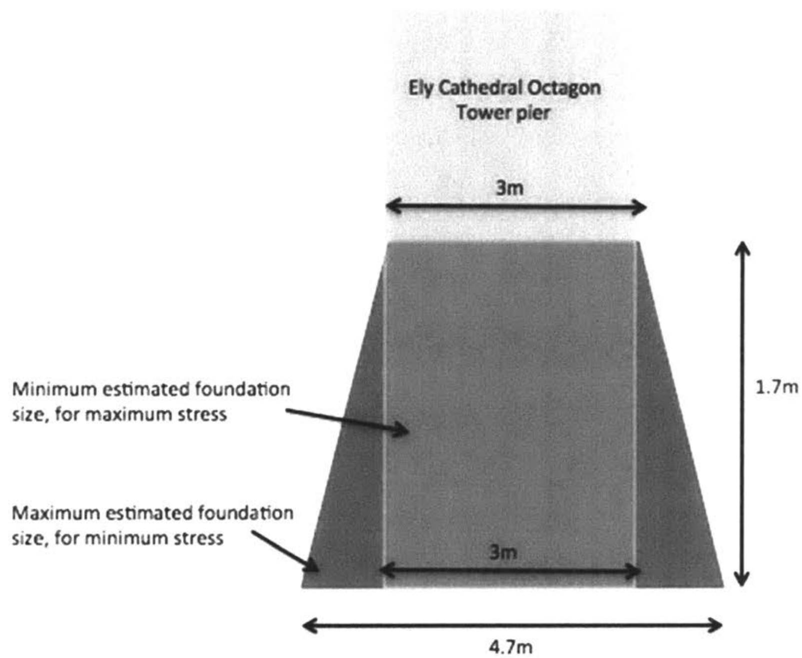


Figure 50: Ely Octagon Cathedral estimated foundation size (Not to scale)

Both the Norman and Octagon towers of Ely Cathedral were analyzed to understand why the original tower was rebuilt as an Octagon. The calculated vales are shown in Table 9.

The estimated differential settlement between the Norman tower and the Octagon tower is about 8cm. This shows how two different structural systems react to similar loads. The Norman tower collapsed while the Octagon has survived. There was also greater differential settlement between the Norman tower and the nave than the Octagon tower and the nave. This is mostly because the nave was built 200 years before the Octagon tower, and by the time the Octagon tower was built, the nave had already settled.

Table 9: Ely Cathedral calculated values

	Ely Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Elastic Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Norman Tower	Average E	17	23958	20947	0.177	0.212	0.270	0.220
	Top E	16			0.182	0.219	0.279	0.226
Octagon Tower	Average E	16	9665	9342	0.112	0.135	0.171	0.139
	Top E	16			0.113	0.136	0.173	0.140
Nave	Average E	16	3434	3216	0.078	0.093	0.119	0.096
	Top E	16			0.077	0.093	0.119	0.096

3.3.6.1. Ely Cathedral Case Study

Ely Cathedral's Octagon Tower is the only one of its size in England. However, as mentioned previously, the Octagon was not the original tower. Ely's original tower was build during the Norman era and was similar to Peterborough's tower. Additional further work will be carried out to understand the cause of the collapse of the Norman tower.

Norman Ely

The Isle of Ely was one of the last to fight against William the Conqueror but the monastic builders were not damaged during the fight. The construction of Ely Cathedral was different than almost every other cathedral because there was a working monastery on the site of the present cathedral, not the ruins of a previous one. As Reverend W. D. Sweeting writes in a Bell's Cathedral edition, Ely: The Cathedral and See, "When the building of the existing cathedral was commenced there was not the same necessity as existed in many other cases. There was no ruin to be rendered serviceable. A church was actually standing and in constant use" (Sweeting, 1902). Ely Cathedral began under Simeon, the ninth abbot (1081-1093), with the transepts, not the east end as was typical, because there was already a choir in use. The Norman tower was sometimes referred to as Simeon's Tower because he began the construction of the piers. Figure 51 shows an "assumed" Norman plan of the cathedral, as created by BAA (BAA, 1979).

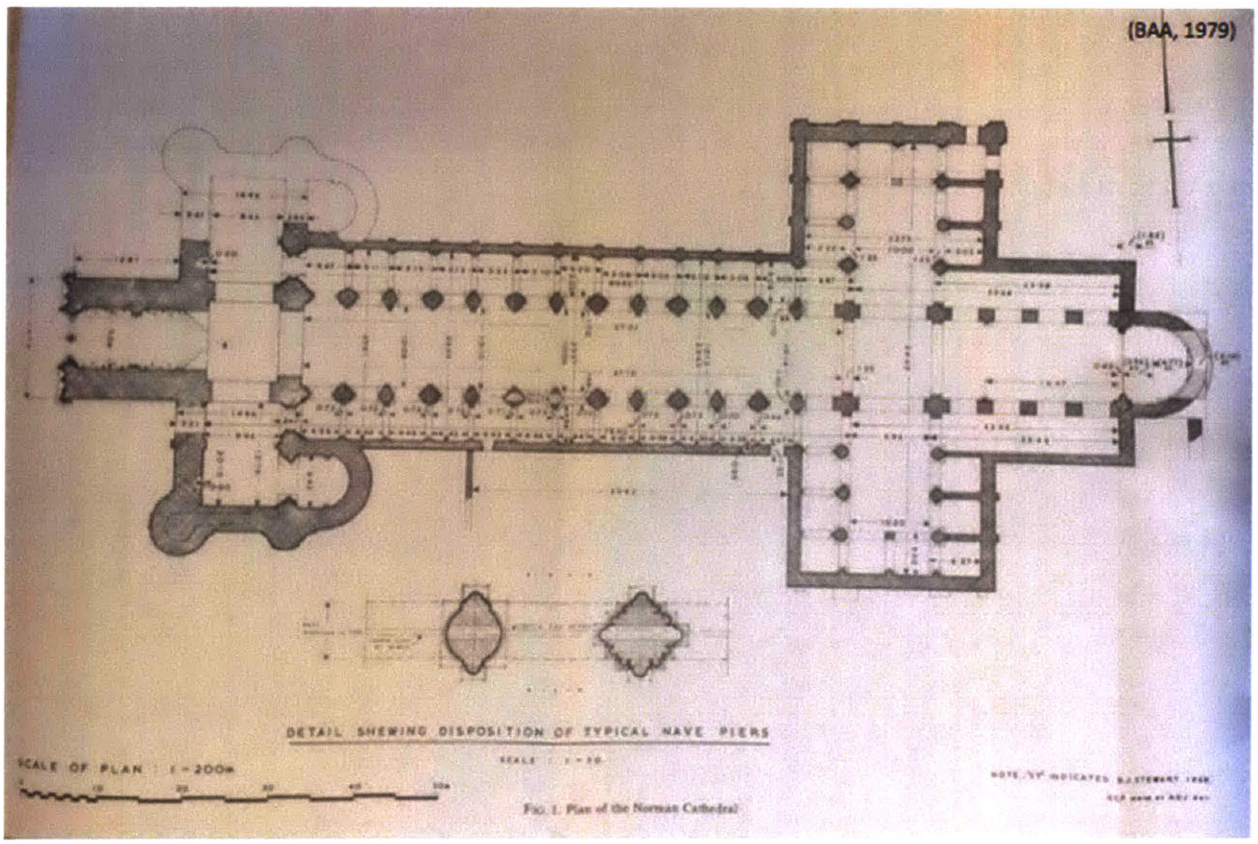


Figure 51: Ely Cathedral Norman floor plan

Tower Collapse

During the early 14th century plans to build the Lady Chapel began. The Lady Chapel is about 15m by 30m and is located very close to the north transept, as shown in Figure 52. The first foundation stone was laid in mid 1321. This means that the excavation of the large space had to be done previously.

It is possible that the excavation of the Lady Chapel affected the central tower, causing differential settlement and impending collapse. As presented in Salzman's Building in England, a translated text from the time states: "In the night before the feast of St. Ermengilde [February, 22, 1322], after matins had been sung in the chapel of St. Catherine, because the convent dared not sing in the quire on account of the threatened fall (of the tower)…. behold! suddenly and swiftly the bell-tower crashed down upon the quire with such a thunderous noise that one might think an earthquake had occurred, but without injuring anyone in its fall" (Salzman, 1952). The Sacrist Rolls of Ely notes that along with the central tower, "four bays of the Norman choir, lay on ground in a heap of ruins" (Chapman, 1907).

The collapse of the tower meant that the cathedral had two large building projects at the time: the Lady Chapel and the Octagon, shown in Figure 52. The Lady Chapel was finished in 1349, likely delayed because of building the Octagon, which was finished in 1340.

(Sweeting, 1902)

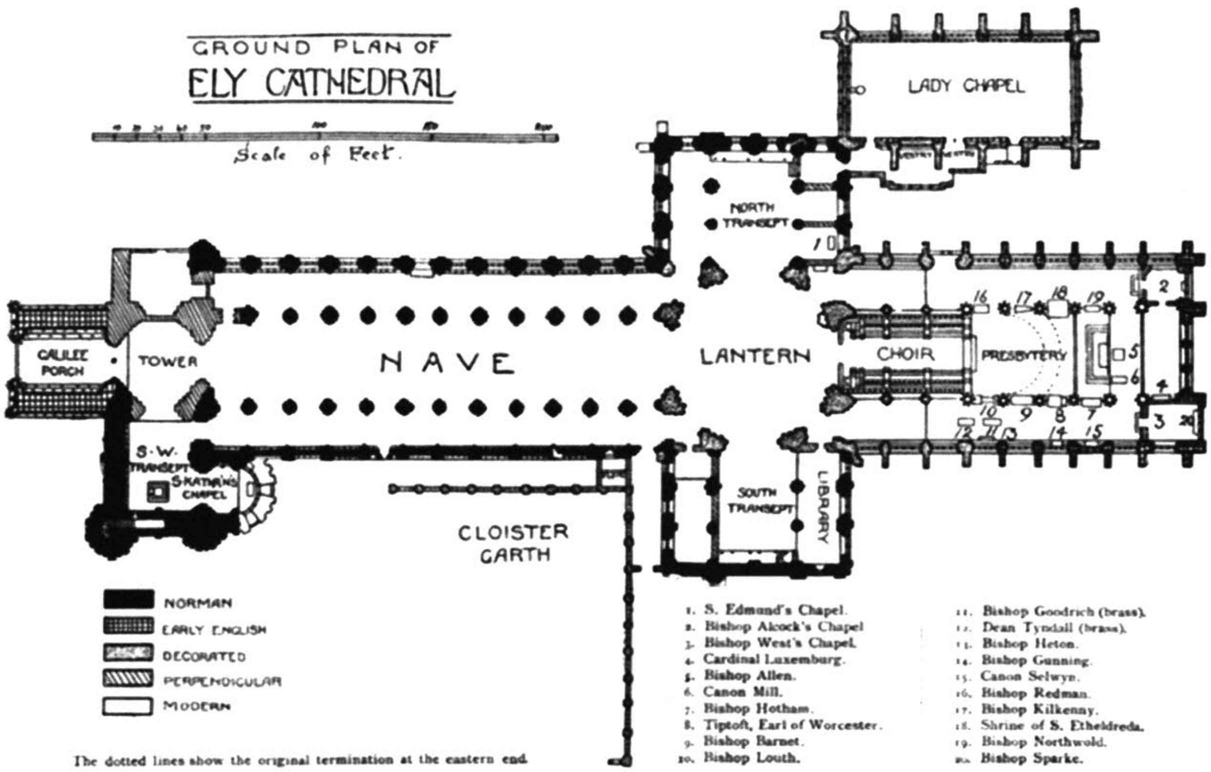


Figure 52: Ely Cathedral post Lady Chapel construction floor plan

Future Work

The Norman Tower could have collapsed for several reasons, including differential settlement of the tower piers leading to an unstable structure, poor masonry construction, or the change in the water table caused by pumping the nearby Lady Chapel excavation. Further work will be done in identifying the cause of collapse.

3.4. Summary

The previous section outlined the settlement for each cathedral. Table 10 shows the soil strata and thickness analyzed for each cathedral.

Table 10: Site Geology

Cathedral	Bearing soil type	Depth of influnce for max foundation (m)	Depth of influence for min foundation (m)	Max layer thickness (m)	Min layer thickness (m)
Peterborough Cathedral	Stiff clay	3.07	2.16	1.90	1.90
	Limestone			1.17	0.26
Durham Cathedral	Sandstone	4.31	3.02	4.31	3.02
Winchester Cathedral	Marly Clay	6.25	3.02	2.00	2.00
	Peat			2.50	1.02
	Silt			0.30	
	Chalk			1.45	
St. Albans Cathedral	Chalk	7.20	3.45	7.20	3.45
Selby Abbey	Firm Clay	3.57	1.44	3.57	1.44
Ely Cathedral Norman	Sand	5.66	2.83	3.00	2.83
	Stiff clay			2.66	
Ely Cathedral Octagon	Sand	3.36	2.16	3.00	2.16
	Stiff Clay			0.36	

Table 11 shows a summary of the calculated data. The average settlement for a central tower was calculated twice: first, considering all cathedrals, and second excluding Durham Cathedral and St Albans Cathedral. These two are excluded because they are founded on rock and settle significantly less than the other cathedrals studied in this thesis. The data from those two cathedrals decreases the average settlement that can be expected. For St Albans Cathedral and Durham Cathedral, and average tower settlement of 0.35cm is expected, and an average nave settlement of 0.15cm is calculated.

For the remainder of the cathedrals, a range of average settlements from 14.4-21.5cm is calculated. This settlement will depend on the soil conditions, tower size and height, and foundation depth. For a nave, the average calculated settlement is about 7cm.

Table 11: Summary of Average Calculated Settlement

Average Settlement (m)		All Cathedrals	Excluding Durham and St Albans
Tower	Average E	0.104	0.144
	Top E	0.154	0.215
Nave	Average E	0.044	0.067
	Top E	0.045	0.067

4. Results

The stress at the base of each cathedral tower pier was the first component calculated in this thesis. To contribute to the work started by Bonde et al (1997), the stress at the base of each cathedral pier (considering maximum and minimum) is compared to the allowable bearing capacity of the soil, as previously shown in Table 3. The results for the six English cathedrals studied in this thesis compared to the allowable bearing capacity are shown in Figure 53. In Figure 53, the vertical lines represent the stress range for each cathedral, considering the smallest possible or the largest possible foundation size. The horizontal lines show the allowable bearing capacity from Mark (1995).

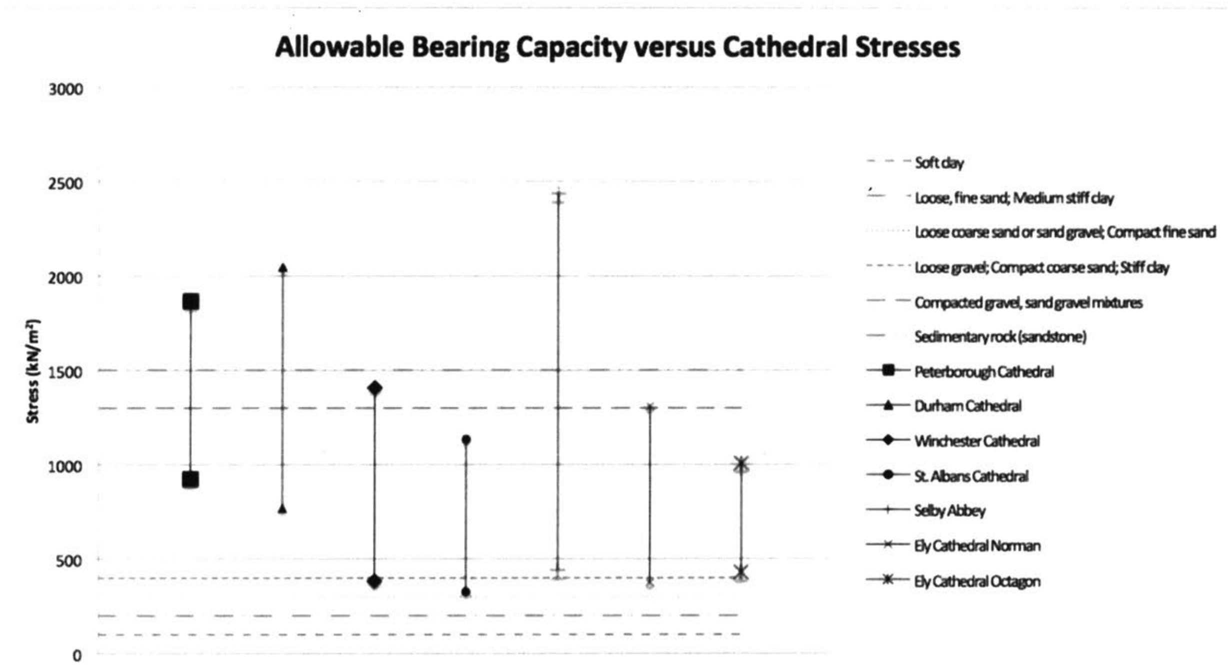


Figure 53: Bearing Capacity versus Tower Pier Stresses

The fact that the stresses in the towers are higher than what is considered "allowable bearing capacity" by Mark can be explained by understanding the range of possible stresses and the variety of soil conditions present. The foundation dimensions and exact soil conditions are not known for any of the cathedrals studied, so Figure 53 shows approximations. The stresses are also not exact because the loads are approximated. It is also important to note that the allowable bearing capacity is in fact a modern allowable capacity for present day structures. A bearing capacity failure would be a shear failure of the soil, and a likely overturning or sliding of the structure above. This does not appear to be the mechanism for collapse or movement in the six cathedrals studied in this thesis. Because a cathedral is within the acceptable range for bearing capacity does not mean that the cathedral is structurally and geotechnically safe from failure. Another mechanism for failure is settlement, especially differential settlement. A cathedral is still inhabitable after it has undergone large amounts of differential settlement, such as previously shown by Selby Abbey, but not always. Studying cathedrals is important so that engineers can understand when a certain amount of deformation becomes dangerous.

Three methods were considered for calculating the average settlement of the tower and nave piers for each cathedral, as discussed previously. Each case was calculated twice, once for E_{avg} and once for E_{top}, as also discussed previously. The average settlement of the tower piers for method considering only E_{avg} is shown in Figure 54. Black symbols represent the stress bulb case, the green symbols represent the rigid plate loading case, and the blue symbols represent the uniform plate loading case.

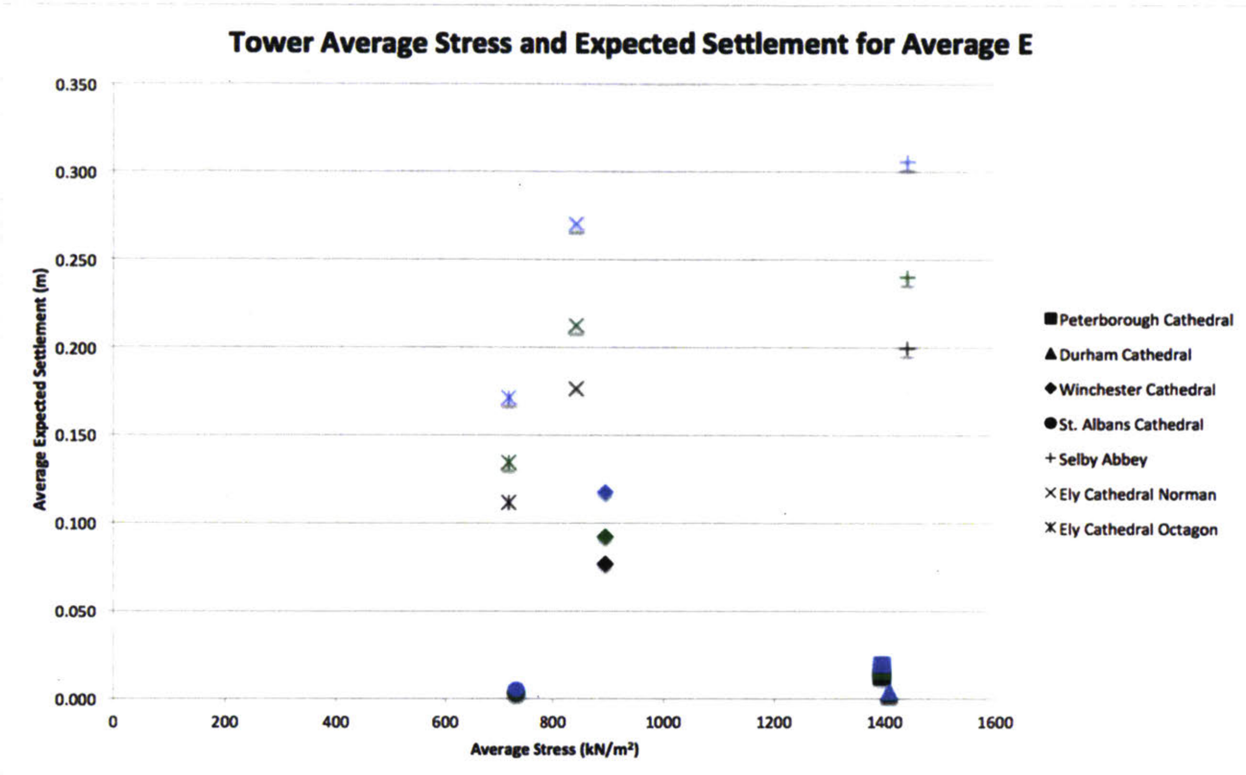


Figure 54: The Tower Average Stress and Average Expected Settlement for E_{avg}

The figure shows the average absolute settlement for the cathedral towers. The corresponding numbers are shown in Table 12. The settlement of Selby Abbey's tower is the largest, as expected, as the differential settlement between Selby Abbey's tower and nave was previously shown in Figure 42. Because E_{avg} was considered for Figure 54, the stiffness of the soil was greater than it would be if E_{top} was considered. This stiffness increase affected several of the cathedrals, especially Peterborough Cathedral, because of the closeness of the limestone layer to the surface and its position within the bulb of influence.

Table 12: Values corresponding to Figure 54

Tower E_{avg}		Stress Bulb Approach (black)	Rigid (green)	Uniform (blue)
Cathedral	Average Stress (kN/m^2)	Average Settlement (m)	Average Settlement (m)	Average Settlement (m)
Peterborough Cathedral	1394	0.013	0.015	0.020
Durham Cathedral	1408	0.003	0.003	0.004
Winchester Cathedral	895	0.077	0.092	0.118
St. Albans Cathedral	730	0.003	0.004	0.005
Selby Abbey	1439	0.200	0.240	0.306
Ely Cathedral Norman	842	0.177	0.212	0.270
Ely Cathedral Octagon	717	0.112	0.135	0.171

Figure 55 shows the settlement of each cathedral for each method considering E_{top}. As shown by Figure 54 and Figure 55, using E_{avg} versus using E_{top} does not significantly change the settlement of some of the cathedrals. These are the cathedrals that are on one soil type, such as St Albans on chalk. Other cathedrals, such as Peterborough Cathedral, which is affected by the stiffness of the underlying limestone, show a significant change in settlement because of the increase in E_{avg} when the limestone layer is considered.

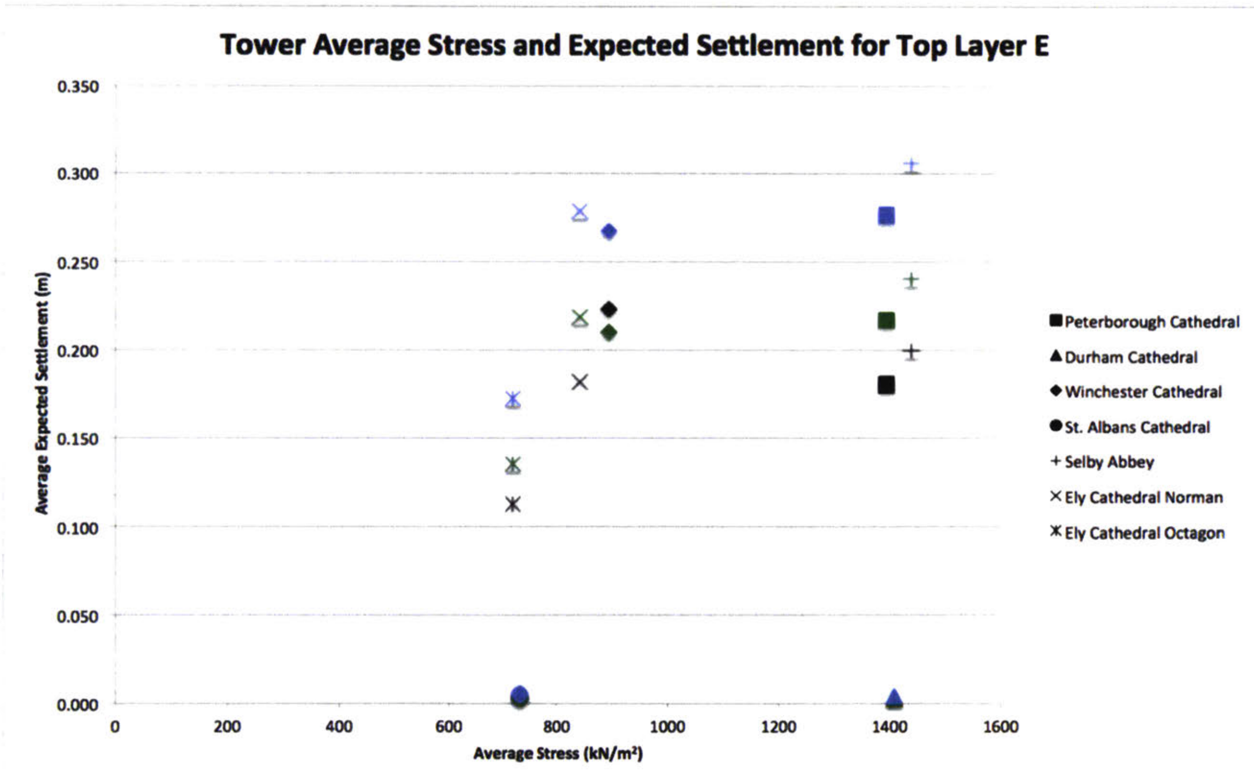


Figure 55: Tower Average Stress and Expected Settlement for E_{top}

The numbers are shown in Table 13.

Table 13: Values corresponding to Figure 55

Tower E_{top}		Stress Bulb Approach (black)	Rigid (green)	Uniform (blue)
Cathedral	Average Stress (kN/m^2)	Average Settlement (m)	Average Settlement (m)	Average Settlement (m)
Peterborough Cathedral	1394	0.181	0.217	0.277
Durham Cathedral	1408	0.003	0.003	0.004
Winchester Cathedral	895	0.223	0.210	0.268
St. Albans Cathedral	730	0.003	0.004	0.005
Selby Abbey	1439	0.200	0.240	0.306
Ely Cathedral Norman	842	0.182	0.219	0.279
Ely Cathedral Octagon	717	0.113	0.136	0.173

The same method was used to calculate the average settlement of the nave with both assumptions, E_{top} and E_{avg}.

The differential settlement between the nave and the tower piers is important to understand because it can lead to cracking, which can later lead to structural instability. Figure 56 shows the difference between the settlement that can be expected by a nave pier versus the settlement to be expected by a tower pier. The nave pier data points are glowing, while the tower pier data points are represented as before.

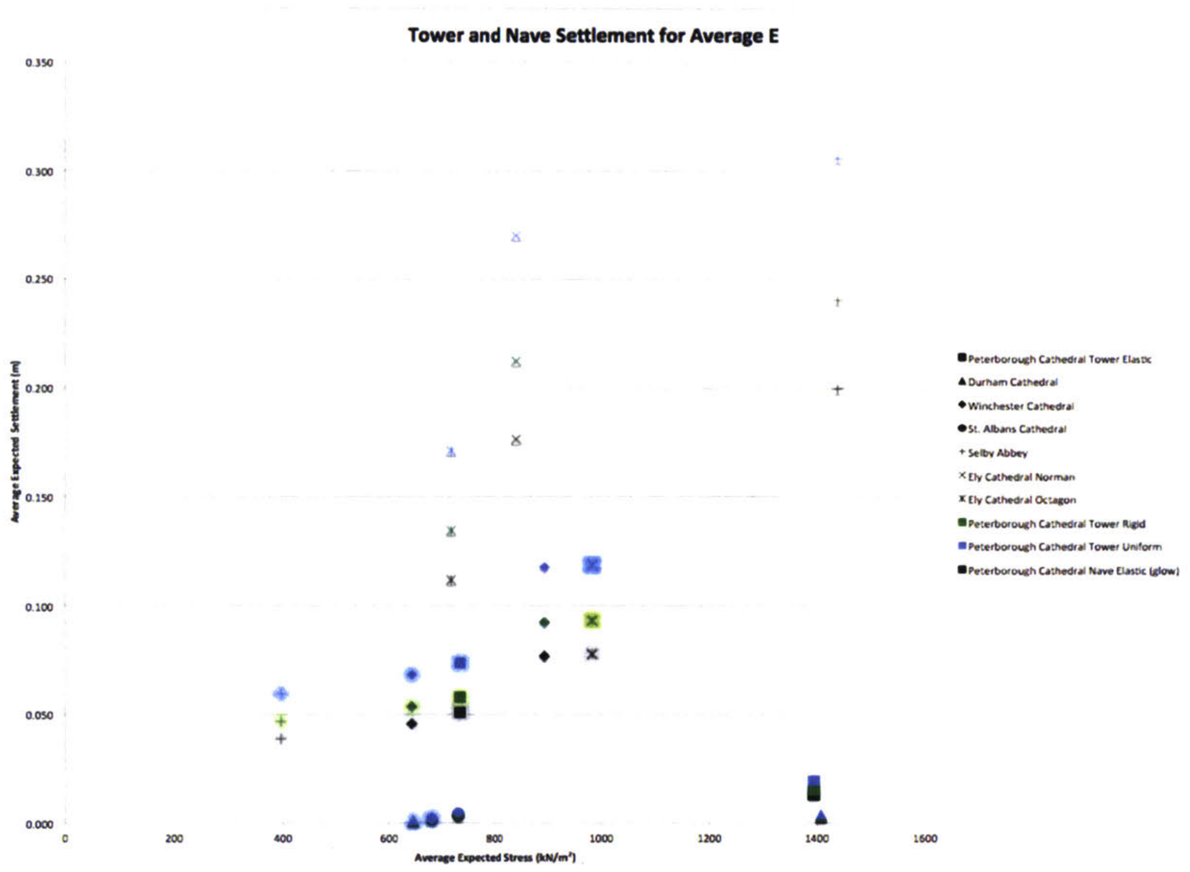


Figure 56: Tower and Nave (glowing) Average Expected Settlement for E_{avg}

The data compiled in Figure 56 are helpful in understanding what settlement can be expected for a cathedral, or other larger masonry structure, given the soil conditions. This figure shows the differential settlement that can be expected between the tower and the nave when using E_{avg}. For example, there is approximately a 0.25m difference between

Selby's Tower and Nave, as previously shown in Figure 42. Figure 57 shows the data for E_{top}. As demonstrated previously, the tower settles much more than the nave.

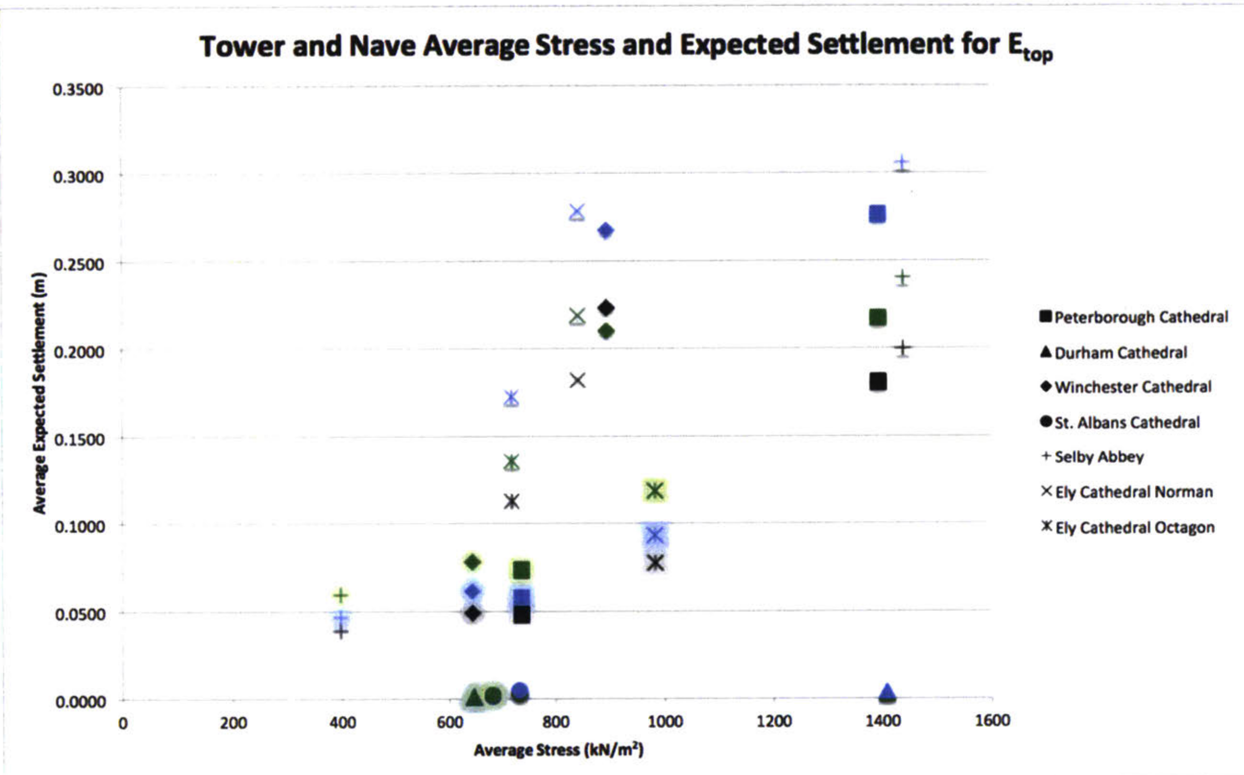


Figure 57: Tower and Nave (glowing) Average Expected Settlements for E_{top}

Figure 57 shows absolute estimated settlements. Estimated differential settlements can be calculated from this figure.

To understand the difference between the nave and tower settlements in a simpler chart, the data are plotted for the E_{top} case for the stress bulb method, as shown in Figure 58. This chart also shows the allowable differential settlement for modern day structures. The black symbols represent the tower settlements, and the gray symbols represent the nave settlements.

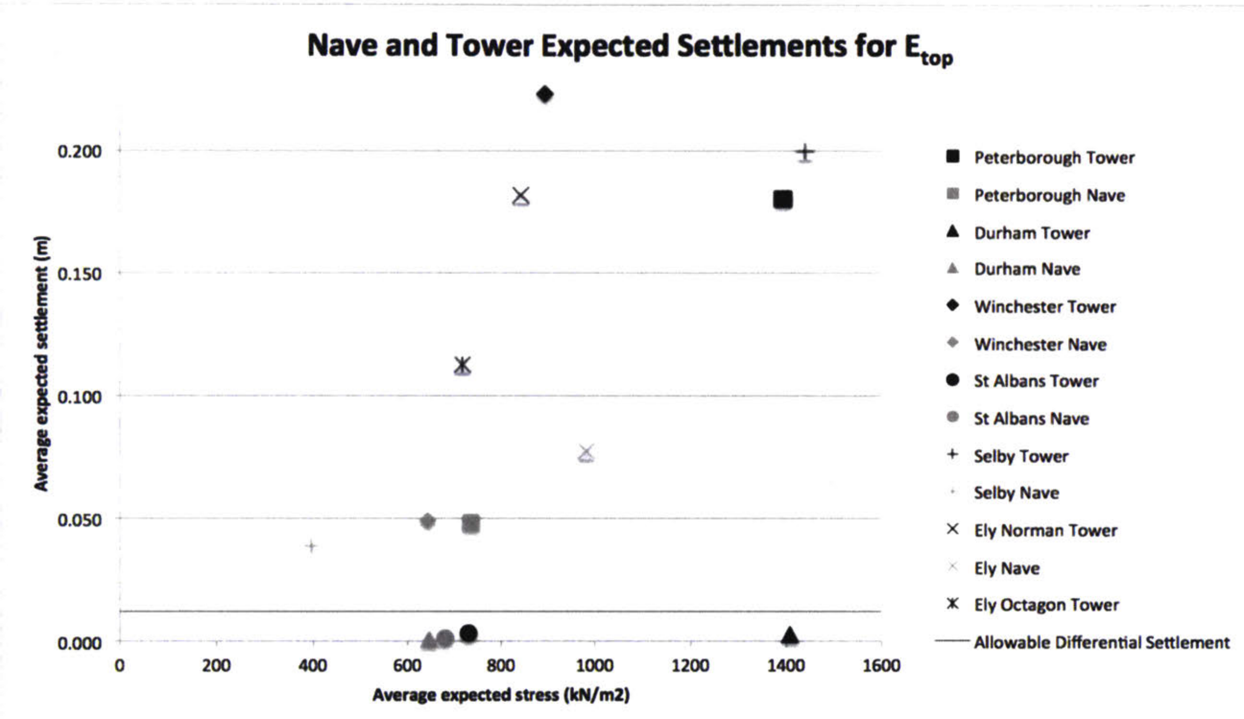


Figure 58: Stress Bulb Approach: Nave and Tower Average Settlement for E_{top}

Although Figure 58 is informative with regard to the differential settlement between the nave and tower of a given cathedral, it does not provide a basis for estimating the settlement of a cathedral not considered in this thesis based on given soil conditions.

Figure 59 shows a range of settlement given the pier stresses and given soil conditions.

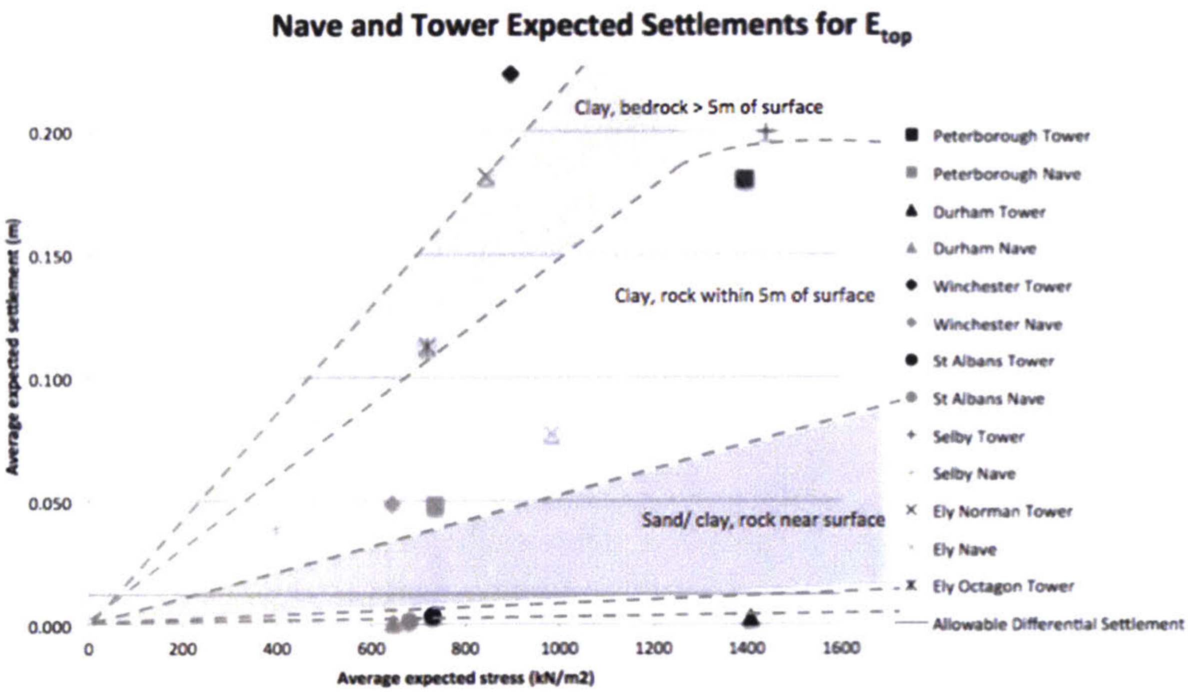


Figure 59: Bands allowing the estimation of settlement given pier stresses

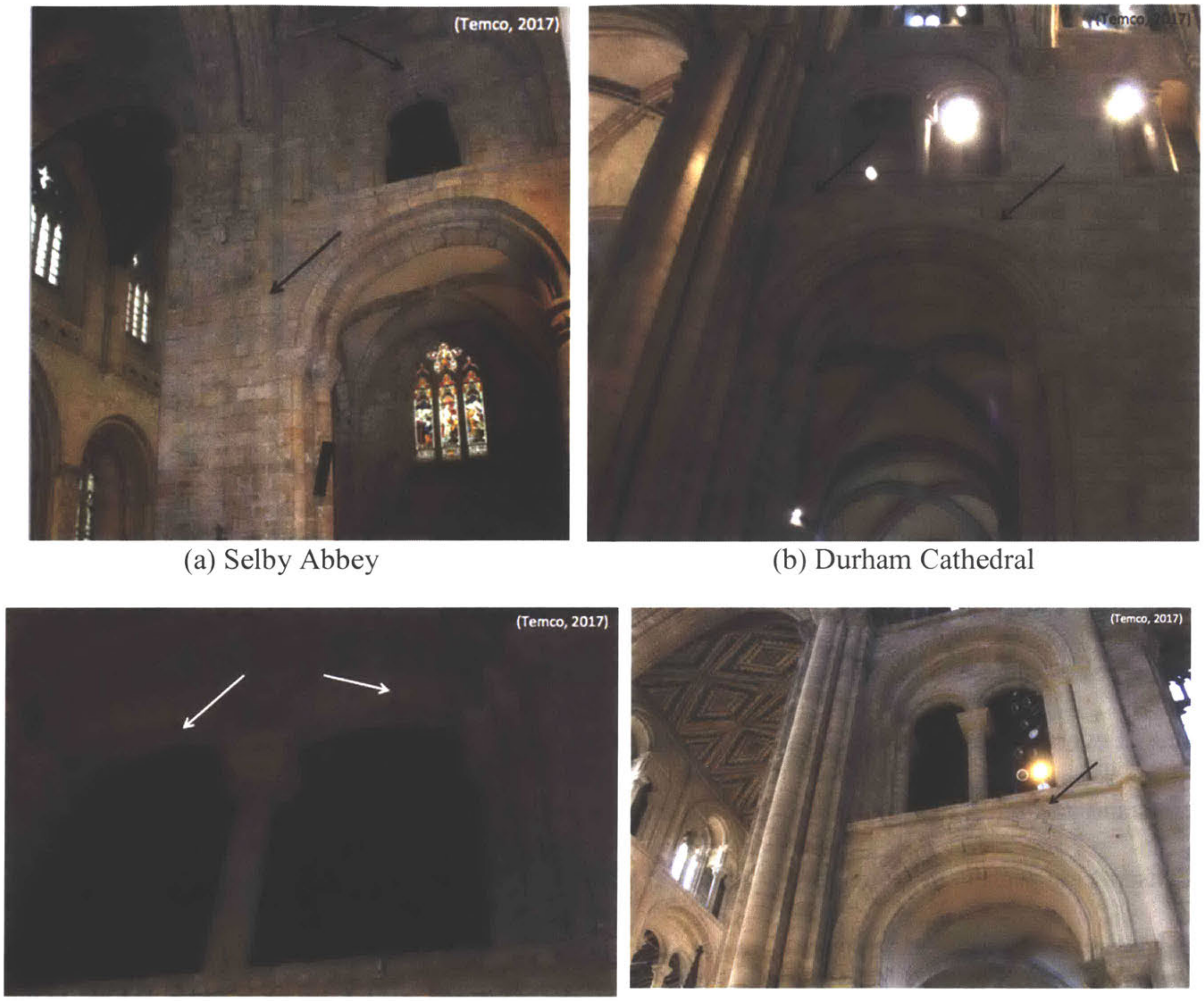
Figure 59 was created considering E_{top} because it is a more conservative approach. The stress bulb method is used for its simplicity and repeatability. The soil bands are subjectively estimated to fit the soil conditions at each cathedral.

This chapter focused on the geotechnical considerations regarding English cathedrals. The following chapter provides a case study for future work.

5. Discussion

The previous chapter showed the results of the calculated differential settlement. This chapter will discuss the settlement and what can be learned from this research. The settlement of the crossing towers of English Cathedrals has not been considered in literature unless there is a problem with a specific cathedral. The purpose of this thesis is to generalize the settlement of English Cathedrals and understand how different soil conditions affect the towers. This is a quantitative study of English cathedrals.

As the previous figures showed, there is a difference in the settlement of towers and the adjoining naves (and also choirs and transepts). This difference can be seen in the photos of cathedrals shown in Figure 60. Each photo shows a crack along the tower pier and connected structural element. Because these cracks are common and visible from below by the naked eye in almost every cathedral, they likely are a result of the differential settlement between the tower piers and adjoining structure. Cracks along the towers and connecting element (nave, choir, transept) are present in almost every cathedral. Of the cathedrals reviewed in this paper, the cracks in the masonry at St Albans are not visible because the masonry is covered in plaster, and although there are a few hairline cracks in the plaster, nothing can be said about the masonry. Similarly, Winchester cathedral was heavily repaired during the 19^{th} and early 20^{th} centuries. However, there are plenty of cracks in Winchester's choir due to inadequate foundations, so cracks between the tower and adjoining components were likely visible before repair.



(a) Selby Abbey

(b) Durham Cathedral

(c) Ely Cathedral

(d) Peterborough Cathedral

Figure 60: Cracks in the tower pier and adjacent structure

Figure 60 shows the cracking present in each cathedral. It is possible that the direction of cracking is roughly perpendicular to the direction of movement. The arrows show the location of the largest cracks. The largest calculated differential settlements between the tower and the nave, corresponding on Figure 60, are shown in Table 14.

Table 14: Maximum Average Differential Settlement

Calculated Maximum Differential Settlement between Tower and Nave (m)	
Peterborough Cathedral	0.165
Durham Cathedral	0.002
Winchester Cathedral	0.178
St. Albans Cathedral	0.002
Selby Abbey	0.200
Ely Cathedral Norman	0.130
Ely Cathedral Octagon	0.044

The largest differential settlement is Selby Abbey, as was expected, and as is shown in Figure 42.

As shown in Figure 60a, Selby Abbey's arch on the south side of the nave, adjacent to the south west tower pier, is cracked. This could be because masonry's natural state is cracked. However, this cracking can also be related to the calculated differential settlement of 0.2m.

Similarly, Figure 60b shows Durham Cathedral's north transept. The arch in the figure is the arch on the west side of the transept, adjacent to the north west tower pier. The differential settlement between these two structural components is calculated to be only 0.002m. As a result, the cracking and movement is not necessarily due to settlement due to soil conditions. It can be caused by settlement or other movement of the masonry foundation itself (if it was constructed with some fill or weak members), or a compression of the mortar, or simply inadequate foundation structures. This cracking is likely not caused by a movement of the sandstone beneath the cathedral.

Figure 60c shows cracking in the Ely Cathedral's south transept, adjacent to the south east octagon tower pier. When Ely's Norman cathedral was constructed, this bay was not the bay that was adjacent to the tower. The adjacent bay to the tower was removed when the octagon was constructed. The cracking in this bay could be caused by differential settlement, but might also have been caused by the movement of removing the remains of the adjoining bay after the collapse of the tower in 1322.

Peterborough Cathedral's north west tower pier and adjoining west side of the north transept/ north nave aisle is shown in Figure 60d. The calculated average differential settlement between the tower and nave piers is 16.5cm. A movement this large would result in cracking, but also could have contributed to the necessity of repairs to the tower in the 1890s.

In the six cathedrals studied, the calculated settlement for the tower was always greater than the tower settlement for the nave. This is due to the greater load carried by the tower, compared to the footing size. The nave piers are much smaller, and therefore the footings are smaller.

6. Conclusions

This thesis studied six cathedrals. The stress at the base of the nave and tower piers was found for each cathedral, and the corresponding estimated settlement was calculated.

English cathedral foundations were studied and an estimation of their size and shape was made. The foundations of English cathedrals were assumed to be similar to the stepped foundations used in Gothic France. Many foundations were also wall-like. Some had timber reinforcing or timber piles that have since rotted. In many cases, the soil was preconsolidated or at least previously built upon. This allowed the cathedrals to reuse preexisting foundations and materials, and to build on consolidated soils. This thesis assumed that for all soil conditions the same style of foundation was used (smooth stepped pyramid) but the depth varied. Builders likely dug to find a firmer ground. When no firmer ground could be found, timber was used as piles or inside the masonry walls of the structure.

The average settlement of nave piers and tower piers was calculated to obtain the differential settlement between the nave and tower. The average of the average settlements of all the cathedrals in this thesis is 10cm for the case where E_{avg} is considered and 15cm for the case where E_{top} is considered. This is a range of estimated settlement of 10-15cm, but this is skewed by cathedrals built on rock, such as Durham Cathedral and St Albans Cathedral. Other cathedrals were not included in this research, such as Salisbury Cathedral. When considering cathedral towers not founded only on bedrock, the range of expected settlement for cathedral towers built on clay studied in this thesis is 14-21cm. Naves can be expected settle an average of 4.5cm when those founded on bedrock are included, 6.7cm when only those founded on soil are considered.

The estimated settlements are related to the soil conditions. More settlement is expected in clay than rock, more settlement is expected when the clay is deeper than shallower. This is the anticipated result.

The estimated differential settlement can be found from the figures and tables presented in this thesis. The differential settlement can be calculated by subtracting the nave's settlement from the tower's settlement. There is differential settlement in every cathedral between the nave and the tower. For Durham and St Albans Cathedral, which are founded on rock, an average differential settlement of 0.2cm was calculated. However, for cathedrals built on clay and other soils, a range of 13cm-20cm is expected, depending on the soil conditions. For this range, the worst case scenario is reported for each cathedral. At the high end of this range is Selby Abbey, where the settlement is visible.

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Appendix A- Calculations

Peterborough Cathedral
1 ft=0.3048m

Dimensions (m)	
Tower pier side 1	3.05
Tower pier side 2	3.05
Tower pier height	16.46
Tower width	11.89
Tower gothic arch height	7.32
Tower norman arch heigł	4.27
Tower arch length	8.84
Tower arch thickness	1.52
Tower arch max height	23.77
Tower height	45.72
Nave arch half spacing	3.96
Nave-Gallery height	9.45
Nave aisle half width	2.97
Nave arch height	3.05
arch thickness	0.61
Gallery-clestory height	7.01
Floor thickness	0.61
Clestory aisle width	0.61
Clestory height	7.32
Timber roof thickness	0.06
Copper roof thickness	0.0008
Roof factor	0.13

Tributary area: Tower width plus nave half aisle width
23.7744

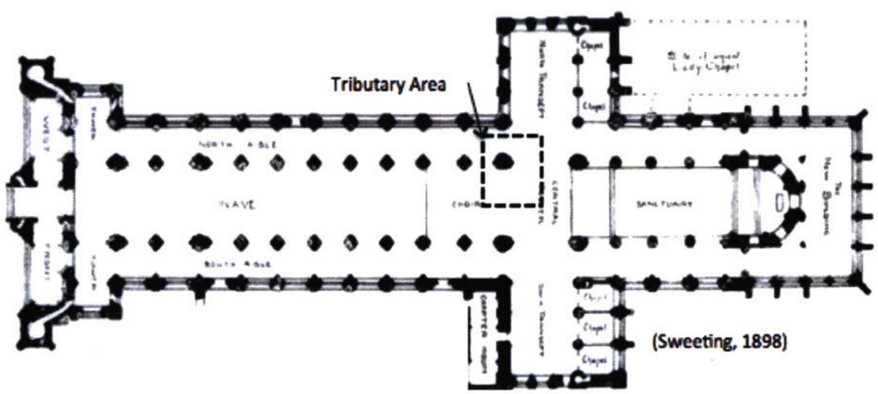
stone (kg/m3)	2400
timber (kg/m3)	740
copper(kg/m3)	8000

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							mass*9.8/1000
Tower piers	4	16.5	3.0	3.0	611.6		
Tower Gothic arch	2	7.3	8.8	1.5	234.5		
Tower Norman arch	2	4.3	8.8	1.5	104.0		
Tower above arch	4	21.9	11.9	1.5	1590.3		
Gallery floor	8	0.6	3.96	2.97	57.4		
Clestory floor	8	0.6	4.0	0.6	11.8		
Nave/transept/choir half arch	8	3.05	4.0	0.6	39.9		
Gallery interior arch	8	7.01	4.0	0.6	45.2		
Gallery outer wall	8	7.01	4.0	0.6	67.7		
Clestory outer wall	8	7.32	4.0	0.6	106.0		
All stone volume					2868	6884119	67464
Timber							
Tower ceiling	1	0.06096	11.8872	11.8872	9		
Timber truss	1	0.1335024	23.7744	23.7744	75		
Total timber					84	62214	610
Copper roof	1	0.00079248	23.7744	23.7744	0		
			Tower width plus nave half aisle width				
Total Copper					0	3583	35

Tower total (kN)	68109
Pier total (kN)	17027

Timber and copper are for the roof only
The area considered is between the tower piers and half of the nave arch length

Pier total (kN)	17027
Pier base area (m2)	9.29
Stress in pier at floor level (kN/m2)	1833
Min load	284
Foundation depth (m)	1.3
Foundation base area (m2)	18.9
Added foundation volume (m3)	19
Added foundation weight (kN)	457
Weight at depth (kN)	17484
Max stress at depth (kN/m2)	1863
Min stress at depth (kN/m2)	925



Nave	
Nave arch half spacing	3.96
Nave-Gallery height	9.45
Nave aisle half width	2.97
Nave arch height	3.05
arch thickness	0.61
Gallery-clestory height	7.01
Floor thickness	0.61
Clestory aisle width	0.61
Clestory height	7.32
Timber roof thickness	0.06
Copper roof thickness	0.0008
Roof factor	0.13
Nave pier side	1.50

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							
Gallery Floor	2	0.61	3.96	2.97	14.36		
Clestory Floor	2	0.61	3.96	0.61	2.94		
Nave pier	1.0	9	1.50	1.50	21.26		
Nave/transept/choir half arch	2	3.05	4.0	0.6	14.72		
Gallery interior arch	2	0.61	4.0	0.6	2.94		
Gallery outer wall	2	7.01	4.0	0.6	33.87		
Clestory outer wall	2	0.61	4.0	0.6	2.94		
All stone volume					93	223303	2188
Timber							
Tower ceiling	1	0.06	5.9436	7.9248	2.87132824		
Timber truss	1	0.13	5.9436	7.9248	6.28820886		
Total timber					9	6778	66
Copper roof	1.0	0.00	5.9436	7.9248	0.03732727		
Total Copper					0	299	3
						Nave pier total (kN)	2258

Nave pier total (kN)	2258
Pier base area (m2)	2.25
Stress in pier at floor level (kN/m2)	1003
	68.796
Foundation depth (m)	1.3
Foundation base area (m2)	5.6
Added foundation volume (m3)	8
Added foundation weight (kN)	180
Weight at depth (kN)	2438
Max stress at depth (kN/m2)	1034
Min stress at depth (kN/m2)	435

Durham Cathedral

Dimensions	m	ft
Tower pier side 1	4.27	14.00
Tower pier side 2	3.35	11.00
Tower pier height	16.46	54.00
Tower width	11.89	39.00
Tower norman arch height	4.27	14.00
Tower arch length	8.84	29.00
Tower arch thickness	1.52	5.00
Tower arch max height	23.47	77.00
Tower height	66.45	218.00
Nave arch half spacing	3.05	10.00
Nave-Gallery height	12.19	40.00
Nave aisle half width	3.20	10.50
Nave arch height	3.05	10.00
arch thickness	0.61	2.00
Gallery-clestory height	4.27	14.00
Floor thickness	0.61	2.00
Clestory aisle width	0.61	2.00
Clestory height	4.27	14.00
Stone roof thickness	0.06	
Copper roof thickness	0.0008	
Roof factor	0.13	

stone (kg/m3)	2400
timber (kg/m3)	740
copper(kg/m3)	8000

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							mass*9.8/1000
Tower piers	4	16.5	4.3	3.4	941.9		
Tower Norman arch	4	4.3	8.8	1.5	227.7		
Tower above arch	4	43.0	11.9	1.5	3114.3		
Gallery floor	8	0.6	3.0	3.2	47.6		
Clestory floor	8	0.6	3.0	0.6	9.1		
Nave/transept/choir half arch	8	3.0	3.0	0.6	30.7		
Gallery interior arch	8	4.3	3.0	0.6	21.1		
Gallery outer wall	8	4.3	3.0	0.6	31.7		
Clestory outer wall	8	4.3	3.0	0.6	47.6		
Stone roof	4	0.6	11.9	3.0	88.3		
All stone volume					4560	10944204	107253
Timber							
Tower ceiling	1	0.06096	11.8872	11.8872	9		
Timber truss	1	0.1335024	24.6888	24.6888	81		
Total timber					90	66592	653
Copper roof	1	0.00079248	24.6888	24.6888	0		
Total Copper					0	3864	38

Tower total (kN)	107944
Pier total (kN)	26986

Pier total (kN)	26986
Pier base area (m2)	14.31
Stress in pier at floor level (kN/m2)	1886
	774
Foundation depth (m)	2.3
Foundation base area (m2)	37.1
Added foundation volume (m3)	65
Added foundation weight (kN)	1534
Weight at depth (kN)	28520
Max stress at depth (kN/m2)	2048
Min stress at depth (kN/m2)	768

Depth of bedrock under cathedral- sandstone

Nave	
Nave arch half spacing	3.05
Nave-Gallery height	12.19
Nave aisle half width	3.20
Nave arch height	3.05
arch thickness	0.61
Gallery-clestory height	4.27
Floor thickness	0.61
Clestory aisle width	0.61
Clestory height	4.27
Stone roof thickness	0.06
Copper roof thickness	0.00
Roof factor	0.13
Nave pier side	2.25

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							
Gallery Floor	2	0.61	3.05	3.20	11.89		
Clestory Floor	2	0.61	3.05	0.61	2.27		
Pier	1.0	12.19	2.25	2.25	61.72		
Nave/transept/choir half arch	2	3.05	3.05	0.61	11.33		
Gallery interior arch	2	4.27	3.05	0.61	15.86		
Gallery outer wall	2	4.27	3.05	0.61	15.86		
Clestory outer wall	2	4.27	3.05	0.61	15.86		
Stone roof	1.0	0.6	5.9	6.1	22.09		
All stone volume					157	376480	3690
Timber							
Tower ceiling	1	0.06	5.94	5.94	0		
Timber truss	1	0.13	5.9436	5.9436	4.71615664		
Total timber					5	11319	111
Copper roof	1.0	0.00	5.9436	5.9436	0.02799545		
Total Copper					0	224	2
						Nave pier total (kN)	3803

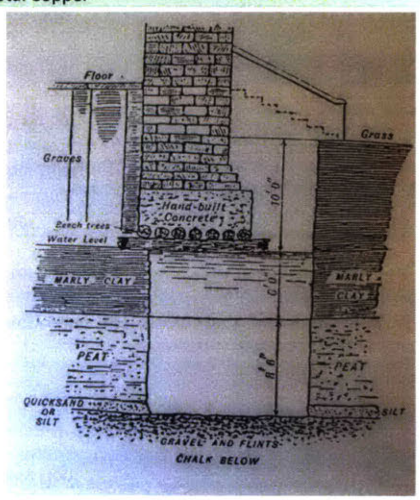
Nave pier total (kN)	3803
Pier base area (m2)	5.06
Stress in pier at floor level (kN/m2)	751
	274
Foundation depth (m)	2.3
Foundation base area (m2)	9.1
Added foundation volume (m3)	26
Added foundation weight (kN)	614
Weight at depth (kN)	4417
Max stress at depth (kN/m2)	805
Min stress at depth (kN/m2)	485

Winchester Cathedral

stone (kg/m3)		2400
timber (kg/m3)		740
copper(kg/m3)		8000

Dimensions	m	ft
Tower pier side 1	4.27	14.00
Tower pier side 2	4.27	14.00
Tower pier height	19.51	64.00
Tower width	15.24	50.00
Tower norman arch height	4.27	14.00
Tower arch length	10.67	35.00
Tower arch thickness	1.52	5.00
Tower arch max height	23.77	78.00
Tower height	45.72	150.00
Nave arch half spacing	2.13	7.00
Nave-Gallery height	15.85	52.00
Nave aisle half width	3.05	10.00
Nave arch height	3.05	10.00
arch thickness	0.61	2.00
Floor thickness	0.61	2.00
Clestory height	7.92	26.00
Timber roof thickness	0.06	
Copper roof thickness	0.00	
Roof factor	0.13	

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							mass*9.8/1000
Tower piers	4	19.5	4.3	4.3	1420.8		
Tower Norman arch	4	4.3	10.7	1.5	289.5		
Tower above arch	4	21.9	15.2	1.5	2038.8		
Gallery floor	8	0.6	2.1	3.0	31.7		
Nave/transept/choir half arch	8	3.0	2.1	0.6	61.2		
Clestory outer wall	8	7.9	2.1	0.6	61.8		
Stone roof	4	0.6	15.2	2.1	79.3		
All stone volume					3983	9559525	93683
Timber							
Tower ceiling	1	0.06096	15.24	15.24	14		
Timber truss	1	0.1335024	27.432	27.432	100		
Total timber					115	84819	831
Copper roof	1	0.00079248	27.432	27.432	1		
Total Copper					1	4771	47



Tower total (kN)	94561
Pier total (kN)	23640

Pier total (kN)	23640	
Pier base area (m2)	18.21	
Stress in pier at floor level (kN/m2)	1298	
	1958	
Foundation depth (m)	4.572	15
Foundation base area (m2)	78.1	
Added foundation volume (m3)	268	
Added foundation weight (kN)	6304	
Weight at depth (kN)	29944	
Max stress at depth (kN/m2)	1406	
Min stress at depth (kN/m2)	383	

Nave	
Nave arch half spacing	2.13
Nave-Gallery height	15.85
Nave aisle half width	3.05
Nave arch height	3.05
arch thickness	0.61
Floor thickness	0.61
Clestory height	7.92
Timber roof thickness	0.06
Copper roof thickness	0.00
Roof factor	0.13
Nave pier side	1.5

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							
Gallery Floor	2	0.61	2.13	3.05	7.93		
Pier	1.0	15.85	1.50	1.50	35.66		
Nave/transept/choir half arch	2	3.05	2.13	0.61	7.93		
Clestory outer wall	2	7.92	2.13	0.61	20.61		
All stone volume					72	173121	1697
Timber							
Nave ceiling	1	0.06	7.62	4.27	1.98217926		
Timber truss	1	0.00	7.62	4.2672	0.02576833		
Total timber					2	1486	15
Copper roof	1.0	0.00	7.62	4.2672	0.02576833		
Total Copper					0	206	2
						Nave pier total (kN)	1713

Nave pier total (kN)	1713
Pier base area (m2)	2.25
Stress in pier at floor level (kN/m2)	761
	242
Foundation depth (m)	4.572
Foundation base area (m2)	12.1
Added foundation volume (m3)	137
Added foundation weight (kN)	3227
Weight at depth (kN)	4940
Max stress at depth (kN/m2)	869

St. Albans Cathedral

Dimensions	m	ft
Tower pier side 1	4.88	16.00
Tower pier side 2	4.88	16.00
Tower pier height	13.11	43.00
Tower width	14.02	46.00
Tower norman arch height	3.66	12.00
Tower arch length	9.14	30.00
Tower arch thickness	1.52	5.00
Tower arch max height	16.76	55.00
Tower height	43.89	144.00
Nave arch half spacing	3.05	10.00
Nave-Gallery height	8.99	29.50
Nave aisle half width	3.51	11.50
Nave arch height	3.05	10.00
arch thickness	0.61	2.00
Gallery-clestory height	4.48	14.70
Floor thickness	0.61	2.00
Clestory aisle width	0.61	2.00
Clestory height	6.74	22.10
Timber roof thickness	0.06	
Copper roof thickness	0.00	
Roof factor	0.13	

Pier total (kN)	24033
Pier base area (m2)	23.78
Stress in pier at floor level (kN/m2)	1011
	2965
Foundation depth (m)	5.3
Foundation base area (m2)	103.6
Added foundation volume (m3)	412
Added foundation weight (kN)	9688
Weight at depth (kN)	33721
Max stress at depth (kN/m2)	1135
Min stress at depth (kN/m2)	326

stone (kg/m3)	2400
timber (kg/m3)	740
copper(kg/m3)	8000

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							mass*9.8/1000
Tower piers	4	13.1	4.9	4.9	1246.8		
Tower Norman arch	4	3.7	9.1	1.5	261.2		
Tower above arch	4	27.1	14.0	1.5	2318.6		
Gallery floor	8	0.6	3.0	3.5	52.1		
Clestory floor	8	0.6	3.0	0.6	9.1		
Nave/transept/choir half arch	8	3.0	3.0	0.6	30.7		
Gallery interior arch	8	4.5	3.0	0.6	22.2		
Gallery outer wall	8	4.5	3.0	0.6	33.3		
Clestory outer wall	8	6.7	3.0	0.6	75.1		
All stone volume					4049	9717919	95236
Timber							
Tower ceiling	1	0.06096	14.0208	14.0208	12		
Timber truss	1	0.1335024	28.0416	28.0416	105		
Total timber					117	86551	848
Copper roof	1	0.00079248	28.0416	28.0416	1		
Total Copper					1	4985	49

Tower total (kN)	96133
Pier total (kN)	24033

Nave	
Nave arch half spacing	3.05
Nave-Gallery height	8.99
Nave aisle half width	3.51
Nave arch height	3.05
arch thickness	0.61
Gallery-clestory height	4.48
Floor thickness	0.61
Clestory aisle width	0.61
Clestory height	6.74
Timber roof thickness	0.06
Copper roof thickness	0.00
Roof factor	0.13
Nave pier side	2.13

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							
Gallery Floor	2	0.61	3.05	3.51	13.03		
Clestory Floor	2	0.61	3.05	0.61	2.27		
Nave pier	1.0	9	2.13	2.13	40.93		
Nave/transept/choir half arch	2	3.05	3.05	0.61	11.33		
Gallery interior arch	2	4.48	3.05	0.61	16.65		
Gallery outer wall	2	4.48	3.05	0.61	16.65		
Clestory outer wall	2	6.74	3.05	0.61	25.03		
All stone volume					126	302118	2961
Timber							
Tower ceiling	1	0.06	7.0104	6.096	2.60514989		
Timber truss	1	0.13	7.0104	6.096	5.70527825		
Total timber					8	6150	60
Copper roof	1.0	0.00	7.0104	6.096	0.03386695		
Total Copper					0	271	3
						Nave pier total (kN)	3024

Nave pier total (kN)	3024
Pier base area (m2)	4.55
Stress in pier at floor level (kN/m2)	664
	567
Foundation depth (m)	5.3
Foundation base area (m2)	14.9
Added foundation volume (m3)	233
Added foundation weight (kN)	5479
Weight at depth (kN)	8502
Max stress at depth (kN/m2)	789
Min stress at depth (kN/m2)	572

Selby Abbey

Dimensions	m	ft
Tower pier side 1	2.04	6.70
Tower pier side 2	2.04	6.70
Tower pier height	9.00	29.53
Tower width	9.00	29.53
Tower norman arch height	2.13	7.00
Tower arch length	6.10	20.00
Tower arch thickness	1.52	5.00
Tower arch max height	15.00	49.21
Tower height	39.62	129.99
Nave arch half spacing	1.68	5.50
Nave-Gallery height	7.00	22.97
Nave aisle half width	1.68	5.50
Nave arch height	2.44	8.00
arch thickness	0.61	2.00
Gallery-clestory height	3.50	11.48
Floor thickness	0.61	2.00
Clestory aisle width	0.61	2.00
Clestory height	4.50	14.76
Timber roof thickness	0.06	
Copper roof thickness	0.00	
Roof factor	0.13	

stone (kg/m3)	2400
timber (kg/m3)	740
copper(kg/m3)	8000

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							mass*9.8/1000
Tower piers	4	9.0	2.0	2.0	150.1		
Tower Norman arch	4	2.1	6.1	1.5	81.3		
Tower above arch	4	24.6	9.0	1.5	1350.8		
Gallery floor	8	0.6	1.7	1.7	13.7		
Clestory floor	8	0.6	1.7	0.6	5.0		
Nave/transept/choir half arch	8	2.4	1.7	0.6	13.5		
Gallery interior arch	8	3.5	1.7	0.6	9.5		
Gallery outer wall	8	3.5	1.7	0.6	14.3		
Clestory outer wall	8	4.5	1.7	0.6	27.6		
All stone volume					1666	3998098	39181
Timber							
Tower ceiling	1	0.06096	9	9	5		
Timber truss	1	0.1335024	15.7056	15.7056	33		
Total timber					38	28023	275
Copper roof	1	0.00079248	15.7056	15.7056	0		
Total Copper					0	1564	15

Tower total (kN)	39471
Pier total (kN)	9868

Pier total (kN)	9868
Pier base area (m2)	4.17
Stress in pier at floor level (kN/m2)	2366
	294
Foundation depth (m)	3
Foundation base area (m2)	25.4
Added foundation volume (m3)	58
Added foundation weight (kN)	1362
Weight at depth (kN)	11229
Max stress at depth (kN/m2)	2437
Min stress at depth (kN/m2)	442

Nave	
Nave arch half spacing	1.68
Nave-Gallery height	7.00
Nave aisle half width	1.68
Nave arch height	2.44
arch thickness	0.61
Gallery-clestory height	3.50
Floor thickness	0.61
Clestory aisle width	0.61
Clestory height	4.50
Timber roof thickness	0.06
Copper roof thickness and n	0.00
Roof factor	0.13
Nave pier side	1.50

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							
Gallery Floor	2	0.61	1.68	1.68	3.43		
Clestory Floor	2	0.61	1.68	0.61	1.25		
Nave pier	1.0	7	1.50	1.50	15.75		
Nave/transept/choir half arch	2	2.44	1.68	0.61	4.98		
Gallery interior arch	2	3.50	1.68	0.61	7.15		
Gallery outer wall	2	3.50	1.68	0.61	7.15		
Clestory outer wall	2	4.50	1.68	0.61	9.20		
All stone volume					49	117385	1150
Timber							
Tower ceiling	1	0.06	4.5	3.3528	0.91		
Timber truss	1	0.13	4.5	3.3528	1.96		
Total timber					3	2121	21
Copper roof	1.0	0.08	4.5	3.3528	1.2		
Total Copper					1.2	9656	95
						Nave pier total (kN)	1266

Nave pier total (kN)	1266
Pier base area (m2)	2.25
Stress in pier at floor level (kN/m2)	563
	68.8
Foundation depth (m)	1.3
Foundation base area (m2)	5.6
Added foundation volume (m3)	8
Added foundation weight (kN)	180
Weight at depth (kN)	1446
Max stress at depth (kN/m2)	593
Min stress at depth (kN/m2)	258

Ely Cathedral Original Tower
Info from Ely BAA norman map

Dimensions	m	ft
Tower pier side 1	4.00	13.12
Tower pier side 2	4.00	13.12
Tower pier height	17.53	57.50
Tower width	13.54	44.42
Tower norman arch height	3.05	10.00
Tower arch length	9.54	31.30
Tower arch thickness	1.25	4.10
Tower arch max height	20.57	67.50
Tower height	45.72	150.00
Nave arch half spacing	3.44	11.27
Nave-Gallery height	8.38	27.50
Nave aisle half width	5.05	16.57
Nave arch height	3.05	10.00
arch thickness	0.61	2.00
Gallery-clestory height	6.71	22.00
Floor thickness	0.61	2.00
Clestory aisle width	0.00	0.00
Clestory height	5.03	16.50
Timber roof thickness	0.06	
Copper roof thickness	0.00	
Roof factor	0.13	

stone (kg/m3)	2400
timber (kg/m3)	740
copper(kg/m3)	8000

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN) mass*9.8/1000
Stone							
Tower piers	4	17.5	4.0	4.0	1121.7		
Tower Norman arch	4	3.0	9.5	1.3	153.1		
Tower above arch	4	25.1	13.5	1.3	1702.4		
Gallery floor	8	0.6	3.4	5.1	84.6		
Clestory floor	8	0.6	3.4	0.0	0.0		
Nave/transept/choir half arch	8	3.0	3.4	0.6	34.6		
Gallery interior arch	8	6.7	3.4	0.6	37.4		
Gallery outer wall	8	6.7	3.4	0.6	56.2		
Clestory outer wall	8	5.0	3.4	0.6	63.2		
All stone volume					3253	7807619	76515
Timber							
Tower ceiling	1	0.06096	13.54	13.54	11		
Timber truss	1	0.1335024	33.74	33.74	152		
Total timber					163	120733	1183
Copper roof	1	0.00079248	33.74	33.74	1		
Total Copper					1	7217	71

Tower total (kN)	77769
Pier total (kN)	19442

Pier total (kN)	19442
Pier base area (m2)	16.00
Stress in pier at floor level (kN/m2)	1215
	1505
Foundation depth (m)	4
Foundation base area (m2)	64.0
Added foundation volume (m3)	192
Added foundation weight (kN)	4516
Weight at depth (kN)	23958
Max stress at depth (kN/m2)	1309
Min stress at depth (kN/m2)	374

Nave	
Nave arch half spacing	3.435
Nave-Gallery height	8.382
Nave aisle half width	5.05
Nave arch height	3.05
arch thickness	0.61
Gallery-clestory height	6.71
Floor thickness	0.61
Clestory aisle width	0.00
Clestory height	5.03
Timber roof thickness	0.06
Copper roof thickness	0.00
Roof factor	0.13
Nave pier side	1.50

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							
Gallery Floor	2	0.61	3.44	5.05	21.15		
Nave pier	1.0	8.38	1.50	1.50	18.86		
Nave/transept/choir half arch	2	3.05	3.44	0.61	12.76		
Gallery interior arch	2	6.71	3.44	0.61	28.08		
Gallery outer wall	2	6.71	3.44	0.61	28.08		
Clestory outer wall	2	5.03	3.44	0.61	21.06		
All stone volume					130	312003	3058
Timber							
Tower ceiling	1	0.06	6.77	6.87	2.835		
Timber truss	1	0.13	6.77	6.87	6.209		
Total timber					9	6693	66
Copper roof	1.0	0.00	6.77	6.87	0.037		
Total Copper					0	295	3
						Nave pier total (kN)	3126

Nave pier total (kN)	3126
Pier base area (m2)	2.25
Stress in pier at floor level (kN/m2)	1389
	90.0
Foundation depth (m)	1.7
Foundation base area (m2)	6.4
Added foundation volume (m3)	13
Added foundation weight (kN)	307
Weight at depth (kN)	3434
Max stress at depth (kN/m2)	1429
Min stress at depth (kN/m2)	536

Ely Cathedral Octagon

Dimensions	m	ft
Tower pier side 1	3.05	10.00
Tower pier side 2	3.05	10.00
Tower pier height	17.53	57.50
Tower width	10.29	33.75
Tower gothic arch height	4.42	14.50
Tower arch length	7.24	23.75
Tower arch thickness	0.91	3.00
Tower arch max height	21.95	72.00
Tower stone height	34.14	112.00
Nave arch half spacing	3.44	11.27
Nave-Gallery height	8.38	27.50
Nave aisle half width	5.05	16.57
Nave arch height	3.05	10.00
arch thickness	0.61	2.00
Gallery-clestory height	6.71	22.00
Floor thickness	0.61	2.00
Clestory aisle width	0.00	0.00
Clestory height	5.03	16.50
Timber roof thickness	0.06	
Copper roof thickness	0.00	
Roof factor	0.13	
Timber octagon height	17.86	

stone (kg/m3)	2400
timber (kg/m3)	740
copper(kg/m3)	8000

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							mass*9.8/1000
Tower piers	8	17.5	3.0	3.0	1302.6		
Tower Gothic arch	8	4.4	7.2	0.9	314.1		
Tower above arch	8	12.2	10.3	0.9	917.5		
Gallery floor	8	0.6	3.4	5.1	84.6		
Clestory floor	8	0.6	3.4	0.0	0.0		
Nave/transept/choir half arch	8	3.0	3.4	0.6	34.6		
Gallery interior arch	8	6.7	3.4	0.6	37.4		
Gallery outer wall	8	6.7	3.4	0.6	56.2		
Clestory outer wall	8	5.0	3.4	0.6	63.2		
All stone volume					2810	6744362	66095
Timber							
Tower ceiling	1	0.06096	10.287	10.287	6		
Timber truss	1	0.1335024	30.487	30.487	124		
Timber octagon	8	17.86	33.75	0.13	643.775273		
Total timber					774	572990	5615
Copper roof	1	0.00079248	30.487	30.487	1		
Total Copper					1	5893	58

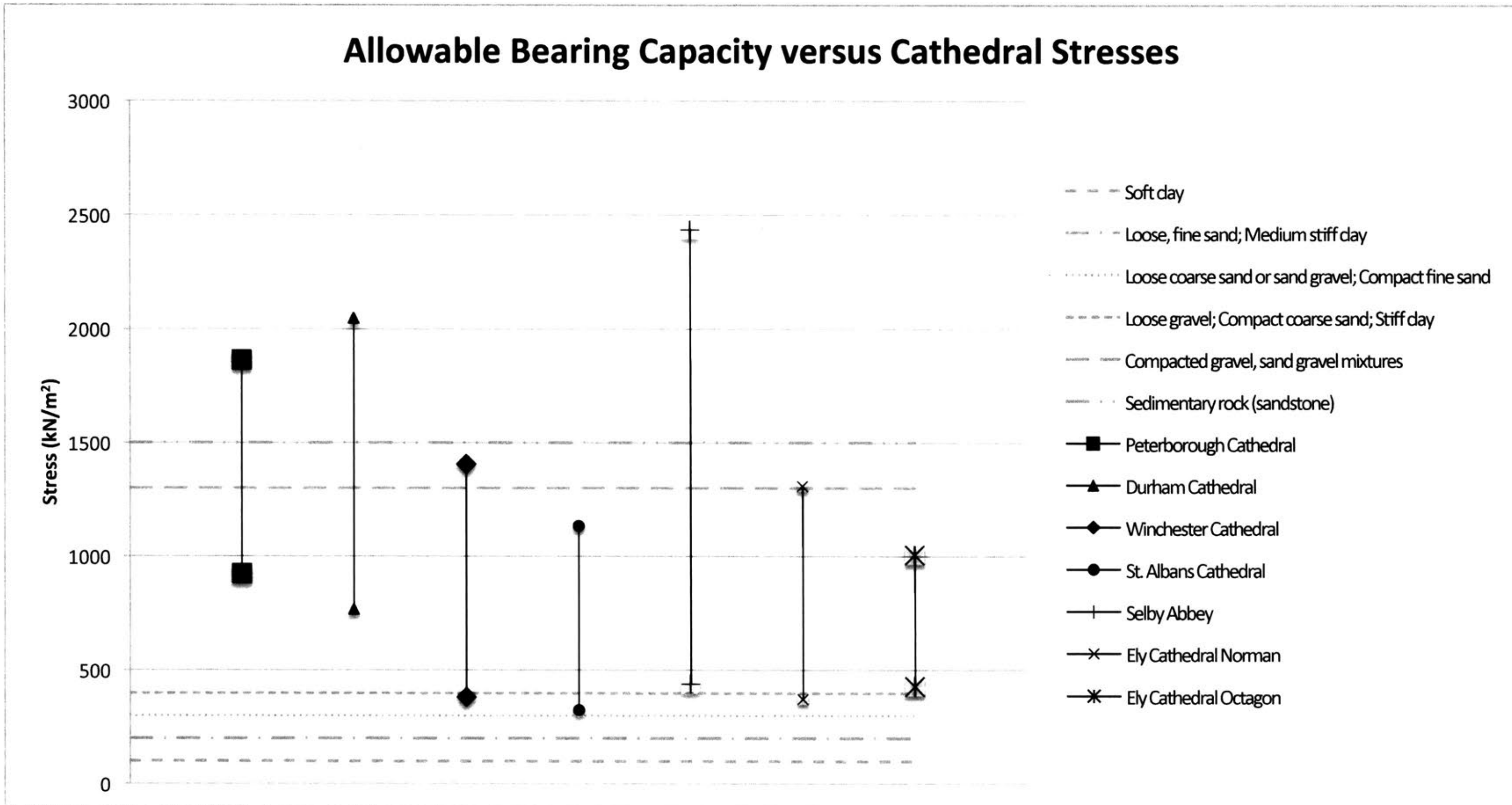
Tower total (kN)	71768
Pier total (kN)	8971

Pier total (kN)	8971
Pier base area (m2)	9.29
Stress in pier at floor level (kN/m2)	966
	371
Foundation depth (m)	1.7
Foundation base area (m2)	22.5
Added foundation volume (m3)	30
Added foundation weight (kN)	694
Weight at depth (kN)	9665
Max stress at depth (kN/m2)	1006
Min stress at depth (kN/m2)	429

Nave	
Nave arch half spacing	3.435
Nave-Gallery height	8.382
Nave aisle half width	5.05
Nave arch height	3.05
arch thickness	0.61
Gallery-clestory height	6.71
Floor thickness	0.61
Clestory aisle width	0.00
Clestory height	5.03
Timber roof thickness	0.06
Copper roof thickness	0.00
Roof factor	0.13
Nave pier side	1.50

	Amount	Height (m)	Length (m)	Width (m)	Volume (m3)	mass (kg)	weight (kN)
Stone							
Gallery Floor	2	0.61	3.44	5.05	21.15		
Nave pier	1.0	8.38	1.50	1.50	18.86		
Nave/transept/choir half arch	2	3.05	3.44	0.61	12.76		
Gallery interior arch	2	6.71	3.44	0.61	28.08		
Gallery outer wall	2	6.71	3.44	0.61	28.08		
Clestory outer wall	2	5.03	3.44	0.61	21.06		
All stone volume					130	312003	3058
Timber							
Tower ceiling	1	0.06	6.77	6.87	2.835		
Timber truss	1	0.13	6.77	6.87	6.209		
Total timber					9	6693	66
Copper roof	1.0	0.00	6.77	6.87	0.037		
Total Copper					0	295	3
						Nave pier total (kN)	3126

Nave pier total (kN)	3126
Pier base area (m2)	2.25
Stress in pier at floor level (kN/m2)	1389
	90.0
Foundation depth (m)	1.7
Foundation base area (m2)	6.4
Added foundation volume (m3)	13
Added foundation weight (kN)	307
Weight at depth (kN)	3434
Max stress at depth (kN/m2)	1429
Min stress at depth (kN/m2)	536



Allowable Bearing Capacity versus Cathedral Stresses
Stress (kN/m²)
3000
2500
2000
1500
1000
500
0
Soft clay
Loose, fine sand; Medium stiff clay
Loose coarse sand or sand gravel; Compact fine sand
Loose gravel; Compact coarse sand; Stiff clay
Compacted gravel, sand gravel mixtures
Sedimentary rock (sandstone)
Peterborough Cathedral
Durham Cathedral
Winchester Cathedral
St. Albans Cathedral
Selby Abbey
Ely Cathedral Norman
Ely Cathedral Octagon

Cathedral	Foundation Depth (m)	Minimum Stress (kN/m^2)	Maximum Stress (kN/m^2)	Tower Height (m)
Peterborough Cathedral	1.3	925	1863	45.72
Durham Cathedral	2.3	768	2048	66.45
Winchester Cathedral	4.6	383	1406	45.72
St. Albans Cathedral	5.3	326	1135	43.89
Selby Abbey	3.0	442	2437	39.62
Ely Cathedral Norman	4.0	374	1309	45.72
Ely Cathedral Octagon	1.7	429	1006	52.00

Tower Settlement Calculations

v 0.2

Cathedral	Min load (kN)	Max Load (kN)	Max foundation width (m)	Min foundation width (m)	Bearing soil type	Max Bearing depth	Min Bearing depth	Max layer thickness	Min layer thickness (m)	amax (equiv radius) (m)	amin (equiv radius) (m)
Peterborough Cathedral	17311	17484	4.35	3.05	Stiff clay	3.07	2.16	1.90	1.90	2.45	1.72
	17311	17484			Limestone			1.17	0.26	2.45	1.72
Durham Cathedral	27760	28520	6.09	4.27	Sandstone	4.31	3.02	4.31	3.02	3.44	2.41
Winchester Cathedral	25598	29944	8.84	4.27	Marly Clay	6.25	3.02	2.00	2.00	4.99	2.41
	25598	29944			Peat			2.50	1.02	4.99	2.41
	25598	29944			Silt			0.30		4.99	2.41
	25598	29944			Chalk			1.45		4.99	2.41
St. Albans Cathedral	26998	33721	10.18	4.88	Chalk	7.20	3.45	7.20	3.45	5.74	2.75
Selby Abbey	10162	11229	5.04	2.04	Firm clay (avg med and stiff)	3.57	1.44	3.57	1.44	2.84	1.15
Ely Cathedral Norman	20947	23958	8.00	4.00	Sand	5.66	2.83	3.00	2.83	4.51	2.26
	20947	23958			Stiff clay			2.66		4.51	2.26
Ely Cathedral Octagon	9342	9665	4.75	3.05	Sand	3.36	2.16	3.00	2.16	2.68	1.72
	9342	9665			Stiff Clay			0.36		2.68	1.72

* used equivalent area

			With Constant Average E											
			Stress Bulb				Rigid				Uniform z=0			
E (MPa)	Average Emax	Avergae E min	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement
19 1500	585	194	0.0207	0.0049	0.0158	0.0128	0.025	0.006	0.019	0.015 0.0154	0.032	0.007	0.024	0.020
1500	1500	1500	0.0031	0.00221	0.0009	0.0026	0.0037	0.002654934	0.0010	0.0032	0.0047	0.003	0.0013	0.0040
19 50 3.75 960	249	29	0.1440	0.00962	0.1344	0.07682 0.07682	0.173	0.0116	0.162	0.092 0.092	0.221	0.015	0.2059	0.1177
960	960	960	0.0041	0.00244	0.0016	0.0033	0.0049	0.00294	0.0020	0.0039	0.0062	0.004	0.0025	0.0050
12.75	12.75	12.75	0.2760	0.1235	0.152	0.1997	0.332	0.149	0.183	0.240	0.423	0.189	0.2336	0.3060
16 19	17	16	0.2314	0.1216	0.1098	0.1765 0.1765	0.278	0.146	0.132	0.212 0.212	0.355	0.186	0.168	0.270
16 19	16	16	0.135	0.08820	0.04726	0.1118 0.1118	0.163	0.106	0.057	0.135 0.135	0.208	0.135	0.072	0.171

	With only considering E from top soil layer											
	Stress Bulb				Rigid				Uniform z=0			
Cathedral	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement
Peterborough Cathedral	0.2114	0.1497	0.0617	0.1805 0.1805	0.254	0.180	0.074	0.217 0.2172	0.324	0.229	0.095	0.277 0.277
Durham Cathedral	0.0031	0.00221	0.0009	0.0026	0.0037	0.00265	0.0010	0.0032	0.0047	0.00338	0.0013	0.0040
Winchester Cathedral	0.2233		0.2233	0.22326 0.22326	0.269	0.1517	0.117	0.210 0.210	0.342	0.193	0.1489	0.2676 0.2676
St. Albans Cathedral	0.0041	0.00244	0.0016	0.0033	0.0049	0.00294	0.0020	0.0039	0.0062	0.00374	0.0025	0.0050
Selby Abbey	0.2760	0.1235	0.152	0.1997	0.332	0.149	0.183	0.240	0.423	0.189	0.2336	0.3060
Ely Cathedral Norman	0.2314	0.1324	0.0991	0.1819 0.1819	0.278	0.159	0.119	0.219 0.219	0.355	0.203	0.1518	0.2787 0.279
Ely Cathedral Octagon	0.135	0.08996	0.04550	0.1127 0.1127	0.163	0.108	0.055	0.136 0.136	0.208	0.138	0.0697	0.1727 0.173

Nave Settlement Calculations

Cathedral	Min load (kN)	Max Load (kN)	Max foundation width (m)	Min foundation width (m)	Bearing soil type	Max Bearing depth	Min Bearing depth	Max layer thickness	Min layer thickness (m)	amax (equiv radius) (m)	amin (equiv radius) (m)
Peterborough Cathedral	2327	2438	2.37	1.50	Stiff clay	1.67	1.06	1.70	1.10	1.34	0.85
	2327	2438			Limestone					1.34	0.85
Durham Cathedral	4076	4417	3.02	2.25	Sandstone	2.13	1.59	2.13	1.59	1.70	1.27
Winchester Cathedral	1955	4940	3.48	1.50	Marly Clay	2.46	1.06	2.00	1.10	1.97	0.85
	1955	4940			Peat			0.50		1.97	0.85
	1955	4940			Silt					1.97	0.85
	1955	4940			Chalk					1.97	0.85
St. Albans Cathedral	3591	8502	3.86	2.13	Chalk	2.73	1.51	2.73	1.51	2.18	1.20
Selby Abbey	1335	1446	2.37	1.50	Firm clay (avg med and stiff)	1.67	1.06	1.67	1.06	1.34	0.85
Ely Cathedral Norman	3216	3434	2.53	1.50	Sand	1.79	1.06	1.80	1.06	1.43	0.85
	3216	3434			Stiff clay					1.43	0.85
Ely Cathedral Octagon	3216	3434	2.53	1.50	Sand	1.79	1.06	1.80	1.06	1.43	0.85
	3216	3434			Stiff Clay					1.43	0.85

*used equivalent area

			Stress Bulb				Rigid				Uniform z=0			
E (MPa)	Average Emax	Avergae E min	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement
19 1500	19	19	0.0627	0.0390	0.0238	0.0508	0.069	0.046	0.023	0.058 0.0578	0.088	0.059	0.030	0.074
1500	1500	1500	0.0009	0.00069	0.0002	0.0008	0.0010	0.000830455	0.0002	0.0009	0.0013	0.001	0.0003	0.0012
19 50 3.75 960	25	19	0.0503	0.04036	0.0099	0.04533 0.04533	0.058	0.0479	0.011	0.053 0.053	0.074	0.061	0.0134	0.0676
960	960	960	0.0012	0.00162	-0.0004	0.0014	0.0015	0.00195	-0.0005	0.0017	0.0019	0.002	-0.0006	0.0022
12.75	12.75	12.75	0.0493	0.0339	0.015	0.0416	0.059	0.041	0.019	0.050	0.076	0.052	0.0237	0.0638
16 19	16	16	0.0948	0.0604	0.0344	0.0776 0.0776	0.114	0.072	0.042	0.093 0.093	0.145	0.092	0.053	0.119
16 19	16	16	0.095	0.06036	0.03440	0.0776 0.0776	0.114	0.072	0.042	0.093 0.093	0.145	0.092	0.053	0.119

	With only considering E from top soil layer											
	Stress Bulb				Rigid				Uniform z=0			
Cathedral	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement	Max settlement (m)	Min settlement (m)	Difference (m)	Avg Settlement
Peterborough Cathedral	0.0577	0.0383	0.0194	0.0480 0.0480	0.069	0.046	0.023	0.058 0.0578	0.088	0.059	0.030	0.074 0.074
Durham Cathedral	0.0009	0.00069	0.0002	0.0008	0.0010	0.00083	0.0002	0.0009	0.0013	0.00106	0.0003	0.0012
Winchester Cathedral	0.0485		0.0485	0.04851 0.04851	0.058	0.0635	-0.005	0.061 0.061	0.074	0.081	-0.0065	0.0776 0.0776
St. Albans Cathedral	0.0012	0.00162	-0.0004	0.0014	0.0015	0.00195	-0.0005	0.0017	0.0019	0.00249	-0.0006	0.0022
Selby Abbey	0.0493	0.0339	0.015	0.0416	0.059	0.041	0.019	0.050	0.076	0.052	0.0237	0.0638
Ely Cathedral Norman	0.0948	0.0600	0.0348	0.0774 0.0774	0.114	0.072	0.042	0.093 0.093	0.145	0.092	0.0533	0.1185 0.119
Ely Cathedral Octagon	0.095	0.05998	0.03477	0.0774 0.0774	0.114	0.072	0.042	0.093 0.093	0.145	0.092	0.0533	0.1185 0.119

	Peterborough Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Stress Bulb Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	390	17484	17311	0.013	0.015	0.020	0.016
	Top E	19			0.181	0.217	0.277	0.225
Nave	Average E	19	2438	2327	0.051	0.058	0.074	0.061
	Top E	19			0.048	0.058	0.074	0.060

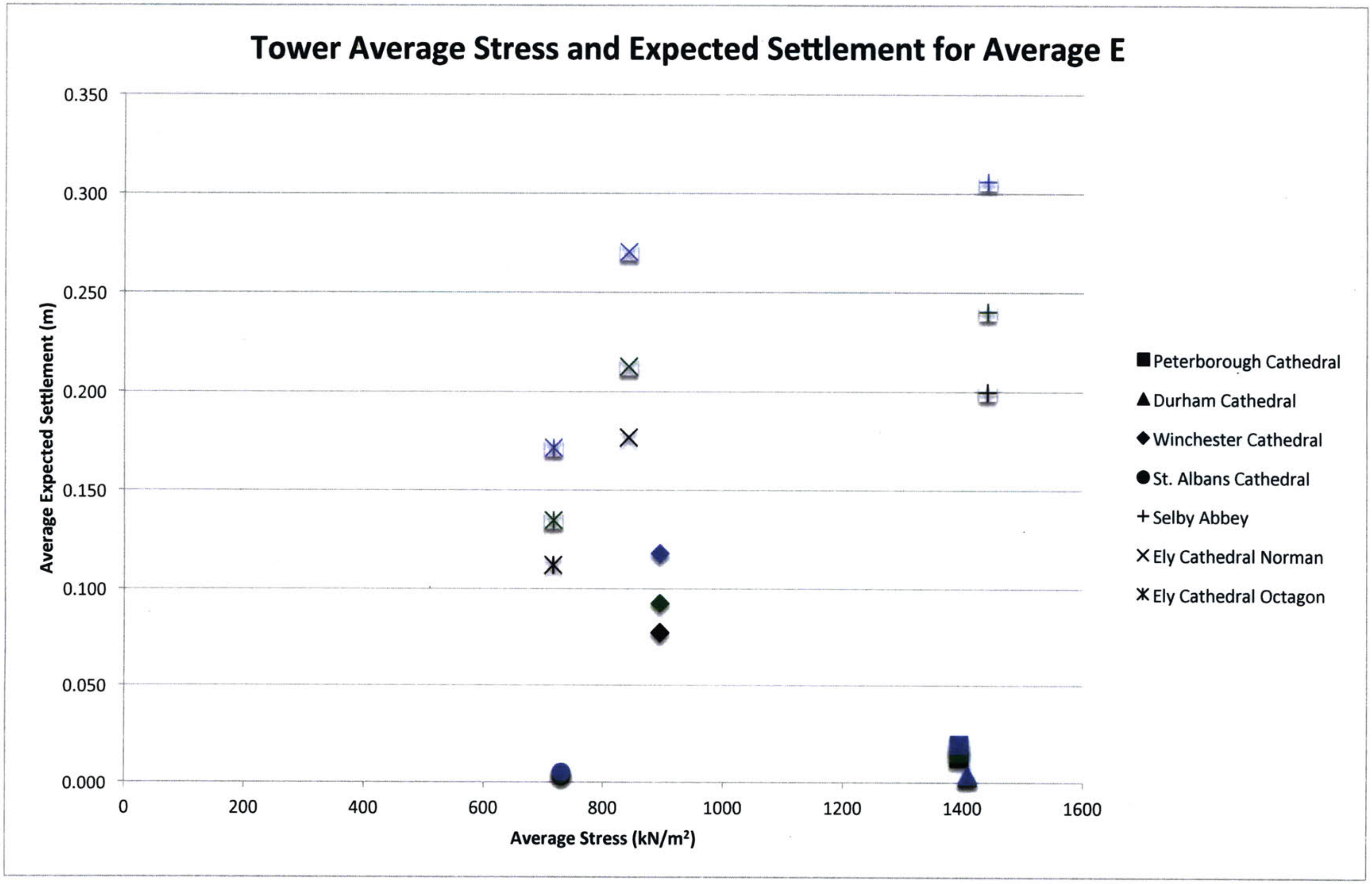
	Durham Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Stress Bulb Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	1500	28520	27760	0.003	0.003	0.004	0.003
	Top E	1500			0.003	0.003	0.004	0.003
Nave	Average E	1500	4417	4076	0.001	0.001	0.001	0.001
	Top E	1500			0.001	0.001	0.001	0.001

	Winchester Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Stress Bulb Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	139	29944	25598	0.077	0.092	0.118	0.096
	Top E	19			0.223	0.210	0.268	0.234
Nave	Average E	22	4940	1955	0.045	0.053	0.068	0.055
	Top E	19			0.049	0.061	0.078	0.062

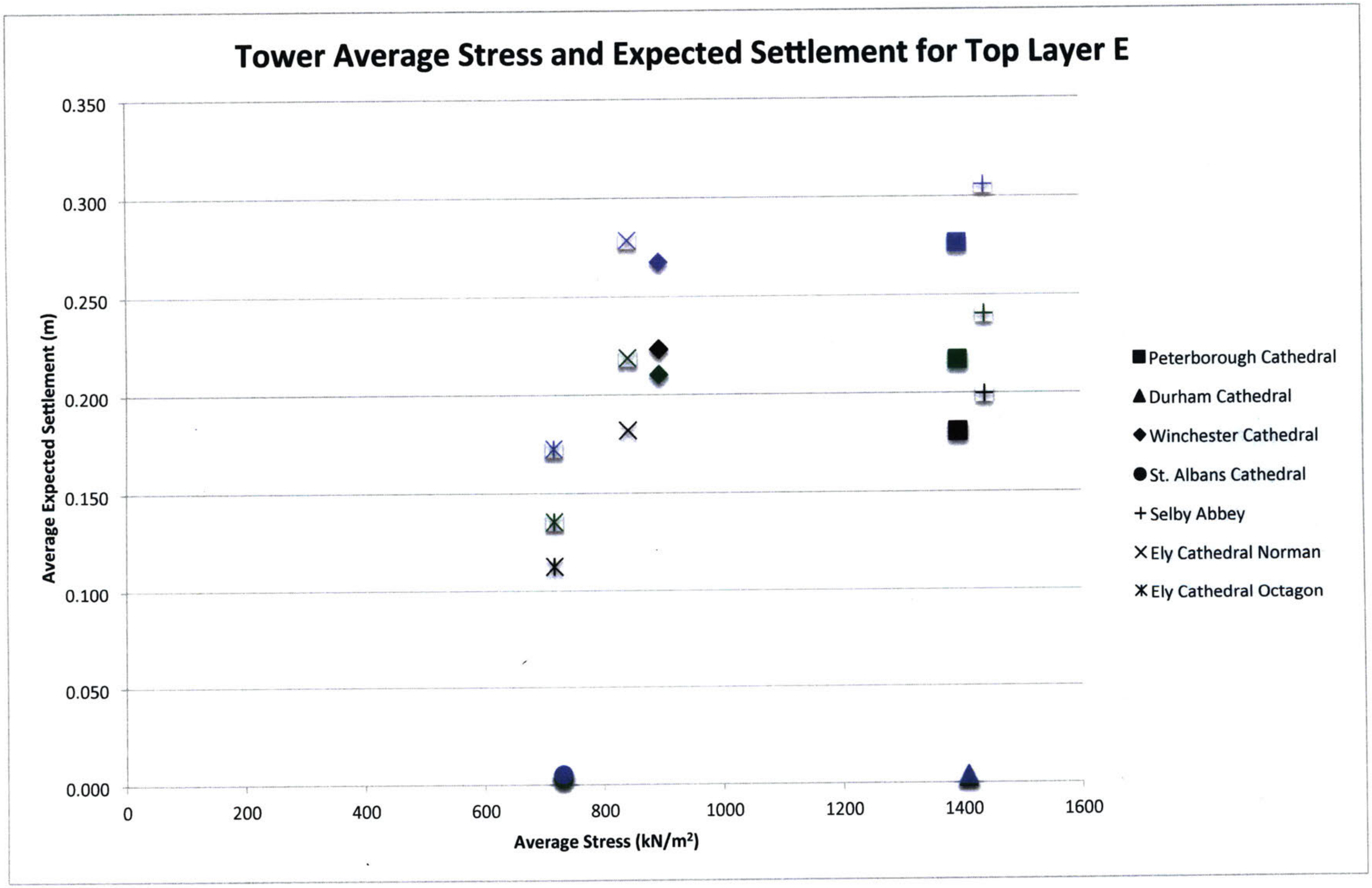
	St. Albans Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Stress Bulb Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	960	33721	26998	0.003	0.004	0.005	0.004
	Top E	960			0.003	0.004	0.005	0.004
Nave	Average E	960	8502	3591	0.001	0.002	0.002	0.002
	Top E	960			0.001	0.002	0.002	0.002

	Selby Abbey	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Stress Bulb Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Tower	Average E	12.75	11229	10162	0.200	0.240	0.306	0.249
	Top E	12.75			0.200	0.240	0.306	0.249
Nave	Average E	12.75	1446	1335	0.042	0.050	0.064	0.052
	Top E	12.75			0.042	0.050	0.064	0.052

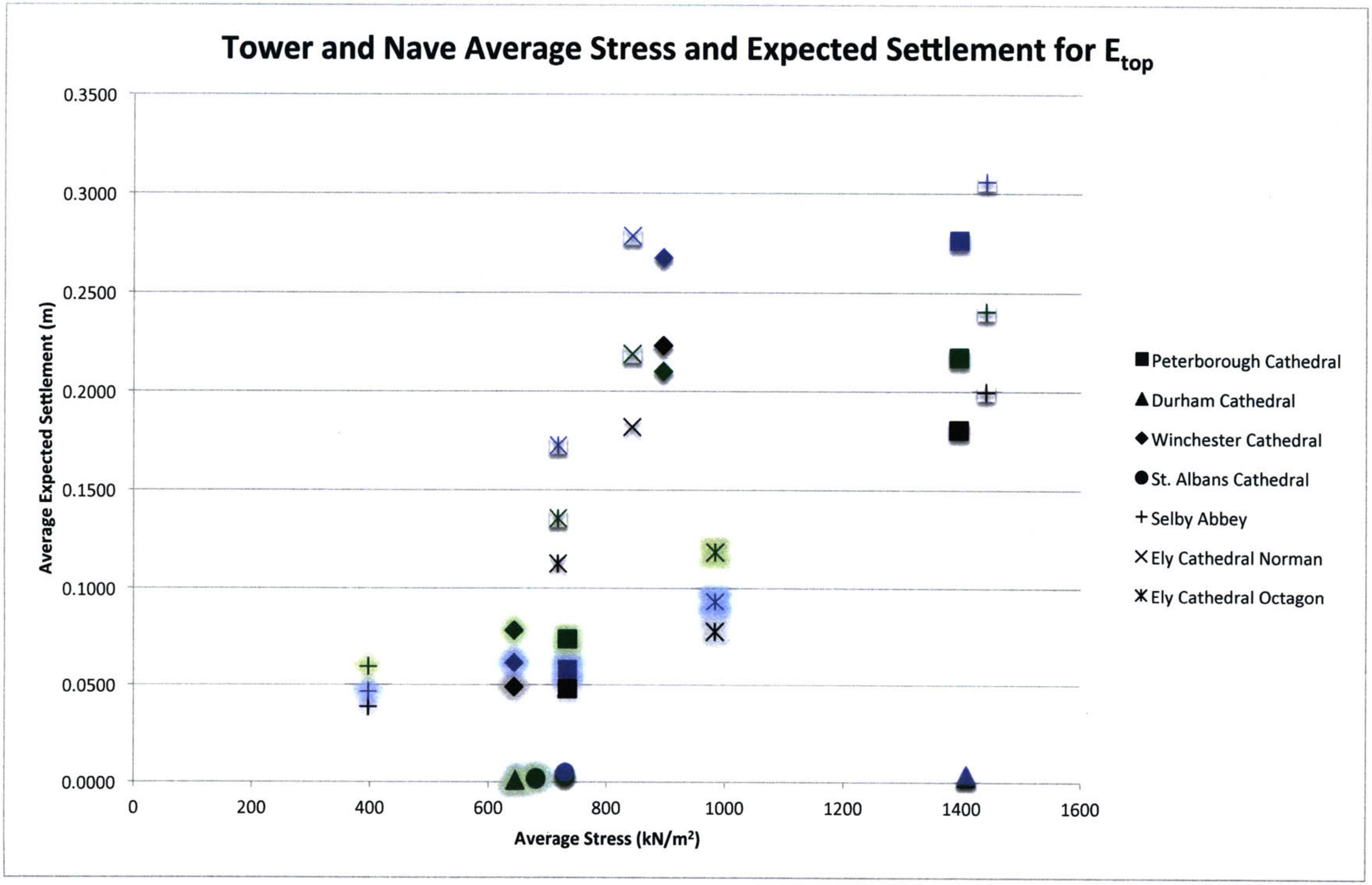
	Ely Cathedral	E (MPa)	Maximum Load (kN)	Minimum Load (kN)	Stress Bulb Average Settlement (m)	Rigid Average Settlement (m)	Uniform Average Settlement (m)	Average Expected Settlement(m)
Norman Tower	Average E	17	23958	20947	0.177	0.212	0.270	0.220
	Top E	16			0.182	0.219	0.279	0.226
Octagon Tower	Average E	16	9665	9342	0.112	0.135	0.171	0.139
	Top E	16			0.113	0.136	0.173	0.140
Nave	Average E	16	3434	3216	0.078	0.093	0.119	0.096
	Top E	16			0.077	0.093	0.119	0.096



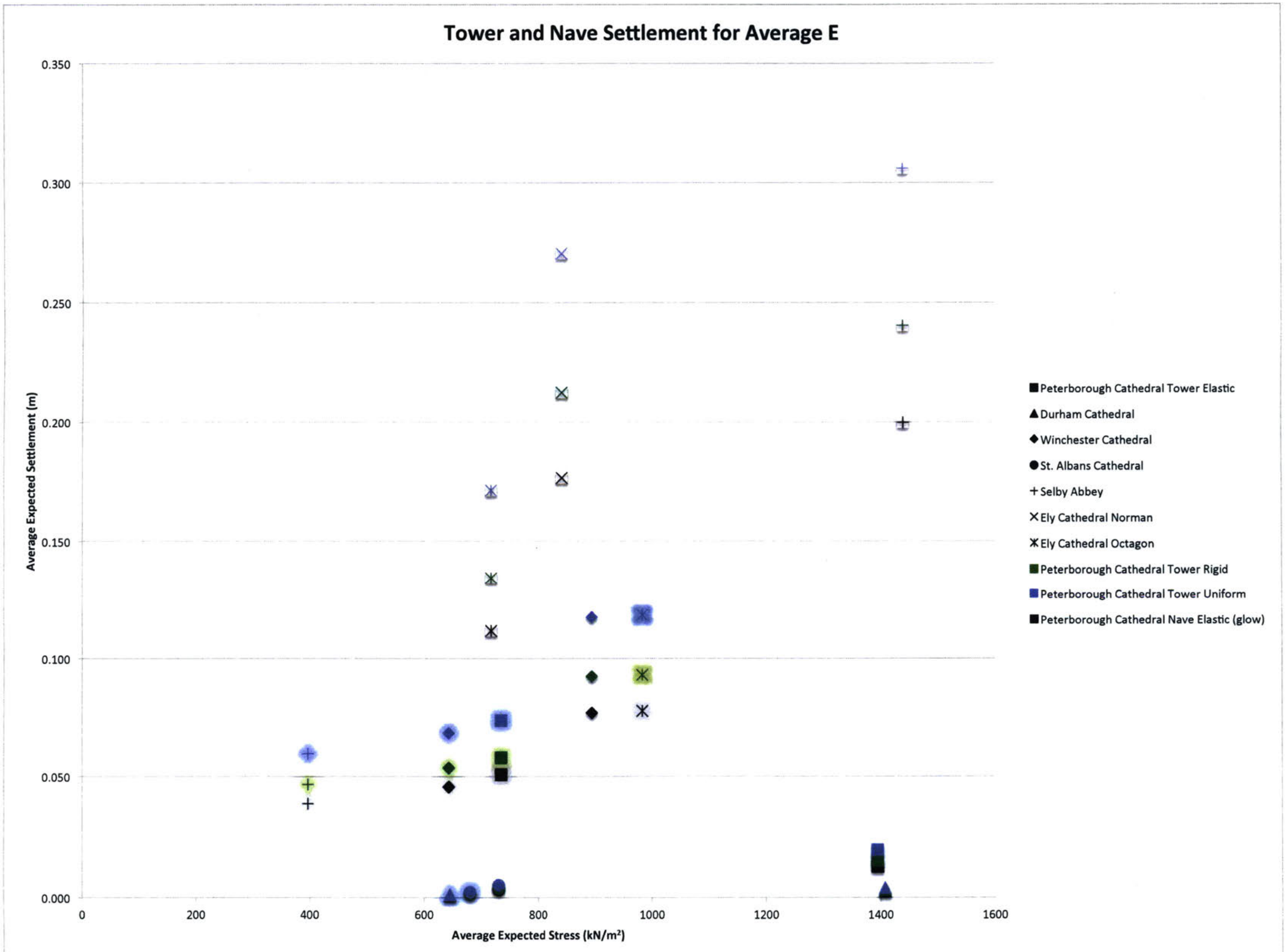
Tower Average Stress and Expected Settlement for Average E
Average Expected Settlement (m)
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0
200
400
600
800
1000
1200
1400
1600
Average Stress (kN/m²)
Peterborough Cathedral
Durham Cathedral
Winchester Cathedral
St. Albans Cathedral
Selby Abbey
Ely Cathedral Norman
Ely Cathedral Octagon



Tower Average Stress and Expected Settlement for Top Layer E
Average Expected Settlement (m)
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0
200
400
600
800
1000
1200
1400
1600
Average Stress (kN/m²)
Peterborough Cathedral
Durham Cathedral
Winchester Cathedral
St. Albans Cathedral
Selby Abbey
Ely Cathedral Norman
Ely Cathedral Octagon



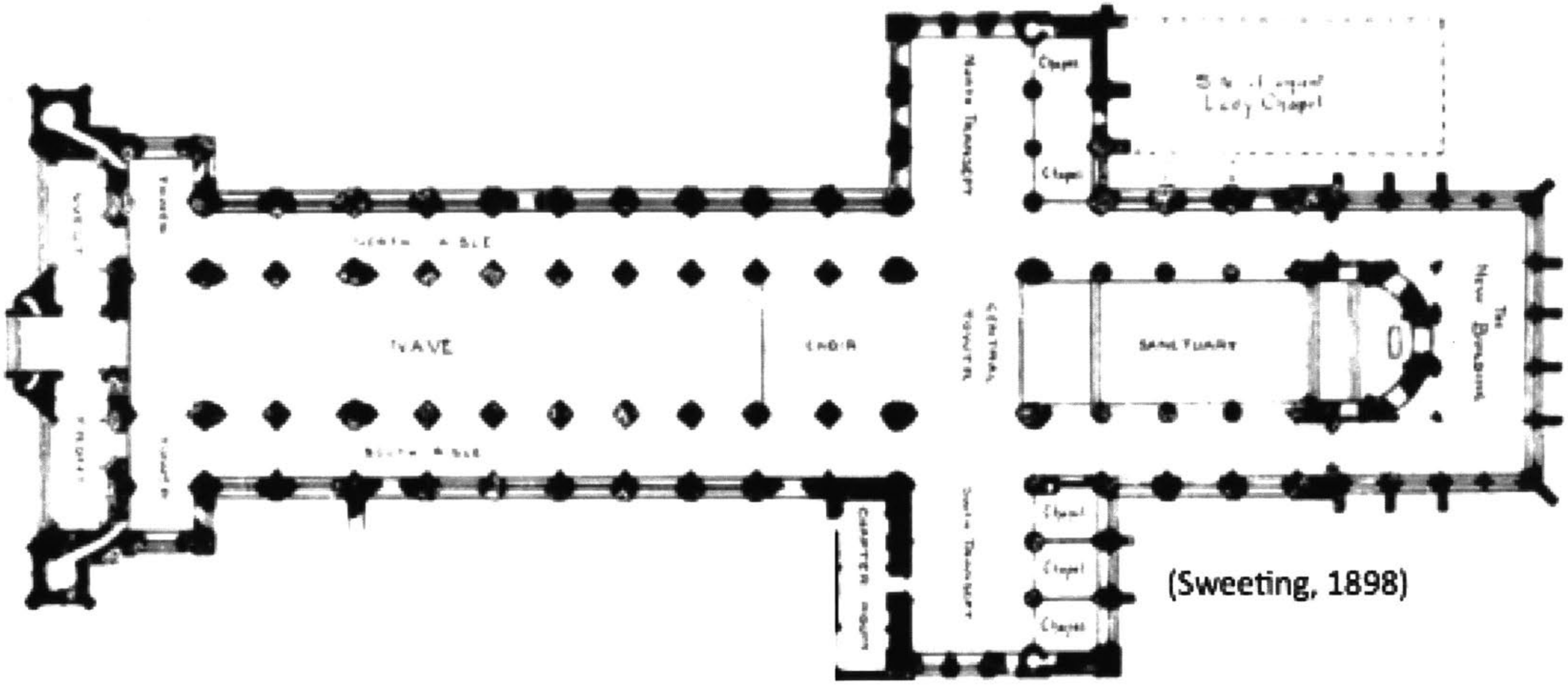
Tower and Nave Average Stress and Expected Settlement for E_{top}
Average Expected Settlement (m)
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0
200
400
600
800
1000
1200
1400
1600
Average Stress (kN/m²)
Peterborough Cathedral
Durham Cathedral
Winchester Cathedral
St. Albans Cathedral
Selby Abbey
Ely Cathedral Norman
Ely Cathedral Octagon



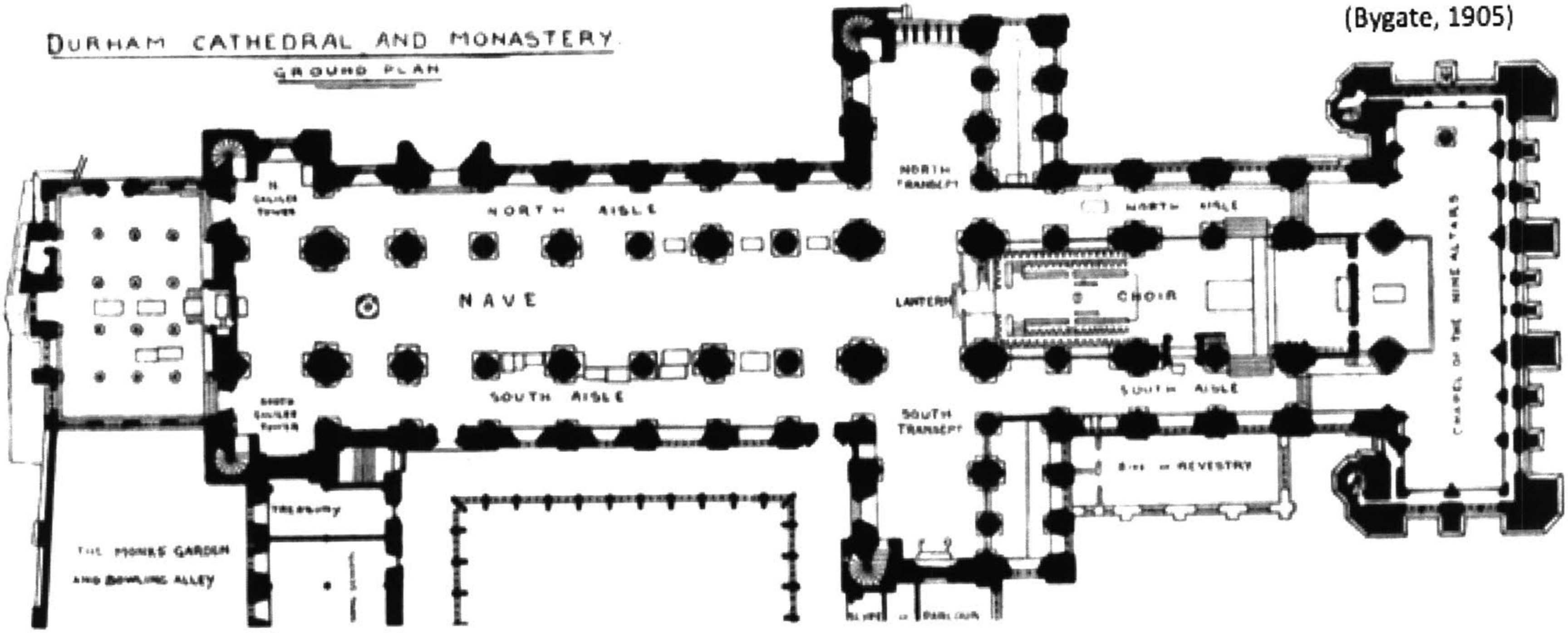
Tower and Nave Settlement for Average E
Average Expected Settlement (m)
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0
200
400
600
800
1000
1200
1400
1600
Average Expected Stress (kN/m²)
Peterborough Cathedral Tower Elastic
Durham Cathedral
Winchester Cathedral
St. Albans Cathedral
Selby Abbey
Ely Cathedral Norman
Ely Cathedral Octagon
Peterborough Cathedral Tower Rigid
Peterborough Cathedral Tower Uniform
Peterborough Cathedral Nave Elastic (glow)

Appendix B- Cathedral Floor plans

Peterborough Cathedral

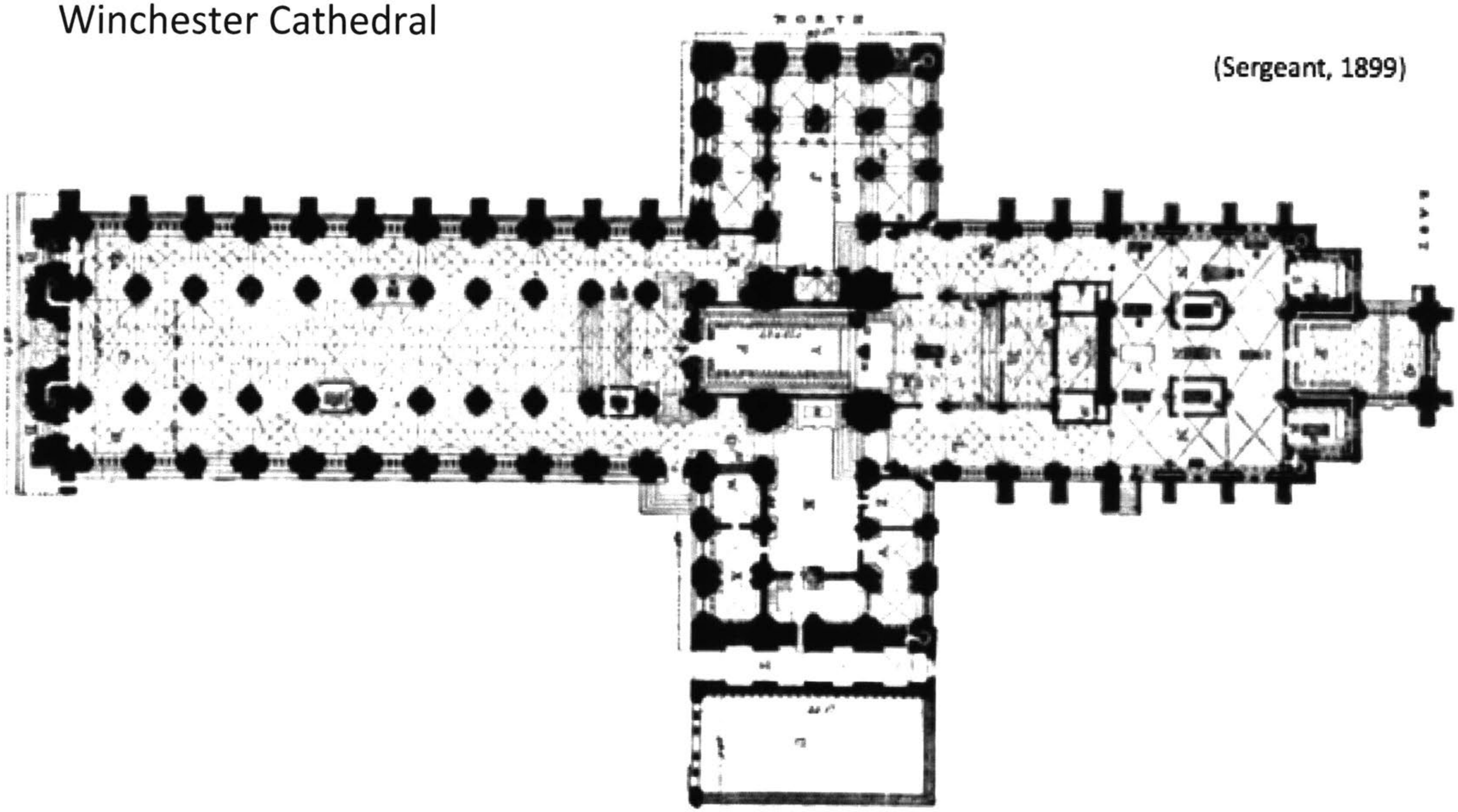


(Sweeting, 1898)


DURHAM CATHEDRAL AND MONASTERY
GROUND PLAN
NORTH AISLE
NAVE
SOUTH AISLE
NORTH TRANSEPT
SOUTH TRANSEPT
LANTERN
CHOIR
NORTH AISLE
SOUTH AISLE
CHAPEL OF THE NINE ALTARS
REVESTRY
TREASURY
THE MONKS' GARDEN
AND BOWLING ALLEY

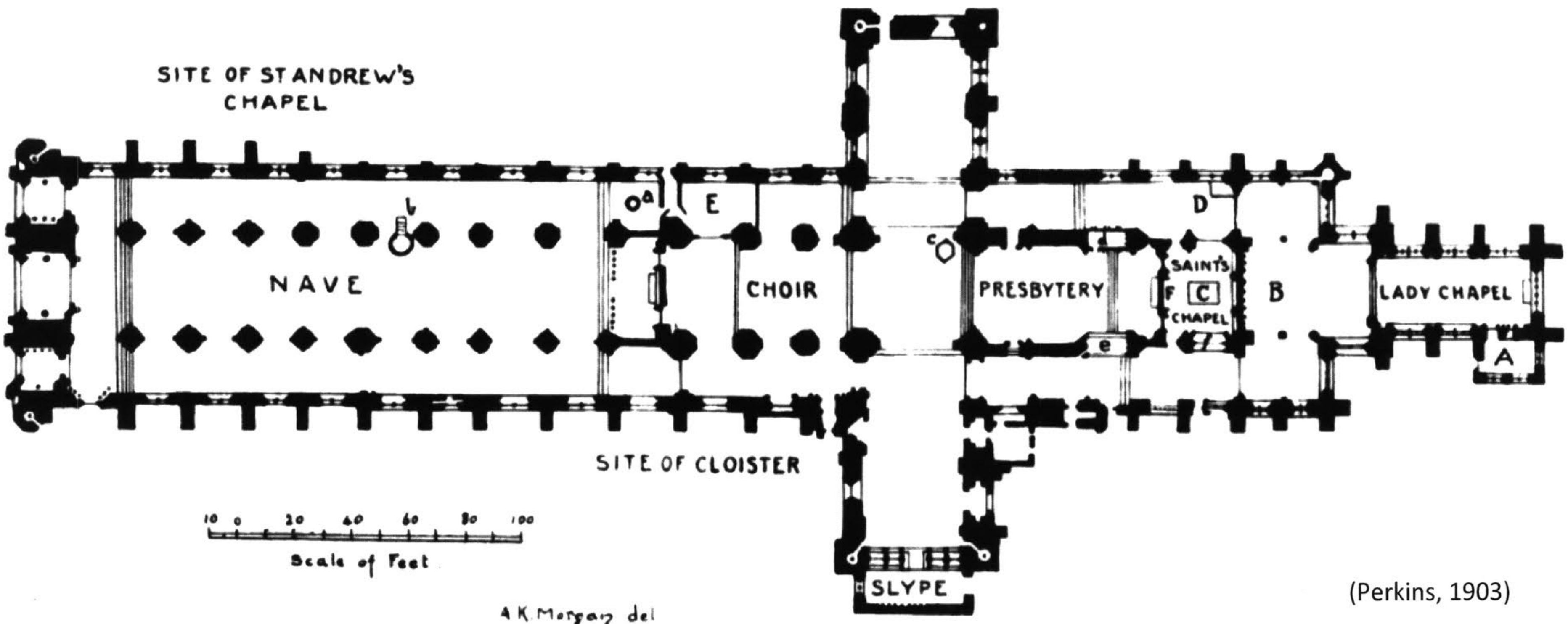
(Bygate, 1905)

Winchester Cathedral



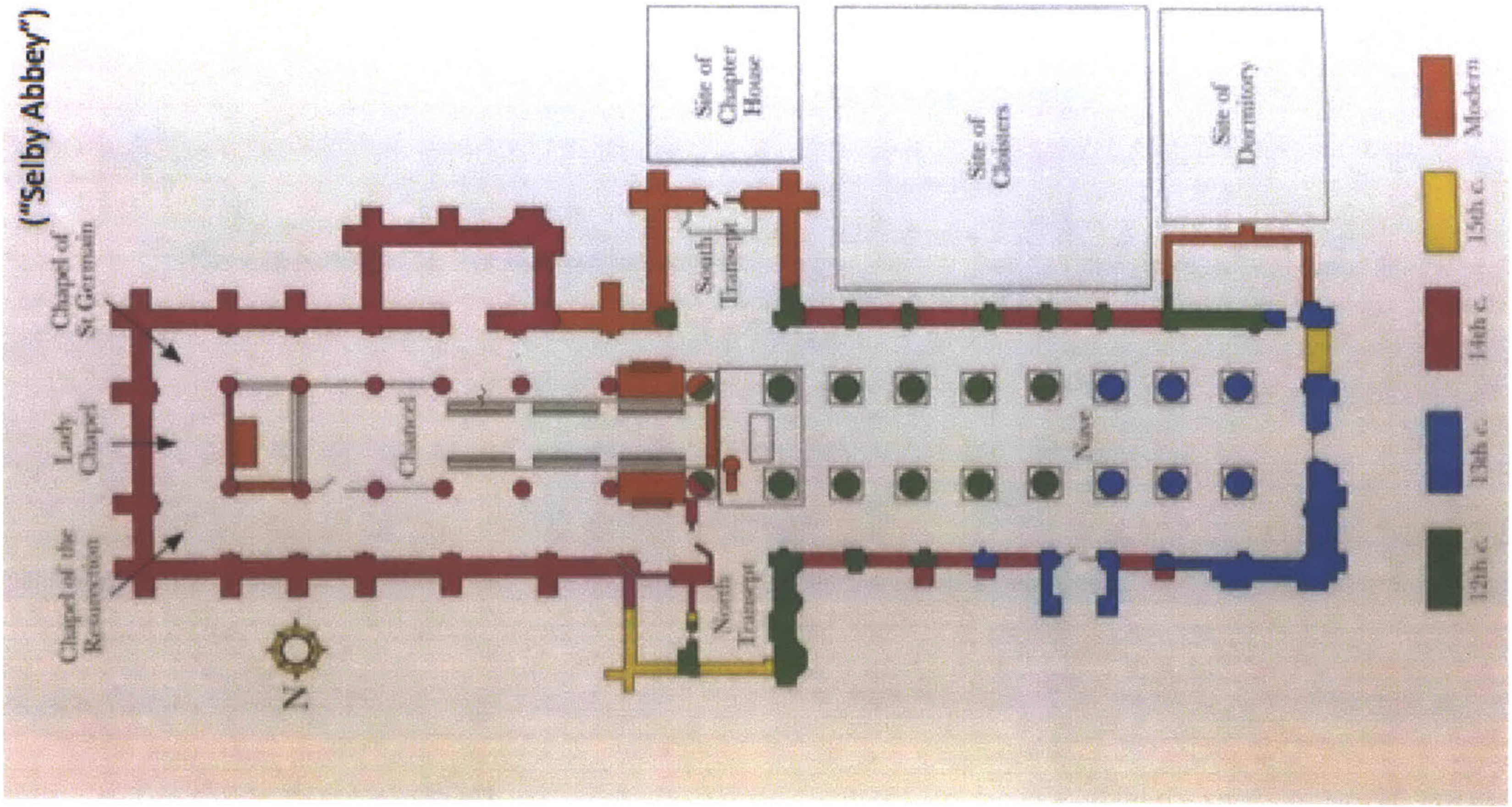
(Sergeant, 1899)

GROUND-PLAN OF
ST. ALBANS CATHEDRAL.

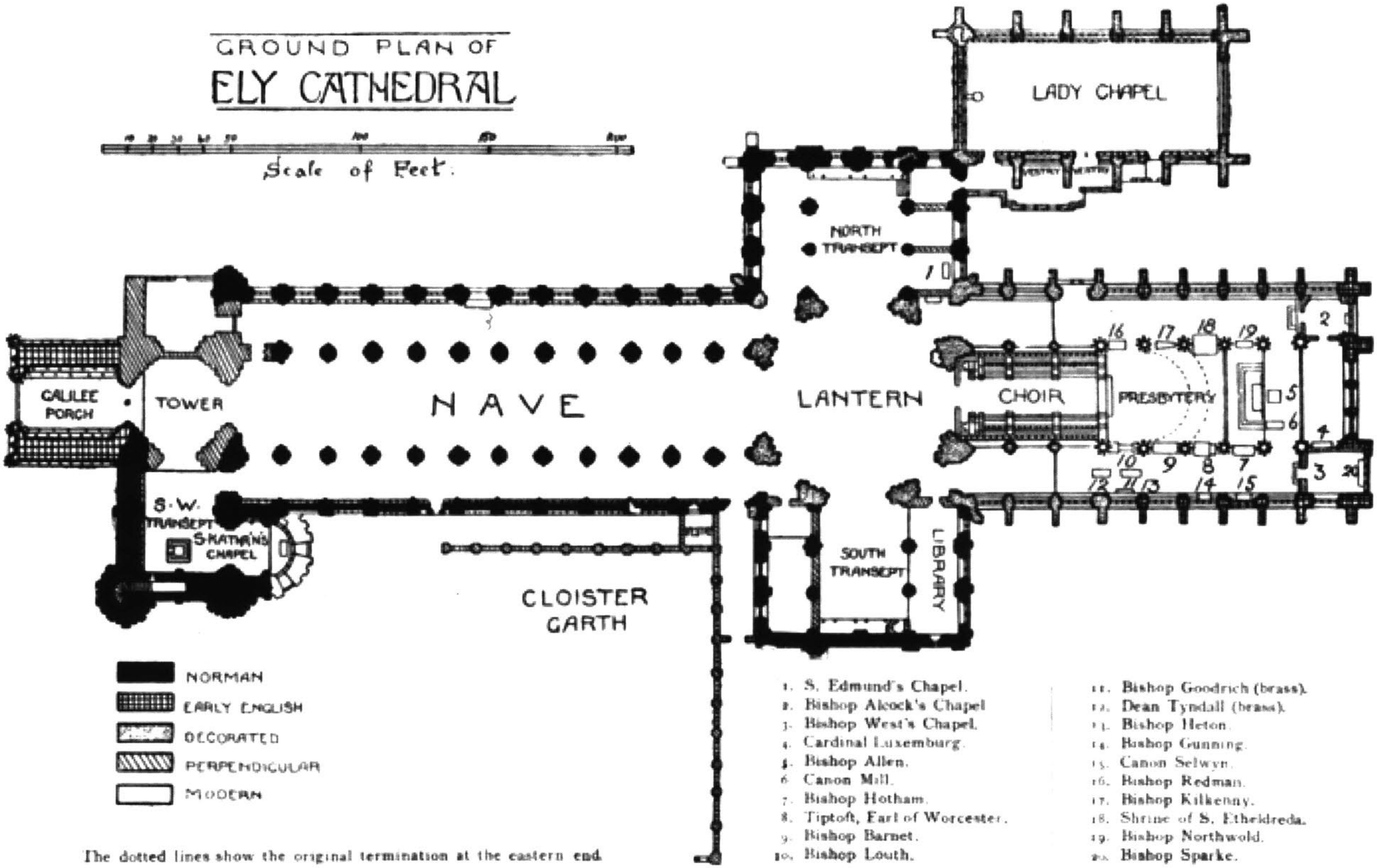


(Perkins, 1903)

Selby Abbey


("Selby Abbey")
Chapel of St Germain
Lady Chapel
Chapel of the Resurrection
Chancel
Nave
South Transept
North Transept
Site of Chapter House
Site of Cloisters
Site of Dormitory
Modern
15th c.
14th c.
13th c.
12th c.
N

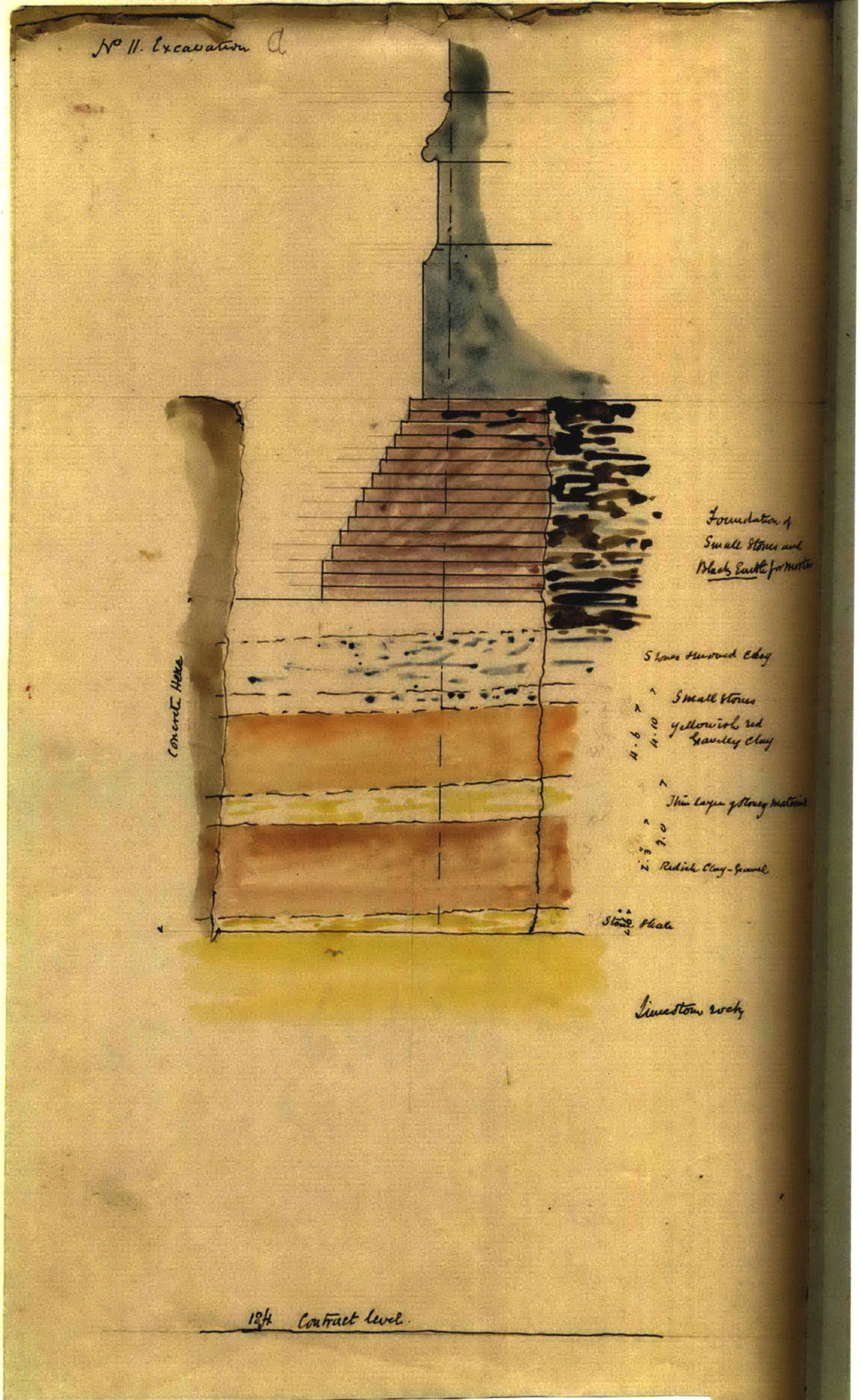
(Sweeting, 1902)



The dotted lines show the original termination at the eastern end.

1. S. Edmund's Chapel.
2. Bishop Alcock's Chapel.
3. Bishop West's Chapel.
4. Cardinal Luxemburg.
5. Bishop Allen.
6. Canon Mill.
7. Bishop Hotham.
8. Tiptoft, Earl of Worcester.
9. Bishop Barnet.
10. Bishop Louth.
11. Bishop Goodrich (brass).
12. Dean Tyndall (brass).
13. Bishop Heton.
14. Bishop Gunning.
15. Canon Selwyn.
16. Bishop Redman.
17. Bishop Kilkenny.
18. Shrine of S. Etheldreda.
19. Bishop Northwold.
20. Bishop Sparke.

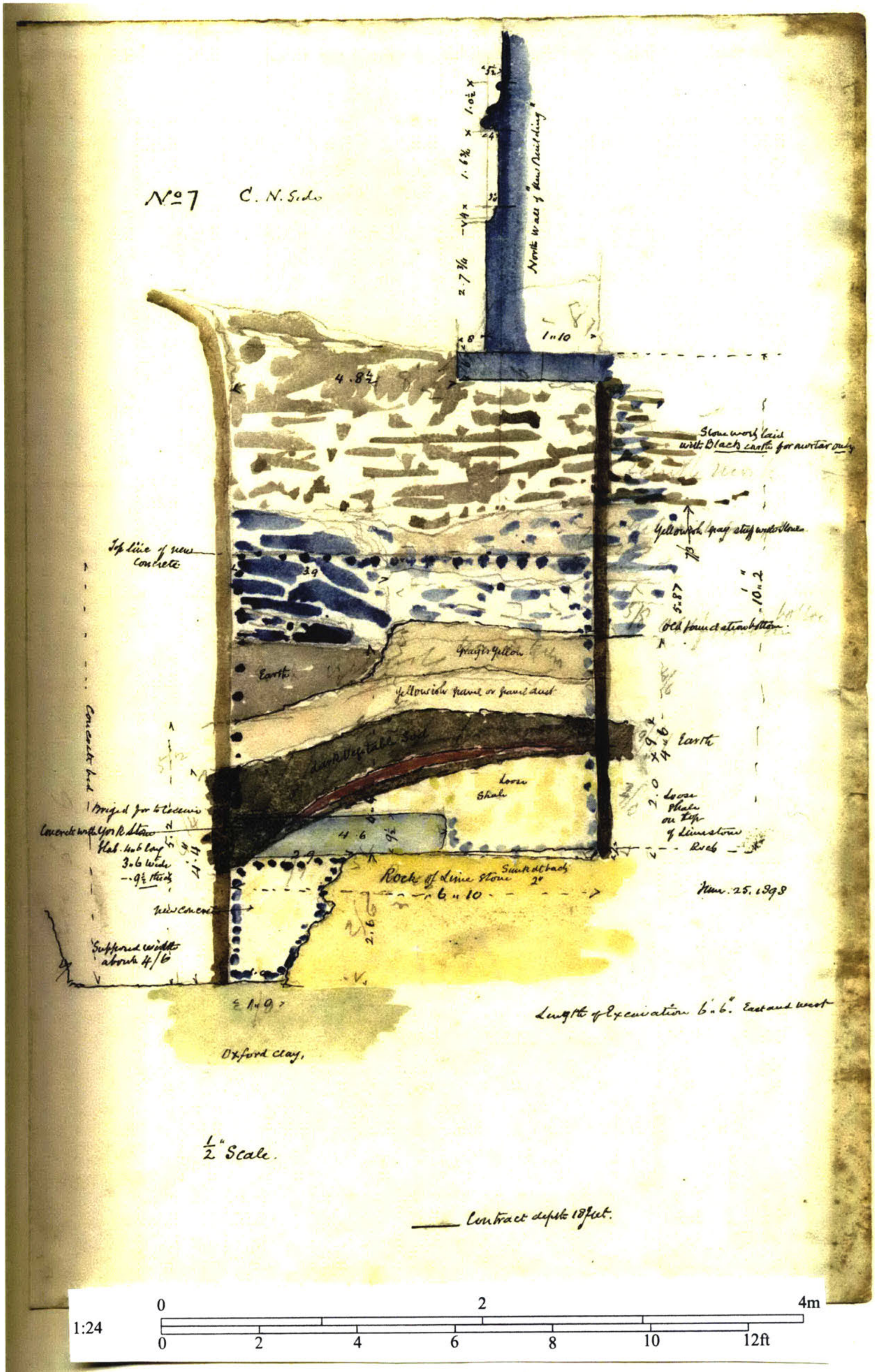
Appendix C- Borings and Geotechnical Information



1:24

0 2 4m

0 2 4 6 8 10 12ft



No 7 C. N. Side
North Wall of New Building
1.10
4.8½
Stone work laid with Black earth for mortar only
Yellowish gray stuff under stone
Top line of new Concrete
3.9
5.87
10.2
Old foundation bottom
Grayish Yellow
Earth
Yellowish gravel or gravel dust
Dark Vegetable Soil
Earth
Loose Shale
Loose Shale on top of Limestone Rock
4.6
2.9
Rock of Lime Stone
6.10
Nov. 25. 1898
Concrete bed
new concrete
Supposed width about 4/6
Length of Excavation 6.6 East and West
Oxford clay.
½" Scale.
Contract depth 18 feet.
1:24
0
2
4m
0
2
4
6
8
10
12ft

DUNELM DRILLING CO.

BOREHOLE RECORD

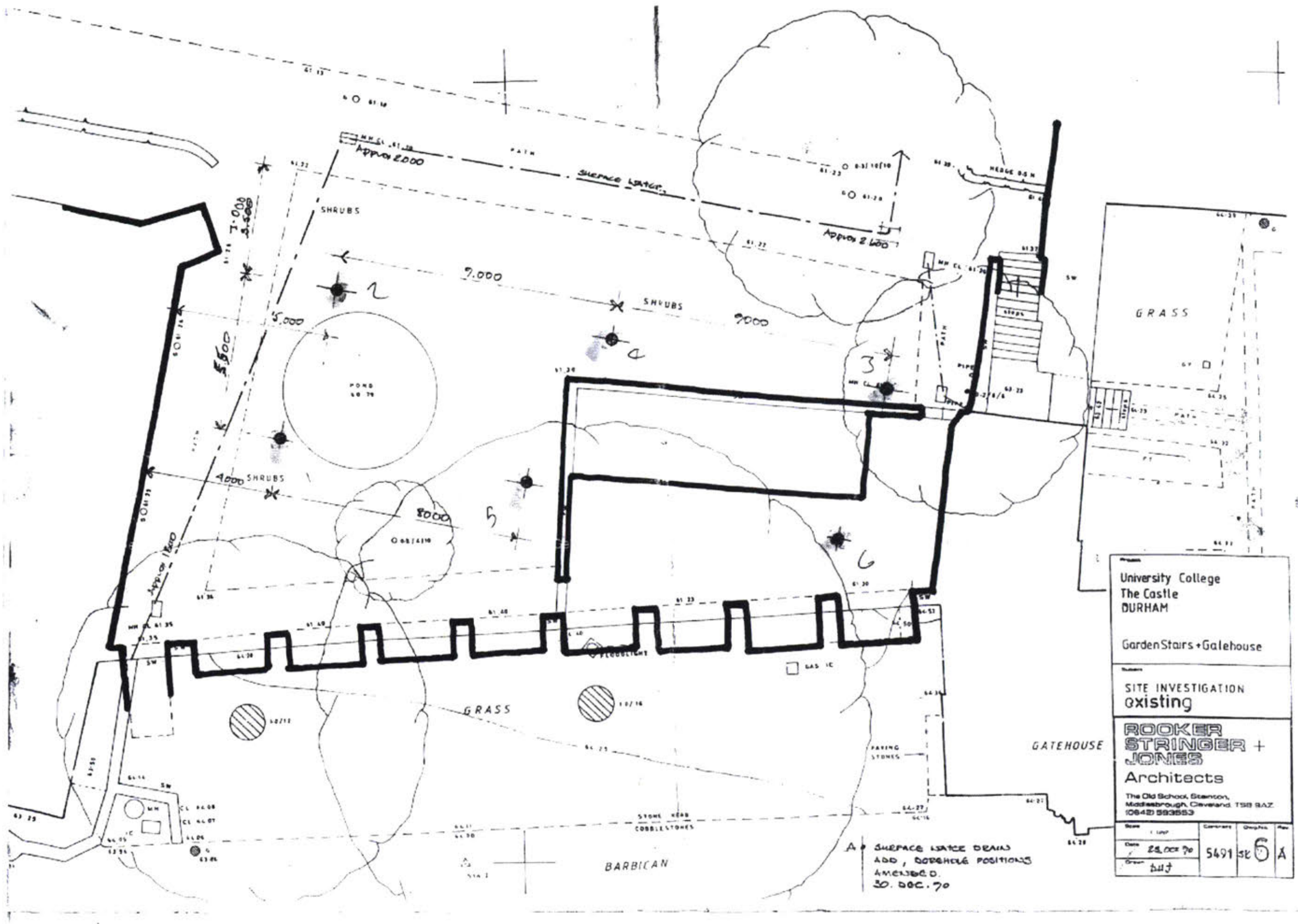
Contract No. C4758 — Client ROOKER STRINGER & JONES

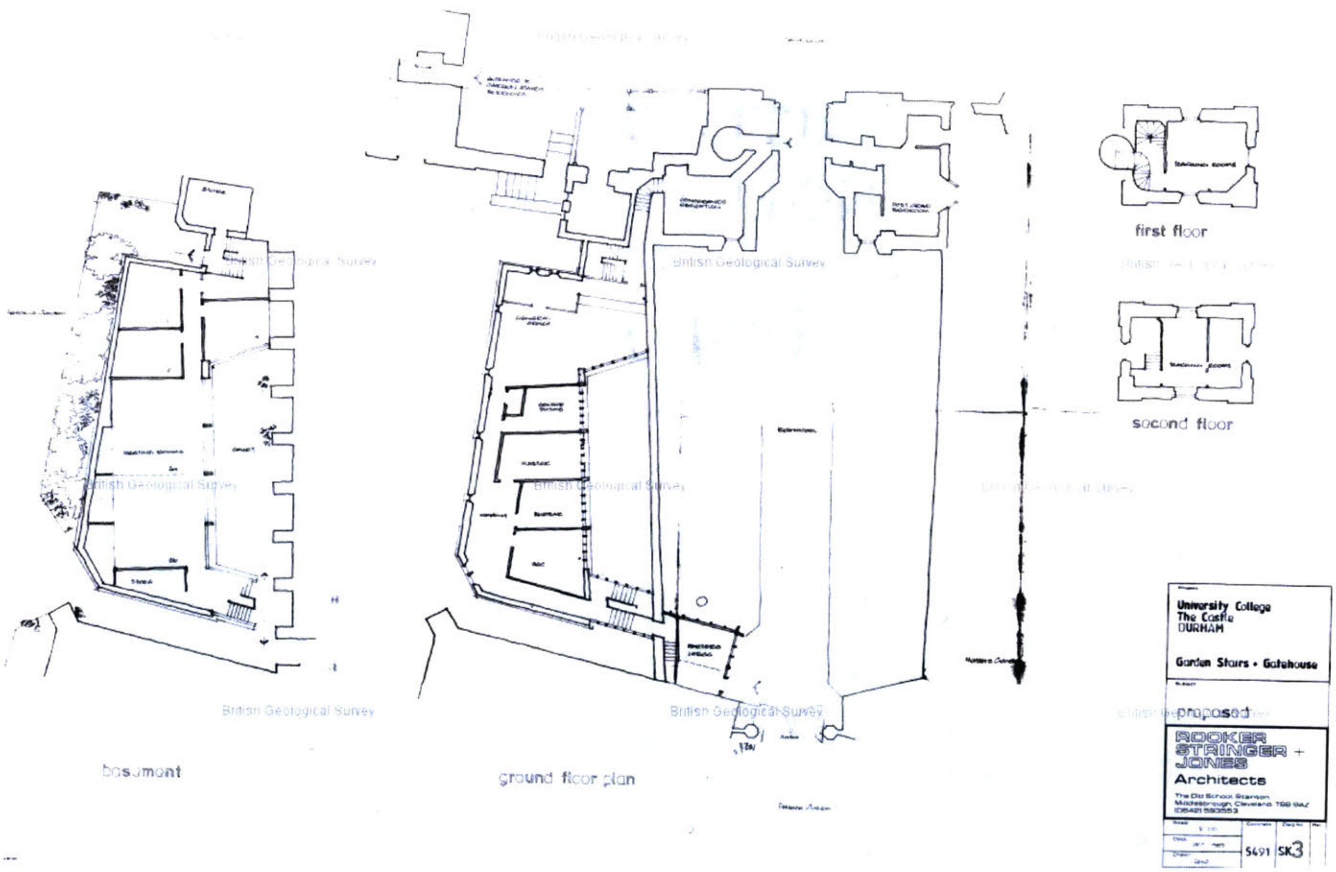
Ground Level .... — Location UNIVERSITY COLLEGE, THE CASTLE – DURHAM

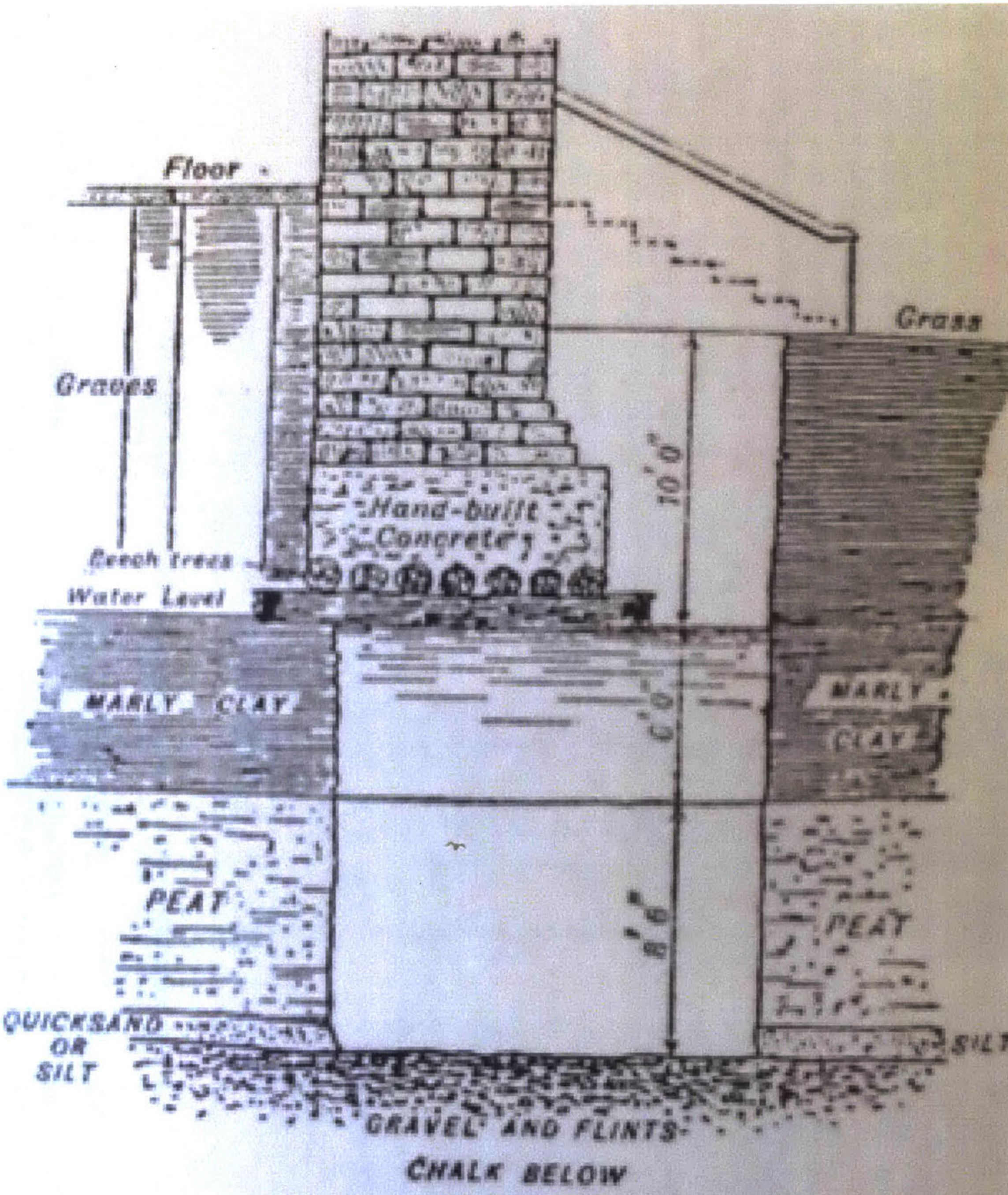
Date DEC '90 — **BOREHOLE No.** BH1

Depth	Thick-ness	Legend	Description of Strata	Type of Sample	C kN/m²	M %	Ø	Density Kg/m³	N
0·70	0·70		SOFT MOIST TOPSOIL						
				U 0·75					
			V. SOFT MOIST BROWN SANDY CLAY FILL WITH OCCASIONAL SMALL STONES.	U 1·50					
3·00	2·30			P 2·00					3
3·50	0·50		SOFT TO FIRM DK. BROWN SILTY SANDY CLAY FILL	U 3·00					
				P 4·00					7
			SOFT LOOSE WET BROWN SAND WITH OCCASIONAL PIECES OF GRAVEL & SMALL FRAGMENTS OF COAL. FAIRLY WELL GRADED	P 5·00					6
8·00	4·50			P 6·50					5
8·50	0·50		MODERATE TO SLIGHTLY WEATHERED LT. BROWN SANDSTONE.	P 8·00					99

Water Struck at 2·00m — Standing Water Level 1·85


SHRUBS
GRASS
POND
GATEHOUSE
BARBICAN
COBBLESTONES
PAVING STONES
FLOODLIGHT
SURFACE WATER
Approx 2000
Approx 2400
7.000
9000
5.000
5.500
8000
4000
Approx 1800
1.000
3.500
2
3
4
5
6
A SURFACE WATER DRAIN ADD, BOREHOLE POSITIONS AMENDED. 30. DEC. 70
University College
The Castle
DURHAM
Garden Stairs + Galehouse
SITE INVESTIGATION
existing
ROOKER STRINGER + JONES
Architects
The Old School, Stanton, Middlesbrough, Cleveland TS8 9AZ
(0642) 593553
25.OCT 70
5491
SE 6
A


first floor
second floor
basement
ground floor plan
University College
The Castle
DURHAM
Garden Stairs + Gatehouse
proposed
ROOKER
STRINGER +
JONES
Architects
S491
SK3



(Henderson and Crook, 1984)

LOCATION	DATE	
LOWER DAGNELL ST - ST ALBANS	1st Dec 1987	**BOREHOLE : 4**

DESCRIPTION	REDUCED LEVEL m	DEPTH m	LEGEND	SAMPLE TYPE	SAMPLE DEPTH	THICKNESS m	SPT	REMARKS
		0.00						
Reinforced concrete over hardcore FILL						0.40		
Clay and brick FILL		0.40						
				CPT	1.00		7	
				D	1.00	1.40		--750 /4 / 1.0D
Firm brown organic gravelly CLAY		1.80		U100	1.80			--750 /4 / 1.8U
				D	2.20	1.00		--750 /4 / 2.2D
				B	2.30			--750 /4 / 2.3B
Lumps of intact chalk in matrix of remoulded CHALK with some clay		2.80		CPT	2.30		9	
				U100	3.00			--750 /4 / 3.0U
				SPT	3.50	1.20	10	
				D	3.50			--750 /4 / 3.5D
Lumps of intact CHALK in matrix of remoulded chalk - Grade V		4.00						
				U100	5.00			--750 /4 / 5.0U
				D	5.40			--750 /4 / 5.4D
				SPT	5.40		13	
				SPT	6.90		14	
				D	6.90			--750 /4 / 6.9D
						8.00		
				SPT	8.40		15	
				D	8.40			--750 /4 / 8.4D
				SPT	10.00		17	
				D	10.00			--750 /4 /10.0D
				SPT	11.50		15	
				D	11.50			--750 /4 /11.5D
		12.00						

TERRAMECH INVESTIGATIONS LIMITED
183 LONG LANE TILEHURST READING

REMARKS :

U100 = 100mm dia. UNDISTURBED SAMPLE U38 = 38mm dia. UNDISTURBED SAMPLE
D = SMALL DISTURBED SAMPLE B = BULK SAMPLE W = WATER SAMPLE
SPT = STANDARD PENETRATION TEST CPT = CONE PENETRATION TEST

Norwest Holst Soil Engineering Ltd.

Borehole No. 7

BOREHOLE LOG

Contract No. F6640
Location Selby Town Centre
Client The Birkett Stevens Colman Partnership
Method of Boring Percussion
Diameter of Borehole 150mm

SE 63 SW 245
6138 3241

Sheet 1 of 3
Chainage see plan
Ground Level 6.00 m.A.O.D.
Date 14/10/85-15/10/85

Description of Strata	Depth Below G.L.(m)	O.D. Level (m)	Sampling and Coring	"N"/ R.Q.D.%
MADE GROUND - tarmac	0.05	5.95		
MADE GROUND - topsoil soft clay, with brick and rock fragments	0.60	5.40	0.55	'6'
MADE GROUND - soft pale brown silty clay with occasional gravel and brick fragments	1.80	4.20	1.55 (12)	
Very soft mottled brown and grey sandy CLAY	2.20	3.80	2.00	
Firm mottled brown and grey silty CLAY with occasional sand pockets	3.50	2.50	2.55 (26) 3.00	
Soft to firm brown laminated silty CLAY			4.05 (28) 4.50	
			5.00	
			5.55 (25) 6.00	
			6.50	
			7.05 (28) 7.50	
			8.00	
			8.55 (29) 9.00	
			9.50	

Type of Sample

Is S.P.T. — Undisturbed
Ic. C.P.T. — X Vane
O Jar — Δ Water
● Bulk — Piezometer

Remarks (Observations of Ground Water etc.) () U100 blows

Water struck at 10.50m (casing at 10.00m) 14/10/85 rose to 9.20m after 20 minutes
Standing level 7.30m (casing at 10.50m) am, 15/10/85
Water struck at 17.00m, 15/10/85 and rose to 10.80m after 20 minutes

Norwest Holst Soil Engineering Ltd.

BOREHOLE LOG

Borehole No. **7**

Contract No. F6640
Location Selby Town Centre
Client The Birkett Stevens Colman Partnership
Method of Boring Percussion
Diameter of Borehole 150mm

SE 63 SW 245

Sheet 2 of 3
Chainage see plan
Ground Level 6.00 m.A.O.D.
Date 14/10/85-15/10/85

Description of Strata	Legend	Depth Below G.L.(m)	O.D. Level (m)	Casing Depth at Sampling	Sampling and Coring	"N"/ R.Q.D.%	Daily Progress
Soft to firm brown laminated silty CLAY					10.05 (42) 10.50		
					11.00		
					11.55 (31) 12.00		
					12.50		
...below 12.70 becomes very silty, very soft to soft					13.05 (24) 13.50		
					14.00		
					14.55 (28) 15.00		
					15.50		
					16.05 (29) 16.50		
		17.25	-11.25		17.00		
Medium dense brown silty fine and medium SAND					17.30		
					17.55	'21'	
					18.30		
					18.55	'26'	
Very dense below 19.80m					19.30		
					19.55		

Type of Sample

- Is S.P.T.
- Ic. C.P.T.
- O Jar
- ● Bulk
- ▮ Undisturbed
- × Vane
- Δ Water
- Piezometer

Remarks (Observations of Ground Water etc.)

() U100 blows

Norwest Holst Soil Engineering Ltd.

Borehole No. 7

BOREHOLE LOG

Contract No. F6640
Location Selby Town Centre
Client The Birkett Stevens Colman Partnership
Method of Boring Percussion
Diameter of Borehole 150mm

SE 63SW 245

Sheet 3 of 3
Chainage see plan
Ground Level 6.00 m.A.O.D.
Date 14/10/85-15/10/85

Description of Strata	Legend	Depth Below G.L.(m)	O.D. Level (m)	Casing Depth at Sampling	Sampling and Coring	"N"/ R.Q.D.%	Daily Progress
Very dense brown silty fine and medium SAND					20.30		
					20.55	'94'	
					21.30		
					21.55	'123'	
		22.00	-16.00				

Remarks (Observations of Ground Water etc.)

() U100 blows

Type of Sample

- Is S.P.T.
- Ic. C.P.T.
- O Jar
- ● Bulk
- ▮ Undisturbed
- × Vane
- Δ Water
- Piezometer

BOREHOLE RECORD

Contract No. 13171/92 Client WARD COLE CONSULTING ENGINEERS

Ground Level Location REAR OF MARKET STREET, ELY

BOREHOLE No. B Date AUGUST, 1992

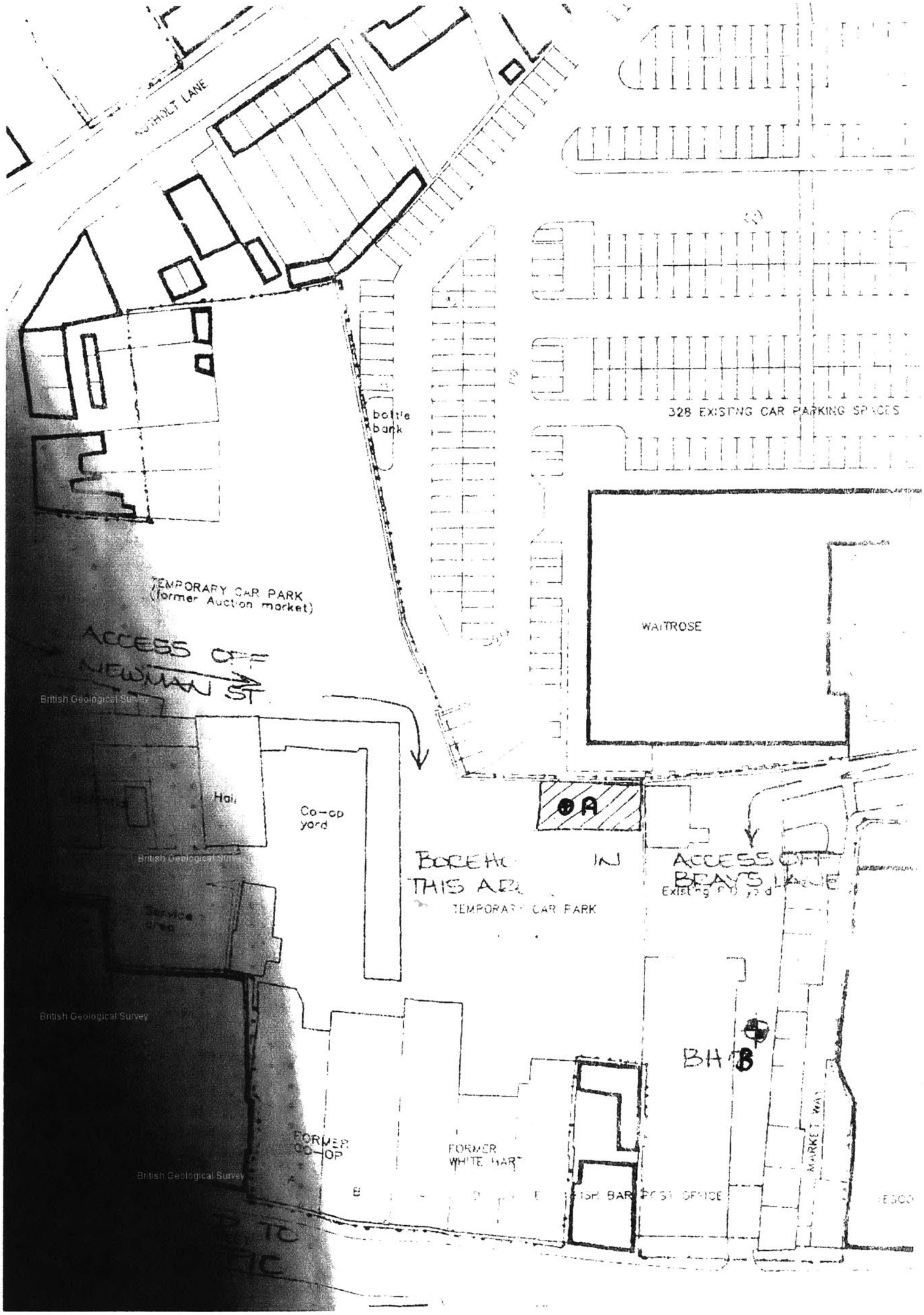
Depth	Thickness	Legend	Description of Strata	Type of Sample	C kN/m2	M %	Ø	Density kg/m3	N
0.250	0.250		Tarmac over reinforced concrete						
0.500	0.250		Made up ground – rubble	1.000 P					34
				2.000 P					23
	3.100		Medium dense sand with occasional gravel						
				3.000 P					12
3.600									
				3.900 U	148.8	20.0		2100	
				5.000 U	144.7	22.0		1955	
				6.500 U	134.1	28.0		2040	
	8.400		Stiff blue/grey silty clay with shells						
				8.000 U	142.5	32.0		1955	
				9.600 P					34
				11.100 P					37
12.000									

Water Struck at 8.900m. Standing Water Level

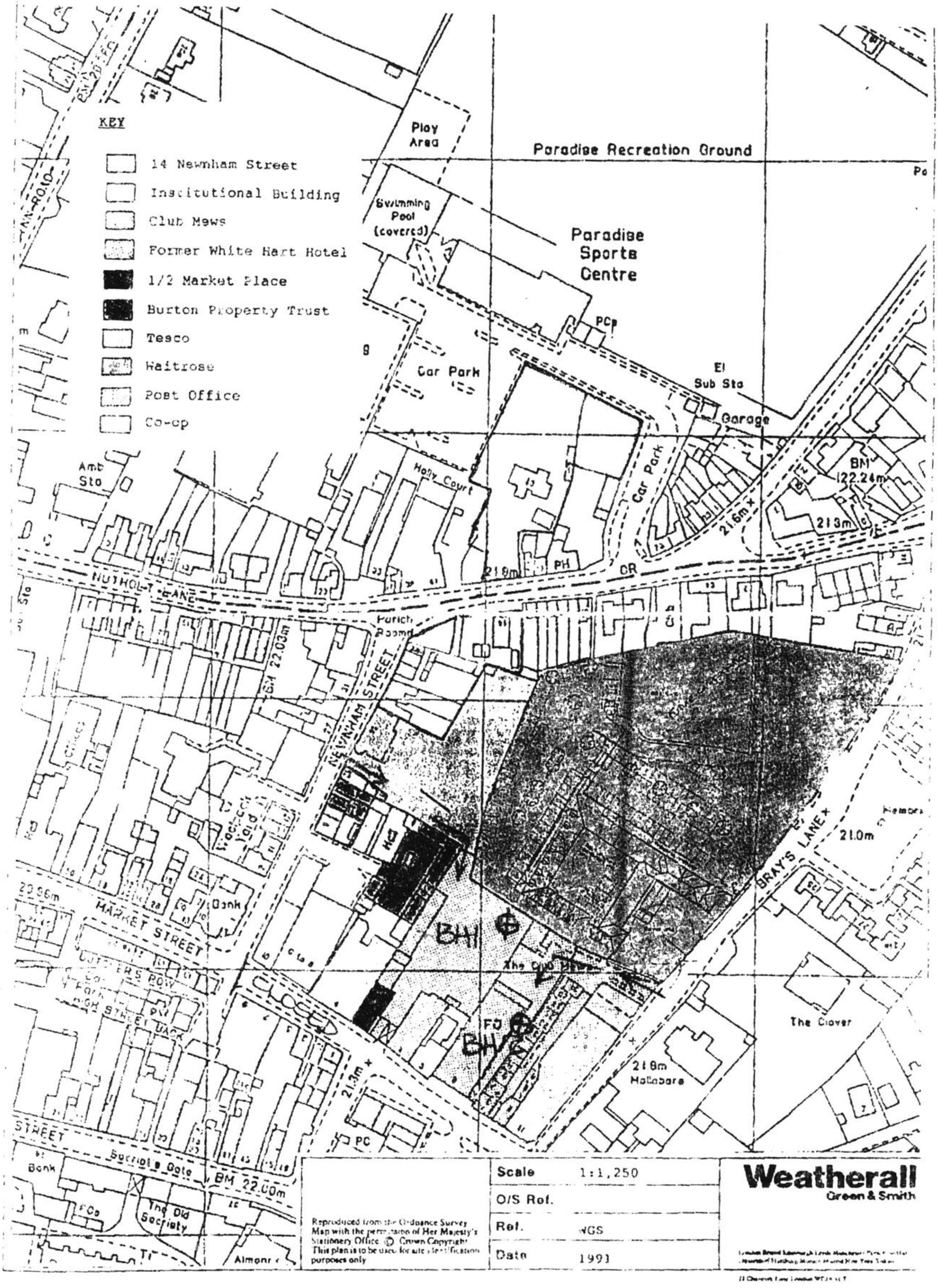
Undisturbed Sample	U
Disturbed Sample	O
Penetration Test	P
Cohesion	C
Angle of Internal Friction	Ø
Moisture Content %	M
Standard Penetration Value	N

J. T. HYMAS (Site Investigation) LTD.

12 Yarm Road, Stockton-on-Tees,
Cleveland TS18 3NE
Tel. 0642 607083 Fax. 0642 612355



NORTHOLT LANE
bottle bank
328 EXISTING CAR PARKING SPACES
TEMPORARY CAR PARK
(former Auction market)
ACCESS OFF
NEWMAN ST
WAITROSE
Hall
Co-op yard
A
BOREHO IN
THIS AR
ACCESS OFF
BRAYS LANE
TEMPORARY CAR PARK
Service area
BH B
MARKET WAY
FORMER CO-OP
FORMER WHITE HART
FISH BAR
POST OFFICE
British Geological Survey


KEY
14 Newnham Street
Institutional Building
Club Mews
Former White Hart Hotel
1/2 Market Place
Burton Property Trust
Tesco
Waitrose
Post Office
Co-op
Play Area
Paradise Recreation Ground
Swimming Pool (covered)
Paradise Sports Centre
PCs
Car Park
El Sub Sta
Garage
Holly Court
Car Park
PH
NUTHOLT LANE
Parish Rooms
NEWNHAM STREET
BM 22.03m
MARKET STREET
Bank
BRAY'S LANE
21.0m
The Clover
21.8m
Hallobars
21.3m
BM 22.00m
Sorriols Gate
The Old Society
Almonr
Bank
STREET
Amb Sta
PC
BHI
FJ
Scale 1:1,250
O/S Ref.
Ref. WGS
Date 1991
Weatherall
Green & Smith
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