St. Isaac Cathedral (St. Petersburg, Russia): A Case History

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ABSTRACT: *St Isaac's Cathedral in St. Petersburg was completed in 1858 after 40 years of construction; it is today the fourth largest domed Cathedral in Europe. The underlying soil is a relatively soft saturated sediment and carries this 3155 MN structure that is 100 meters high with an imprint of 92 m by 100 m. It is founded on a 7.5 m thick mat of granite and limestone blocks resting on relatively short timber piles of different lengths. The Cathedral has progressively experienced significant deformation including differential settlement causing cracks in the pillars and tilting of the porticoes. The paper summarizes the available geotechnical engineering and engineering geology aspects of the soil on which the Cathedral is built as well as classical issues such as foundation ultimate capacity and settlement analysis through simple calculations and numerical simulations. It also includes some less classical issues such as the influence of microbial activity on the behavior of the Cathedral through the changes the microbes and their activity create in the engineering properties of the soil and in the groundwater composition. The paper concludes with the results of a numerical simulation of the soil and the foundation under load and a comparison with the limited measurements that have been collected.*

KEYWORDS: Monuments, St. Isaac's Cathedral; Engineering properties of soil; Foundation capacity; Settlement analysis; Microbial activity; Numerical simulation

SITE LOCATION: Geo-Database

INTRODUCTION

The historical monuments in downtown St. Petersburg including St. Isaac's Cathedral are listed as World Cultural Heritage and have been protected by UNESCO since 1990. The current St. Isaac's Cathedral is the fourth church at this site dedicated to St. Isaac. The first church was made of wood and was built in 1707 in honor of St. Isaac. Peter the Great made the decision to construct the Cathedral in part because his birthday (May 30th) coincided with St. Isaac feast day. The first church was too close to the Neva River bank and was soon destroyed by floods. The second bell-tower church was built out of stone by Georg Mattarnovi in 1717 at a location between the first Cathedral and the current Cathedral but was finally dismantled. The third St. Isaac Cathedral was built in 1802 by architect Rinaldi and completed by architect Brenna but was later partially replaced. The fourth and current St. Isaac Cathedral was built in 1858; it has a Greek architectural cross ground plan with a large central dome and four smaller domes at each corner. The engineer in charge was August de Montferrand.

The main problems with St. Isaac Cathedral is cracking of the columns due to excessive differential settlement and a slight overall tilt of the structure to the southwest. The purpose of this paper is to analyze the behavior of St. Isaac Cathedral based on existing historical documents, on site investigations performed in 1954 and 2009 including in-situ and laboratory tests, on settlement calculations and observations, and on a series of numerical simulations of the Cathedral foundation and soil by the finite element method using ABAQUS.

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BRIEF HISTORY OF ST. PETERSBURG

St. Petersburg is a relatively young city, by both Russian and European standards as it was only founded on May 27, 1703 by Tsar Peter the Great in the Neva River delta (Fig. 1). The Neva River runs from Lake Lagoda to the Gulf of Finland (Baltic Sea). For a long time prior to 1700, the Neva River delta area was ruled alternatively by Sweden and Russia. By the end of the 17th century Peter the Great was determined to change the status quo, to regain access to the Baltic Sea and to establish stronger ties with the West. In the hope of achieving these goals he embarked on the Northern War with Sweden (1700-1721) and finally gained control over the Neva River.

Figure 1. Map of the Neva River delta.

St. Petersburg was built on about 20 islands within the marshy, swampy and wetland delta. In 1698, about 70% of the current downtown area of St. Petersburg consisted of peat bogs and peaty soils. In order to build the city on the swamps, a large amount of coarse grain fill and seabed soils were brought in to raise the islands above water level and increase the construction area. The ground elevation today in the downtown area varies from 0.5 to 9 m above mean sea level or a.s.l. (Baltic system of elevations) with an average of about 3.5 m. St. Petersburg is often referred to as the Venice of the North.

GEOLOGY OF DOWNTOWN ST. PETERSBURG

Fig. 2 shows a typical soil profile through downtown St. Petersburg. The two main strata from the geological point of view are surficial non-lithified saturated sand-with-clay deposits of quaternary age which are about 400,000 years old underlain by an older lithified clay strata called the Upper Vendian clay which is about 600 million years old. The quaternary soils were deposited during a series of periods including three glacial periods, two interglacial periods, an upper glacial period and a post glacial period. The thickness of the quaternary deposits varies from 20 m to 120 m and the elevation of the top level of the lithified Vendian clay depends on the erosion depth of the ancient rivers into the lithified Vendian clay. The thickness of the quaternary deposits is 20-25 m outside the buried river valleys and 20-120 m inside the buried valleys.

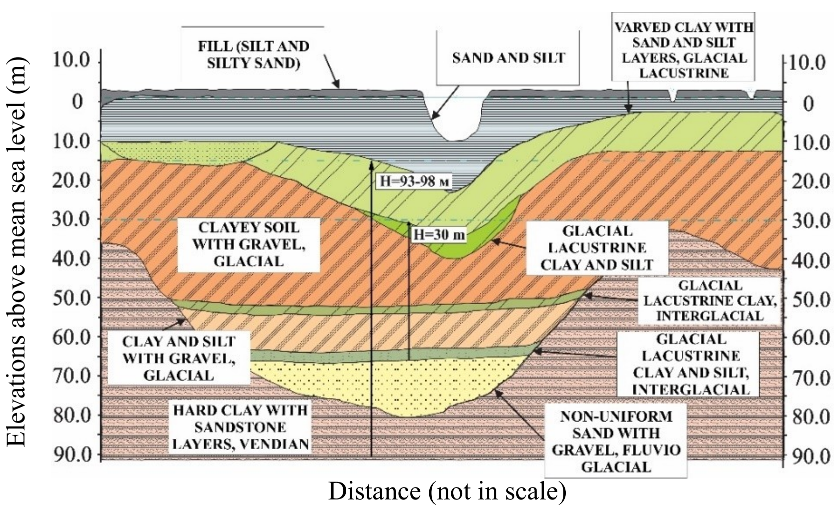

Figure 2. Soil stratigraphy below the downtown St. Petersburg.

The buildings in downtown St. Petersburg including the historical monuments are mostly founded on the postglacial deposits; these deposits are characterized by coarse grain fills and organic swamp soils with a thickness of 2-11 m, very fine and fine sand of marine and lacustrine origin and of Holocene age with a thickness of 6-12 m, and clayey soils including fat varved clay and lean clay of lacustrine-glacial origin with a thickness of 8-15 m. Under the postglacial deposits is a layer of moraine that consists of silt and lean clay with a gravel content of 5-15%. The thickness of this moraine varies from 10 to 20 m.

More than five aquifers with different chemistry and dynamics may be found in the geological profile. The groundwater level (GWL) in downtown St. Petersburg is found at a depth varying from 1 to 3 m. This groundwater is associated with the surface sandy fills of marine and lacustrine origin. At larger depth the groundwater has different pressure heads. For example, at a depth of 65 m the pressure head H is 30 m (Fig. 2). Yet the deep aquifer found in the Vendian sandstone below the Vendian hard clay at a depth of about 115 m has a pressure head of 93 to 98 m. (Dashko et al. 2013a). Both the groundwater and the soils are characterized by the presence of organic matter and microorganisms coming mostly from natural sources (peat bogs) and anthropogenic sources (such as leaking sewers) (Dashko et al. 2013a).

ST. ISAAC CATHEDRAL CONSTRUCTION, DIMENSIONS, AND LOADING

Excavation for the foundation of the current St. Isaac Cathedral started in 1768 and followed the recommendations of an Italian architect, Antonio Rinaldi. This cathedral could have become the finest structure that Rinaldi ever built, however he was unable to complete the work and another Italian architect, V. Brenna, completed the construction. Brenna reduced the building size and eliminated the minor domes. The resulting structure proved to be a low and squat building, quite out of concord with the celebrity looks of central St. Petersburg; thus, Tsar Alexander I decided to destroy the building and rebuild the Cathedral in 1809 using part of the foundation which had been built by Rinaldi.

After the Napoleon war, plans were made for a new cathedral to replace the previous (third) Cathedral. The new St. Isaac Cathedral was to be the most magnificent Cathedral of the whole Russian empire. Tsar Alexander I chose French architect August de Montferrand to lead the new project. The construction started in 1818 at the same location. The new design preserved the existing foundation under the western section of the third Cathedral. The new Cathedral would see an increase in length while its width would be retained. Construction of the Cathedral was completed in 1841, but the internal decoration took another 17 years. St. Isaac Cathedral was consecrated in 1858.

The foundation of the Cathedral posed serious problems as the soil was quite soft. Eventually Montferrand used a technique which had been commonly used for centuries in Venice: thousands of wooden piles driven into the soil to provide a solid foundation. Construction of the new foundations started with a 5-m deep excavation. Then pine timber piles 0.26 m in diameter and 6.4 m to 10.7 m in length were driven. Montferrand decided to use the 13000 existing piles from the Cathedral built by Rinaldi which were 0.26 m in diameter, 10.5 m long under the columns and 8.4 m long elsewhere. The total number of piles used for the construction of St. Isaac Cathedral was about 24000. The bottom of the piles is in the saturated postglacial marine and lacustrine sand and silt as well as the lacustrine-glacial clay; the piles act as friction piles as the end bearing is small compared to the friction capacity.

The pile cap consisted of a full-size mat made of massive granite blocks under the most heavily loaded elements, with limestone masonry for the remainder of the foundation. The mat was 7.5 m thick and rose 2.5 m above the ground level. In the 7.5 m thick mat, 2.5 m by 2.5 m galleries were constructed. The weight of the mat is estimated to be 997 MN (Sotnikov, 1986). The total height of St. Isaac Cathedral is 100 m (Fig. 3). The overall length of the Cathedral with porticoes is 100 m, and its width is 92 m. The total weight of the Cathedral structure above the mat is 2158 MN for a total weight on the soil below the mat of 3155 MN. This makes St. Isaac Cathedral the heaviest building in Saint Petersburg. The outside dimensions of the mat are 100 m long by 92 m wide. The mat is in the shape of a cross (Fig. 3) and has a total area of 7600 m^2. The average pressure under the mat is therefore 415 kPa. The weight of soil removed for the 5-m deep excavation using a unit weight of soil equals to 20 kN/m^3 is 760 MN and the corresponding pressure is 100 kPa. Therefore, the net pressure for the Cathedral is 315 kPa.

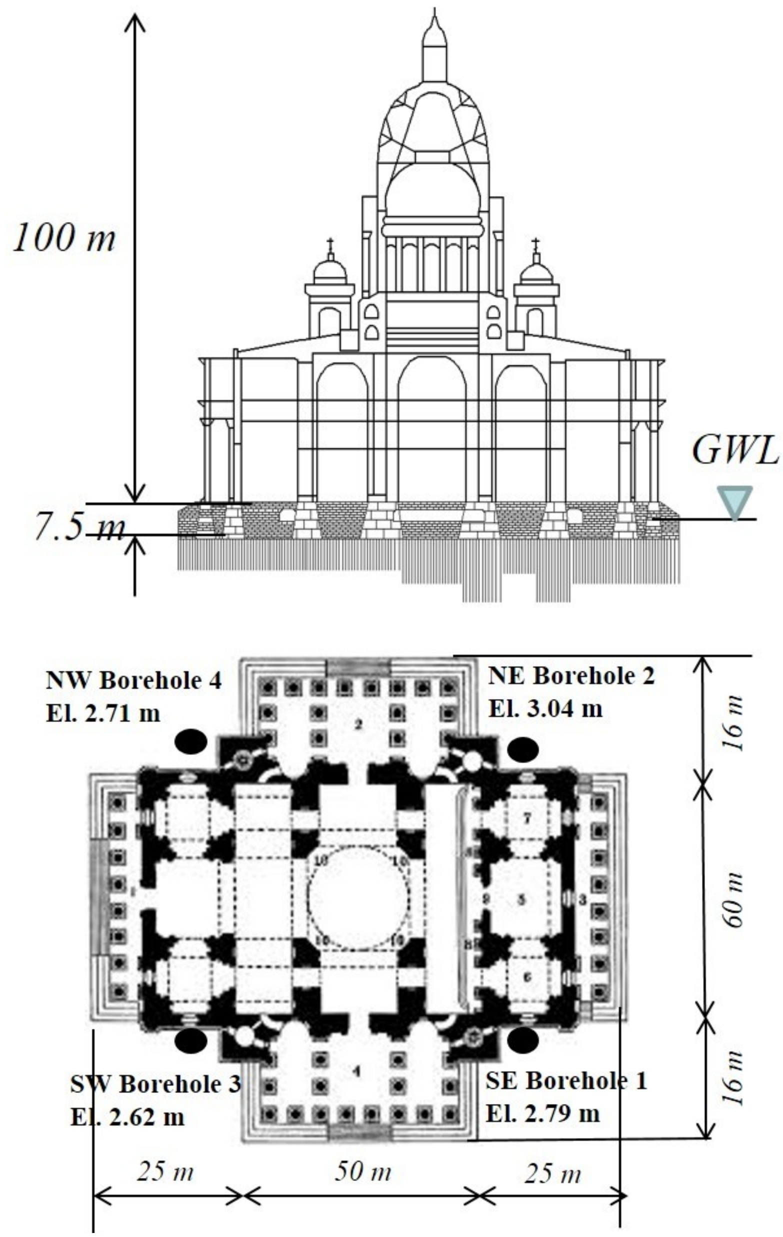

Figure 3. Cross section and plan view of St. Isaac Cathedral

CONE PENETRATION TEST, SOIL BORINGS AND STRATIGRAPHY

St. Isaac Cathedral is located on one of the islands of the Neva River about 300 m from the left river bank. Ground elevation around the Cathedral varies from 2.62 m to 3.04 m a.s.l. A total of 8 existing borings were identified at the site of the Cathedral (Table 1). These borings varied in depth from 20 m to 50 m. The first four borings were drilled in 1954 to a depth of 50 m. In 2009, four additional borings were drilled along the Cathedral perimeter at approximately the same location; two were down to 50 m, and two down to 20 m (Fig. 3 and Table 1). A cone penetration test (CPT) was also carried out near the location of the borings in 2009 (Fig. 4). The stratigraphy obtained from one of the CPT penetration resistance profile is also shown on Fig. 4.

Table 1. Soil borings [Florin, 1954].

Boring date	Number of borings	Boring depth, m	Company	Comments
1954	4	50	Leningrad State Polytechnic Institute	Southeast, southwest, northwest, and northeast
2009	2	20	Saint-Petersburg University of Mines and Trest GRII	Southeast and northwest
	2	50		Southwest and northeast

All the results from the borings in Table 1 were used to determine the underlying stratigraphy, soil type, and soil properties. A summary stratigraphy is shown in Fig. 5. The quaternary soil deposits consist of saturated soft sandy and clayey layers down to a depth of 44.5 m or more. The Upper Vendian clay is found at a depth of 44.5 m on the southwest corner of the Cathedral while it could not be found at a depth of 50 m on the northeast corner of the Cathedral because the boring stopped at a depth of 50 m. The quaternary deposits include inter-moraine, glacial, lacustrine glacial, and lacustrine marine origin formations, overlain by fill deposits and peaty soils (Fig. 5).

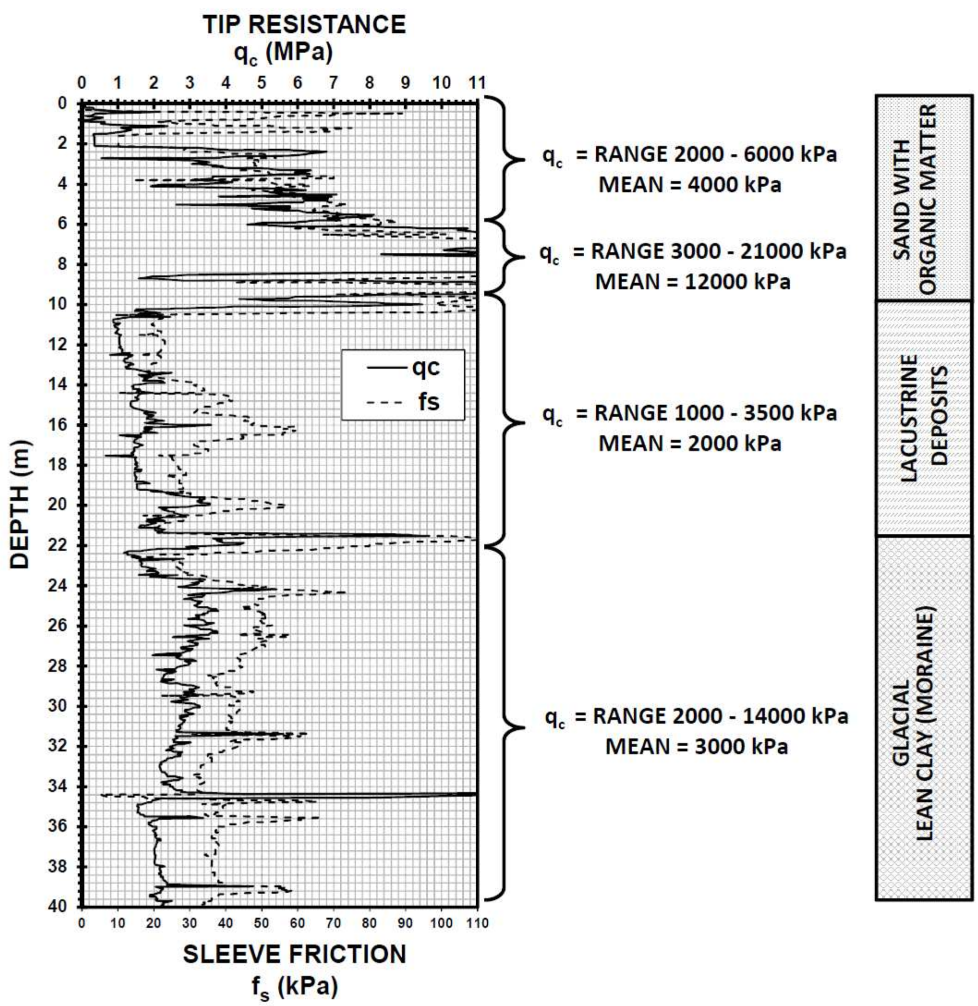

Figure 4. CPT profile near St. Isaac Cathedral.

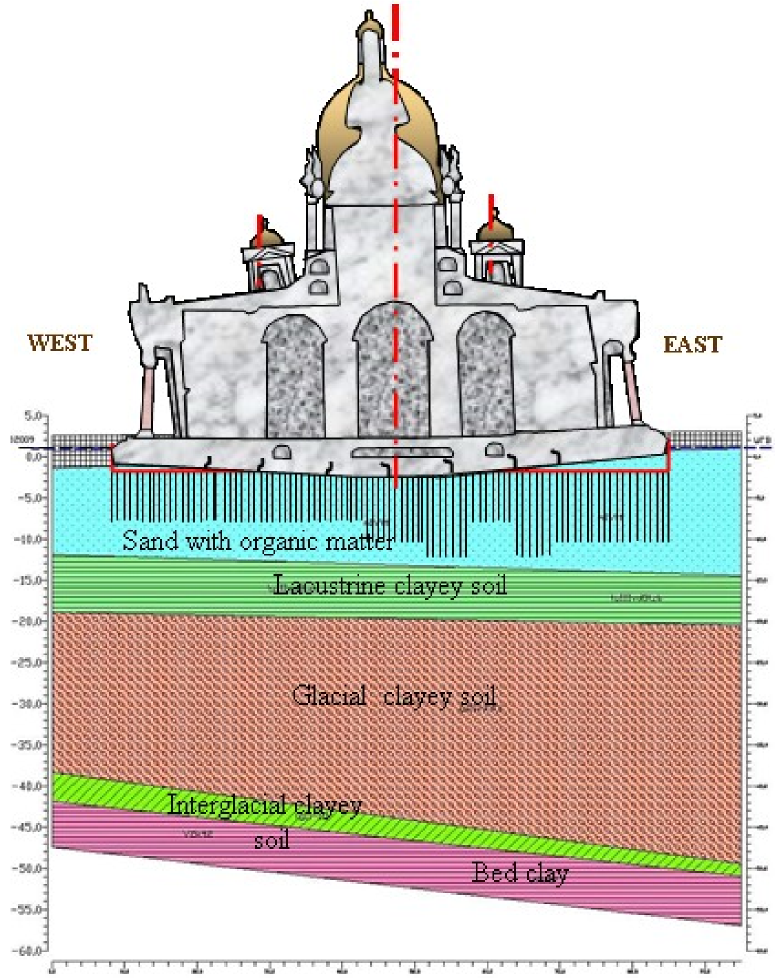

Figure 5. Soil profile of St. Isaac Cathedral.

THE GROUNDWATER AND ITS CHEMISTRY

The groundwater level (GWL) at the time of the borings in the summer of 2009 was 1.8 m to 2 m below the ground surface. The chemistry of the groundwater is shown in Table 2. The salinity varies from 994 mg/l (BH#2) to 4733 mg/l (BH#1) showing a wide range of contamination of the groundwater. Indeed, the salinity of the uncontaminated groundwater in the St. Petersburg region does not exceed 1000 mg/l. The peaty soils were found to also have an impact on the chemistry of the groundwater because they create a reduction environment due to the oxidation of the peat organic matter [Dashko et. all, 2013a, 2015]. Additional organic matter was found in the groundwater as a result of sewers leaking into the soil around the Cathedral. The permanganate oxidability value (POV) is 415 mgO_2/l which indicates the presence of slightly oxidized organic matter. The biochemical oxygen demand (BOD) is a measure of the number of microorganisms in anaerobic forms. The BOD was measured to be 281 mgO_2/l which shows the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down the organic material present. The chemical oxygen demand (COD) quantifies the amount of total organic matter and was measured to be 2821 mgO_2/l.

A typical geotechnical engineering project does not include an evaluation of the reduction/oxidation (redox) environment in the groundwater yet the redox processes have a significant impact on the soil behavior and corrosion of buried structural materials (Dashko et al. 2015, 2016). The value of the redox potential (Eh) in the groundwater was measured in the field to be – 100 mV. This indicates that the groundwater is strongly reduced or anaerobic and that free oxygen is no longer available. The organic matter and some groups of anaerobic microorganisms such as sulfate-reducing organisms and methanogens play a crucial role in reducing Eh down to negative values thereby starving the soil of oxygen. The number of bacteria in sewage can reach 10^7 - 10^8 cells in 1 ml of wastewater. The suspended organic matter in the sewage was found to represent 58% of all suspended solids including black suspended material.

Table 2. Chemistry of the groundwater (in 2009).

Component	Units	BH #1 SE	BH #2 NE	BH #3 SW	BH #4 NW
Ca^{2+}	mg/l	560.1	448	133.5	89.8
Mg^{2+}	mg/l	55.3	44.5	29	39
K^{+}+Na^{+}	mg/l	816	10.2	75.1	27.3
NH_4^{+}	mg/l	0.28	0.1	2	5
SO_4^{2-}	mg/l	20.9	34.5	81.8	<2
Cl^{-}	mg/l	1418	63.8	53.2	81.5
HCO_3^{-}	mg/l	1572	239	410.5	42.7
Salinity	mg/l	4733	994	1389	2888
pH	-	8.6	9.2	8.6	8.7
Eh	mV				-108
POV	mgO_2/l	1529	11.5	415.2	3128
BOD	mgO_2/l			281	
COD	mgO_2/l			2821	

A comparison between the groundwater chemistry in 1954 and 2009 shows that during that 55-year span there has been a considerable change in groundwater chemistry (Fig. 6). In the bar graphs, each chemical is represented by two side-by-side columns; the first column gives the concentration in 1954 and the second column in 2009. During that period (1954-2009), a dramatic increase in water salinity can be observed indicating an increase in groundwater contamination. The salinity of uncontaminated groundwater is typically around 1000 mg/l. High contents of chlorides (1418 mg/l) and sulphur (81.8 mg/l) also indicate contamination by sewage. Furthermore, the increase in calcium content suggests leaching from the limestone blocks and the limestone-based mortar from the foundation mat located below the groundwater level.

SOIL PROPERTIES AND PROCESSES

Soil properties were obtained in 1954 and 2009 and are combined in the following figures. The natural water content is presented in Fig. 7 and the plasticity index in Fig. 8. Fig. 7 indicates that there is no clear trend in the evolution of the water content with time and that the largest water contents occur in the layer of silty sand with peat at a depth about 3-5 meters and in the varved clay at the depth of 15-20 meters. Fig. 8 indicates that the varved clay at a depth of 15-20 meters exhibits the highest plasticity.

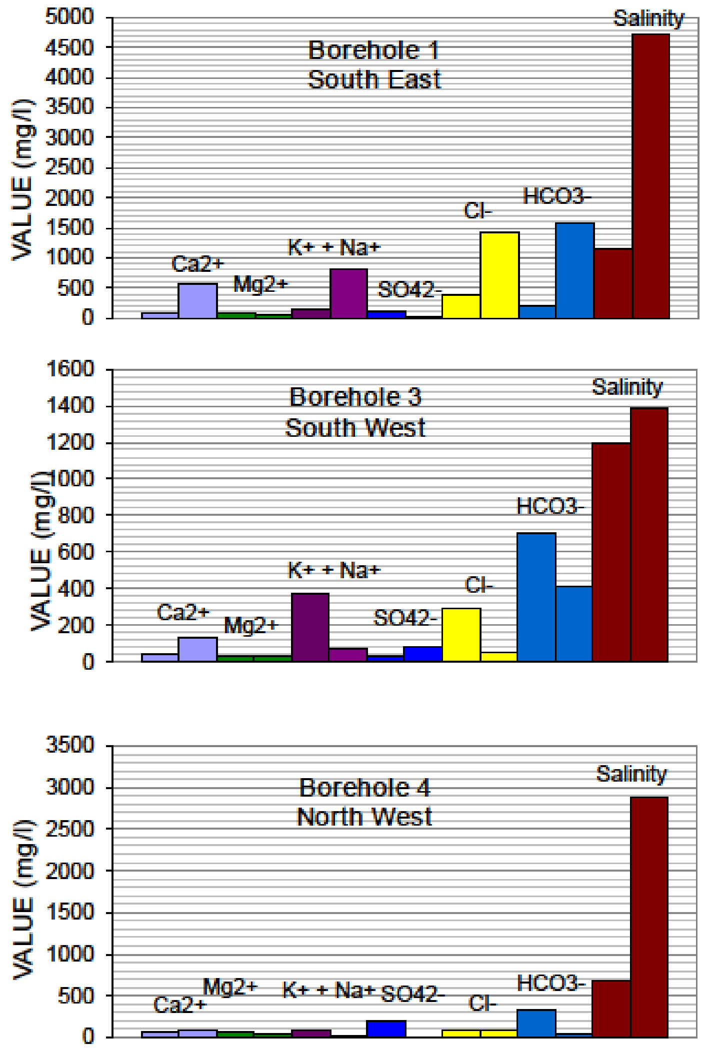

Figure 6. Chemistry of groundwater (1954 and 2009 data).

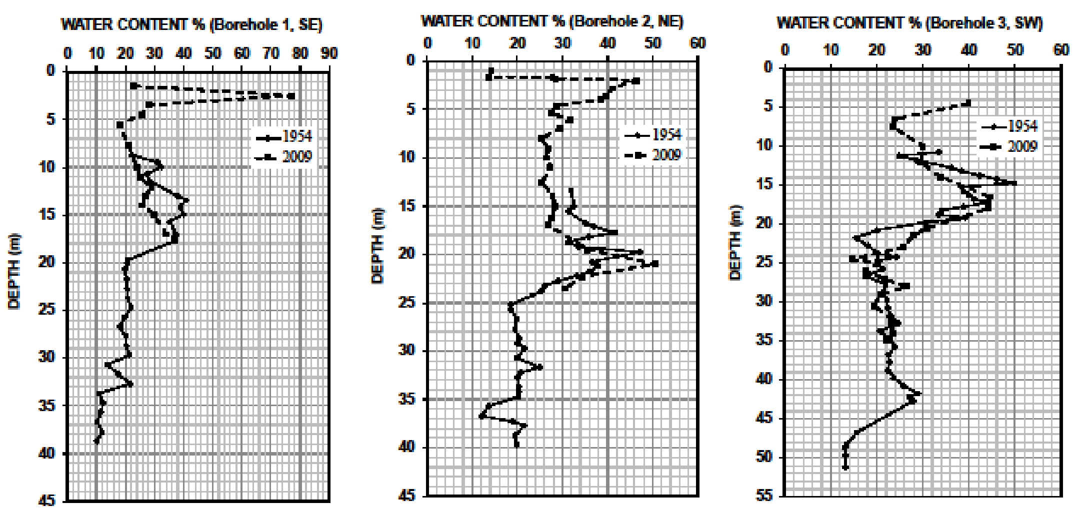

Figure 7. Variation of natural water content versus depth at different locations.

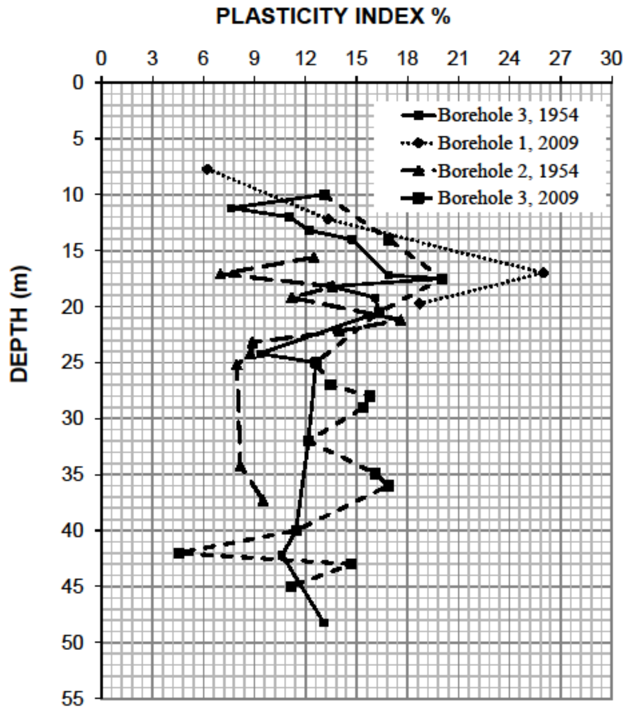

Figure 8. Variation of plasticity index versus depth at different locations.

Falling head permeameter tests were performed in 2009 on the silty sand samples (Fig. 9) and indicated relatively low hydraulic conductivity varying from 1.1 x 10^{-5} to 6.8 x 10^{-5} cm/sec. These low values are likely due to the presence of organic matter clogging the pore space in the sand (Dashko et al. 2015, 2016). Permeability tests were also performed on the silty sand after oven drying the samples at 105 ^{0}C; the permeability of the dry silty sand increased to 1 x 10^{-3} to 1 x 10^{-4} cm/sec (Fig. 9). This likely occurred because the drying process burnt some of the organic matter thereby increasing the size of the pores.

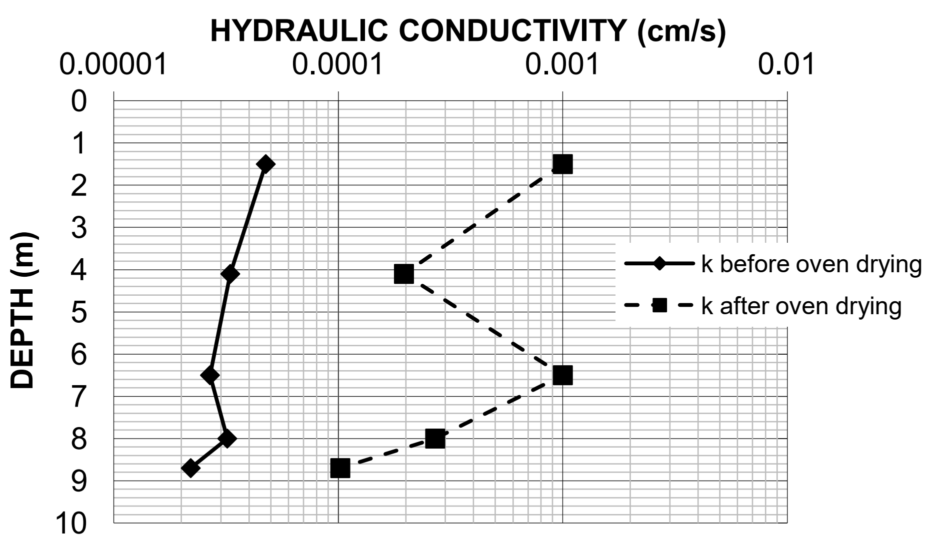

Figure 9 - Hydraulic conductivity of sand vs. depth before and after oven drying.

The shear strength properties, cohesion and angle of internal friction, available from the archives of 1954 are limited to direct shear test results (Table 3). In 2009, unconsolidated undrained triaxial tests were performed. The undrained shear strength (s_u) vs. depth profile obtained from these tests is shown in Fig. 10. Figs. 11 and 12 show the deviator stress vs. normal strain for some of the tests; the samples failed mostly in general deformation mode (barrelling) rather than along a single plane of failure. As indicated by the stress strain curves, the varved lacustrine clay underlying the pile foundation is very soft with s_u values between 18 and 20 kPa. The glacial clayey soil below the varved clay is a bit stronger with values in the range of 25 to 72 kPa. The Vendian clay below that glacial soil has s_u values which vary with depth from 18 kPa at the top of the layer to 125 kPa at depth. This significant variation could be due to the micro-fissures present in the upper zone of that clay layer which weaken the global strength.

Table 3. Soil strength from 1954 borings (after Florin, 1954).

Soil type	Total unit weight, kN/m^3	Cohesion, kPa	Angle of internal friction, degrees
Lacustrine Marine Silt	19.4	15	20
Lacustrine Glacial Lean Clay	18.4	15	20
Glacial Silty Lean Clay	20.2	25	26

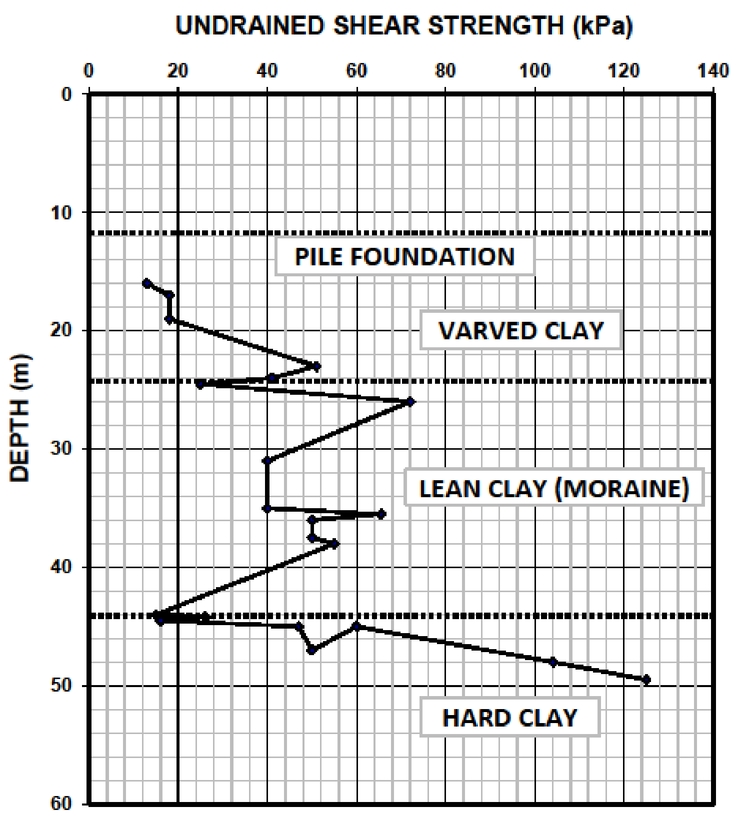

Figure 10. S_u profile versus depth.

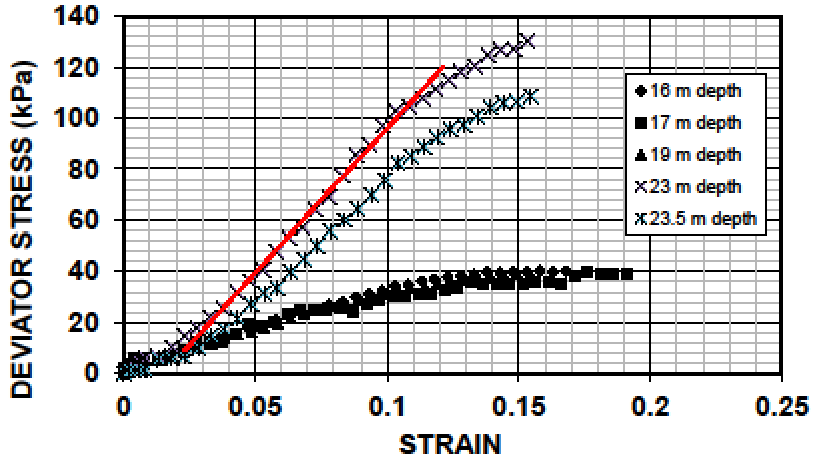

Figure 11. Deviator stress – normal strain curves from UU triaxial tests on varved clay.

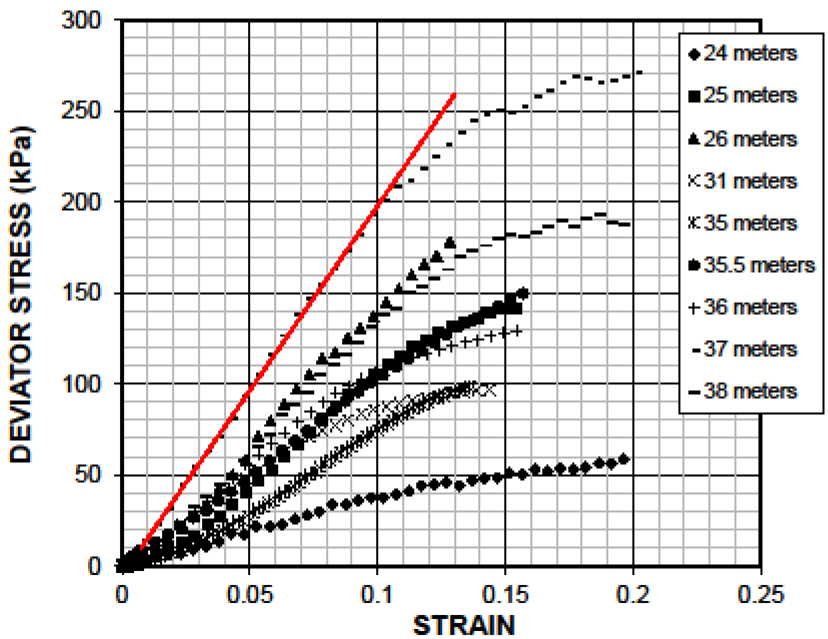

Figure 12. Deviator stress – normal strain curves from UU triaxial tests on moraine.

Values for the modulus of deformation of the soil were calculated from the triaxial test results. They are presented in Table 4 while Fig. 13 shows the modulus profile versus depth. The modulus E was obtained as the slope of the initial linear part of the deviator stress vs strain curve. The red lines on Fig. 11 and 12 show examples of how the linear part was selected. The modulus equation is:

$$E = \frac{\sigma_1 - 2\upsilon\sigma_3}{\varepsilon_1} \quad (1)$$

Where σ_1 is the major principal stress, ν is Poison's ratio taken as 0.5 for undrained behaviour, σ_3 is the minor principal stress, and ε_1 is the principal normal strain. The modulus (E) reaches 5000 kPa in the top layer of lacustrine marine soil, becomes much lower in the glacial lake clayey soil with values between 290 to 1000 kPa, and then increases slightly in the moraine from 415 to 2000 kPa. Additional soil properties are shown in Table 4.

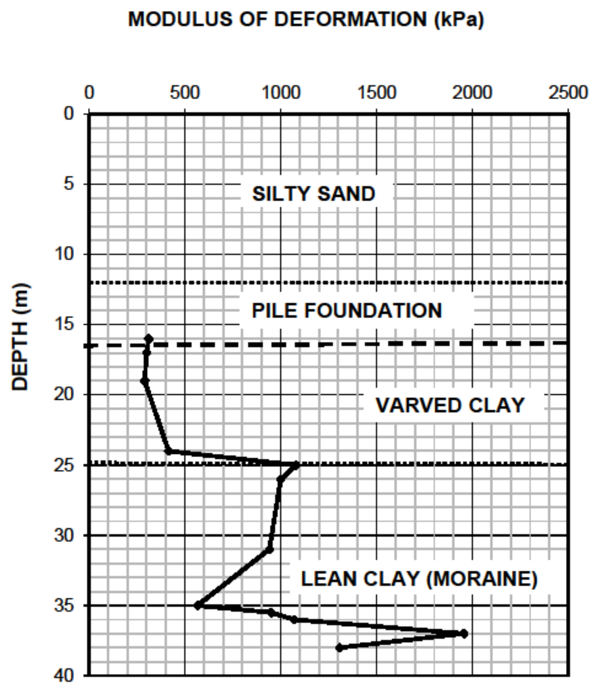

Figure 13. Undrained soil modulus versus depth.

Table 4. Engineering soil properties (2009 data).

Soil type	Depth, m	Water content, %	Total unit weight, kN/m^3	s_u, kPa	E, kPa	Confining pressure, kPa
Lacustrine marine soil	12	24	-	15	5000	-
	14	25	18.5	13		-
Glacial lake clayey soil including varved clay	16	34.1	18.6	18	312	180
	17	33.8	19.6	18	300	220
	19	51.3	18.3	-	290	400
	23	26.4	19.7	50	1000	440
	23.5	28	19.7	41	800	240
Moraine (lean clay)	24	14.6	21.9	41	415	400
	25	25	20.4	25	1080	340
	26	15	22.0	72	1000	250
	31	20	20.9	40	940	400
	35	20.6	21.6	40	565	500
	35.5	19	22.5	65.5	950	450
	36	18	22.8	50	1070	550
	37	19	21.2	50	2000	600
	38	20.6	20.9	55	1307	600

The oxidation-reduction conditions have an impact on the soil properties. As mentioned earlier, the groundwater is in a strong reduction (anaerobic) state (Eh < 0 mV) and rich in organic matter. The organic matter coupled with the microbial mass (MM) and the biogas generation cause a decrease in the engineering soil properties such as the modulus of deformation, the strength, and the permeability; relationships between microbial mass and soil properties were developed for some St. Petersburg soils by Dashko and Shidlovskaya (2015). The microbial mass and biofilms create slippery substances which coat the particle contacts and facilitate the movement of particles with respect to each other (lower modulus of deformation and lower strength) and clog the pores (lower permeability) (Dashko et al. 2013a, 2015). Indeed, for example, hydrogen sulfide (H_2S) as a metabolic product of sulfate-reducing bacteria in anaerobic state and bivalent iron (Fe^{2+}) leads to the generation of hydrotroilite $FeS*nH_2O$ in the form of black and dark grey powder that was observed in all soil samples below the groundwater level. Fig. 14 shows the MM distribution through the soil profile. The peaks of MM at 20 m and 50 m depth correspond to the lacustrine varved clay (up to 500 micrograms per gram) and to the Vendian clay (up to almost 700 microgram per gram).

The sand layers are made of very fine sand with more than 50% of the particles by weight in the range of 0.05-0.1 mm and some in the range of 0.1-0.25 mm. These sand layers are found at depths between 2 and 8 m. Hydrometer analyses indicate that the sand does not settle much during the first 24 hours when mixed with distilled water; indeed after 24 hours the volume of suspended sediments is still about 95%.

(a) NATURAL SCALE **(b) LOG SCALE**

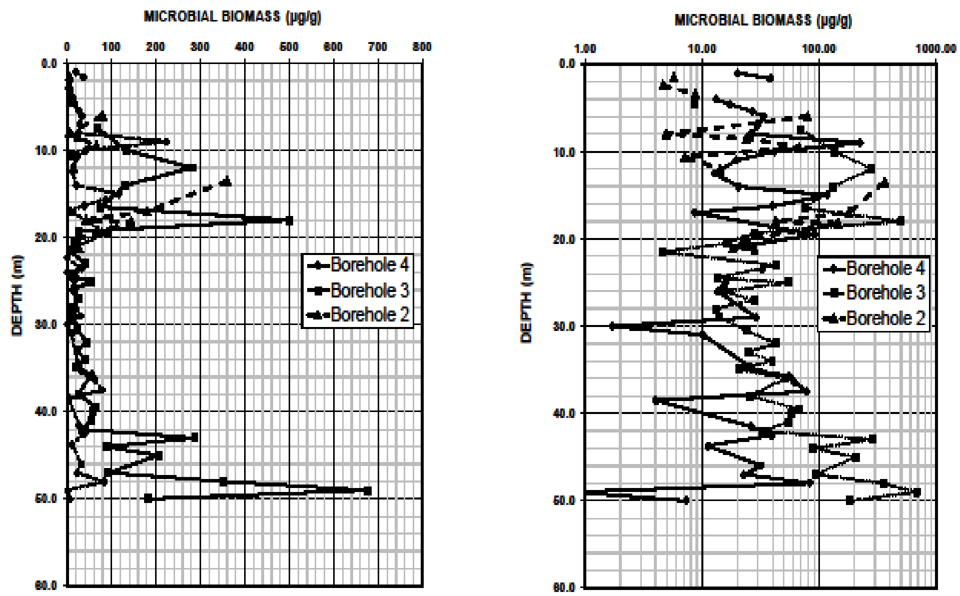

Figure 14. MM in soil vs. depth (2009 data): (a) natural scale, (b) decimal log scale.

There is also evidence of colloidal particles (< 0.0001 mm) and silt particles (0.002-0.05 mm) in the sand. The water held inside the pores of the sand is actually encapsulated in the bacterial films formed by the microbes much like a water balloon; therefore, the water cannot drain, cannot be pumped and consolidation is impaired. This is what leads the sand to behave in a microbial quick condition (Dashko et al. 2015). This microbial quick sand condition is very different from the upward seepage quick sand condition or the liquefaction quick sand condition. This type of microbial quick sand can be considered in geotechnical practice as a heavy liquid without friction; it can flow under its own weight but in this case the flow does not depend on the hydraulic gradient. In boreholes, these sands can form clots or flow down the borehole as observed during the site investigation in 2009.

ULTIMATE BEARING CAPACITY OF THE FOUNDATION

An undrained analysis was carried out; this undrained analysis is warranted even 150 years after construction as the bearing capacity failure, if it were to occur today, would occur in a rapid undrained fashion. The undrained shear strength available at the time of a potential failure would of course depend on the effective normal stress on the plane of failure which would be affected by the consolidation of the soil over time. The ultimate bearing capacity p_u of a square shallow foundation on clayey soil under undrained conditions can be calculated using Skempton equation (1951):

$$p_u = N_c s_u + \gamma D \quad (2)$$

Where N_c = bearing capacity factor depending on the foundation shape and the relative embedment depth; s_u = undrained shear strength; γ = total unit weight of the soil within the embedment depth; and D = embedment depth. The relative embedment depth for the mat is 5/92 = 0.054 and the corresponding value of N_c = 6.3 (Skempton, 1951). The overburden pressure γD is taken as 20x5 = 100 kPa. Selecting the right s_u value is difficult considering the profile of Fig. 10. Given that the Cathedral is close to 100 m in width, the zone of influence is significant and it is reasonable to estimate it to be down to the hard Vendian clay at a depth of 45 m as discussed in the next section. Yet edge bearing capacity failures may develop in the shallow layers. If s_u is taken equal to 20 kPa, the ultimate bearing capacity is 216 kPa, for 30 kPa it is 279 kPa, and for 40 kPa it is 342 kPa. Note that the pressure immediately under the Cathedral foundation is 415 kPa, therefore, by most estimates, the Cathedral has been close to failure and this explains the large observed settlement which will be discussed later. If one uses the cone penetrometer profile (Fig. 4), it is possible to use the CPT bearing capacity equation (Briaud, 2013) which is:

$$p_u = k_c q_c + \gamma D \quad (3)$$

Using Fig. 4 and a lower-bound cone tip resistance of 1500 kPa together with a cone bearing capacity factor of 0.35 (Briaud, 2013) the bearing capacity is 615 kPa. This is much higher than the bearing capacity based on the Skempton (1951) equation and when compared to the applied pressure of 415 kPa gives a much more reassuring factor of safety against bearing capacity failure of 615/415 = 1.48. The low bearing capacity based on the undrained strength from the samples may be due to sample disturbance. Indeed, the cone N_k factor linking the undrained shear strength of the cone tip resistance is back-calculated to be about 50; this is unusually high.

SETTLEMENT DISCUSSION

Settlement calculations are usually done by using the results of consolidation tests or by using the modulus of drained triaxial tests as the settlement has taken place over the last 150 years. None of this data was available to the authors. However, settlement measurements were made as follows (Fig. 15, 16): At the time of construction the 7.5-m thick mat was 2.5 m above the ground surface. Today the mat was measured to be 1.9 m above the ground surface at the southwest corner and 1.8 m above the ground surface at the northwest corner. This indicates that the Cathedral has sunk 0.6 and 0.7 m at those corners respectively. Furthermore, the ground surface at the base of the Cathedral is lower than the street level by 0.5 m at the southwest corner and 0.35 m at the northwest corner. These simple measurements allow one to conclude that the total settlement of the Cathedral is of the order of 1 m.

Figure 15. Settlement measurements at the southwest corner.

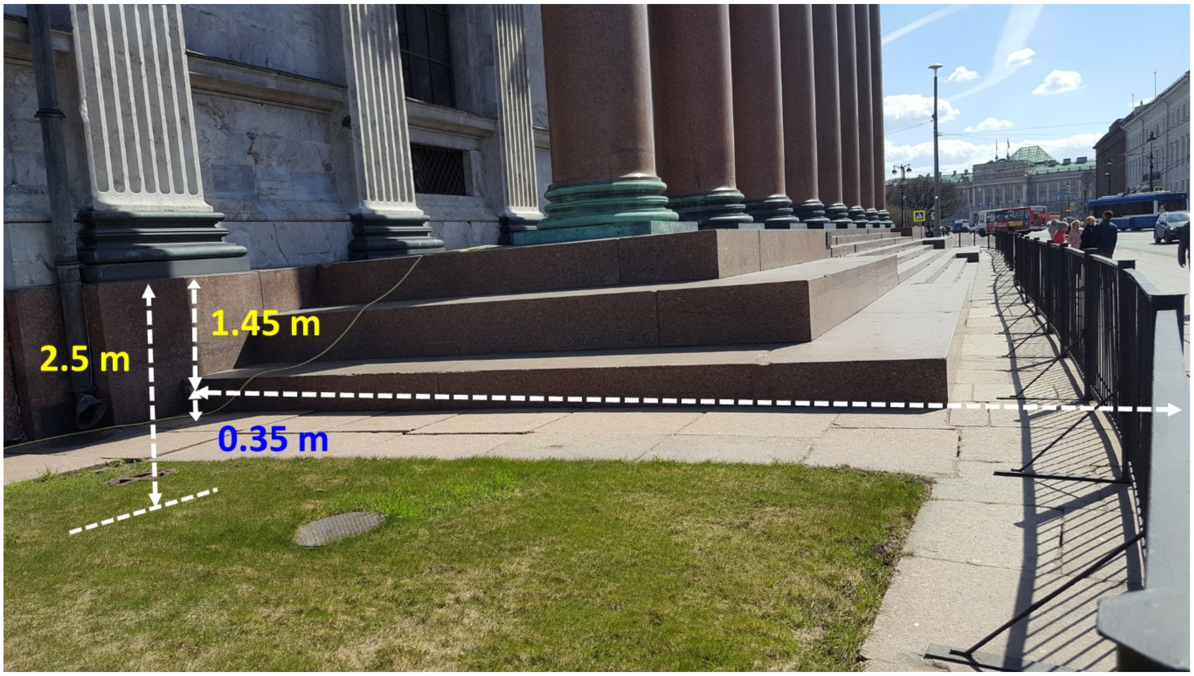

Figure 16. Settlement measurements at the northwest corner.

It is possible to use this settlement estimate to back calculate the soil modulus, which would give 1 m of settlement. Settlement calculations start by obtaining the depth of influence z_i which is defined as the depth at which the increase in total vertical stress due to the weight of the structure is equal to 10% of the pressure under the foundation. This is typically taken as 2 times the width of the foundation for a square foundation which would be 2 x 92 m or 184 m for the Cathedral. However, with the assumption that the hard Vendian clay below the moraine is much stronger than the surface layers (Fig. 10) z_i is taken as corresponding to a depth of 45 m below the ground surface or 40 m below the foundation level. The elastic equation is (Briaud, 2013):

$$s = I_s I_e I_h (1-\nu^2)\frac{pB}{E} \tag{4}$$

Where s = settlement, I_s = shape factor, I_e = embedment factor, I_h = depth to hard layer factor, ν = Poisson's ratio taken as 0.35 for drained behavior, p = net pressure, B = width of the foundation, E = average soil modulus. Thus:

$$E = 1\times\left(1-0.1\times\frac{5}{92}\right)\times 0.29\times\left(1-0.35^2\right)\times\frac{315\times 92}{1} = 7335\,kPa \tag{5}$$

Briaud (2013) using a pressuremeter database suggested that the ratio of the long-term modulus E to the cone penetrometer tip resistance q_c is about 2.5 for clays. Using this ratio and the value of 7335 kPa for E gives an equivalent q_c of 2934 kPa. This falls well within the range of measured values in the q_c profile (Fig. 4). However, the 7335 kPa value of E is much higher than the modulus values obtained in the unconsolidated undrained triaxial tests (Table 4). This indicates that sample disturbance may be present due to the difficulty in obtaining undisturbed samples of this soft clay. The simple calculations reported above were followed by a more detailed analysis using a layered soil and the finite element method.

ABAQUS ANALYSES OF VERTICAL DISPLACEMENT OF ST. ISAAC CATHEDRAL

A numerical simulation of the behavior of the Cathedral was conducted using ABAQUS 3D (ver. 6.12, 2012) to better understand the behavior. The simulation domain included the soil mass, the pile foundation, and the mat on top of the piles with an applied distributed pressure to represent the load from the Cathedral. The mesh representing the soil mass was 700 m long, 400 m wide and 140 m deep. The stratigraphy was a 12-m thick layer of sand, a 7-m thick layer of varved clay, a 20-m thick layer of lean clay, and a 100-m thick layer of hard clay (Fig. 17). The plan view of the foundation was selected to match the records. The piles under the Cathedral are longer under the East side than under the West side (Fig. 5); they were represented by an 8-m deep block under the East side and by a 6-m deep block under the West side (Fig. 17). The mat is 7.5 m thick with 5 m below the ground surface; it was represented by a 5-m thick block while the 2.5 m above ground were added to the weight of the structure. In total the mesh contained 243,700 eight-node brick elements with reduced integration (C3D8R) [ABAQUS, 2012]. All the nodes on the vertical boundaries of the soil mass were fixed in the horizontal direction and free to move in the vertical direction; the nodes on the bottom boundary were fixed.
The materials included the soil, the foundation mat and the piles. Again, the choice of the soil model was limited by the information available to the authors. For the soil, the clay layers were simulated as elastic plastic materials using the modulus which would match the observed settlement (trial and error with values in proportion to the cone penetrometer profile) and the measured undrained shear strength as input. The sand layer was modeled as an elastic material as were the piles and the mat foundation. The material properties are shown in Table 5 and 6. For the mat, a likely optimistic modulus of concrete (E = 20GPa) was selected for the foundation stones. Since the piles were represented by a solid block, an equivalent modulus for the block was calculated by using an average modulus based on matching the global AE stiffness where A is the cross section of the material and E is the modulus of that material:

$$A(total)E(equivalent) = A1(pile\ area) \times E1(\text{wood modulus}) + A2(\text{soil } area) \times E2(\text{soil modulus}) \quad (6)$$

The loading of the foundation by the structure was represented by a uniform pressure. This pressure was calculated as the weight of the structure above the foundation (2158 MN) plus the weight of the 2.5 m stick up of the mat foundation (332 MN) for a uniform pressure of 2490000/7600 = 327.6 kPa.

Table 5. Soil and mat properties (E: Young modulus, s_u : Undrained shear strength, γ: Unit weight).

Stone (Foundation)	Sand	Varved Clay	Lean Clay	Hard Clay
E = 20 GPa	E = 10 MPa	E = 2 MPa	E = 4 MPa	E = 40 MPa
		s_u = 18 kPa	s_u = 50 kPa	s_u = 60 kPa
γ = 17.5 kN/m^3	γ = 20 kN/m^3	γ = 20 kN/m^3	γ = 20 kN/m^3	γ = 20 kN/m^3

Table 6. Parameters used to calculate the equivalent modulus of the block representing the piles (A Total: Half area of the foundation, E: Young modulus).

A Total m^2	West				
	E(equivalent) kPa	A1(Pile Area) m^2	E1(Wood) kPa	A2(Soil Area) m^2	E2(Wood) kPa
3800	7779459	285.5	103421359	3514.5	10000
	East				
	E(equivalent) kPa	A1(Pile Area) m^2	E1(Wood) kPa	A2(Soil Area) m^2	E2(Wood) kPa
	28039921	1030	103421359	2770	10000

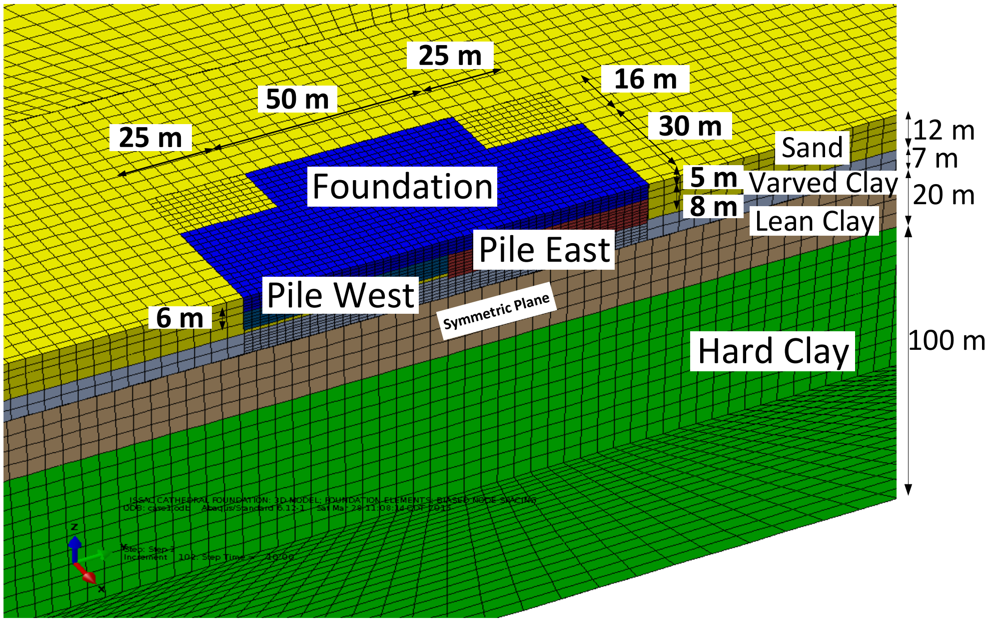

Figure 17. Mesh dimensions, Cathedral dimensions and soil stratigraphy.

Fig. 18 shows the settlement of the Cathedral along the centerline East-West axis for the case that matches the measured total settlement of 1 m. A tilt is observed due to the uneven depth of the pile foundation; indeed, the Cathedral does not settle evenly due to the different lengths of piles in the foundation (Fig. 19) and the calculated difference in elevation between the eastern most point and the western most point of the Cathedral is 0.16 m. A parametric study was also conducted to investigate the influence of the structural parameters on the results. Fig. 20 shows the impact of the modulus of the foundation material on the bending of the foundation mat and associated distortion of the structure leading to increased cracking. Additional results of the analysis including ground surface settlement profiles, contours of vertical settlement with depth, and stress distribution in the soil mass can be found in Mohammadrajabi et al. (2015).

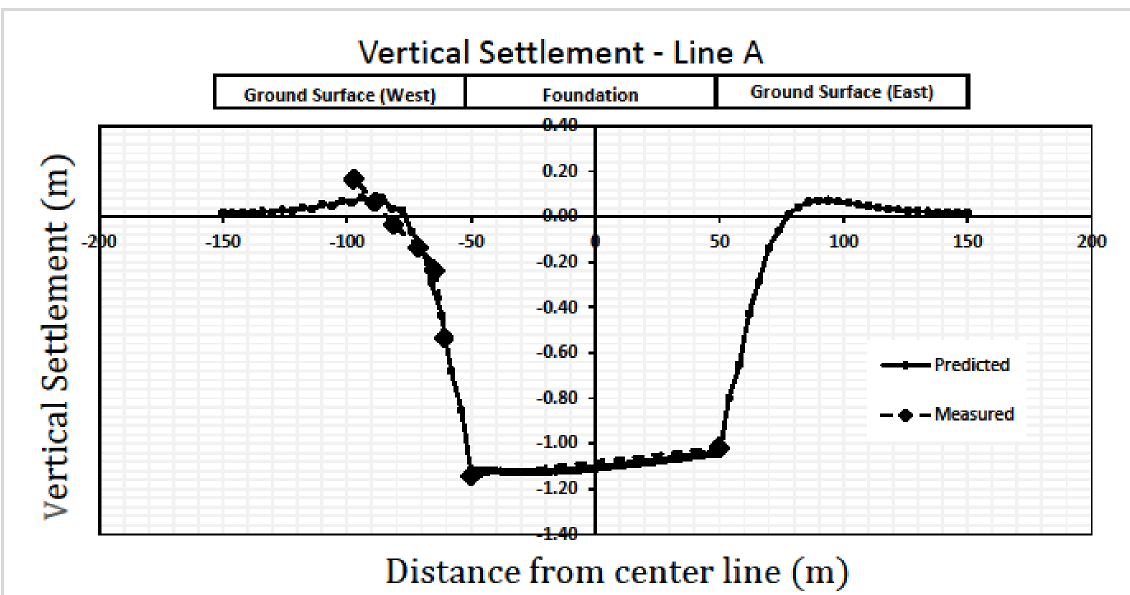

Figure 18. Ground surface settlement around and under the Cathedral.

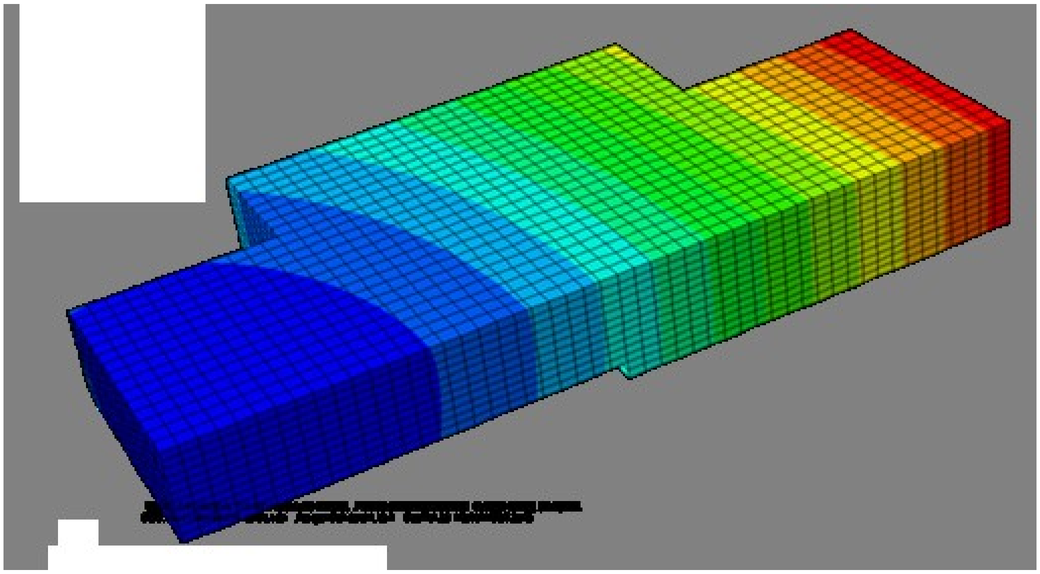

Figure 19. Contours of vertical settlement of the foundation (m).

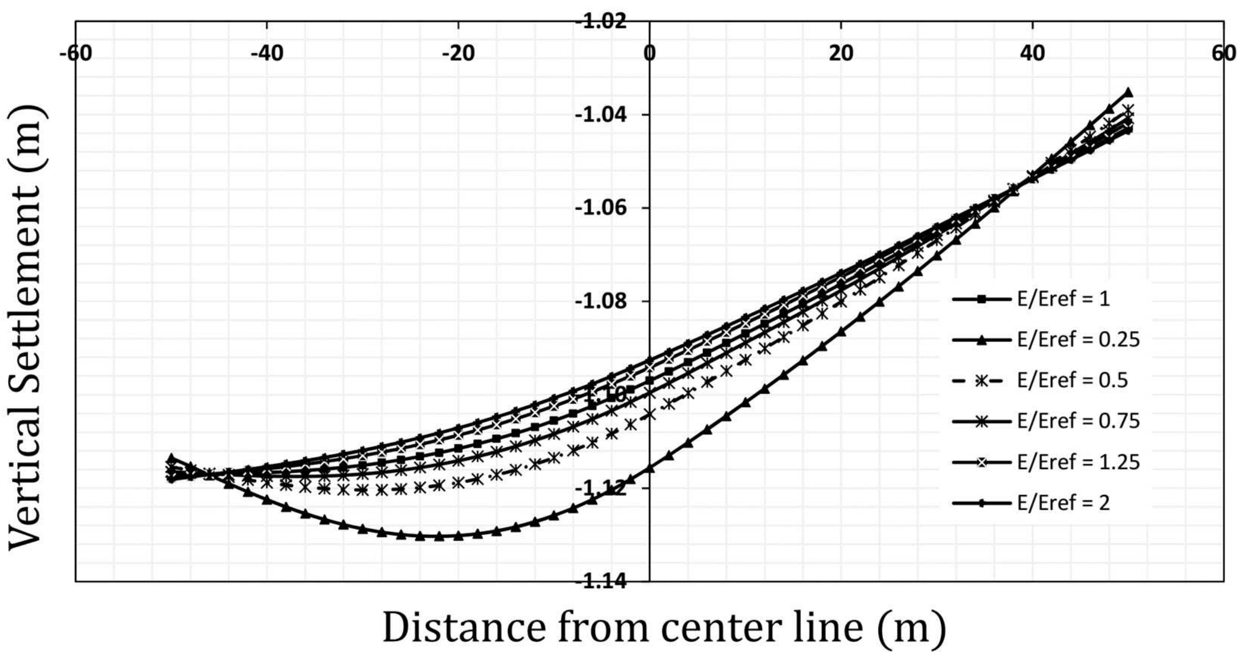

Figure 20. Bending of the mat foundation for different assumed moduli of the stone mat foundation (E_{ref} = 20 GPa).

SETTLEMENT OBSERVATIONS AND COMPARISONS

The Cathedral started to experience differential settlements during construction in 1841. The central part of the Cathedral settled more than the perimeter. It was also observed that the West part of the Cathedral built by Montferrand settled more than the East part built by Rinaldi before Montferrand. The columns started to tilt slightly and cracks appeared. Between 1873 and 1898, all 48 columns and 4 porticoes were straightened up. However, the tilting continued to increase over time

[Nikitin, 1939] and in 1927, it was again observed that all columns of the porticoes tilted towards the center of the Cathedral with a maximum tilt of 15 cm (difference between top and bottom of the column). The tilt of the floor of the Cathedral was measured and indicated tilt values (slopes) averaging 0.004 (Table 7). The difference in settlement between the East and West sides of the dome underneath the cross had reached 0.27 m (Nikitin, 1939).

The magnitude of this differential settlement continued to increase as well as the severity of the cracks in the columns and the tilting of porticoes. In 1950, the deterioration of the bearing structures was documented including cracks in the pilonces, the arches, and the columns (Florin, 1954; Butikov, 1974). In 1983, a survey of the ground surface near the southwest end of the Cathedral was performed and indicated a maximum difference in elevation around the southwest part of the Cathedral of 0.85 m (Sotnikov, 1986, Fig. 21). The summary results of all the surveys performed at different times are shown in Table 7. Today the differential settlement has intensified causing additional cracking in the pillars supporting the dome, tilting of porticoes, deformation and dilapidation of the columns (Fig. 22).

The survey of Sotnikov (1986) gave the elevation contours of the ground surface West of the Cathedral (Fig. 21). These elevation contours were used to create a settlement profile along a direction perpendicular to the contours. This settlement profile is plotted on Fig. 18 and is compared to the numerical simulation predictions. The match on Fig. 18 is reasonably good and gives some credibility to the theoretical work. As explained previously and as shown on Figs. 15 and 16, the Cathedral has likely settled about 1 m including some punching of the mat into the soil. Fig. 23 shows the plastified elements in the stress field at the Cathedral edges; this certainly indicates a very likely yet limited and localized punching failure at the edges.

The observed tilt of the structure seems to be due to the difference in length of the pile foundation on both sides of the structure. The differential movement is estimated to be about 25 cm according to the measurements as compared to 16 cm by the simulations. The value of 25 cm comes from using the elevation of the borings shown in Fig. 3. On the West side, they are 2.62 m and 2.71 m for an average of 2.665 m while on the East side they are 2.79 m and 3.04 m for an average of 2.915 m leading to a difference of 25 cm. The differential movement can also be estimated using the 0.004 value of the tilt measured in 1984 by the Leningrad Construction Institute (LISI) (Table 7) and the distance of 78 m between the two points. Using this approach, the differential movement of the cathedral is about 31 cm which corresponds approximately to the data obtained using the elevation of the borings.

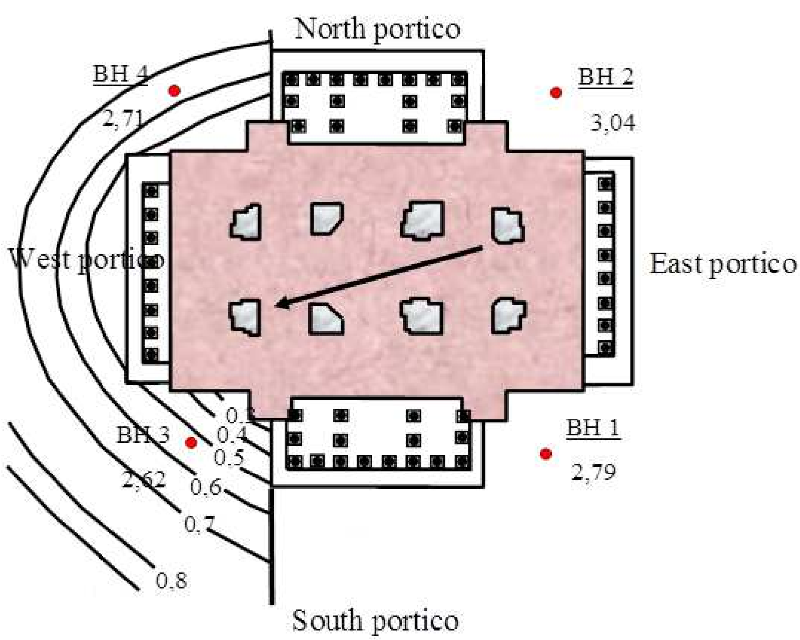

Figure 21. Ground surface survey around the Cathedral (Sotnikov, 1986).

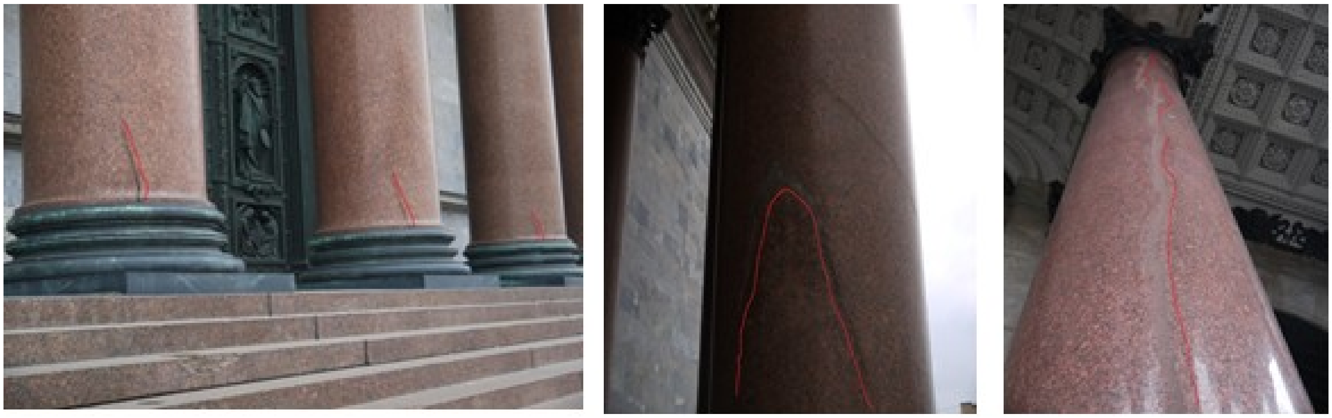

Figure 22. Intensifying cracks in the columns.

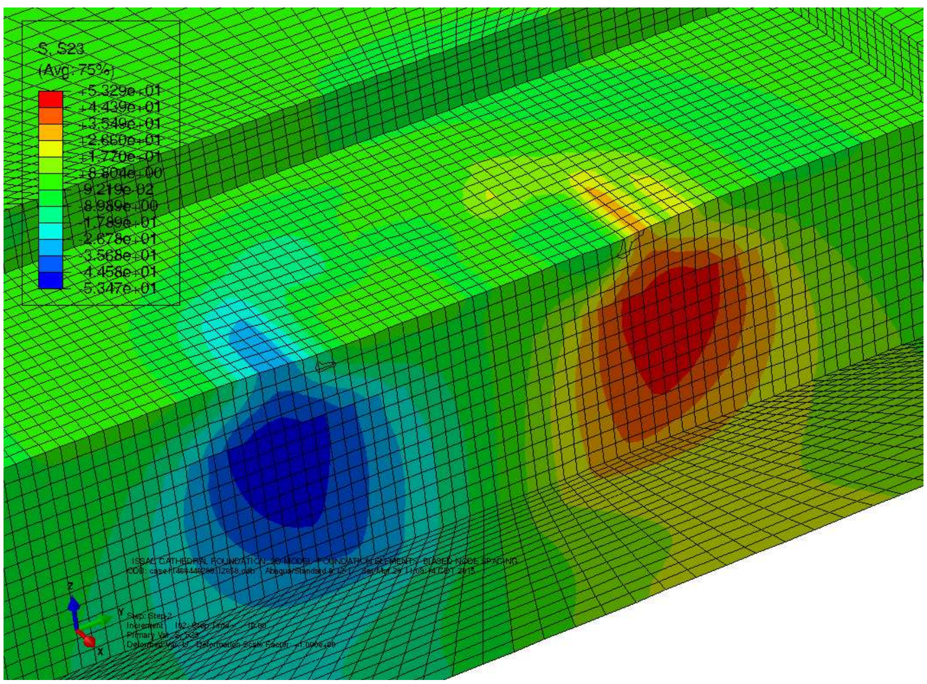

Figure 23. Zones of plastification at the edges of the Cathedral foundation.

Table 7. Results of surveys performed on the Cathedral (Florin, 1954).

Location	Maximum difference in levels between two points, mm	Distance between points, m	Slope or tilt between points	Company performing the survey and year
Underground Galleria	42.7	90	0.005	“Glavnauka”, 1927
Floor of the porticoes	43.3	100	0.004	TREST GRII, 1952
Floor of the porticoes	43.0	100	0.004	LISI (Leningrad Construction Institute), 1983
Top level of foundation mat	30	78	0.004	

CONCLUSIONS

St Isaac Cathedral in St Petersburg, Russia, is a remarkable historical monument and among the World Heritage Monuments. It is a very heavy structure founded on soft soils. The engineering properties of these soils including stiffness, strength, and permeability are decreasing as they are affected by an increase in microbial activity. These microbes are multiplying because of the organic soils (peat) and the leaking sewage. The pressure under the mat foundation is 415 kPa, the net bearing pressure is 315 kPa while the estimated ultimate bearing capacity of the soil is 279 kPa when using the results of laboratory undrained shear strength and 615 kPa when using the tip resistance of the cone penetrometer sounding. Based on limited measurements, the settlement of the cathedral is estimated to be around 1 m. The elastic settlement equation and a series of numerical simulations are used to back-calculate the moduli that match the observed settlement. These back-calculated long term modulus values are related to the cone penetrometer tip resistance through the relationship $E = 2.5\ q_c$. The differential movement over the 100-m length of the structure is about 25 cm due to the uneven distribution of the piles below the foundation. The dishing effect of the mat combined with the long term creep of the soft soil leads to continuous cracking of the structure and of the columns supporting it. Future monitoring of the structure is necessary to better assess the situation and develop an action plan to avoid further deterioration.

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