Faculty of Science

The Sinking Town:
The Causes and Effects of Settling Around Linnéstaden

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Abstract

Settling is a problem in Gothenburg causing damages on older buildings over time. Earlier research by Norin (2004) and Ljungdahl (2015) has shown that lowered groundwater levels is a main contributing factor to settling in Gothenburg. The aim of this study was to find other factors, why settling occurs at a different rate on buildings and to create a database over the damages on the façades with focus around Linnéstaden.
The database is structured in an excel spreadsheet in a way so that it can be processed in GIS programs and also so calculations can be made inside excel.

The methods of gathering the data was done by observing the façades in field over two weeks of this study and gave good results

Data showed that slope and soil depth were the two factors behind the damages on buildings caused by settling that could be measured in this study. Out of 471 buildings observed about 68% of them showed damage on the façade due to settling around Linnéstaden. A case study of a building made in 1898 near Linnéplatsen showed that proper piling and foundation were not made but instead, the building was set on top of the clay on a slope. Today, that building is severely damaged due to settling making piling and foundation an interesting parameter for further studies. The role of filling material in settling was also an interest of discussion and further studies of this is suggested.

Key words: *Settling, GIS, Gothenburg, Linnéstaden, Clay, Filling material*

Sammanfattning

Sättningar är ett problem i Göteborg som orsakar skador på äldre byggnader över tid. Tidigare studier av Norin (2004) och Ljungdahl (2015) har visat att sänkta grundvattennivåer är en huvudorsak som bidrar till sättningarna i Göteborg. Syftet med denna studie var att hitta andra faktorer, varför sättningar sker i olika utsträckningar på byggnader och att skapa en databas över skador på fasaderna med fokus runt Linnéstaden.

Databasen är uppbyggd i ett Excel ark på ett sätt så det kunde utvecklas i GIS program och uträkningar kunde utföras i Excel. Metoden för att samla data gick ut på att observera husfasaderna i området i fält över två veckor och gav goda resultat.

Datan visade att sluttningar och jorddjup var de två bakomliggande faktorer för skador på byggnader som kunde mätas i denna studie. Av 471 byggnader som observerades visade 68 % utav dessa skador på fasaden kopplade till sättningar runt Linnéstaden. En fallstudie utförd på en byggnad från 1898 nära Linnéplatsen visade att ordentlig pålning och grundläggning inte utfördes utan byggnaden uppfördes ovanpå lera i en sluttning. Idag är denna byggnad svårt skadad på grund av sättningar vilket gör pålning och grundläggning en intressant parameter för framtida studier. Fyllnadsmaterialets roll i sättningar var också intressant för diskussion och vidare studier inom detta föreslås.

Nyckelord: *Sättningar, GIS, Göteborg, Linnéstaden, Lera, Fyllnadsmaterial*

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1. Introduction

1.1 Background and Aims of this study

Damages on buildings due to settling is not a new phenomenon. Earlier research regarding groundwater in urban areas has mentioned this issue in the districts Linnéstaden and Haga in Gothenburg (Norin, M. 2004). It is also known that the older buildings in Linnéstaden are askew, even outside the geological community. A walk along Linnégatan reveals evidence of settling in form of uneven streets, damaged façades and whole buildings leaning toward the street. Another observation to be made is how modern buildings lie next to old buildings that has been renovated. This could be an indication that some buildings were damaged to the point of no repair and had to be torn down and rebuilt.

Settling occurs at a very slow pace in clay (Sällfors, 2013). It can be difficult to see it happen and act to prevent it from damaging buildings beyond repair. On the streets and around the buildings it seems to happen at a faster rate due to constant stress from heavy traffic and asphalting of infiltration surfaces (Albertsson, A. 2014). These damages are easy to see and are fixed by evening them out with filling material. This, however, is contra productive except for in the very short term because the weight of the filling material will increase the stress on the soil and therefore the settling will be more severe (Norin, 2004). The question arises:

- Where does all this filling material go?
- Is it responsible for the settling to any extent?

A closer study and analysis haven't been conducted to our knowledge around Linnéstaden and Haga considering the settling and damages it has caused on buildings. The aim of this study was to map the damages in the field by observing the façade of every building in the mentioned areas (see figure 1.2) and analyse data in GIS so that connections could be made between settling and possible causes.

- By looking at maps of soil depth and slope the hopes were to find a connection between these aspects and the settling in the studied area. Is there however another factor responsible for settling other than the soil conditions underneath?

Building techniques have changed over the years. As technology and knowledge advances so does the quality of material, risk assessment, sustainability and other factors which improves the quality of buildings.

- Is there any difference in damages due to settling on older buildings compared to modern ones? And if so, are there factors other than time responsible for the difference?

1.2 Geology in Gothenburg

The bedrock in Gothenburg consists of Proterozoic igneous and metamorphic rocks. It was created 1550-1700 Ma years ago and transformed during the Sveconorwegian orogeny 900-1100 Ma years ago (SGU, 2019).

Most of the superficial deposits found in Gothenburg were created and deposited during the Weichselian glaciation. It began 115 000 years ago and ended ca 10 000 years ago (Engdahl and Jelinek, 2013). The soils deposited varies in size and properties depending on the position of the inland ice. Clay, which is a post glacial sediment, is of interest in this study and will be described further.

The weight of the kilometre-thick ice which covered what today is Gothenburg made the land sink due to isostasy. When the deglaciation occurred in the Gothenburg area, 14 500 years ago, the weight of the ice disappeared, and it did so at a faster rate than the uplift of the lithosphere. Because of this the land was under sea level for a long time (SGU, 2019). Even to this day the land is uplifting at a rate of 2-3 mm/year in Gothenburg (Lantmäteriet, 2019).

The glacial and post-glacial sediments on the west coast were deposited in a marine environment, which means that it consisted mostly of silt and clay (Stevens and Hellgren, 1990). When the ice retreated, the southern parts of Sweden were in a shallow marine environment between 20-30 m under sea level before the uplift could start bringing the land above the coastline (SGU, 2019). This is when the post glacial sediments were deposited, mostly clay. The sediments covering the Gothenburg area is mainly marine clay (Stevens and Hellgren, 1990).

The thickness of the clay in the Gothenburg area can go as deep as 100 m in some localities. On top of this, in most places, is also a layer of filling material with an average thickness of 1-7m. In Linnéstaden and surrounding area the filling material has a thickness of 1.5-3 m. Linnégatan is a special case since it used to run a stream along it, Djupedalsbäcken, towards the harbour which in 1879 were laid underground in culverts and covered with filling material.
The filling material is human depositions of e.g. gravel, concrete, wood, tiles etc. It is usually from earlier buildings or, as in the case of Linnégatan, put there to even out the topography and stability of the ground (Hultén, 1997).

1.3 Properties of clay

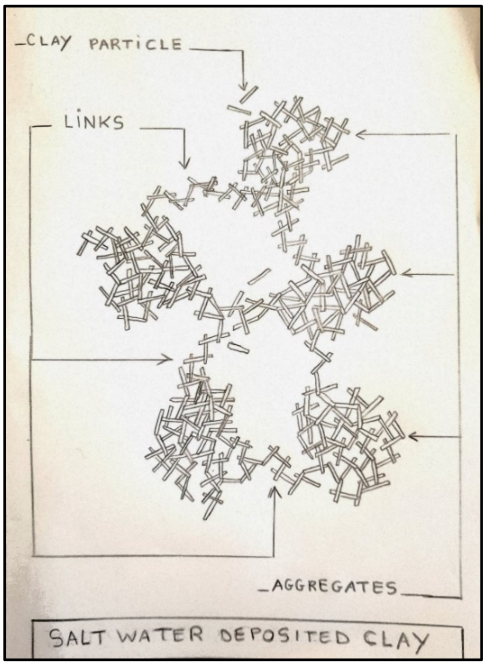

Figure 1. 1. *Shows the structure of clay deposited in saltwater.*

Clay particles have a flaky structure meaning that they are thin and elongated. They have a negative electric charge which attracts water molecules (University of the West of England, 2000). When clay particles are deposited in saltwater, they do so in units connected with links of clay particles (see fig 1.1, Sällfors, 2013). This structure creates many pores where water can be retained and eventually drained and compressed if subjected to stress (University of the West of England, 2000, Sällfors, 2013).

When the soil is subjected to a load it will deform. Consolidation is the term for when water is pressed out of the soil due to an overlying burden which results in a decrease of volume. In the case of clay this happens over the course of a long time because of the material's low permeability (Sällfors, 2013). Initially, the load will increase the pressure on the pores filled with water. Over time, as the water is pressed out from the soil, the load will be held up by the soil skeleton which then will start to compress.
The factors that determine consolidation are permeability, compressibility, layer thickness and boundary conditions (Persson, 2019).

Preconsolidation happens when the soil previously had a higher load before and is therefore already consolidated to an extent due to plastic deformation. This occurs for example when a previous overlying layer of sediment erodes. Preconsolidation is an important parameter for clays since it dictates how much burden it can take before it consolidates further (Sällfors, 2013).
There are two types of consolidation; primary and secondary. Primary consolidation occurs until the pore overpressure is evened out due to water being drained. Secondary consolidation, also called creep, occurs at a slower rate and is a plastic deformation due to readjustment of soil molecules (Persson, 2019).

1.4 Geotechnical problems

Due to increased loads from buildings and infrastructural projects, several parts of Gothenburg have had consolidation of the ground. During the 70's and 80's several tunnels were built in the city and this caused the groundwater to retreat with settling of the soil consequently (Engdahl and Jelinek, 2013). The damages on the buildings can be observed around Linnéstaden (see examples in chapter 3.3).
Lowering of the groundwater in cities which are situated upon unconsolidated sediments can lead to subsidence or consolidation of clay. This, in turn, can cause drainage pipes to break and release water enriched with bacteria into the groundwater which eventually reaches the wooden poles of the building foundations. This in combination with lowered groundwater levels allows oxygen to decompose the wooden poles and cause them to rot (Norin, 2004).

1.5 Piling and foundation

Piling is a deep foundation method used to spread the load from the building onto the soil beneath it. It’s applied in soils which are sensitive to loads and consolidation which would occur if a superficial foundation would be used (Hugosson and Nilsson, 2014).

Piling can be classified in different ways, one of them by its function. Its either done by inserting the pile down to the bedrock or a more stable soil beneath, or by inserting it into a friction or cohesion soil. In the former method, called *end bearing piling*, the load is transferred from the tip of the pole down to the desired layer or bedrock. The latter method, called *friction or cohesion piling*, derive its function by friction or cohesion from the soil surrounding the pole. In fig 1.2 below, an illustration of the two methods are shown. A combination of both methods can also be used for piling a foundation.
Piling can also be classified according to the material which is used for the piles. The most common materials used are timber, steel, concrete or composite which are a mix of different materials (The Constructor, 2019).

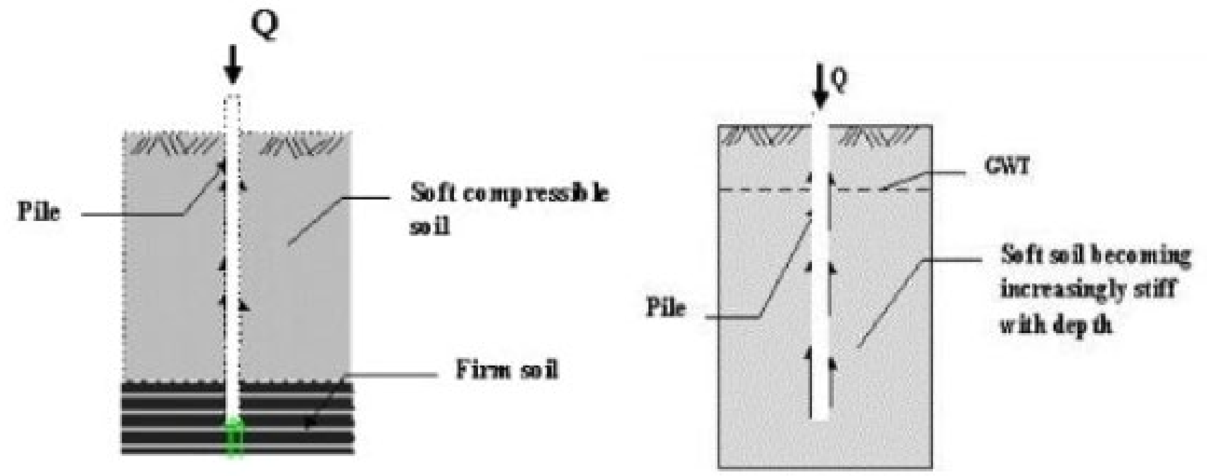

Figure 1. 2. *End bearing piling shown to the left and Friction/Cohesion piling to the right (The Constructor, 2019).*

1.6 Study areas

In Figure 1.2 below the area is shown where the study was conducted, and it stretches 1.05 km from Linnéplatsen in the South to Järntorget in the North. Laterally the area is 1.2 km with Annedal in the East and Masthugget to the West.

Figure 1. 2 *Overview of the studied area.*

1.6.1 Linnéstaden

Linnéstaden has since the 16th century been an important part of Gothenburg due to its location close to the Götaälv river. At first, simple wooden houses were built but due to many fires during the 18th century decisions were made to further build in stone and in the 1860s the project commenced. Linnéstaden and the surrounding area was finished in the 1930s, hence the variety of styles in buildings (Stadshem, 2019).
Djupedalsbäcken, which ran through what today is Linnégatan, was redirected in culverts underground and up to 3 m fill material was laid upon it in the 1860s.
The topography in the area is varied with areas of exposed bedrock and places with a soil depth of up to 60 m, most of it being clay (see fig 3.1).

According to Ljungdahl (2015, p. 5) "*the subsidence that has occurred in Linné depends on groundwater lowering, rotting of wooden foundation piles, consolidation of clay, compaction of clay due to external load and compaction of filling material*". During the tunnel constructions in the 70's mentioned above, the groundwater levels were lowered 2-3 m in some areas, causing subsidence and damage to buildings (see examples in chapter 3). To solve the problem of the subsidence in Linnéstaden groundwater re-infiltration has been done (Ljungdahl, 2015).

1.6.2 Haga

In the mid-1840s the industries in Gothenburg attracted a large amount of people from the countryside to the city. Haga became a place where many of them would settle and between 1876-1895 more than a hundred of the characteristic Landshövdingehus were built with two storeys in wood and a bottom storey in stone.
Because of public interest most of these old buildings still stand today even if some of them were demolished and the damages caused by settling are in some parts severe (Stadshem, 2019). There are however modern buildings in Haga, most of which shows no or only mild damages on the façade.

2. Method

2.1 General Description

The method was divided into fieldwork and data processing. On the field the façades were studied from a street view and closeup. There were no chance of entering the buildings or see them from all sides since it would break regulations of trespassing. A few buildings were entered as there are many cafeterias and restaurants which allow it, but most observations were made on the streets.

Figure 2. 1. *The map shows how the buildings was divided into blocks to structure the work on field.*

The buildings got divided into smaller blocks as seen in fig 2.1 and were mapped methodically following the list of observation in table 1. In total 50 areas containing 471 buildings got mapped and the amount of each observation is presented in table 2.

Notes were taken at every observed damage along the buildings and an index on the rate of one to three were given. The index of one represents little damage, two moderate and three severe. It is a suggestion for further research for pattern of specific buildings or regions. The goal with the study as mentioned earlier was to sample data that might show a pattern of the settlement, where it gets worse and why.

Buildings with no damages were either under construction or had recently been renovated and cracks in plaster facades had been covered with new plaster.

In the area we expected to find different types of façades where the overrepresented part would be of bricks. However, there was also expectations to find plastered façades, wooden buildings and combinations of them all. All the observations of damages that were done do not fit with every façade and that is represented in table 1.

Table 1. *List of the expected observations along with their shortening, what has happened to the facades but also questions we thought about during our field work.*

Observation/damage	Shortening	Expected Façade	Describing Question	Figure
Sliding Bricks	**SB**	Bricks	Have the bricks slid as a result of the building sinking faster in some places that others?	**3.2, 3.3**
Replaced bricks	**RB**	Bricks	Have some bricks been replaced to fill out gaps?	
Cracks in Plaster façade	**CP**	Plaster	Do cracks occur on façades with plaster?	**3.4**
Deformed House Skirting	**DefSk**	Bricks, Plaster	Are the frames on the building deformed in any way?	**3.5, 3.6**
Oblique Windows	**OW**	Bricks, Plaster, Wood	Have windows on the façade become crooked?	**3.7**
Crushed Windowsills	**CWS**	Bricks, Plaster	Have the windowsills of stone been crushed?	**3.8**
Deformed Windowsills	**DWS**	Bricks, Plaster	Have the windowsills of stone or other material been deformed?	**3.8**
Protracted Vault	**PV**	Bricks, Plaster	Has the vaults in entries and passages become protracted?	**3.9**
Leaning Building	**LB**	Bricks, Plaster, Wood	Does the building lean to an extent where its visible?	**4.4**
Sunken Fire Wall	**FW**	Bricks, Plaster, Wood	Has the fire wall between buildings noticeably settled or deformed?	**3.10**
Bolted Building	**Bolt**	Bricks, Plaster	Are there bolts in the building to stabilize it?	
Deformation of Base Stone	**BSDef**	Bricks, Plaster, Wood	Are there damages or deformation on the base stone?	**3.11**

2.2 Data processing and visualisation

The gathered data was sampled in an excel spreadsheet and processed in QGis 3.4 and ArcMap 10.6. Open Geodata layers was obtained from SGU, Swedish Geological Foundation and Lantmäteriet. The maps were first presented in EPSG:4326 (WGS 84) but transformed into EPSG:3006 (SWEREF 99TM) for further analyses.

The spreadsheets in excel gathered all collected information from the field and divided the information in a way that all different types of observations could be visualized at the same time or part by part.

In QGis, important information from the buildings was sampled by *extract points to values* after the polygon was replaced by a point layer. The tool for this was the geometry tool *polygon centroid* which then got saved as a new point layer.

An interpolation shown in fig 3.12 was made in ArcMap where the *spline* interpolation tool gave best result.

3. Results

3.1 Data Collection

In table 2 a summary of the observations has been made showing how many times the different observations were done and how much it represents in percentage of the total amount of buildings that were observed. Also, the table shows the amount of building that was observed without any damages with a percentage calculated from them as well.

Table 2. *Summary of the amount of observations that were made during the days in the field.*

Observation	Shortening	Observation count	Count (% of Total amount of Building)	Count (% of Damage Buildings)
Sliding Bricks	SB	93	20	29
Cracks in Plaster	CP	83	18	26
Deformed Skirting	DefSk	260	55	82
Oblique Windows	OW	136	29	43
Crushed Windowsills	CWS	34	7	11
Deformed Windowsills	DWS	146	31	46
Protracted Vault	PV	98	21	31
Sunken Fire Wall	FW	19	4	6
Bolted	Bolt	1	0.2	0.3
Deformation of Base Stone	BSDef	32	7	10
No Damage		**153**	**32.5**	
Damage		**318**	**67.5**	
Amount of Buildings		**471**		

3.2 Visualization

In figure 3.1 the mapped buildings are presented and categorized by how many observations that were made in total for each one. The amount varies from zero to eight observations. In the background is an orthophoto of the area with a transparent 10x10m layer of soil depth on top. The color scheme varies from green to purple and it clearly shows how the layers evolves between valleys towards the river which connects to the ocean not far north of the figure.

3.2.1 Slope and Soil Depth

Figure 3. 1. *Map created in QGis that shows buildings categorized by amount of observations and soil depth in meters.*

The map illustrates that regions with deeper clay like the northern part around Masthugget and Haga has buildings that experienced more damages than the buildings that stand on the elevated part in Olivedal in the Midwest part of the map.

It also illustrates that many buildings standing on slopes has suffered from more damages from settling. Perhaps the most severe example can be seen in the South and East parts of the map in Annedal (*see* fig 3.12, 3.13 and 3.14).

3.3 Observations in field

3.3.1 Sliding Bricks – SB

For the buildings made of bricks the sliding was a common observation and was noted 92 times. That means about 20% of all observed buildings had bricks falling apart at some rate. The bricks in the picture breaks with a similar pattern of about 45 degrees and was seen repeatedly (*see fig 3.3, 3.7 and 3.9)*.

Figure 3. 2. *This figure demonstrates a building with bricks sliding apart in the typical 45-degree pattern. Sveagatan 22. Code: KA0512*

Figure 3. 3. *Photo taken from the South East part of Hagabion. Linnégatan 21. Code: OD0101*

Figure 3.3 demonstrates Hagabion which is an old building originally built as a school in mid-1870 but then rebuilt to a cinema 1983. It was built with old techniques on deep clay (25-30 m, *fig 3.1*) and suffers from many of the observations seen in table 1.

Discussion about old building technique were made and how piles made of timber might be damaged will be further made in chapter 4, *Discussion*.

3.3.2 Cracks in Plaster façades – CP

The wide distribution of the cracks led to 83 observations. Figure 3.4 shows a crack between two windows of a building that gets deformed due to the heavy load of the firewall.

Figure 3. 4. *Examples of cracks in a plastered facade at Andra Långgatan 6, Masthugget. Code: MH0804*

3.3.3 Deformed House Skirting – DefSk

The most common observation was deformed house skirting and was noted on more than half of all the mapped buildings (see, *Table 2)*. The skirting lays horizontally along the building which makes any slight deformation easy to observe. What was often seen was that the skirting started to get wavy shapes and started to break down as seen in figure 3.6.

Figure 3. 5. *Photo taken of deformed house skirting. The picture also shows an example of protracted vault. Västra Skansgatan 11, Haga. Code: HA1206e*

Figure 3. 6. *This figure shows example of crushed house skirting. Plantagegatan 9, Masthugget. Code: MH0116*

3.3.4 Oblique Windows – OW

Figure 3. 7. *Oblique window on a building in Masthugget. Nordhemsgatan 24, Masthugget. Code: MH0811a*

In total 136 buildings with oblique windows were observed.

In figure 3.7 the hand points towards one of the worst scenarios of an oblique window. This window belongs to a building located at Tredje Långgatan in Masthugget which is known for the heavy damage that the settling has brought to it over the years.

3.3.5 Deformed and Crushed Windowsills – DWS, CWS

Figure 3. 8. *On the top right a cracked and deformed windowsill is shown. Also, a pattern is seen along with the sliding bricks. Tredje Långgatan 13, Masthugget. Code: MH0811c*

Windowsills has shown signs of deformation in different manners depending on their length and what material they are made of. The reason why it has been presented together is because the crushed windowsill as shown in figure 3.8 has also been mapped as a deformation, not only as crushed.

The difference between them are that sills made from bricks or other material rather deform plastic than getting crushed.

3.3.6 Protracted Vault – PV

On the field about 20% of the buildings observed had protracted vaults which corresponds to 98 buildings in total. In fig 3.9 the vault is deformed in a typical way towards the firewall which also can be seen in fig 3.5 and 3.10.

Figure 3. 9. *Example of a protracted vault in a damaged area around kommedantsägen. Sveagatan 20-22. Code: KA0513*

3.3.7 Leaning Building

This observation was made with caution since it was difficult to determine and only a few buildings were noted as leaning. To strengthen the argument that buildings are leaning is to look where the firewall stands and see if it expands upwards. More about this in the next chapter, discussion.

3.3.8 Sunken Fire Wall – FW

19 fire walls showed clear signs of settling. It was easily noted since the buildings that were adjacent to the fire wall showed signs of settling strongly with it (*see* fig 3.10 and 3.5).

Figure 3. 10. *Evidence of a sunken fire wall by looking on how the skirting deforms. Mellangatan 9, Haga. Code: HA1211c*

3.3.9 Bolted buildings – Bolt

Only Hagabion was observed to have bolts in the building to prevent the settling.

3.3.10 Deformation of Base Stone – BSDef

In the studied area 32 buildings showed deformation on the base stone. There were two types of base stones, one made of stone and one made of plastered façade. The latter type showed most of the observed deformations since plaster is a weaker material than stone, which in most cases were granite.

Figure 3. 11. *Deformation of base stone found in Kommedantsängen. Majorsgatan 6. Code: KA0501*

3.4 Case Study

Another pattern that was found is that buildings partly built on solid ground and on soil tends to get damaged, and often between the contact of where the soil suddenly gets deeper. An example on this was found East of Linnéplatsen, *Konstepedimins Väg 2*, where the surface and the underlaying bedrock was tilting causing the building to get damaged.

In figure 3.12 we see an interpolated map of 82 points of depth from the original construction map of the area whereas parts of it can be seen in figure 3.13. The points were gathered by connecting contour lines of the surface with contour lines of the soil depth and the interpolation was made with the *Spline* interpolation tool in ArcMap. On the southern to western parts of the interpolated area the bedrock goes along with the surface and the depth gradually increases towards the west. The case study focuses on the building marked with a yellow dot and as seen the depth underneath varies from zero to about six meters.

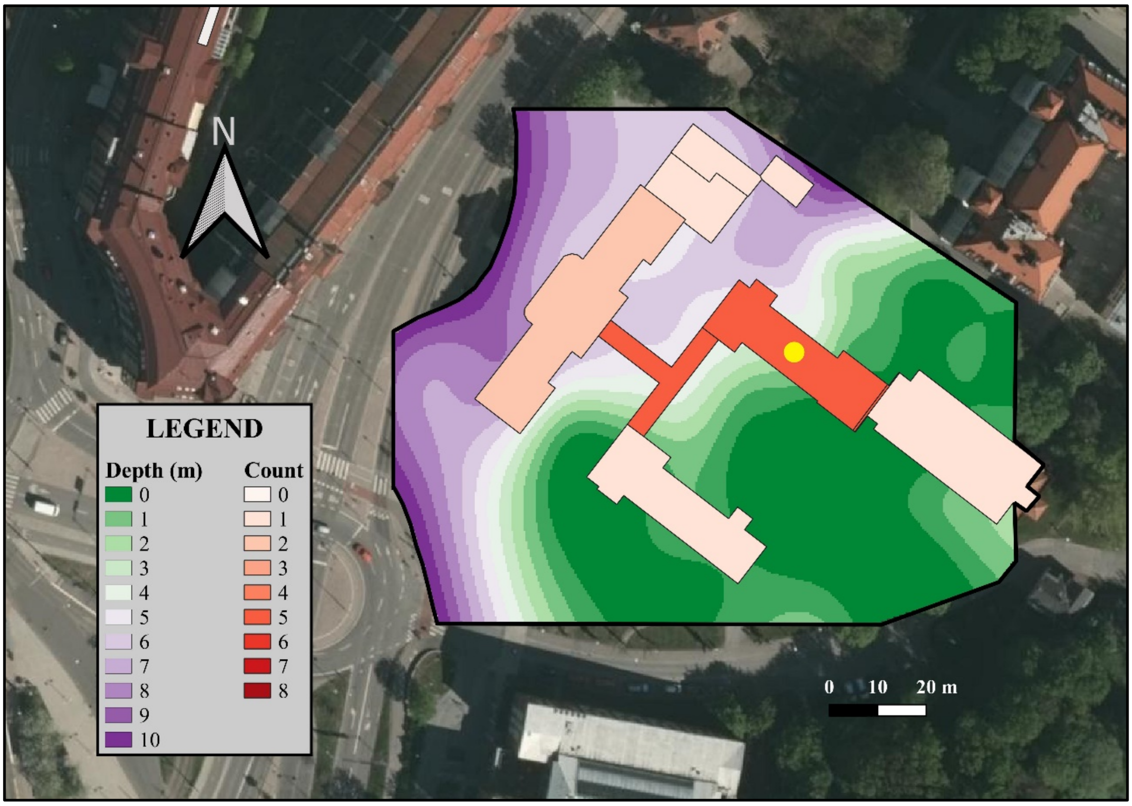

Figure 3. 12. *Interpolated map of the area with the depth ranging from zero to 10 meters.*

The picture taken in figure 3.13 demonstrates how the building looks like from the northeast side where the damages was clearly observed. The interpolation proves that the building stands on a heel of the bedrock and the location of the damages correlates to where the most graduated depth lies underneath. The picture has been taken quite far away so to see the observations clearer, the sliding bricks has been highlighted inside the red rings. The building also shows deformed sills and skirts, tilted windows and in figure 3.14 below we see that steel beams has been mounted in the left corner to steady up the weight.

Figure 3. 13. *This picture was taken from the north-east side, looking south-west and is marked with a yellow dot in fig 3.12. The building varies with depth from zero meters in the south-east part (left outside the picture) to depth of 5 meters in the north-west. The red rings enclose bricks sliding apart. Konstepedimins Väg 2, Code: KV2002c*

Figure 3. 14. *Same building as in 3.13. but this time shown from the Northwest side. Konstepedimins Väg 2 Code: KV2002c*

When looking at the documents from 1898 when it was built (*see* fig. 3.15 and 3.16) we see that there was no evidence that piling was made in the region between the thin layer of soil in the right part to where the piles are shown of the deeper left side of fig 3.15. Instead the building hang free in the soil where settling can happen. At other regions in Linnéstaden buildings tend to show the same pattern and a surprisingly new observation of sliding bricks was seen on a façade in Kommedantsängen East of Linnégatan. This building will be further discussed in chapter 4.2.

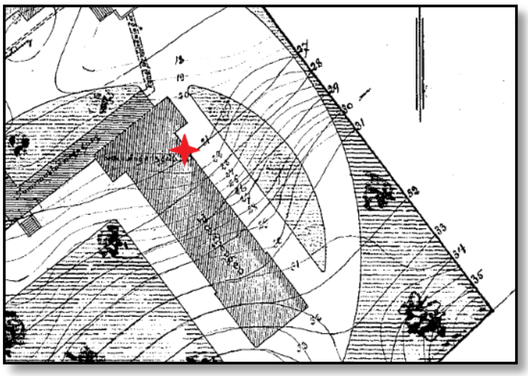

Figure 3. 15. *Part of original construction map showing two sets of contour lines. The red star marks where the picture in fig 3.9 was taken (Stadsbyggnadskontoret, 2019).*

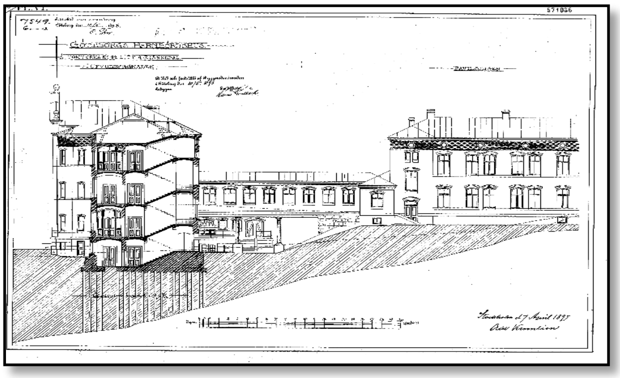

Figure 3.16. *Drawing of the building in the case study that shows no signs of piling in the studied regions of the building. (Stadsbyggnadskontoret, 2019).*

4. Discussion

4.1. Issues Related to Piling and Foundation

A main factor behind the issues we see on the older buildings in Linnéstaden and Haga could be due to the building technique and the infrastructure that followed with the urbanisation. Before the 1970s the piles used were made of timber. Since its cohesion soil (clay) underneath the area with a depth of up to 60 m this generally is a liable method. Problems arise, as mentioned earlier, if the groundwater levels drop below the timber pile and they rot. This is what has happened due to urban constructions like tunnels, asphalt and culverts etc. From the 70's to today, concrete piles are used since it has proven to be a more stable and liable material.

There are also several tunnels in the area, many which are confidential due to national interests so further studies haven't been possible. However, according to M. Persson (personal communication 3rd May 2019) these tunnels are a cause for much of the settling in the area consequently from lowered groundwater levels. This makes the piles lose some of their cohesion.

Another problem that has led to settling in combination with timber piles is filling material. As previous mentioned the streets and roads are also subjected to settling and the solution to even it out has been to put filling material in the depressions. The extra weight on the soil causes further consolidation and to solve that more filling material is added. The question arises where all this filling material ends up, is it going sideways under the building? Since no geophysical measurements has been done in this study it is not possible to present the exact final deposition of it. Further studies are suggested to find out where the filling material ends up. It is however believed that the filling material gets pushed down underneath the buildings until it encounters the piles and eventually break them due to overload of sideway shear pressure. This decreases the stability of the building, especially on the ones with wooden piles, and increases the pressure on the soil which leads to further settling.

When timber piles are driven into cohesion soils, they will disturb it. Lateral displacement and soil heave are two examples that are common when piling in clay because of mass displacement. The immediate effect on the soil when piling, is loss of shear strength and increased pore pressure. Over time, the clay will reconsolidate back to its previous state of consolidation except if the clay was over consolidated before piling. In that case, the clay will return to a state of normal consolidation. The area which is affected is said to be cylindrical around the pile with 1-2 times diameters of the pile. The increase of pore pressure can be measured at a distance of 10 times the diameter of the pile around it (Hugosson and Nilsson, 2014).

This can be a problem before the construction is finished and sometimes before starting it. Lateral displacement from piling can displace the piles that were driven down earlier making them askew before the load of the building is there. This might explain the situation of Le Village (see picture 4.1) since the bottom level is heavily settled while the upper levels are only slightly deformed. This indicates that the bottom level was deformed before the upper levels were even built.

Figure 4. 1. *A photo of Le Village shows severe settling in the left corner. However, on the second storey the settling is not as strong as in the ground level. Nordhemsgatan 24, Masthugget. Code: MH0811a*

To mention an example of lateral displacement in Gothenburg, there is a theory of lateral displacement being the cause for recent damages on the Götaälv bridge. A new bridge that will connect Hisingen and central Gothenburg is in the process of building. It will replace the Götaälv bridge and it will be placed in the same spot. The piling has already started for the new bridge and during the same period damages on the Götaälv bridge were noticed when the bridge had to be opened. At first, the cause was believed to be because of the unusual warm summer. When the solid piles were replaced by hollow piles, which cause no lateral displacement, the problems suddenly seized, however. The theory is therefore that the solid piles led to lateral displacement which was the cause for the issues at the Götaälv bridge (Sturkell, 19th of May 2019).

Heaving of the soil due to piling is also a problem. When timber piles are driven down as a group or with small spacing the effect is accumulative. The heaving and increased pore pressure can cause the piles to move upward, especially with piles that are floating in the soil (Massarsch, 1976). According to Massarch (1976), 6 out of 48 cases found in literature deal with the pilings influence on adjacent structures. On this base, it is reasonable to believe that piling in Linnéstaden and Haga has had effects on the settling of the buildings. This argument is strengthened with the fact that most of the modern buildings in Linnéstaden were built over a span of 70 years between 1860-1930 and in Haga over 19 years between 1876-1895.

The quality of the timber is a matter of concern for piling. Today the regulations are strict but earlier in this century they might have not been. On top of this fact, according to Massarch, (1976) earlier studies by Fellenius (1972) and Bergdahl and Nilsson (1974) shows that the lateral resistance of piles is very low. Lateral displacement seems therefore to be a factor contributing to the severe settling in Linnéstaden and Haga.

4.2 Slopes

Slopes has shown to have a strong connection with settling damages on buildings, as seen in the case study in chapter 3.4. Even if the piles are end bearing, slopes may cause settling because of the piles not being driven down into the bedrock but just leaning on it.

To mention an example that strengthens this theory, Lilla Risåsgatan 21 at Kommandantsängen will be discussed in the following section.

It is a modern building made in 1968 with a better technique of piling. The buildings made from around the 70's and onward used concrete for piling which has proved to be a more liable method (Persson, 3rd of May 2019). The mentioned building has damages in form of sliding bricks (see fig. 3.13). No other modern building shows this strong indication of settling in the studied area which makes this an interesting case. It is our theory that since it lies on a slope close to an elevated bedrock, soil movement has occurred, and in the process, it has detached the end of the pile since it hasn't been piled down into the bedrock.

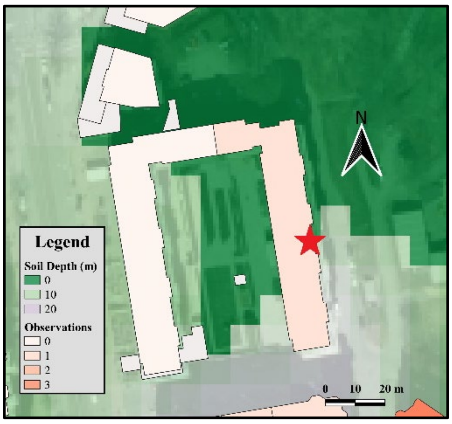

Figure 4.2. *Fixed map of the centre of fig 3.1 that illustrates the soil depth where the damage occurs at the red star. Lilla Risåsgatan 22, Code: KA0110*

Slopes might also be the reason to why some buildings are leaning towards Linnégatan. As seen on the map over the soil depth in figure 3.1 Linnégatan is situated in a valley with slopes on both sides and a thickness of clay beneath that increases towards the middle. This also correlates with the thickness of the clay and a faster rate of settling which will be discussed in next paragraph.

Figure 4.3. *A closer look on the damages in the form of sliding bricks on the building at Kommandantsängen. Lilla Risåsgatan 22, Code: KA0110*

4.3 Thickness of soil layer

There was a strong correlation between damages due to settling and the thickness of the clay beneath. This was an expected factor going into the field and when further research was done during this project, we found that studies had already shown this correlation in an earlier study made by Bergström, J in 1981.

4.4 Damage parameters

The method of sampling the data gave good results. The methods of walking around parts of cities looking on how settling has damaged buildings was presented in a new way and got tested in this study.

The observations in table 1 could all be seen but *replaced bricks* and *tilting house*s which was irrelevant to the rate that it sometimes was hard to tell if bricks were replaced and method for measuring leaning of the houses was unknown.

4.4.1 Hagabion and Bolting

Before the field work was conducted Hagabion was known to be severely damaged due to settling. To mitigate further damages bolting has been done on several places on the building. That was why it was a parameter that was searched for but no other building in the studied area had bolting done as reinforcement. Therefore, this category is not relevant as common observation and further studies of how bolting might slow down the rate of damage the building has suffered is suggested.

The tram travels only 40 meters away from Hagabion, causing vibrations to the ground. A telecommunications tunnel and storm water well run directly beneath the building (Sturkell, 19th of May 2019) which probably enhances the rate of settling. Also, the wooden piles used for the foundation might have rotted or lost the grip of cohesion due to lowered groundwater levels.

4.4.2 Cracks in Plaster Façade

The cracks on plaster façade were common. Several of the cracks were of small scale and it was hard to judge if it what was due to settling or superficial cracks from moisture and dry seasons.

4.4.3 Oblique Windows

A clear connection was observed where oblique windows repeatedly occurred in buildings where the bricks were sliding, and the fire walls had settled. It was very rare that a building had oblique windows without any of the other damages mentioned.

4.4.4 Fire walls

Firewalls was to begin with only a factor to consider when mapping the damages in the field. We did not expect to see any trend in settling related to them. It became evident however that the settling was strongly enhanced due to the fire walls making the buildings on both sides often sink down towards it. This probably only applied to the so called “landshövdingehus”. These houses are typical for Gothenburg, as the town prohibited wooden houses higher than two floors because of the fire hazard. But the real estate developers wished to build higher (but cheap) so a house type with the first floor in stone (bricks) and the two above in wood. This design is known as the “landshövdingehus”. The short end of these houses situated to the succeeding neighbour having a three-floor fire wall of bricks, that gives an increased weight and consequently can cause deformation of the buildings (Sturkell, 19th of May 2019).
It is our assumption that the firewalls carry a heavy weight on a small area that causes it to settle at a faster rate than rest of the building.

In table 2 we see that 19 notations of a sunken firewall were made and that is due to the firewalls being hard to determine to which it belongs to. The notations were made where scientifically settling of firewalls were seen and causes both buildings to sink towards the fire wall as shown in chapter 3. Therefore, the amount of observations might be incorrect.

4.4.5 Leaning Buildings

It was difficult to observe the rate of tilt on the buildings that were leaning. There were also buildings that had settled unevenly making the whole building lean towards the street as shown in fig 4.4. In this case the tilt of the building was clearly seen from the street. In some cases, however, the building seemed to have no tilt at all but when the fire wall was inspected there was evidence of it widening out towards the top, see fig 4.5.

Figure 4.4. *The building on the end of the streets shows clear evidence of leaning. Linnégatan 26 in Olivedal. Code: HA1608*

Figure 4.5. *Seen from this angle the widened fire wall is evidence for the building leaning. Linnégatan 11 in Olivedal. Code: MH0204*

4.4.6 Sliding Bricks

In many cases sliding bricks showed a pattern where they occurred continuously vertically (see fig. 4.6). We believe that sliding bricks is an indication of the "breaking point" of a building meaning that one side of the sliding bricks pattern is settling faster while the other side has less or no settling.

As shown in picture 4.6 below, the left side has no sliding bricks while the right side has a vertical pattern of it. This was, as mentioned, a repeated pattern but an important notation is that this theoretical "breaking point" was not as clear in all building. As seen in figure 4.7 there is no such clear pattern of the sliding bricks. It might however indicate that there are several "breaking points" where the building settles unevenly in several places. Both pictures are taken on the same street, Andra Långgatan between Järntorget and Masthugget.

Figure 4.6. *Sliding bricks can be seen from centre to right side but not on the left side. Andra långgatan 24, Code: MH0701b*

Figure 4. 7. *Sliding bricks can be seen without any clear pattern. Andra Långgatan 4a, Code: MH0807*

5. Conclusions

- There is no clear evidence of where the filling materials final deposition lies. Observations and theoretical analyses indicate however that it might end up under the buildings causing damages to the piling and foundation.
- Piling technique and material might be an important factor for the rate of settling on a building and may therefore influence the damage it will have. This is strengthened by the absence of severe damage on new buildings.
- Infrastructure and tunnels are a main contributor to increased rate of settling because of lowered groundwater levels.
- Damages on buildings correlate with soil depth and slope.
- This study has evolved a database that has been modified along the way. An example of the database can be seen in the appendix and it is structured so that it can be used methodically to collect and store data from the field. All buildings are encoded after the area (ex. Annedal, Haga, Masthugget etc.) and house number and are listed in an excel spreadsheet. For every building the observations can be marked with a one if it exists and a zero if it doesn't. In that way we can count how many of each observation that were made and to compare it to other observations.
- For the index of one to three which indicate the rate of damage the buildings experience each observation was listed in the same way as the ones and zeroes only that the number has been changed to what index that fits with each observation. This number can also be summed up for each building so a total can be made.
- With the lack of time this study was focused on mapping and get an understanding of Linnéstaden. There was no experience from any similar project so how much time the observations would take had to be tested and the methods of observing the damages evolved as our eyes got used to look for them.
- This study can be expanded to a large extent. The studied area is only a small part of a large city with many regions of settling buildings. Linnéstaden was of our interest because there was knowledge of severe settling in that area before.

6. Appendix

In this appendix an example of how the spreadsheet of the database looks like in excel has been presented. In the top column we see the shortening of all the observations and the list in the first column represents the buildings encoded with what area they are located in (for example OD stands for Olivedal) and what block they belong to.

The observations are marked with number one in the right field for the right building and observation. In this way it is easy to summarize the totals of each observation but also the total amount of damage of each building.

House ID	SB	RB	CP	DefSk	OW	CWS	DWS	PV	LB	FW	Bolt	BSDef	Total
OD1104	1			1					1				3
OD1105								1					1
OD1106	1												1
OD1107	1			1	1			1					4
-	-	-	-	-	-	-	-	-	-	-	-	-	-

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