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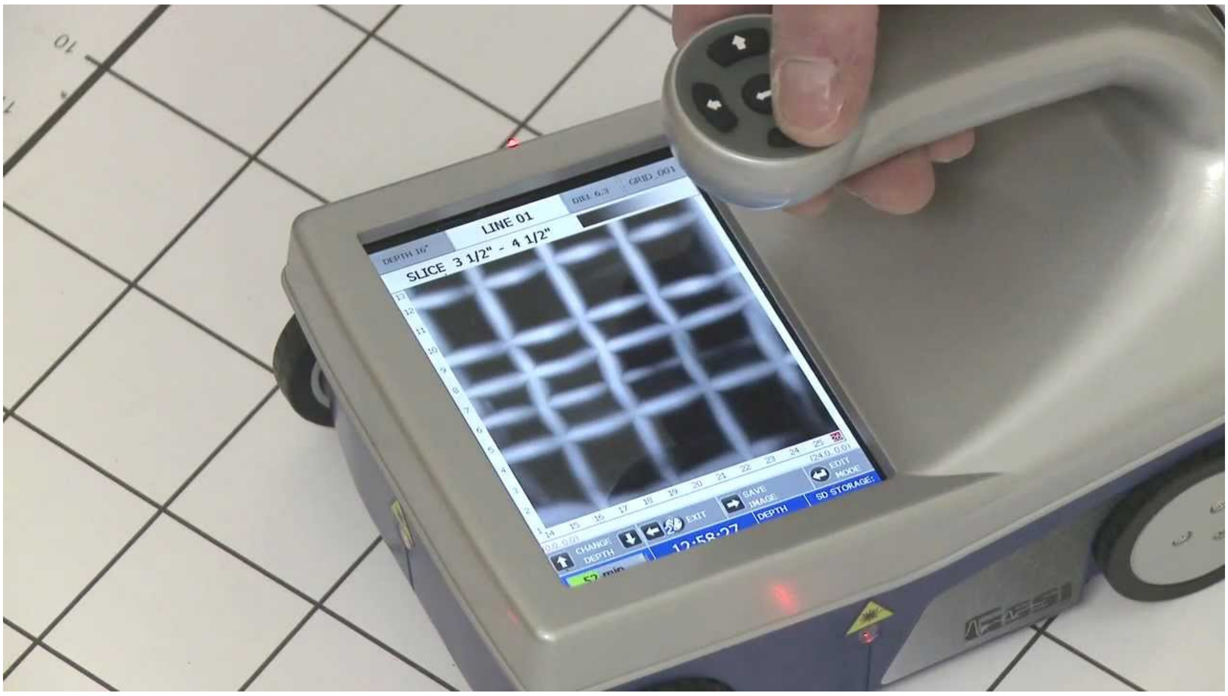

Evaluation of Ground Penetrating Radar as a Non-Destructive Investigation Method in Concrete Elements

Master of Science Thesis in the Master's Programme Geo and Water engineering

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Department of Civil and Environmental Engineering
Division of GeoEngineering
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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014
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Cover:
Graphical results of a 3D scan shown on a StructureScan Mini HR (GSSI, 2013c).

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ABSTRACT

There are today a number of different non-destructive investigation methods that can be applied for investigating building materials such as concrete. The interest is high of being able to investigate and evaluate what is imbedded inside the concrete without destroying a construction. This is especially valuable when performing damage studies on objects such as floors, pillar and bridges.

Ground penetrating radar, GPR, has been around for a long time, but has mainly been used to perform ground survey studies. The first types of commercial available units were big and bulky; however with the rapid technological development handheld high resolution units are now available.

The aim of the report is to evaluate the possibilities and limitations of using ground penetrating radar an investigation method in concrete structures. The evaluation is performed with the apparatus Structure Scan Mini HR from Geophysical Survey System Inc. Measurements is performed in both a controlled environment and in field investigations.

The results show that the GPR is sensitive to moisture and that it can reduce the penetration depth of the signal. To perform accurate scans the object has to be homogenous and the dielectric constant be known.

The results of the study also show that under the right circumstances the GPR is a time efficient and accurate investigation method. It provides the user with the possibilities of performing 2D scans for a fast mapping of imbedded objects and 3D scan for a more detailed investigation in complex structures. 3D scans might also show conditions when there is a risk for high chloride concentration and corrosion.

Key words: ground penetrating radar, non-destructive testing, concrete, 3D mapping, corrosion

Utvärdering av Georadar som en icke-destruktiv undersökningsmetod i betongkonstruktioner
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SAMMANFATTNING

Det finns idag ett antal olika icke-destruktiva undersökningsmetoder som kan användas för att undersöka byggmaterial, såsom betong. Intresset är stort av att kunna undersöka och utvärdera vad som finns ingjutet I betong utan att förstöra en konstruktion. Detta är anses speciellt värdefullt vid skadeundersökningar av objekt såsom golv, pelare och broar.

Georadar, GPR, har under lång tid använts som undersökningsmetod, främst till geologiska undersökningar. De första kommersiella enheterna var stora och otympliga, dock i takt med den hastiga tekniska utvecklingen, finns nu handhållna högupplösta enheter tillgängliga.

Syftet med denna rapport är att utvärdera de möjligheter och begränsningar som finns med att använda georadar som undersökningsmetod i betongkonstruktioner. Utvärderingen görs med hjälp av enheten Structure Scan Mini HR från Geophysical Survey System Inc. Mätningar har utförts både i en kontrollerad miljö samt i fältundersökningar.

Resultaten av dessa undersökningar påvisar att georadar är väldigt känslig mot höga fukthalter, då det kan reducera signalens penetrationsdjup. För att utföra undersökningar med hög tillförlitlighet bör materialet ifråga vara homogent och dess dielektriska konstant vara känd.

Resultaten påvisar även att under georadar är en väldigt tideffektiv och noggrann undersökningsmetod, under rätt förutsättningar. Den ger användaren möjligheten att utföra 2D scanningar för att snabbt kartera ingjutna objekt eller 3D scanningar för en mer detaljerad bild i komplexa strukturer. 3D scanningar kan även påvisa förhållanden där det finns risk för höga klorid koncentrationer och korrosion.

Nyckelord: georadar, icke-destruktiva undersökningar, betong, 3D kartering, korrosion

Contents

Preface

The Master thesis has been carried out at the department of Civil and Environmental Engineering, division of Road and Traffic Group, at Chalmers University of Technology and at CBI AB

The informations gathering and the tests in controlled environments have been performed at CBI AB. The field test have been performed at locations correlated to projects carried out by CBI.

I would like to thank my examiner Gunnar Lanner for the attention and help he has provided during this thesis. I would also like to express my deepest gratitude to my supervisor at CBI, Katarina Malaga, for all the help and guidance which has been crucial during this thesis. Furthermore I would like to thank Urs Muller and Mats Holmqvist for their time and efforts they have provided to help me especially during the controlled environment tastings.

Göteborg 2014

Paul Popa

1 Introduction

1.1 Background

Concrete is the most widely used construction material in the world. It is one of the most durable building materials and it provides superior fire resistance. The service life of structures made from concrete can be very long, but inspections of the structure's condition have to be made to assess the condition. There are today a number of different non-destructive investigation methods that can be applied for investigating building materials such as concrete. The interest is high of being able to investigate and evaluate what is imbedded inside the concrete without destroying a construction. This is especially valuable when performing damage studies on objects such as floors, pillar and bridges.

Ground penetrating radar, GPR, has been around for a long time, but has mainly been used to perform ground survey studies. The first types of commercial available units were big and bulky; however with the rapid technological development handheld high resolution units are now available and have opened new possibilities of performing non-destructive investigations on concrete structures.

1.2 Aim

The aim of the study is to evaluate the possibilities and limitations of ground penetrating radar as an investigation method in concrete structures

1.3 Limitations

The evaluation will be performed with the apparatus StructureScan Mini HR and the software RADAN 7.0 from Geophysical Survey System INC. The conclusion of this report will be based on a limited amount of controlled environment investigations and field investigations.

1.4 Method

The evaluation will be performed with the help of the following steps:

- State of the art - a theoretical study will be performed and the latest level of knowledge will be presented.

- Tests in a controlled environment – several concrete panel will be molded with imbedded artifact such as rebar and pipes. These will then be investigated with the GPR and the results will be correlated to the state of the art

- Field investigation- the results and knowledge gained will then be applied in field tests.

2 State of the art

2.1 Ground Penetrating Radar

Ground penetrating radar, GPR, is an electromagnetic investigation method that uses radio waves to probe any low loss dielectric material. The first published use of GPR was recorded in the 1920s when an Austrian scientist attempted to determine the thickness of an Arctic ice sheet (Cardno, 2013). However it was not until the 1970s when commercial GPR unit started showing up. The first units that were for sale were bulky non-portable units and because of the limitations of the design, the early units were mainly used by geoscientist to investigate such thing as ice thickness and water table mapping.

During the 1990s the rapid technology development lead to advancement in both hardware and software design. The GPR units became smaller and more portable as well as more functional software was developed. However the major contributor to GPR reaching acceptance, as a viable investigation method, was the development of shielded antenna. With a shielded antenna there was now a possibility to collect data in all areas regardless of surface clutter.

Current GPR units have evolved into compact and user-friendly instruments that can gather large amount of data in a relative short time, see figure 1 for an example of a modern high resolution GPR unit.

Figure 1 Example of a handheld GPR unit (GSSI, 2013c)

2.2 Types of GPR

The design of ground penetrating radar system, GPR, is conceptually simple. The objective is to measure field amplitude versus time after transmitting a radio wave into the desired material, therefore one of the main parts of the GPR is the timing unit which controls the generation and detection of signals, see figure 2

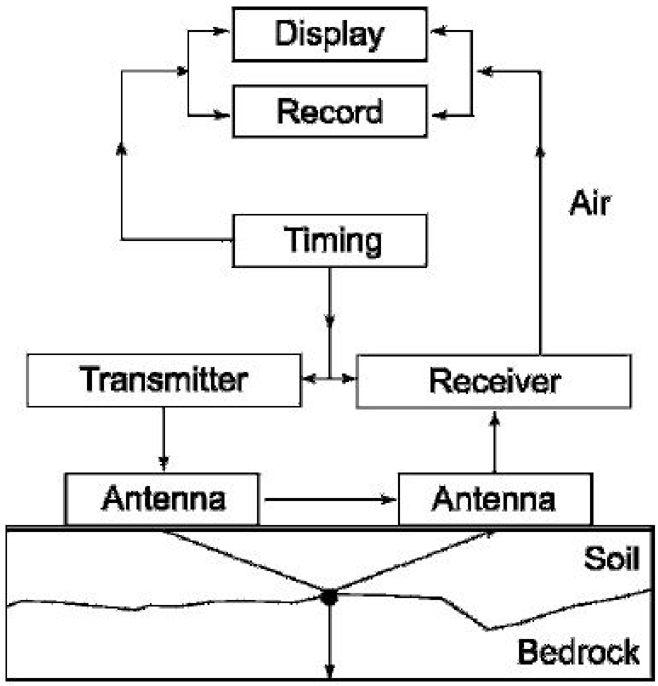

Figure 2 Conceptual picture of a GPR unit and its containing parts (Koppenjan, 2009)

There are several types of GPR, however the main aspect that separates them apart is the way that data is acquired (Koppenjan, 2009), either the time domain or the frequency domain. The most common systems are based on impulse radar or continuous-wave, CW, technique.

2.2.1 Impulse

Impulse based GPR types are the most common and are dominating the commercial market (Koppenjan, 2009). The impulse radar technique acquires data in the time domain, a pulse is transmitted and the reflected energy is received as a function of time. A resulting waveform of the function will then show the amplitude of the energy that is scattered from subsurface object and range, time of flight principle is used when determining the range.

The main advantages with are the simplicity of generating an impulse wave and the usage of low-cost parts.

2.2.2 Swept frequency-modulated and stepped frequency-modulatet continuous wave

Differently from the impulse radar the CW technique acquire the data needed in the frequency domain (Koppenjan, 2009). This concept is based on transmitting a frequency sweep over a fixed bandwidth. The reflected energy is received as a function of frequency and show the amplitude of the energy scattered from subsurface objects. The sampled waveform is then transformed into the time domain.

A similar method is the stepped frequency-modulated continuous wave except that the transmitting frequency is stepped in linear increments over a fixed bandwidth. The swept frequency advantage over stepped frequency are the simpler design and lower cost for implementation, however in some cases swept frequency may show lower performance.

2.3 Antennas

The frequency of the emitted and recorded radar signal is defined by the antenna (Hugenschmidt, 2010). Choosing the right antenna is crucial for performing efficient radar scan. If there is a demand for high resolution imaging, a high frequency antenna should be chosen. However the higher frequency an antenna has the lower depth it is able to penetrate. Antennas are today available with center frequencies from a few MHZ, low resolution with high penetration depth that is mainly used in geological applications, up to some GHz, high resolution antennas with low penetration depth mainly used for non-destructive investigations.

2.4 GPR for evaluation of reinforced concrete structures

The usage of GPR is very advantageous as it is a non-destructive method and very fast investigation method (Saarenketo, 1999), hundreds of measurements can be performed per second. The existence of numerous low loss dielectric material environments and the broad radio frequency spectrum makes the method applicable to a wide range of problems such as:

- layer thicknesses, including concrete cover of rebar, asphalt pavement and concrete tunnel walls
- locating structures such as tendons or tendon ducts, anchors, dowels, and cavities
- Material properties, including humidity, chloride content, voids, and air content.

2.5 2D scanning

The result of radar scans can be acquired and displayed in different modes (Hugenschmidt, 2010). When measuring in a single point, a-scan, the results are presented either as a curve or color coded, see Figure 3, where the vertical axis is a time axis.

If the antenna is used to scan along a horizontal line, b-scan, measurements can be made at closed intervals and the recorded time series can be plotted side by side, see Figure 4. The display format is called a radargram, where the horizontal axis represents the line in which the antenna is moved.

When the scanning is carried out over an area by making measurements along many parallel lines, c-scan, a time-slice can be displayed, see Figure 5. The axis of the time-slice correspond to the two horizontal axes of the assessed area.

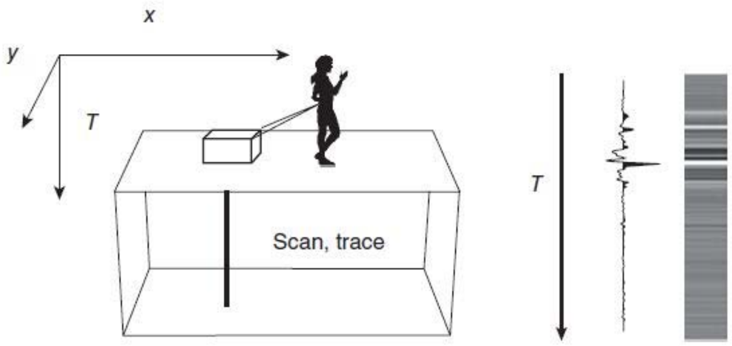

Figure 3 Acquiring data for an a-scan and example of the results shown in a single times series (Hugenschmidt, 2010).

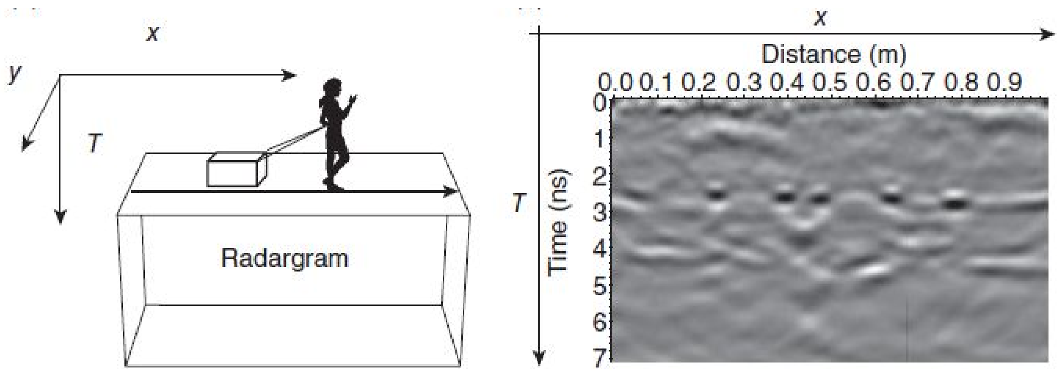

Figure 4 Acquiring data for a b-scan and example of the results shown in a radargram (Hugenschmidt, 2010)

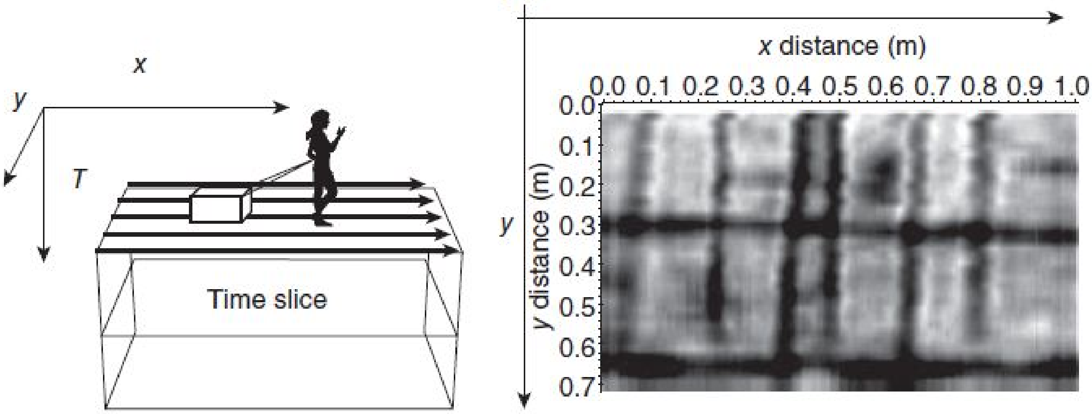

Figure 5 Acquiring data for a c-scan and example of the results shown in a time slice (Hugenschmidt, 2010)

2.6 3D scanning

With the development of GPR units and the increased possibilities in computing power there are possibilities of creating 3D imaging (Hugenschmidt, 2010). The three-dimensional data gathering requires considerably more effort, however it provides more information that may be vital when performing scans.

Three-dimensional imaging is created with the help of inversion, a process where a numerical model is used to represent a physical environment. When the dataset has been acquired the model starts to build synthetic data, which are then compared to the real data and the model is adjusted. This process is then iterated until the synthetic data correspond with the real data.

A successful inversion model represents the physical representation of the inspected object, see Figure 6, for an example of a model of reinforced concrete.

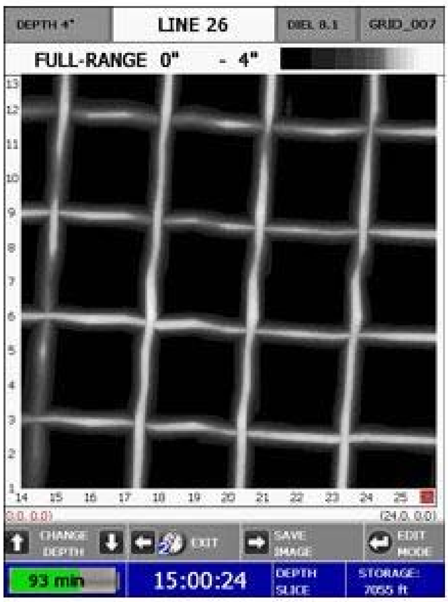

Figure 6 Results from a 3D scan performed on reinforced concrete (Hugenschmidt, 2010)

2.7 Data Processing

After performing the scans there are many processing and analysis techniques that can be applied to interpret the collected data (Daniels, 2004). However, many users will interpret data directly from the screen on-site. This may be sufficient in many cases but the dynamic range of the information produced on a screen is about 10-20 dB, whilst the dynamic range of a GPR system is at least 60 dB.

The main goal of applying advanced analysis method is to extract additional information that can help characterize the physical/natural properties. These methods should on the other hand be used with care as they can introduce user-dependent bias into the process. If this occurs, in the best case scenario it will distort the final interpretation and in worst case it will introduce non-existing features. It is very easy to over process GPR data and the different processing steps that exist will never make up for the lack of good data.

2.7.1 Time-zero

When performing scans thermal drift, electronic instability and variations in antenna air gap can create jumps in the air-ground wavelets first arrival time, time-zero point, which will have an effect on the position on the ground interface, see Figure 7. To be able to process the collected data an adjustment has to be made to correct the time-zero position. This is usually attained by using particular criteria, such as first positive peak of the trace (Cassidy, 2010). Under normal conditions this is often sufficient, but it can be problematic in noisy traces as there often is no start or peak to the initial part.

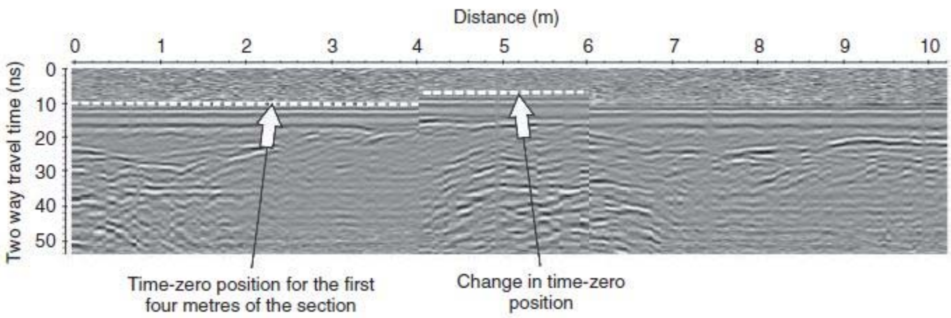

Figure 7 Example of time-zero variations (Cassidy, 2010)

2.7.2 Filtering

Filters are mainly used to improve the visual quality by removing cultural or system noise. They are also very useful in extracting particular aspects from the data and thereby aiding interpretation (Cassidy, 2010). There are many different filter types, from simple band-pass filters to sophisticated domain and transform filters. The simple filters are very effective in removing low- or high-frequency noise while the more sophisticated often aimed at specific issues. Complex filters are however not always necessary as the filtering process introduces elements of subjective bias. This is often more problematic in heterogeneous environments, where coherent reflections returns are less common and scattering or cluttering is more widespread. Also in cases like this filtering may also remove important information.

2.7.3 Gain functions

Gain functions improve the visual form, but they also alter the data structure in some way (Cassidy, 2010). Therefore, it is vital to understand the effects of the function before it is applied. There are a lot of different types of gain functions, such as constant gain, exponential gain and AGC, and they each have different characteristics. There are many different filters

Constant and exponential gains are user defined and apply a mathematical and multiplication operator to the signal amplitude.

An automatic gain function, AGC, is applied to each trace in the scan, based on the difference between the mean amplitude of the signal and the maximum amplitude in the trace. An AGC is a convenient way to display deeper and weaker event, although it also amplifies noise. See Figure 8 for examples of different gain functions applied to trace data.

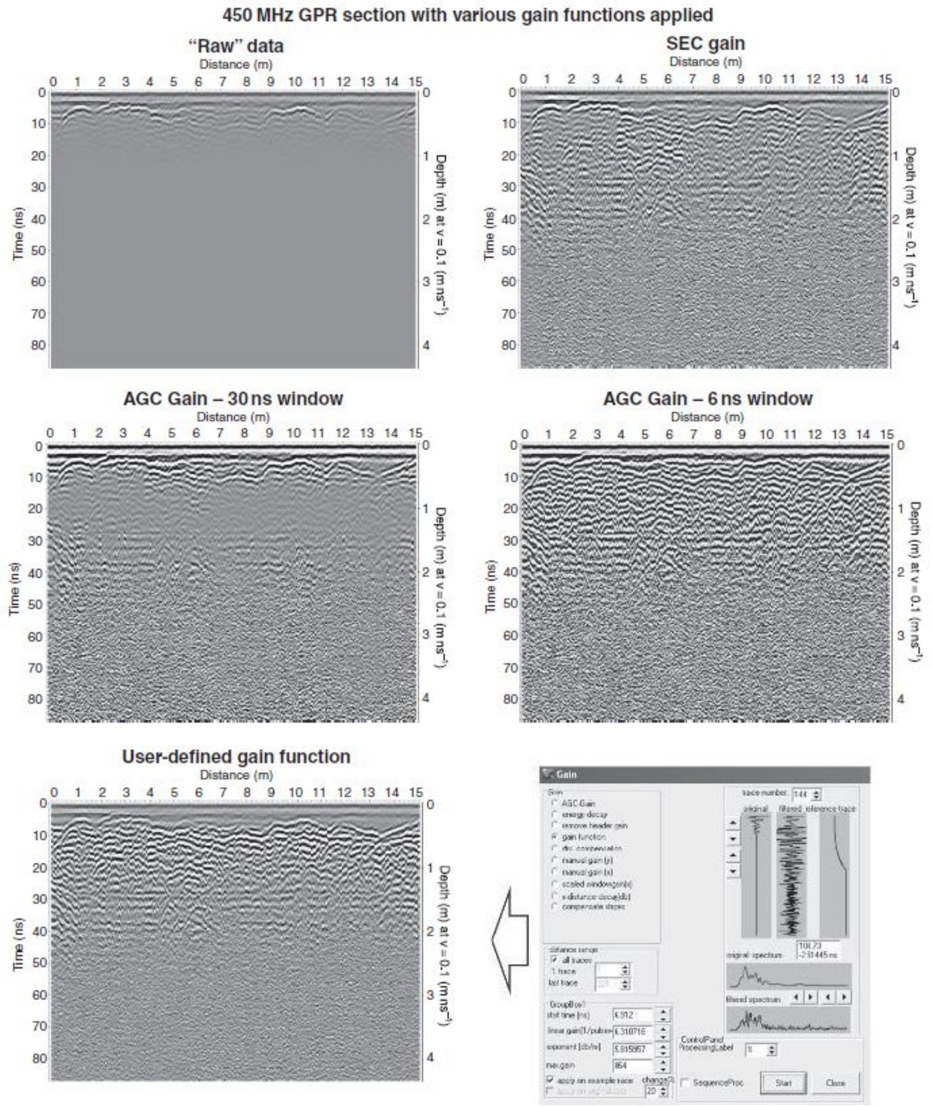

Figure 8 Example of raw data processed with different gain functions (Cassidy, 2010)

2.7.4 Migration processing

The migration techniques were originally developed for the seismic industry and it is mainly used to improve section resolution and develop a more spatially realistic image (Cassidy, 2010). Migration is one of the most controversial processing techniques and it tends to be less successful with GPR, especially when scanning complex heterogeneous sites. However, migration technique can in certain situation be applied very successfully on a range of different applications, see Figure 9 for a successful migration. This method can be very advantageous when investigating the existence of rebar in concrete, as a good performed migration will collapse hyperbolae to a point source and dipping reflections will be repositioned into their correct location.

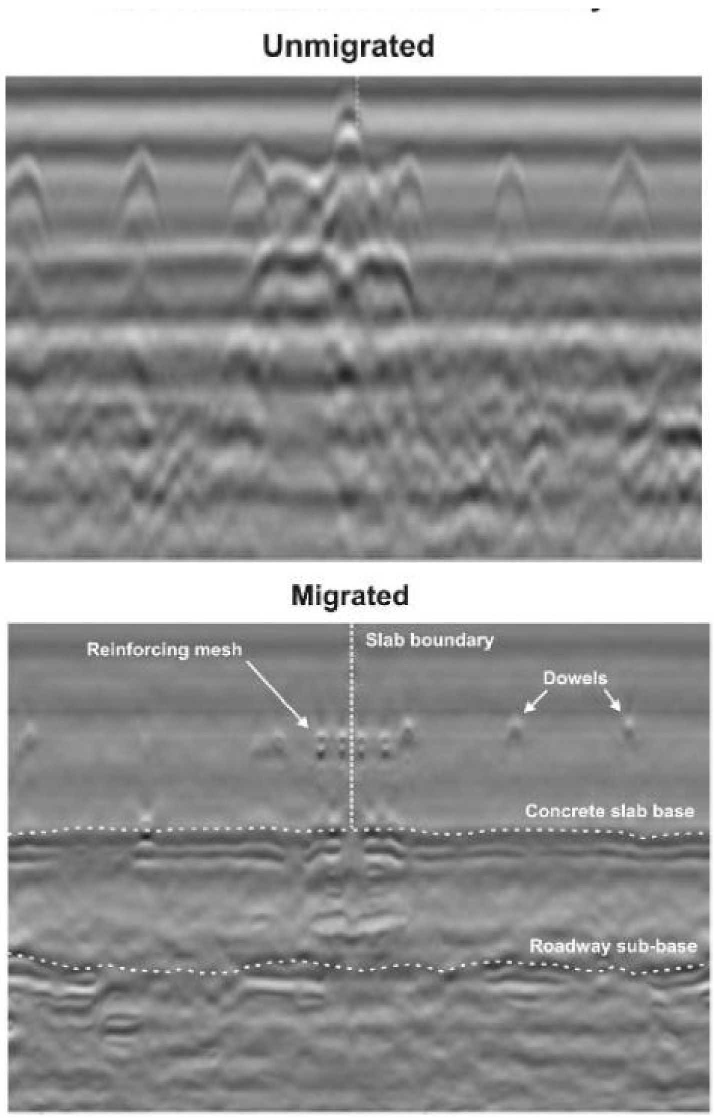

Figure 9 Example of a successful performed migration (Cassidy, 2010)

2.8 Interpretation of radar data

The way radar responds to different materials is governed by two physical properties, electric conductivity and dielectric constant (GSSI, 2013b). Because GPR uses electromagnetic energy it is subject to attenuation as it passes through a material. The signal will as a result of this stay intact longer and be able to go further into low conductivity materials, such as dry sand or dry concrete. If the materials are conductive, such as salt water or wet concrete, the signal will be absorbed before it has a chance to penetrate deep into the material.

Dielectric constant is the other physical constant and it indicates how fast the radar energy passes through a material. Radar energy passes as quickly as possible through a material, however certain materials slows down the energy. By knowing the dielectric properties of the examined concrete, a more precise estimate of how deep a certain object is can be made. The higher dielectric constant, the slower the radar wave moves through the material.

Another aspect of the importance on dielectrics is the reflection that is created when the radar wave passes through material with different dielectric values. A reflection is produced in the boundary between different materials where the dielectric changes. A higher difference in dielectric values will result in a stronger reflection. The difference in electric conductivity will affect the brightness of the reflection. Metal will show as very bright reflections because they are conductive, also metal targets will return an extra signal that results from them becoming charged, see Table 1 for example of how different materials will be visualized in a GPR scan.

Table 1 Visualization of GPR data collected from different materials (GSSI, 2013b)

Boundary	Dielectric Contrast	Reflection Strength
Asphalt-concrete	Medium	Medium
Concrete-sand	Low	Weak
Concrete-air	High, phase reversal	Strong
Concrete deck-concrete beam	None	No reflection
Concrete-metal	High	Strong
Concrete - water	High	Strong
Concrete - PVC	Low to Medium, phase reversal	Weak

Further information can also be provided by the reflection polarity. In a GPR antenna the transmission pulse has a certain polarity, for example in a GSSI antenna there is a positive peak first, which is followed by a negative peak and sometimes possibly another positive peak. When performing a grayscale line scan this look like a white band followed by a black band. However, a phase-inversion occurs at a concrete-air interface because of the low dielectric of air. A concrete-air reflection starts with a negative peak followed by a positive peak, see the concrete bottom in Figure 10. Air-filled voids and air-filled PVCs will also show a phase inverted reflection.

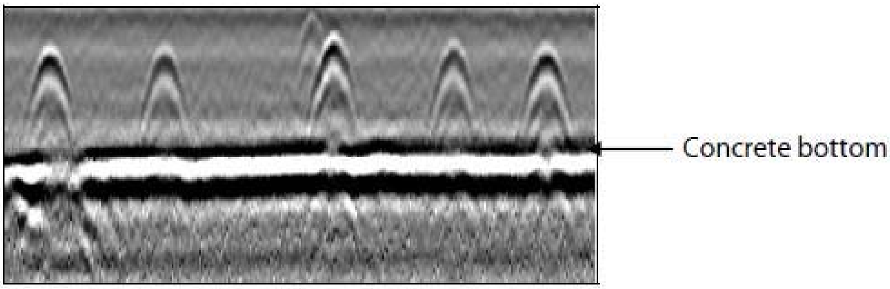

Figure 10 Radargram of a concrete slab (GSSI, 2013b)

2.9 Target reflection

When a line scan is performed and the antenna crosses a pipe-like target at a right angle, the resulting image looks like an inverted U or V, a hyperbola, see Figure 10. This shape is drawn because of cone shaped antenna beam, which leads to the radar being able to see the object several scans before and after its location (GSSI, 2013b). The location of the object coincides with the peak of the hyperbola. However the shape of the hyperbola is dependent on two parameters, scan spacing and radar wave velocity. A smaller scan spacing, more scans per cm, will produce wider hyperbolas. A higher wave velocity, lower dielectric, will also lead to wider hyperbolas.

The brightness of a single hyperbolic reflection follows the same rules as the examples given in Table 1. Metal objects produce strong clear reflections, while a PVC pipe reflection will have the same shape, but much lower amplitude.

Composite targets like a PVC conduit with electric wires inside can produce distorted hyperbola reflections, as the wires can produce reflections that do not always have perfect form.

Hyperbolas may also look distorted when the scan line crosses the target diagonally. If the scan line is almost parallel, the reflection appears as a slightly curved line. If the scan line is parallel, the target will appear as a continuous layer.

2.10 Limitations of GPR

In many aspects GPR is a more beneficial method compared to other non-destructive method; however there are conditions where there are several limitations to the use and accuracy of the results (Saarenketo, 1999). GPR are sensitive to moisture, as it can attenuate the electromagnetic wave and limit the penetration depth.

Another issue that may affect the penetration is the electric conductivity of the materials (Hugenschmidt, 2010). Radar waves in conducting materials lead to stray currents reducing the depth of penetration of radar signals. In certain situations the problem can be solved by using lower frequency antennae, in most materials lower frequency waves experience lower dampening. Though this will lead to a reduced resolution, which may not be feasible.

When investigating layer thickness, the velocity of the certain material has to be known to make an accurate evaluation. Assumptions can be made of constant velocity within the layer, in many cases this is a successful method, but velocity variations will lead to errors in the results. Issues with determinate layer thickness may also exist if there are insufficient contrast differences. Without contrast difference the boundary between different layers will not show in the radar data.

2.11 Future possibilities

Radar surveys have mainly been used to obtain structural information such as thickness of concrete, concrete cover of rebar or position of tendons. However material properties such as moisture or chloride content have become an interesting subject to research (Hugenschmidt, 2007). In countries where salt is applied for deicing, corrosion of rebar is a major problem. Reinforcement in concrete is normally protected from corrosion, due the high pH-value. However if the chloride concentration passes a certain threshold value in combination with water and oxygen, the corrosion of reinforcement can take place. Corrosion is the main cause to structural concrete deterioration and thereby one of the major source of the cost for rehabilitation of concrete structures.

To monitor the condition of the concrete, there are established methods as periodical visual inspection or measuring the potential of steel to detect active corrosion in the reinforcement. However, these types of method are not viable on bride decks covered by asphalt pavement. Maintenance planning for bridges is often based on experience and not on data of the real conditions; therefore a method to evaluate the condition of bridge decks is desirable.

In a laboratory experiment, Hugenschmith and Loser investigate the effects that moisture and chloride content have on the amplitudes of radar content. Nine concrete samples were cast with tree different chloride content and three different relative humidity. The samples were scanned and the results can be seen in Figure 11. In the result it can be seen that there is a clear relationship between the amplitudes and the chloride/moisture content of the specimens.

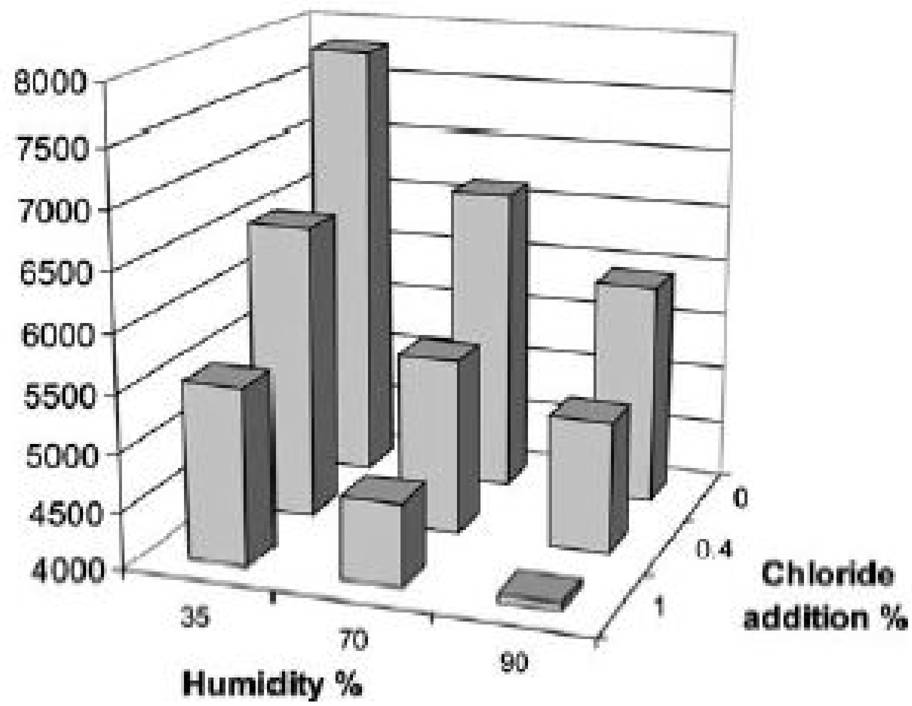

Figure 11 Reflected amplitudes of specimens with different chloride and moisture content (Hugenschmidt, 2007)

Another approach to the problem has been performed by Kabir and Zaki, where they try to detect damage on reinforcement steel using GRP (Kabir & Zaki, 2011). Rebar are corroded by being immersed in 5% sodium chloride and being exposed to the solution by using DC power supply. Four rebar are exposed to the solution during different time duration, 0 day for no corrosion rebar, 1 day for low corrosion, 3 days for middle corrosion and 7 days for high corrosion. The rebar are then induced into a concrete slab. The images of the B-scans, C-scans and 3D image can be seen below in Figure 12 and 13.

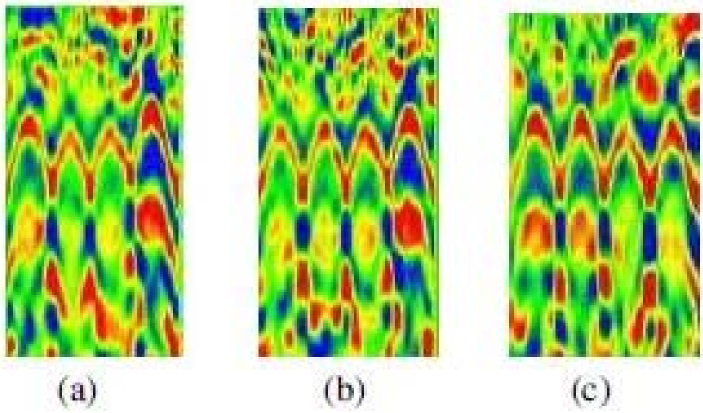

Figure 12 B-scan of the investigated rebar, (a) at the end of rebar, (b) at corroded rebar, (c) at beginning of rebar (Kabir & Zaki, 2011)

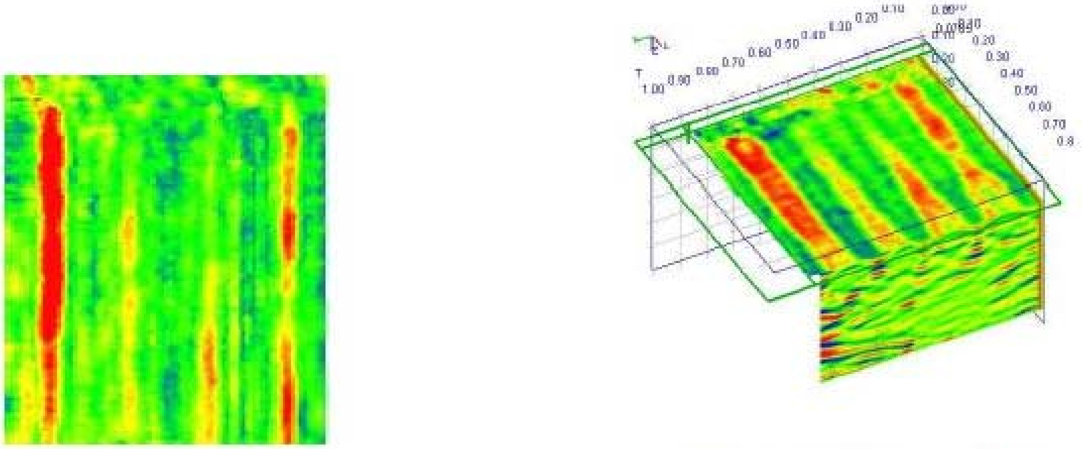

Figure 13 C-scan (left figure) and 3D-scan (right figure) of rebar with different degree of corrosion (Kabir & Zaki, 2011)

With help of these scan the authors can make a conclusion that corroded rebar can be identified with the help of 3D scans as there are there is different pattern on corroded rebar and the diameter of corroded rebar is less than non-corroded rebar.

3 Equipment

3.1 StructureScan Mini HR

The StructureScan Mini HR is developed and sold by Geophysical Survey System Inc, GSSI (GSSI, 2013a), which is one of the world's leading manufacturers of GPR equipment and solutions. The company was founded in 1970 and in 1971 it sold its first commercial GPR system. GSSI's main markets for their GPR products are concrete inspection, utility mapping and locating, road and bridge deck evaluation, geophysics and archaeology.

The first StructureScan Mini was released in 2009 and is an all-in-one handheld GPR system, see Figure 14, and in 2011 a high resolution version of the StructureScan Mini was released (GSSI, 2013c). The StructureScan Mini HR comes with a 2600 MHz antenna and the possibilities of performing 2D and 3D scan with a penetration depth up to 40 cm. The wavelength of the antenna also determines the unit ability to see two closely spaced targets separately. The average wavelength of a 2600 MHz antenna in concrete is about 4.5 cm. As a rule of thumb the radar signal will penetrate a mesh with horizontal spacing lager than the wavelength. Vertically the required spacing should at least be about 1,125 cm for the antenna to register two different objects. The accuracy of the depth measurement with correct dielectric values is +/- 6,4 mm.

According to GSSI the main purposes for the StructureScan Mini HR is to perform concrete inspections and locate metallic and non-metallic targets, structure inspections such as bridges, walls balconies and garages, measure slab thickness and void location (GSSI, 2013c).

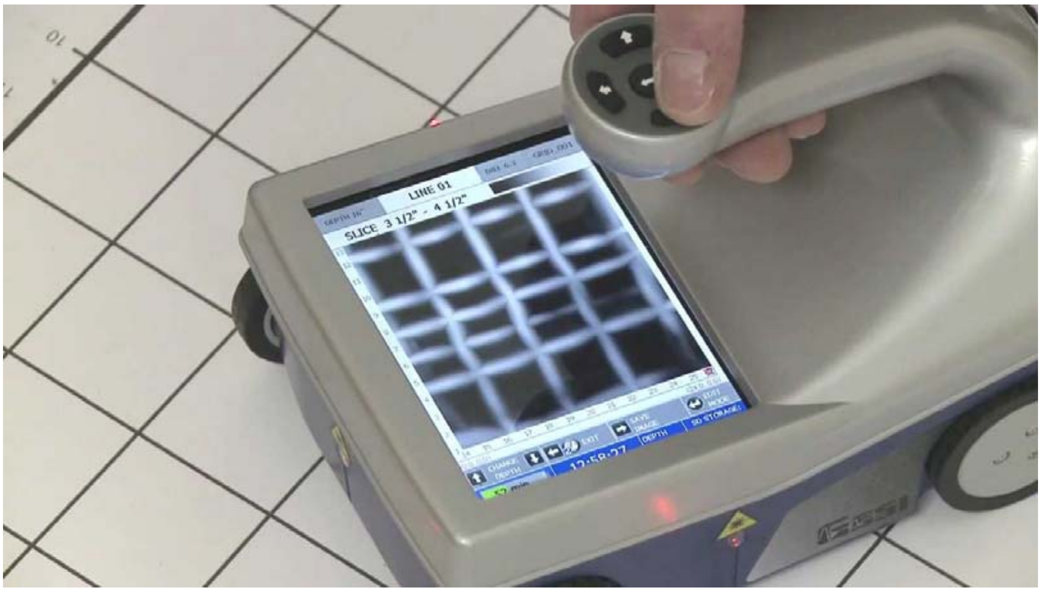

Figure 14 Image of the StructureScan Mini HR when performing a 3D scan (GSSI, 2013c)

The possibilities of evaluating the collected scan data does not end with the StructureScan Mini hardware, but it can also be processed with the help of computer software. Radan 7 is a Windows based post-processing for GPR data developed by GSSI. The software makes it possible to analyze both 2D and 3D data simultaneously, visualize the data and highlight important information.

3.1.1 2D scan

The StuctureScan Mini HR can be used in two different modes, 2D and 3D. When using the apparatus in 2D mode a b-scan is performed (GSSI, 2013c). However the information from an a-scan can be retrieved afterwards and with the help of the Radan software a c-scan can be created. Before starting a 2D scan the settings of the apparatus can be modified to the user’s preference, see figure 15. All setting can be modified post scan in both the apparatus and in Radan, except for the scan depth

Figure 15 Available settings on the StructureScan Mini HR before starting a 2D scan (GSSI, 2013c)

After choosing the desired setting the StructureScan Mini HR is ready to use and scan the desired object. A scan is performed by rolling the apparatus over the object. The apparatus measures the distance of the performed scan with the help of its wheels. To be able to register GPR data at least one of the wheels has to be moving during the scan.

3.1.2 3D scan

Performing a 3D scan is like performing two c-scans, one in the x-direction and one in the y-direction (GSSI, 2013c). The StructureScan Mini HR can only perform 3D scan in four predetermined grids, 30x30 cm, 60x60 cm, 100x100 cm and 120x60 cm. Before starting a 3D scan the setting can be changed to the user’s preference, see Figure 16, however scan depth and grid cannot be changed after the scans are performed. See Figure 17 for an example of a grid that used when performing a 3D scan.

Figure 16 Available settings on the StructureScanMini HR before starting a 3D scan (GSSI, 2013c)

Figure 17 3D scan is performed on a 60x60 cm grid (GSSI, 2013c)

4 Controlled environment testing

4.1 Test specimens

Tests in a controlled environment will help to evaluate the possibilities and limitations of both GPR as an investigation method and the used hardware. To perform these tests five concrete specimen have been cast.

4.1.1 Test specimen 1

Test element 1 is a 120x60x50 cm concrete cuboid. Different artefacts have been placed inside the specimen at different positions to create a testing environment where identification of different object will be performed. Also in the left part of the element, see Figure 18, an area has been created to test the 3D capability of the hardware.

Figure 18 The moulding form and the embedded artefacts of test specimen 1

4.1.2 Test specimens 2-5

Test specimens 2-5 are 50x50x8 cm concrete cuboids with two rebar placed in each. In two of the specimen rebar with the thickness of 16 mm in diameter have been placed and in the other two rebar with the thickness 8 mm in diameter, see Figure 19. The rebar in specimen 2-5 are all placed 25 mm from the bottom. The purpose of the elements is to be able to create structures with different layers

Figure 19 The moulding forms and the embedded artefacts of test specimens 2-5

4.2 Moisture

To investigate how different moisture content can affect the scan results, one of the 50x50x8 cm concrete test specimens, test specimen 2, was lower into water for 10 weeks. After the specimen was weighed and scanned it was put into an oven heated to 105 degrees Celsius. The specimen was then weighed and scanned twice with 4 days intervals. The results of the scans can be seen in Figure 20.

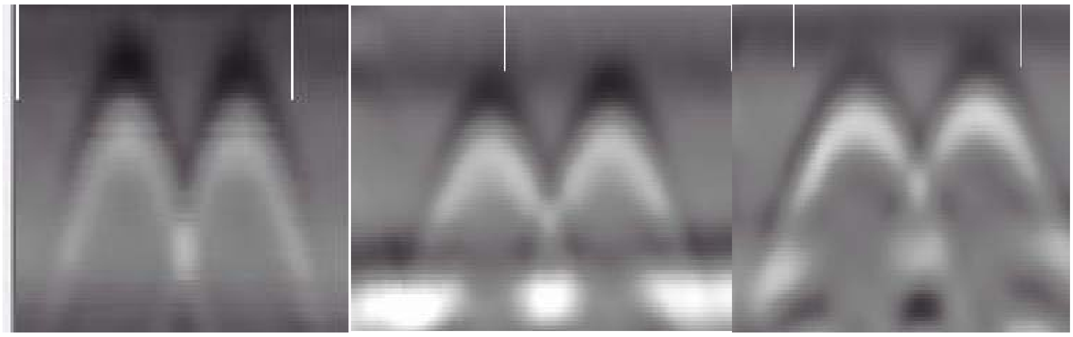

Figure 20 B-scans of test specimen 2, (left) after 10 weeks in water, weight 41,7 kg, (middle) after 4 days in an oven at 105 degrees Celsius, weight 40,7 kg, (right) after 8 days in an oven at 105 degrees Celsius, weight 40,0 kg

The scans show that a higher moisture content reduces the strength of the signal reflection. Also it can be seen that the shape of the hyperbola changes with the moisture content, lower moisture gives a rounder and wider hyperbola.

Moisture also has an impact on the scan results from test specimen 1, see Figure 21. The moisture content in test specimen is so high, which will attenuate the GPR signal and limit the penetration depth.

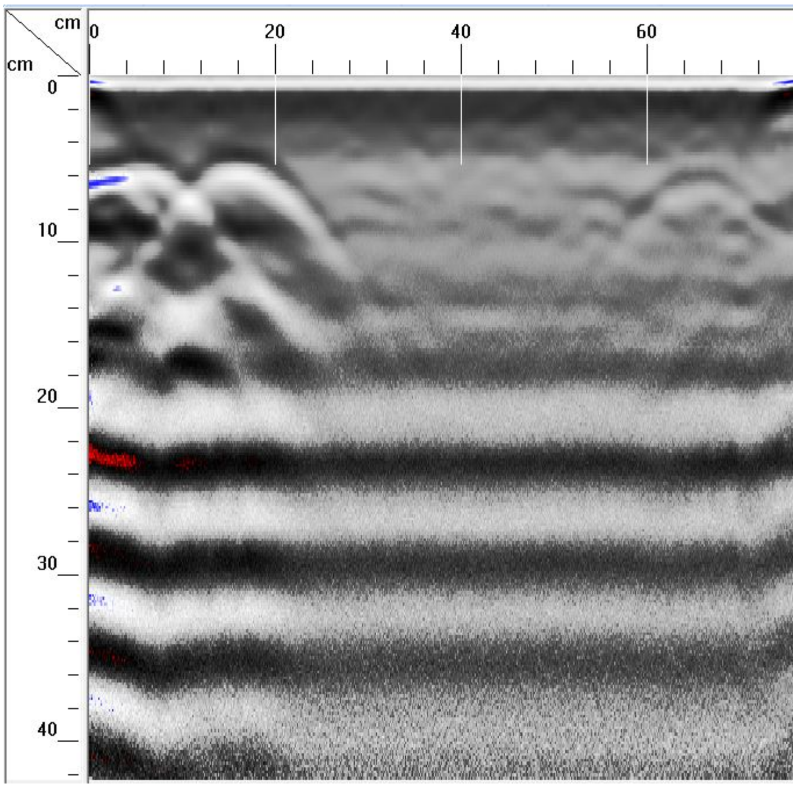

Figure 21 B-scan across test specimen 1

4.3 Identifying different artefacts

Numerous different artefacts have been embedded in the different test specimens, in Figure 22-27 the different artefacts are shown with the corresponding scan results.

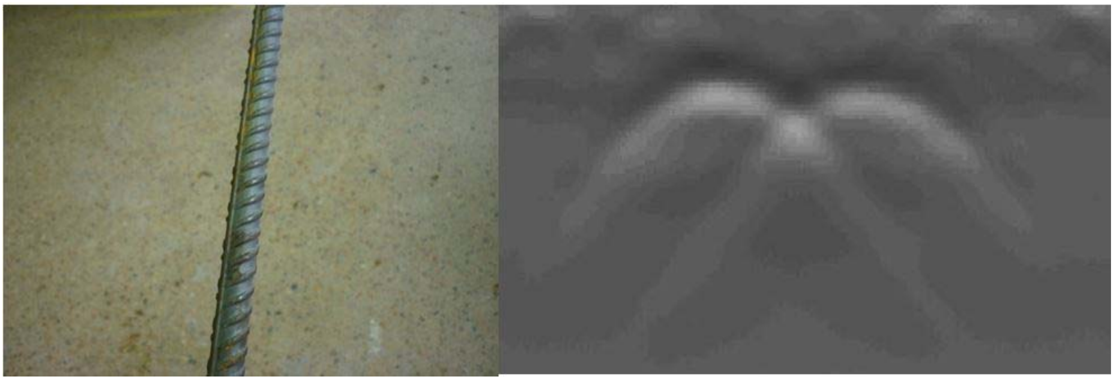

Figure 22 Rebar used in test specimen 1, diameter 16 mm, and its corresponding scan result, left hyperbola.

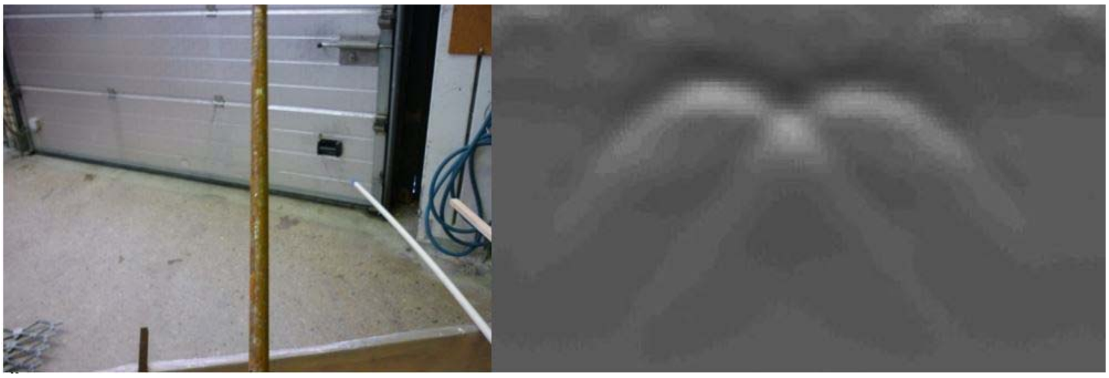

Figure 23 Metal rod in test specimen 1, diameter 12 mm, and its corresponding scan result, right hyperbola.

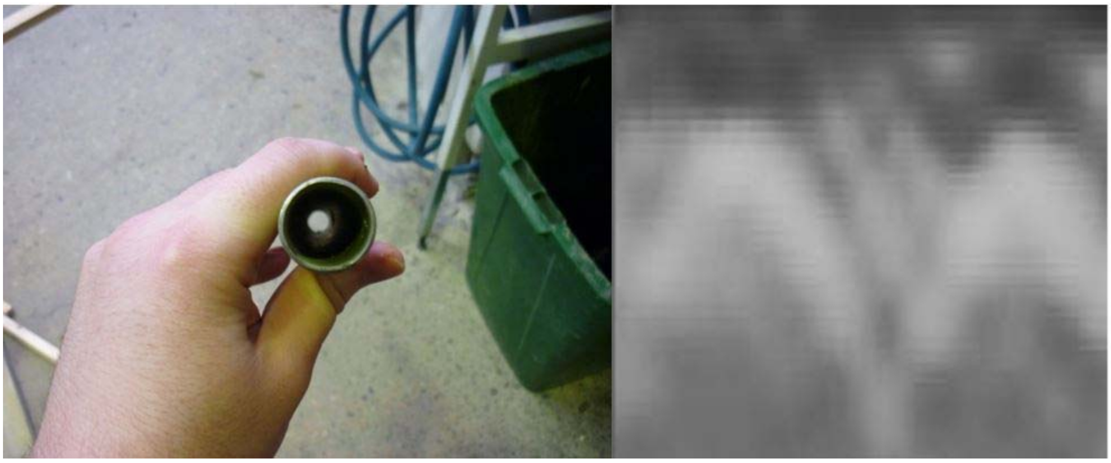

Figure 24 Metal pipe used in test specimen 1, diameter 27 mm, and its corresponding scan result, right hyperbola.

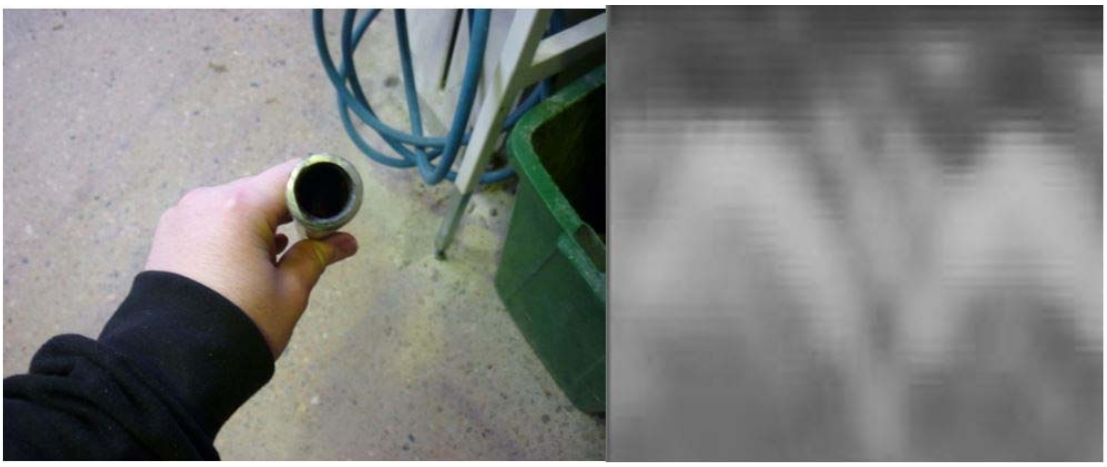

Figure 25 Metal pipe used in test specimen 1, diameter 24 mm, and its corresponding scan result, left hyperbola.

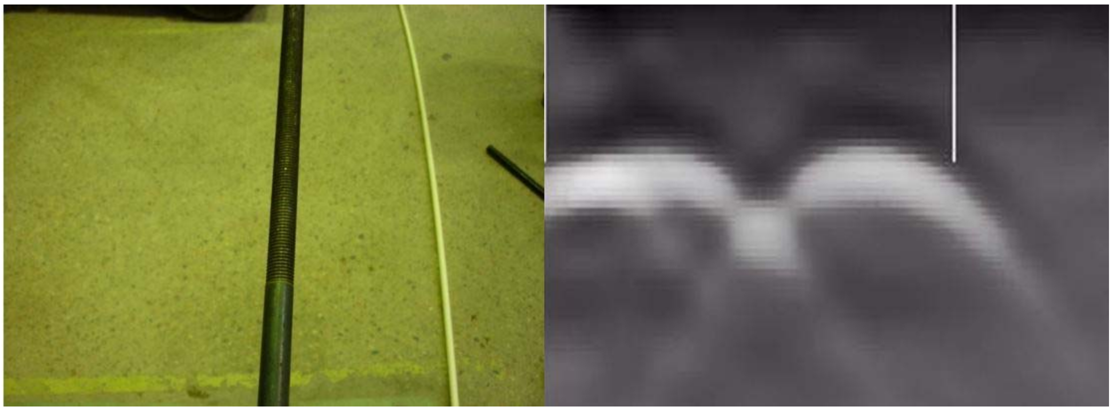

Figure 26 Metal rod used in test specimen 1, diameter 15 mm, and its corresponding scan result, both hyperbola show the same metal rod.

Figure 27 PVC pipe used in test specimen 1, diameter 20 mm, and its corresponding scan result

The results show that all the metallic artefact result in almost identical hyperbolas. The PVC pipe shows a result with a weak signal reflection and a phase inversion.

4.4 3D scan of test specimen 1

3D scans are useful when investigating more complex constructions. Figure 28-30 shows a rebar mesh, its location in test specimen 1 and the result of the 3D scan

Figure 28 Rebar mesh used in test specimen 1

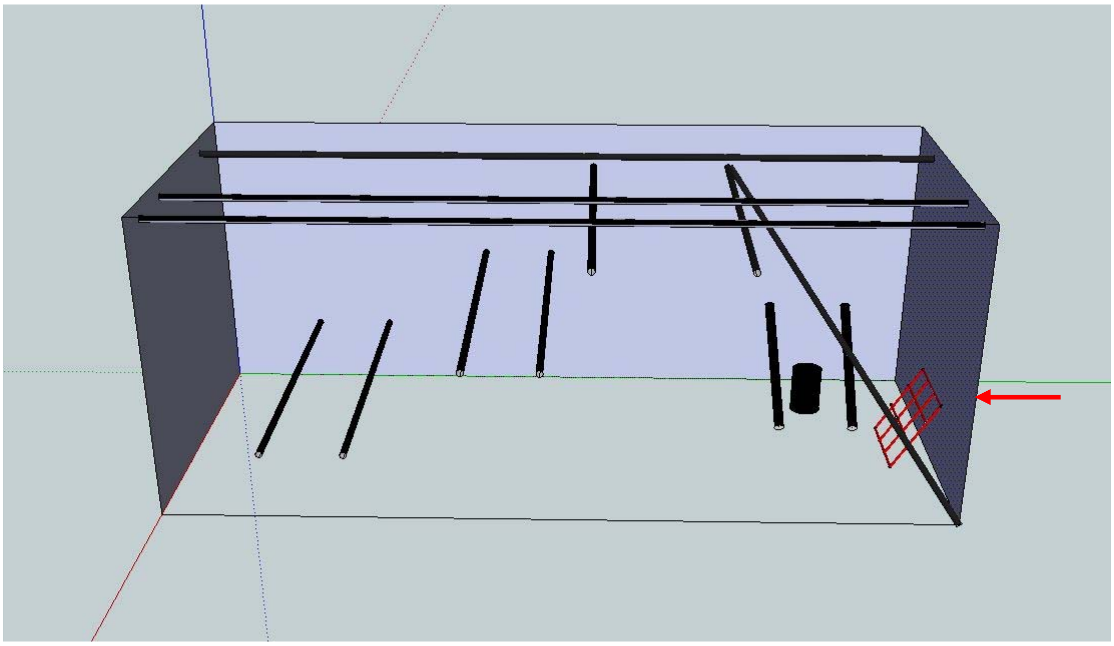

Figure 29 The position of the rebar mesh in test specimen 1. The arrow indicates the area where the 3D scan was performed.

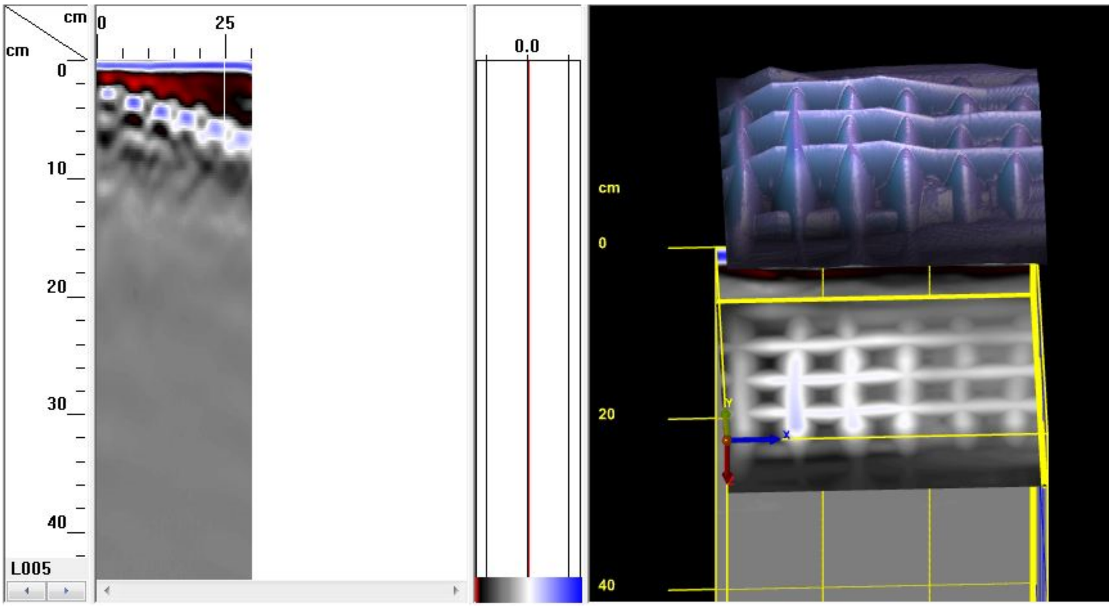

Figure 30 Results from the 3D scan of the rebar mesh

The 2D scan in Figure 30 show the inclined position of the rebar mesh, this cannot be intrepreted in the 3D scan due to the thickness of the displayed slice. By reducing the thickness and slicing at different depth a better view is acheived, se Figure 31-33

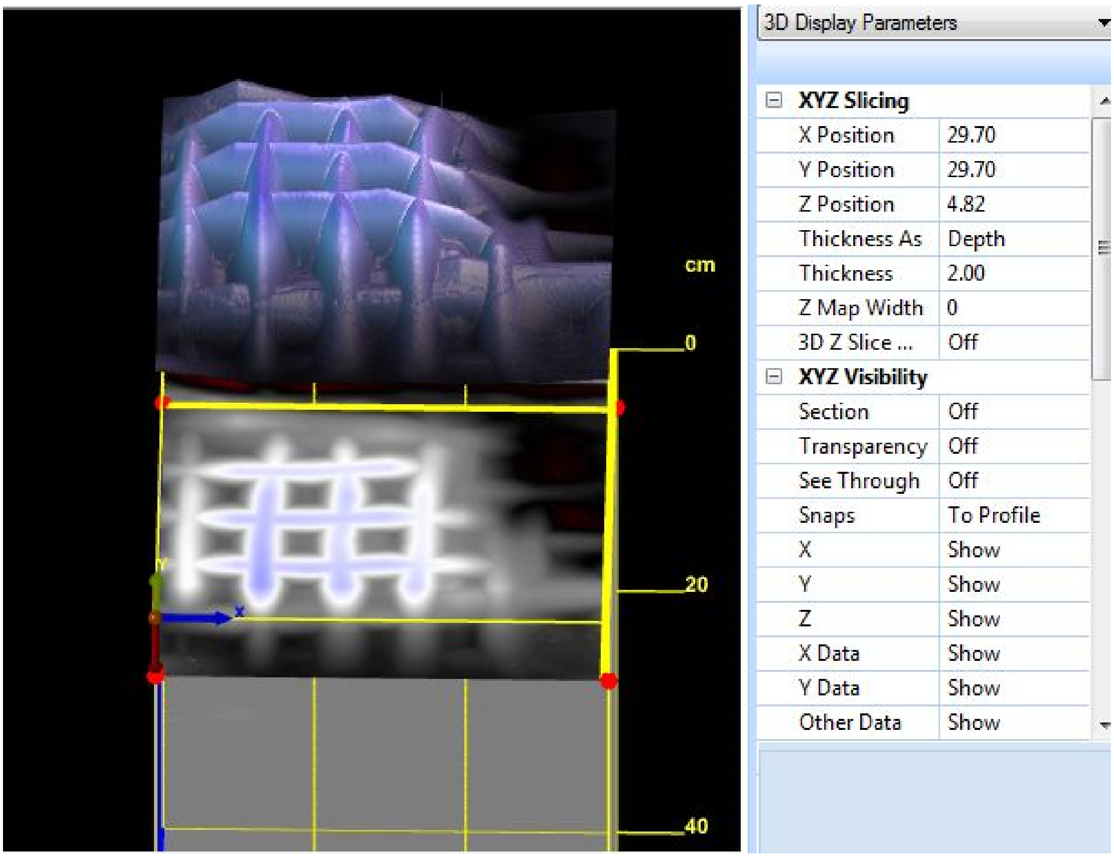

Figure 31 3D scan of the rebar mesh sliced at a depth of 4.82 cm

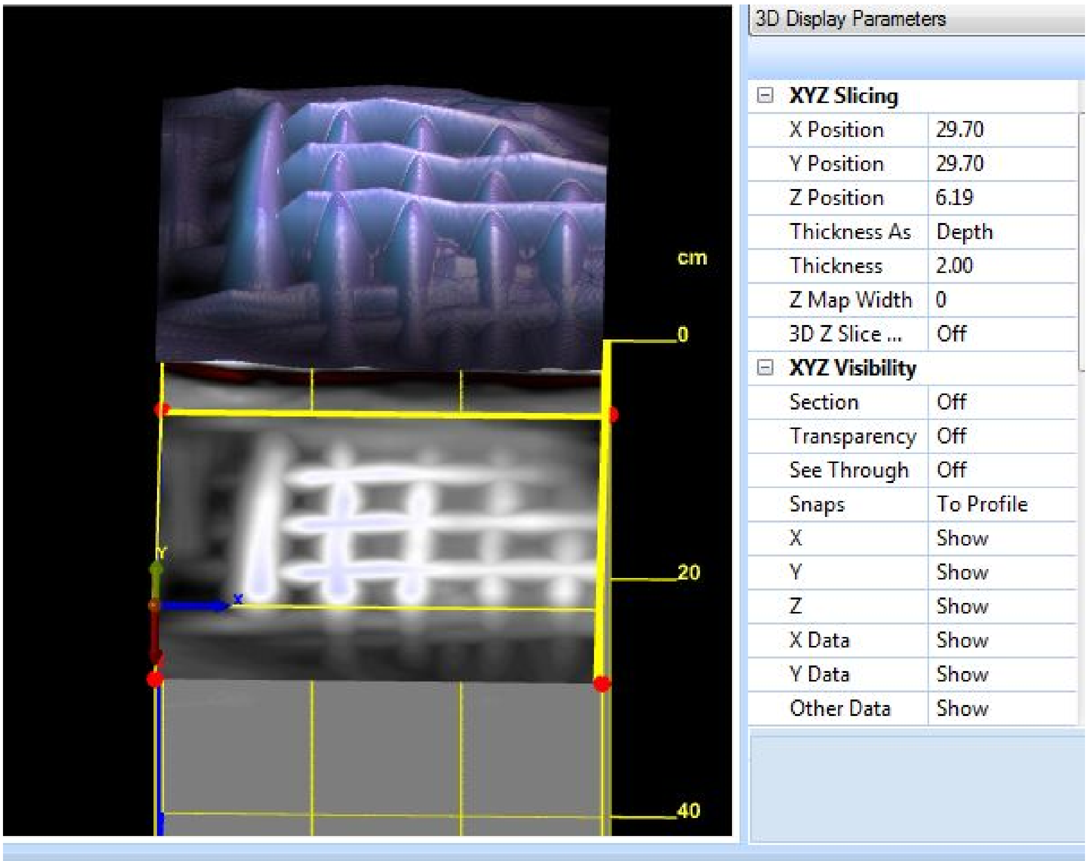

Figure 32 3D scan of the rebar mesh sliced at a depth of 6.19 cm

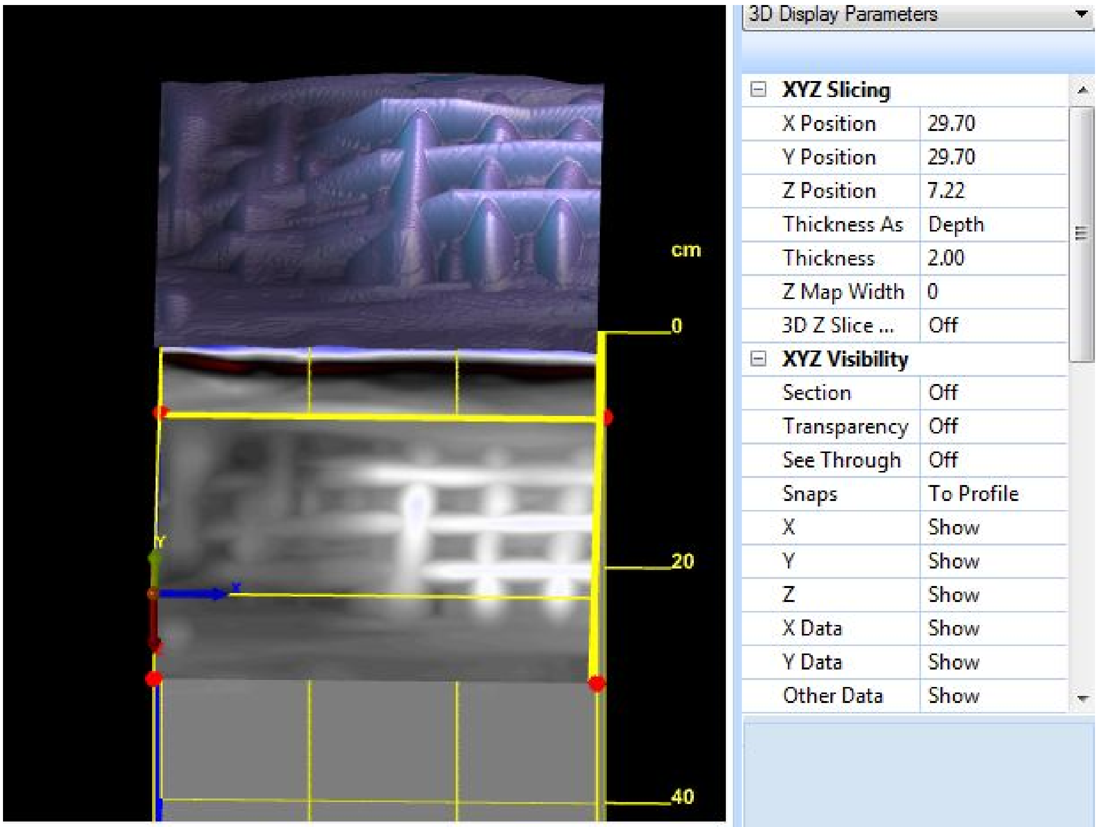

Figure 33 3D scan of the rebar mesh sliced at a depth of 7.22 cm

4.5 Measurement accuracy

According to GSSI, the StrutureScan Mini HR has a measurement accuracy of +/- 6,4mm. To evaluate the accuracy of this statement three of the test specimens 3-5 have been scanned, as the depth of the rebar are known. The results of the scan, see Figure 34, show that the depth measurements are within the acceptable margin of error.

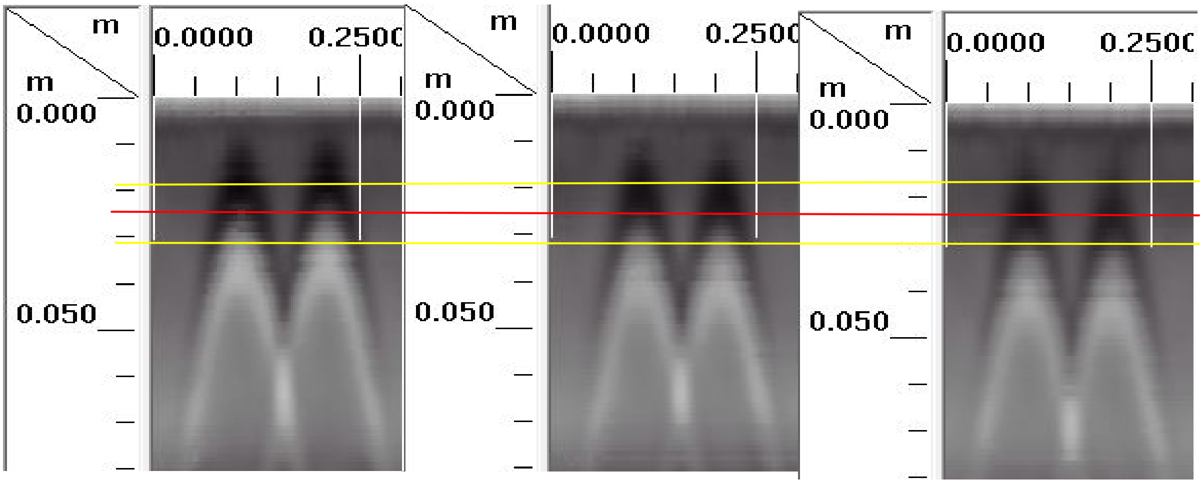

Figure 34 result of B-scan of test specimen 3-5. The red line indicates the location of the rebar, the yellow line indicates acceptable measurement error according to GSSI.

4.6 Difference in dielectric constant

A test specimen was created with layers consisting of different materials, a 3D model of the specimen can be seen in seen in Figure 35 and the scan result in Figure 36.

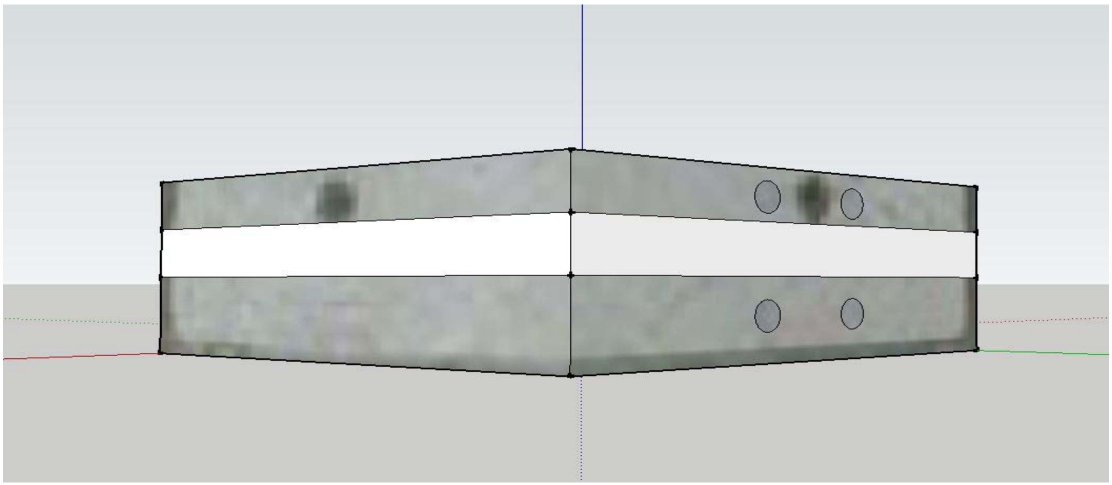

Figure 35 Sample created to imitate constructions with changes in the dielectric constant. The sample consist of 5 cm concrete in the top and bottom and 5 cm cellular plastic insulation in the middle

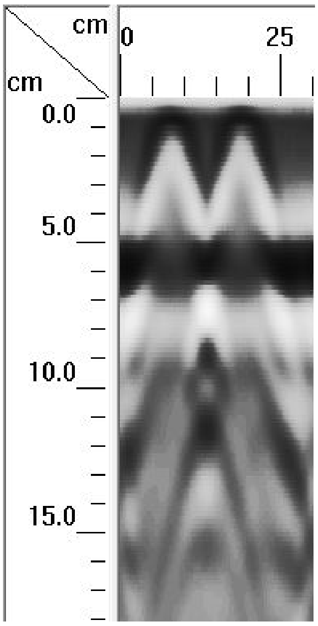

Figure 36 Scan result of the sample in Figure 34

The result show that the thickness of the different layers are incorrect in the scan. The dielectric constant is adjusted so the first layer of concrete will have an accurate thickness. This leads to an error in the thickness of the cellular plastic insulation, which has a thickness of 2 cm in the scan.

4.7 Void and crack detection

To simulate a crack, two concrete specimen are placed on top of each other, see Figure 37. The scan results are shown in Figure 38.

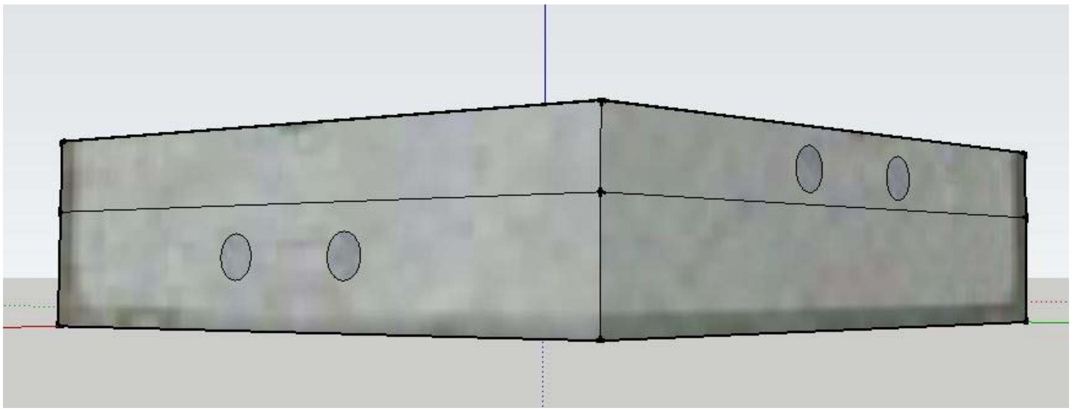

Figure 37 Sample created to imitate a crack in a concrete construction. The sample consists of a 5 cm concrete slab on top of an 8 cm concrete slab.

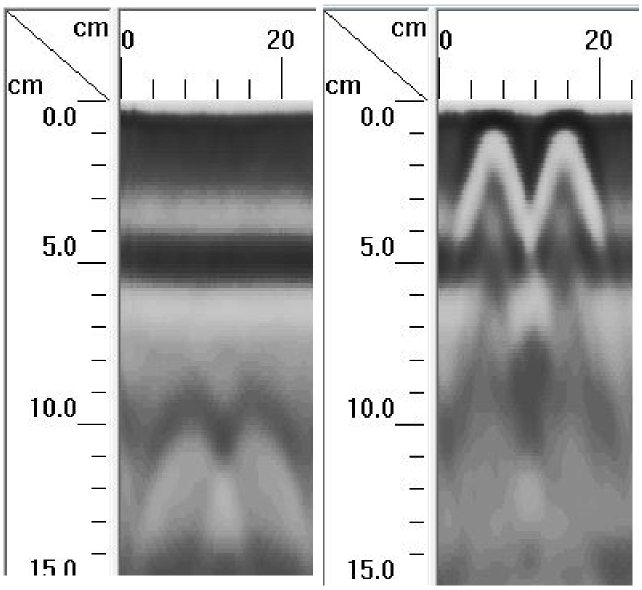

Figure 38 B-scan results from Figure 36

4.8 Discussion controlled environment testing

According to the theory in Chapter 2.9, to high moisture content can decrease the penetration depth and signal strength of GPR. This can clearly be seen in Figure 21, where the GPR is only able to penetrate about 15 cm, even though it is set to scan at depths up to 40 cm. The penetration is not affected when investigating test specimen 2, even after it has been stored in water for 10 weeks. However the specimen is only 8 cm thick and it is likely that the apparatus has enough signal strength to penetrate through it.

The relation between moisture content and signal reflection can also be seen in Figure 20, as the content decreases the reflection strength increases. Another aspect shown is the change in the shape of the hyperbola. When the content decreases the shape goes towards a rounder and wider shape. This change has actually to do with the fact that the results are displayed with the same dielectric constant. When the moisture content decreases the GPR signal is able to pass at a higher velocity, thus detecting the rebar at a distance farther away and giving it a wider shape. This property can possibly be used in field tests and show indications if certain construction elements have a higher moisture content.

Unfortunately, it was not expected that the moisture content could have such a drastically reduction in penetration depth. If this had been know earlier, the design of test specimen 1 would probably have been very different. Because of its large size it will probably take several years before scans can be performed at maximum scan depth. This has also led to very low quality data when scans has been made on test specimen 1. This can be observed in Figure 22-27, the data quality is very poor and it has been necessary to apply a linear gain of 20-60 to be able to see the hyperbola. Also only the artefacts embedded near the surface have been possible to investigate.

When it comes to identifying different artefacts, the results were pretty expected and confirm the theory in chapter 2.8. A limitation that GPR has, is to not be able to differ between objects that have a diameter or width smaller than 1 wavelength, in this case

4.5 cm. The ability to differ between different object would probably been very useful when mapping reinforced concrete structures.

GPR can under the right condition be a very precise when measuring the depth of embedded reinforcement. If an accurate dielectric constant can be determined the measurement can be more precise than the error margin stated by GSSI as +/- 6,4mm, which can be seen in Figure 34. This is although not so surprising as GSSI’s value probably has some margins of safety. However if the conditions are not so favourable and the object being scanned does not consist of a homogenous material, the results of the scan can be very flawed. This scenario is mentioned in Chapter 2.9 as one of the limitations to GPR. An example of this scenario can be seen in Figure 36. The thickness of the cellular plastic insulation is displayed as 2 cm, when its real thickness is 5 cm. Because the difference in the dielectric constant of concrete and cellular plastic insulation is so large the data cannot be displayed so it gives a fair image of the different layers at the same time, therefore GPR cannot be used to measure depth in inhomogeneous construction elements.

Detecting voids and cracks in concrete is of great importance, as they can indicate the existence of corrosion and delamination. To simulate a crack two concrete specimens were stacked and the small air layer between them should represent the existence of a crack. The fabricated crack was detected by the GPR and is shown as a phased inversed layer with a strong reflection, confirming the theory in chapter 2.8. The sized of the crack cannot be measured and in the thickness of the air layer is 2 cm, which in reality was about 1-2 mm.

5 Field tests

5.1 Field test 1 – Jungmansgatan 55

The main objective of this project was to investigate remediate and protective measures for parking slabs and vertical elements for the case when chloride ingress was present but did not progress to the reinforcement and did not cause damage by corrosion. There are today no proven and cost efficient methods to reduce the chloride concentration and protect against further chloride ingress in concrete. To replace the old concrete with new is both economically and environmentally unfavorable. A treatment was tested under site conditions, in a lab study and its effectiveness as a treatment method evaluated.

As a part of the study a damage investigation was performed on the garage at Jungmansgatan 55 in Gothenburg, see Figure 39. The parts presented below are a part of the damage investigation, however only parts relevant to the GPR investigation will be included.

Figure 39 Picture taken outside of Jungmansgatan 55

5.1.1 Problem Description

Deicing of salts are a major problem for residential parking garage and cause enormous damage to the concrete and reinforcement. Snow, which contains deicing salts, is accumulated in the wheelhouses of cars and brought in to the parking garages. If the concrete structure does not have a drainage system of the concrete is not protected, the chlorides will start to penetrate the concrete elements. When the chloride has reached a certain penetration depth and concentration the rebar start to corrode and the structural integrity might be at risk, see Figure 40

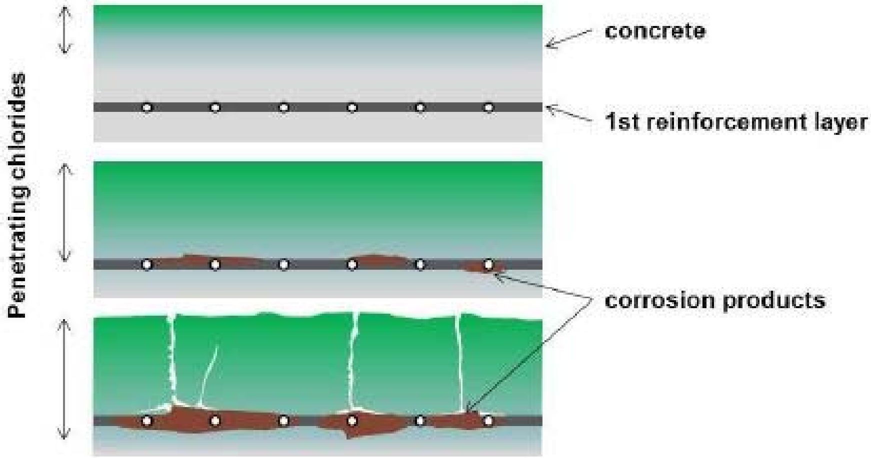

Figure 40 Scheme of corrosion by penetration depth of chlorides (CBI, 2013)

5.1.2 On-site investigation

The garage consists of a two level underground garage, where each level has a separate entrance. The lower level of the garage was in much better condition than the upper level. On the upper level reinforcement corrosion was found on many vertical elements and rust stains were visible, see Figure 41. A 5 mm bituminous layer strip was applied perpendicular to the driving strips, where it was observed that water was accumulating along the edges, see Figure 42.

Figure 41 Column, located in the upper level, showing rust stains and corrosion cracks.

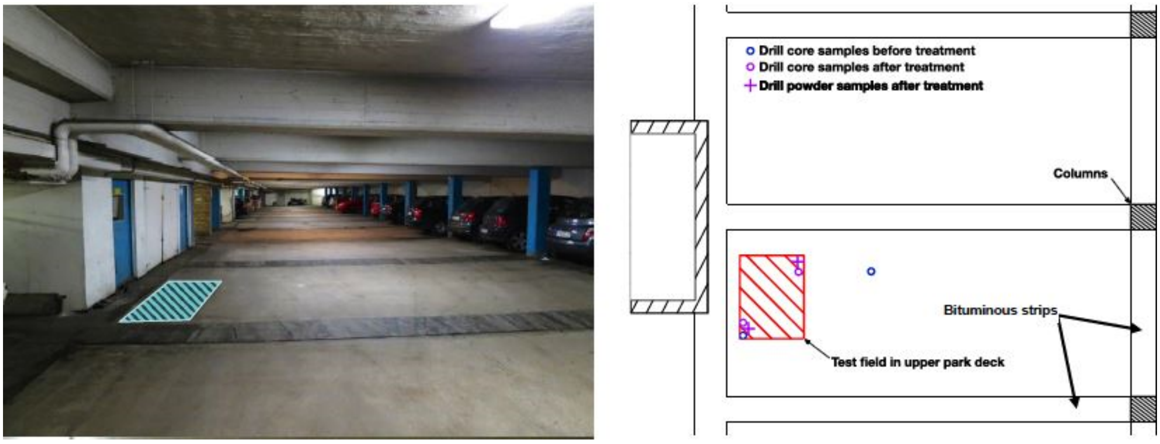

Figure 42 The position of the sample area and the drill core samples(CBI, 2013)

5.1.3 Laboratory investigation

Drill core and drill powder samples were collected during the onsite investigation to measure the chloride content and the carbonization depth. The results of the chloride analysis on the upper deck can be seen in Figure 43. The maximum measured level measured was 4,8 mass-% and the other samples show a result of levels over 3 mass-%.

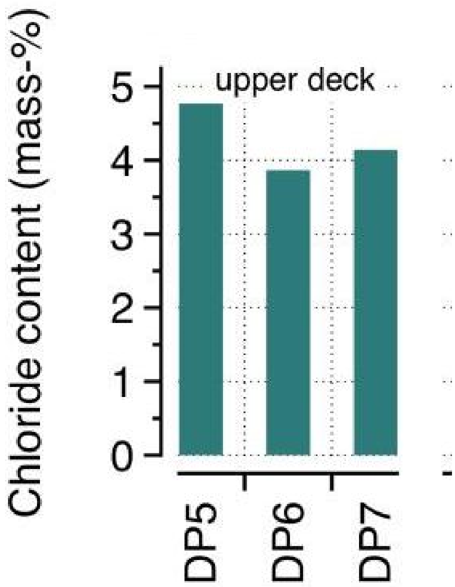

Figure 43 Chloride content in the three samples from the upper deck (CBI, 2013)

In three of the drill cores there were samples of the reinforcement, which show that the depth of the first level is between 50 and 90 mm. In two of the samples there was strong corrosion on the reinforcement, see Figure 44.

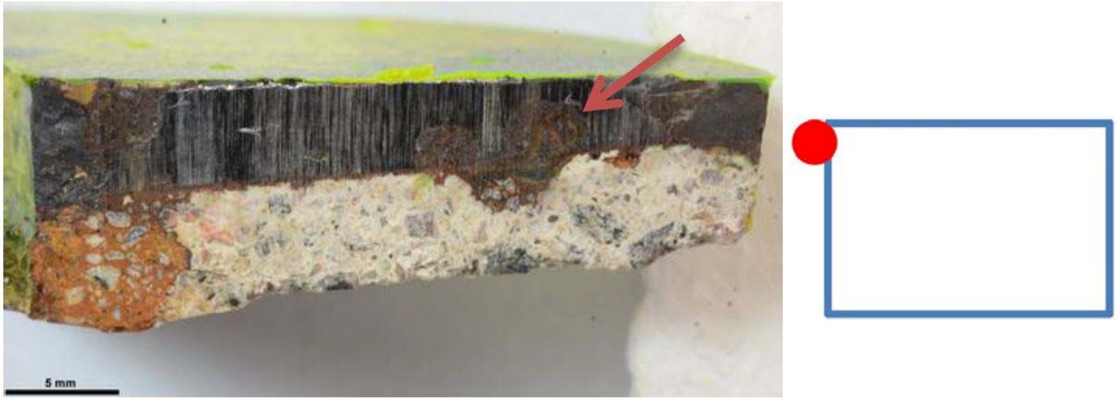

Figure 44 Cross-section of rebar embedded in a collected drill core from the upper level. The position of the drill core relative to the sample area can be regarded at the image to the right (CBI, 2013)

5.1.4 Half-cell potential measurement

To evaluate the risk of corrosion a half-cell potential measurement was performed. The method measures the negative charge and an increased risk of corrosions is encountered when the measurements reaches values below -250 mV, see Figure 45 for the results of the half-cell potential measurement. The measurement shows that there are locations with very high negative values and high probability of corroded reinforcement. The drill core with corroded reinforcement in Figure 44 is extracted just outside of the upper left corner, indicating that this area is severely corroded.

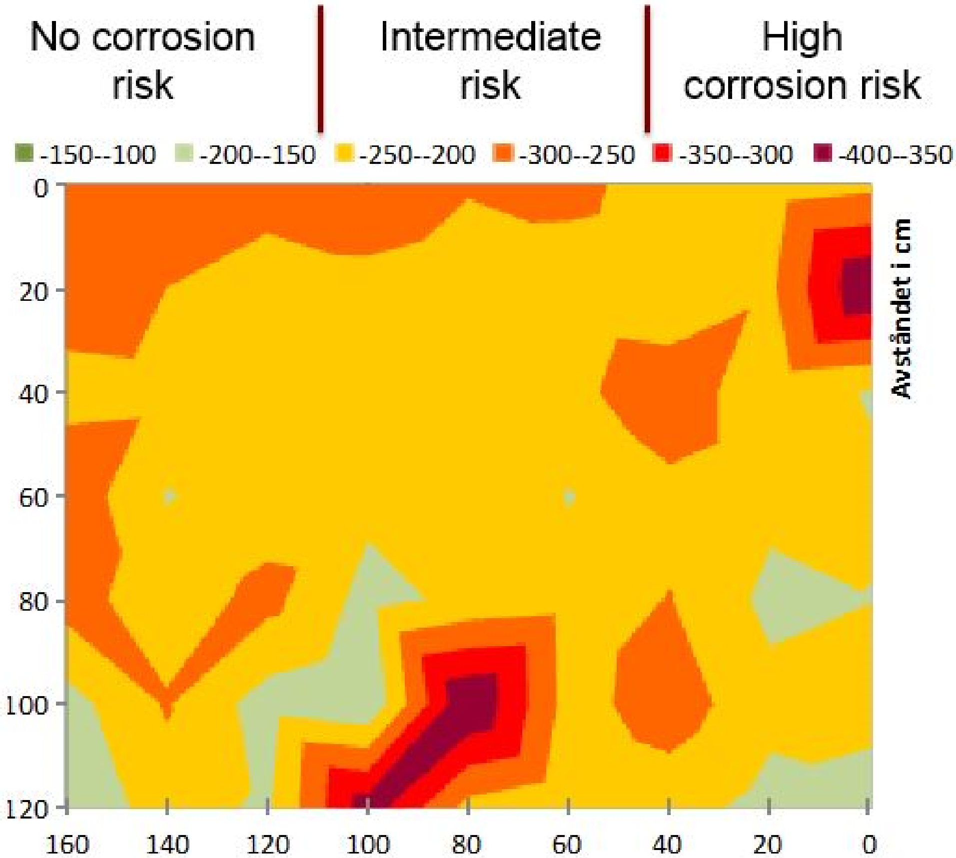

Figure 45 Result of HPC test on the sample area (CBI, 2013)

5.1.5 GPR investigation

A 3D scan was performed on the upper left part of testing area. The location and results of the can be seen in Figure 46-48

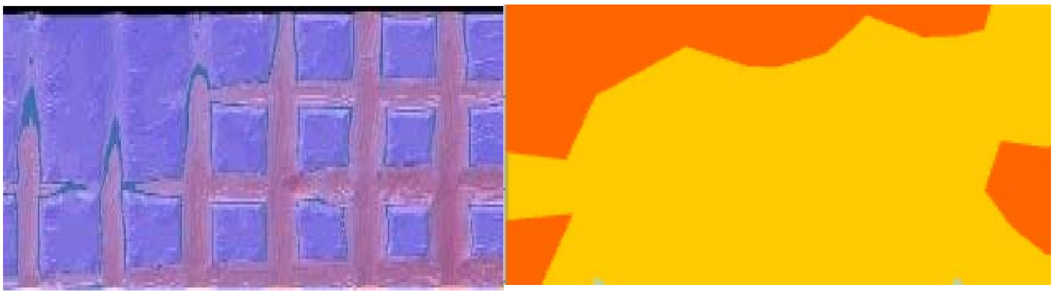

Figure 46 Results of GPR (right) and HPC (left)measurement of the same position

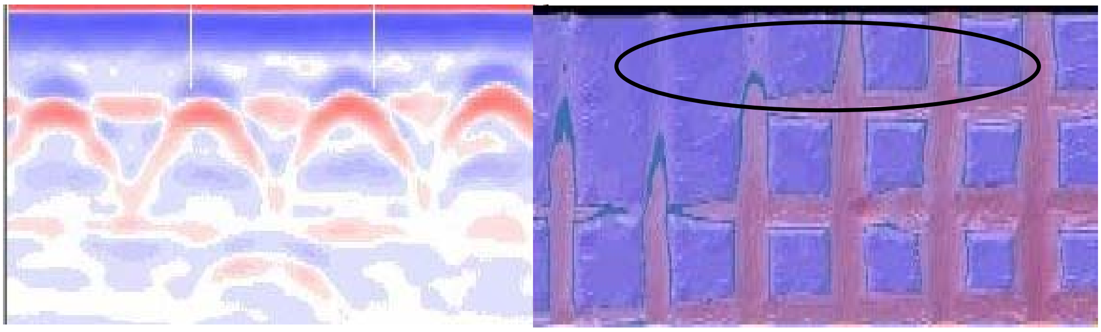

Figure 47 B-scan of the highlighted in the 3D scan

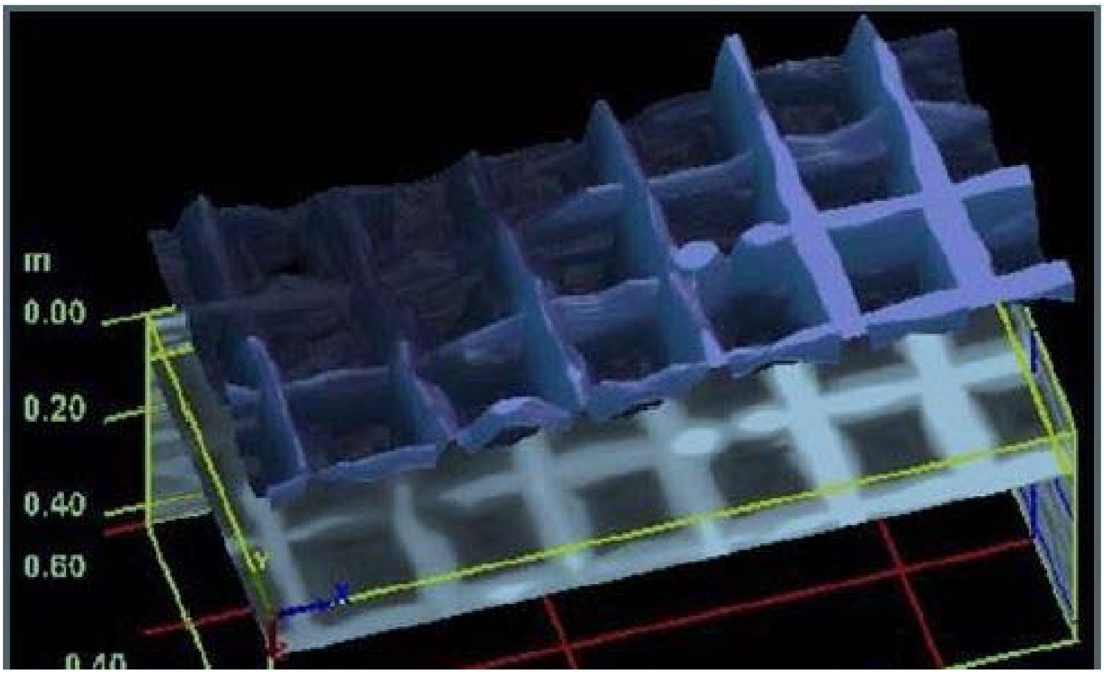

Figure 48 3D image showing the intensity of the reflected amplitude

5.2 Field test 2– Ivargårdsgatan

Ivargårdsgatan is a residential area in Kungsbacka with 289 apartments, which was built between the year 1983 and 1987, see fig 49. The area was projected and built by Aranäs Fastigheter, who also is the proprietor at the moment.

Figure 49 Apartment buildings at Ivargårdsgatan, Kungälv

However the residential area have problems with the condition of their balconies and want to investigate the extent of the damage and which measurements are need to extend their life length.

The entire case will not be included in this report, as it is not relevant for this study. The parts that will be include short summaries of the on-site investigation and laboratory investigation, thereafter more detailed description of the GPR investigation.

5.2.1 On-site investigation

The construction of the balconies is not favorable when it comes to protecting the concrete slab from different weather conditions. The slab is unprotected from rain and as can be seen in Figure 50, the balcony plates are placed in the inside of the edge of the concrete slab and will lead the rainwater directly onto the edge. This exposure will raise the relative humidity of the concrete and raise the carbonization rate of the concrete.

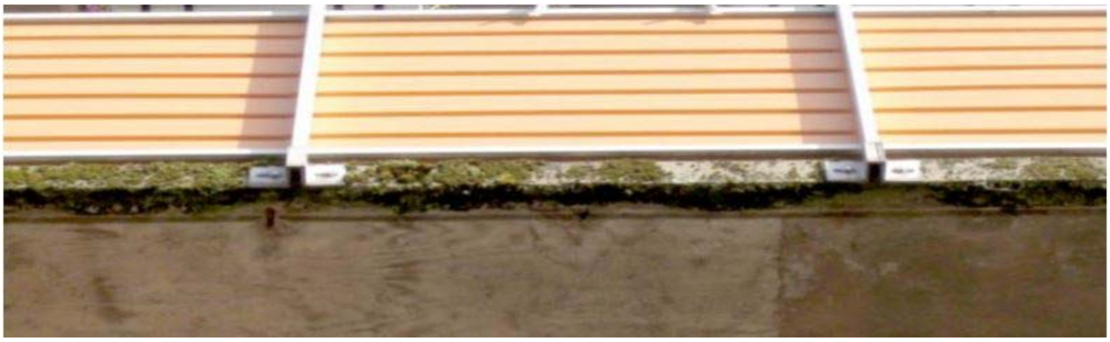

Figure 50 Image showing the construction of the balcony plates

Another consequence of the unprotected concrete slab is the hefty growth of moss on the edges, which will create and acidic environment and speed up the concrete deterioration and rebar corrosion. Corrosions that has already started and can be seen in Figure 51 and 52

Figure 51 Corrosion crack found on the underside of a balcony

Figure 52 Corroded rebar on the underside of a balcony at Ivargårdsgatan

5.2.2 Laboratory investigation

To investigate the carbonization depth and chloride concentrations two concrete samples were collected from two balconies, one on the ground floor and one on the 1st floor. The results of the laboratory test can be seen in Table 2-3.

Table 2 Carbonization depth of the investigated balconies.

Carbonization depth (mm)	Average	Max
Bottom floor topside	7	15
Bottom floor underside	15	19
1st floor topside	8	15
1st floor underside	17	22

The carbonization depth on the underside is on average double that on the topside. If either of these depths is an issue at the moment depends on how thick the concrete cover is. If the cover is smaller than the depth of the carbonization, there might be problem with corrosion.

Table 3 Chloride content of the investigated balconies

Chloride content (mass-%)	Topside (Bottom floor)	Top side (1st floor)
Depth 0-20 mm	0,07	0,07
Depth 20-40 mm	0,05	0,05
Depth 40-60 mm	0,03	0,04

The chloride content is at a very low level and cannot be considered an issue in this case.

5.2.3 GPR investigation

The GPR investigation is performed on the same balconies as the samples from the laboratory investigation were taken. The main purpose of the investigation is to determine the average concrete cover on top of the rebar, but also to look for other issues in the concrete such as voids and cracks. To achieve these goals 3D scans were performed on the topside of each balcony and 2D on the underside. No 3D scans were performed on the underside mainly because of time constraint and unfortunate weather conditions. As the day of the investigation was a very windy and rainy day there was no possibilities attach the 3D grid in the underside of the balconies. Even to perform 3D scans on the topside proved to be a challenge and took considerably more time than it would under good conditions.

The 3D scan on the topside were performed on the outer half of the balconies and can be seen in Figure 53 for the balcony on the bottom floor and Figure 54 for the 1st floor. No voids, crack or other anomalies could be detected in the 3D scans; however the scans show the placement of the rebar and how the balcony is constructed.

The 3D scans, Figure 53 and 54, are processed with time-zero and the hyperbolas have been removed by migration, to give a clearer picture of the rebar and their location. The images are also displayed with contour to help improve the presentation.

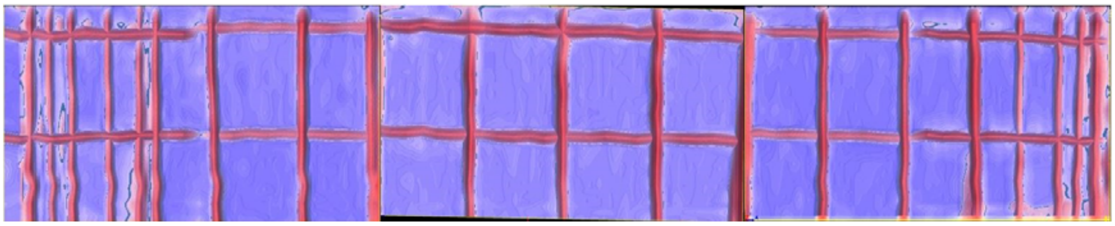

Figure 53 Results of 3D scans, 1st floor

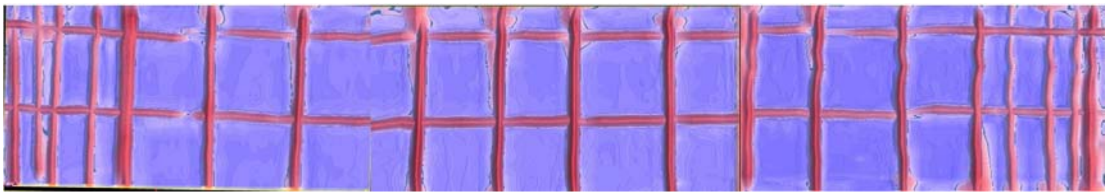

Figure 54 Results of 3D scans, bottom floor

The average concrete cover is calculated with help of the performed 2D scans but also with the 2D scans that are performed when doing a 3D scan. For the calculation to be as precise as possible, an appropriate dielectric constant has to be determined. This is done by processing the scans so that the end of slab in the scan has the same value as the thickness of the slab, which is 15 cm. A processed 2D scan can be seen in Figure 55. The result of the average concrete cover can be seen in table 4

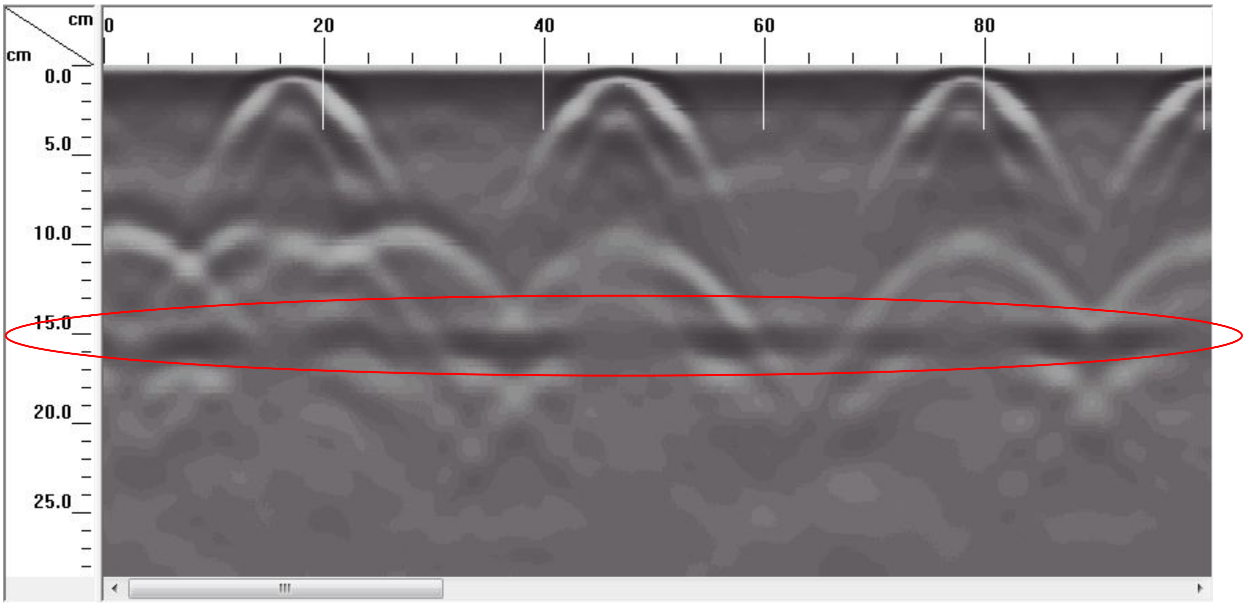

Figure 55 2D scan of the bottom floor balcony, the end of slab is highlighted in the Figure.

Table 4 concrete cover topside and underside of the investigated balconies.

Concrete cover (mm)	Average	Minimum
Bottom floor topside	22	8
Bottom floor underside	11	5
1st floor topside	22	10
1st floor underside	12	5

When comparing the concrete cover thickness and the carbonization depth, there can be seen the average values on the topsides of the balconies should not be an issue. However on the undersides of the balconies, the average carbonizations depth is deeper than the average concrete cover. There is a high possibility of corrosion on the rebar, a possibility that is reinforced by the visual inspection, see Figure 52.

However the average values do not give us a complete image, as there are worst case scenarios. The minimum value of the concrete cover on the topside of both balconies is lower than the maximum carbonization depth. As the GPR scans maps the depths of each individual rebar the problematic areas can easy be visualized, see Figure 56 and 57.

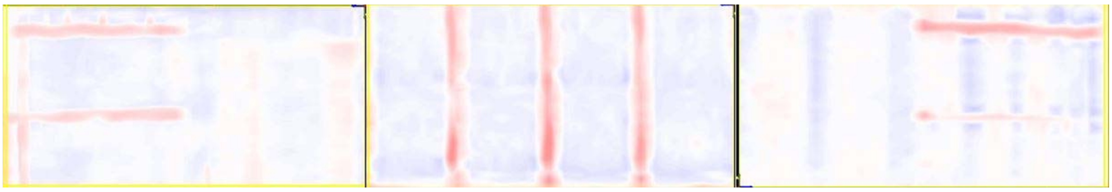

Figure 56 Rebar located at a depth of 15 cm or less, bottom floor

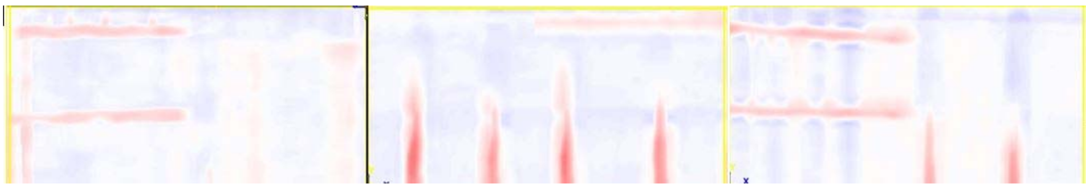

Figure 57 Rebar located at a depth of 15 cm or less, 1st floor

The scans above are both sliced at 15 mm depth, maximum carbonization depth, and show that there is a risk that the carbonization depth may have reached rebar on the topsides of the two balconies. This might mean that some of the rebar are corroded or have started to corrode.

Figure 56 and 57 are untouched scans, except for time-zero which is necessary to achieve a correct depth of the rebar. The difference in color is mainly because to filter out distortions through visualization and not by changing the signal.

5.3 Field test 3 – Lisa Sass gata

The three storey garage at Lisa Sass Gata was built during the 1970s with prefabricated elements and has been used as a car park for the residents in the area since then. During the 1990s the mid storey of the car park was rented by the police department and transformed into a heated garage. However ever since the police department stopped using the mid storey has been unused and left to decay. The proprietor Göteborgs Stads Bostadsaktiebolag are now performing a status investigation to decide the future of the garage. The purpose of the investigation is to evaluate the damage extent and the remaining lifespan of the building. If the building is in good condition there is an interest from the proprietor to investigate the possibility of building additional stories.

5.3.1 GPR investigation

As a part of the status investigation the GPR has been used to examine the thickness of the concrete cover and to map concrete elements. To perform the examination with high accuracy a proper dielectric value has to be determined. With the help of existing drill core holes, the thickness of the floor slab could be measured and a dielectric constant of 6,5 be determined.

5.3.2 Concrete cover thickness

The concrete cover thickness has been calculated for both the floor elements and the wall/column elements of the building, the results can be seen in table 5.

Table 5 Average concrete cover of column/wall and floor elements

Concrete cover (mm)	Average
Column and wall elements	30
Floor elements	38

5.3.3 Reinforcement mapping, Column

As the there is an interest in building additional expansion to the existing building, the knowledge of how the existing elements are constructed is highly valued. To map the columns, 3D scans were performed on each side of the column, se figure 58.

Figure 58 Performing 3D scans on column

However as only the 30x30 cm grid could be used the information provided by 3D scan were not sufficient as they did not provide a good overview of the reinforcement in the column. To achieve a better view of the reinforcement in the column onsite mapping was necessary and the position of each rebar was marked on the construction. With the help of the onsite mapping a 3D image could be created column and the position of the reinforcement, see Figure 59

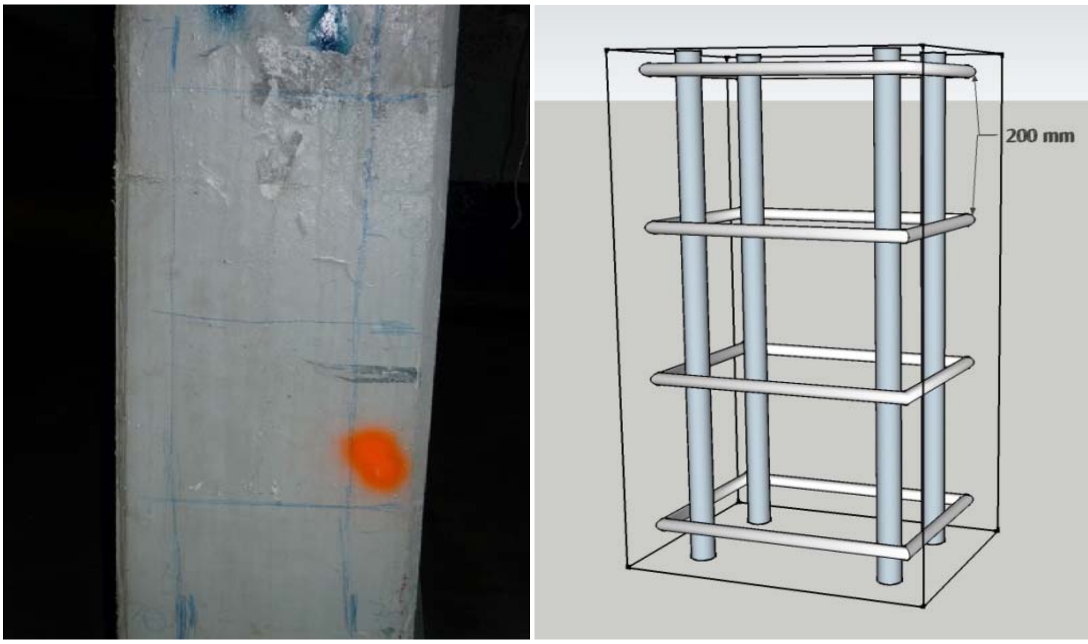

Figure 59 Markings from the onsite mapping of the column, a 3D model of the result from the onsite mapping

5.3.4 Reinforcement mapping, floor element

The mapping of the floor element is more complex and both 3D and onsite mapping had to be used to map the position of the reinforcement. In Figure 60 and 61 the element can be seen onsite and in a 3D model.

Figure 60 Onsite images of the floor element

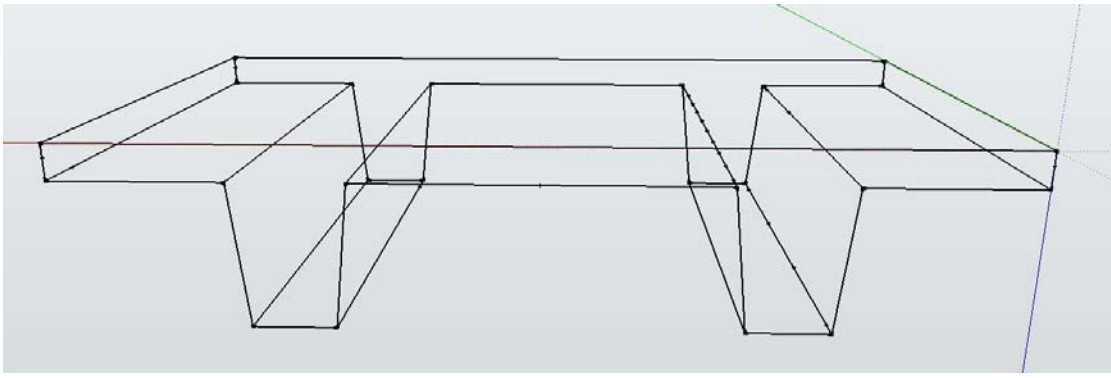

Figure 61 3D model of the floor element

Two 3D scans were performed from the topside of the element. The results of the 3D scans can be seen in Figure 62 and 63. The scans show that there are at least two layers of reinforcement. The first layer at a depth of 3 cm and the second layer at depth of 6 cm.

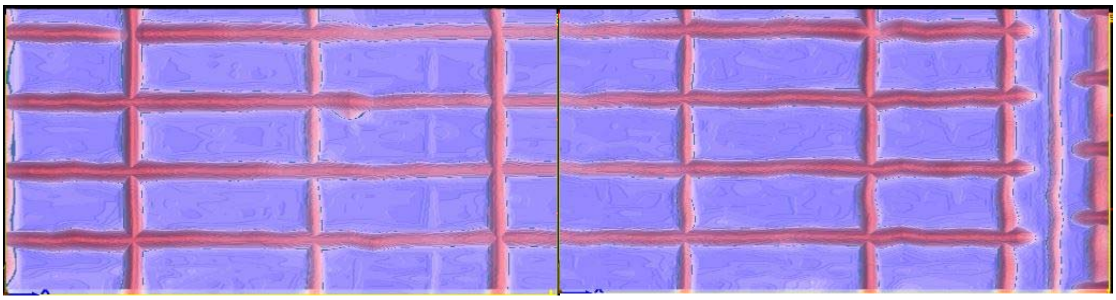

Figure 62 Results from 3D scans, topside. The image is sliced at 3 cm depth with a layer thickens of 1cm.

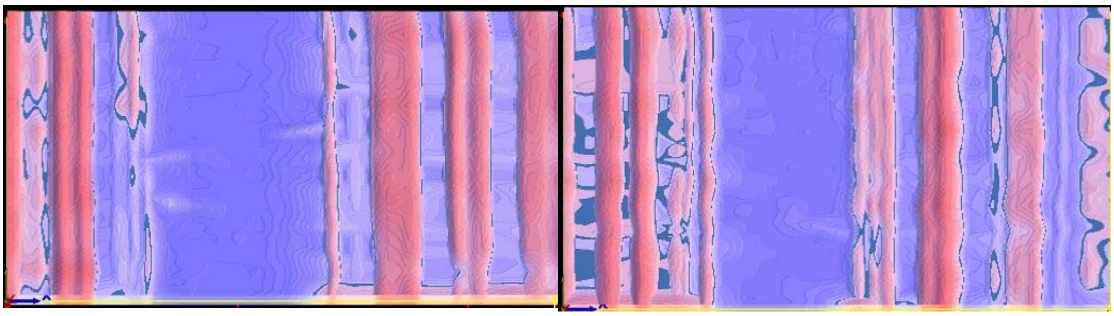

Figure 63 Results from 3D scans, topside. The image is sliced at 3 cm depth with a layer thickens of 1cm.

In the second layer of reinforcement there are uncertainties regarding the number of rebar. The results in Figure 63 some that in certain positions there is only one thicker rebar and in other positions there are two rebar very close together. This is also shown in the 2D scan of the same layer of reinforcement, see Figure 64, and were the absence of distinct hyperbolas creates uncertainties. In Figure 65 the two layers of reinforcement are added to the 3D model.

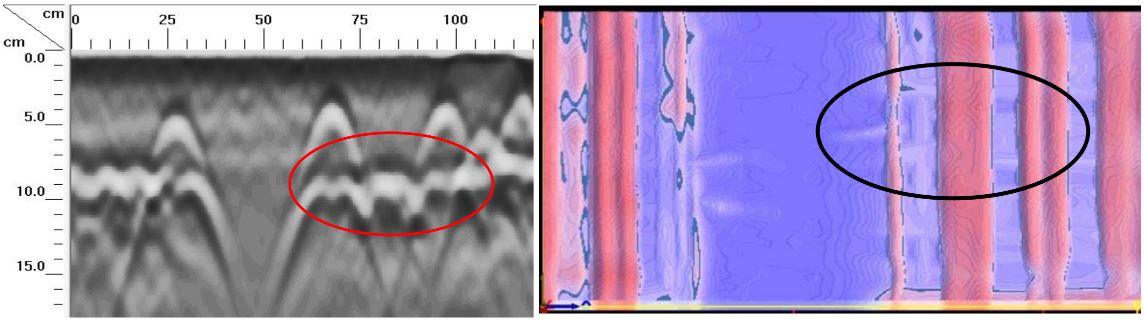

Figure 64 B-scan over

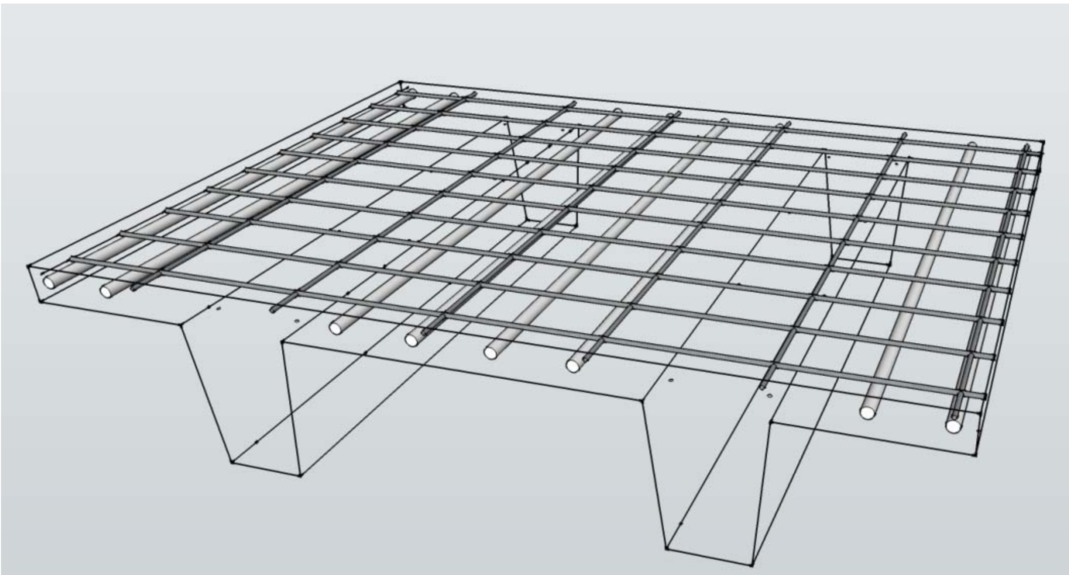

Figure 65 3D model based on the results from mapping the topside

The underside of the element is mapped onsite as the available grid size for 3D scans did not match the areas interesting for investigation. The result from mapping the underside of the element can be seen in Figure 66. In Figure 67 a consolidated 3D model is seen from the mapping results from the topside and the underside

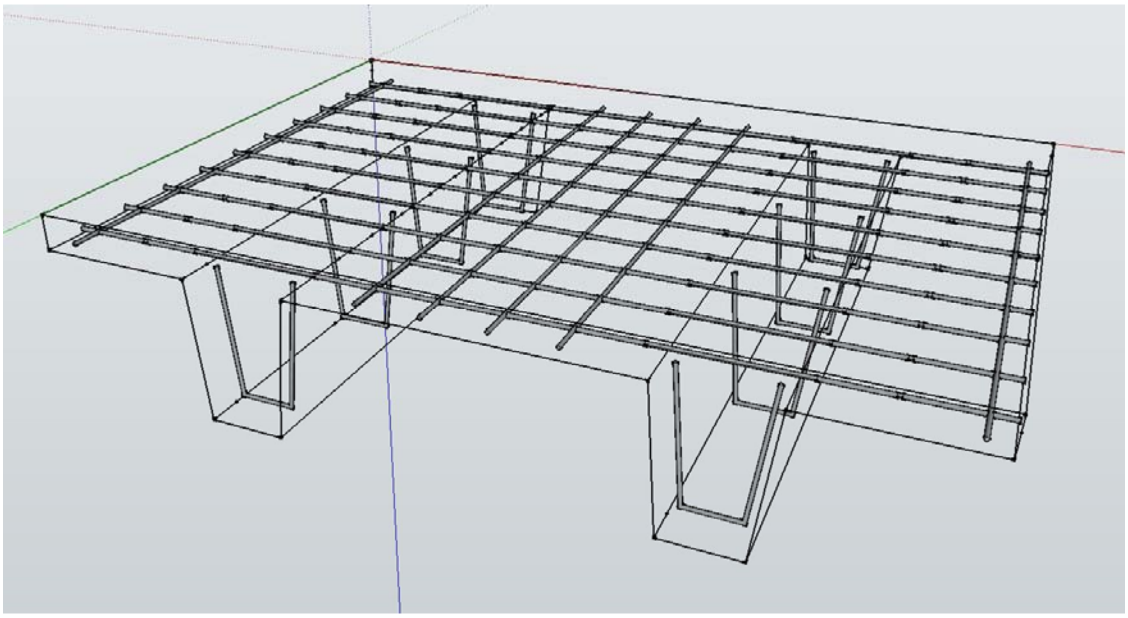

Figure 66 3D model created with the results from mapping the underside of the floor element.

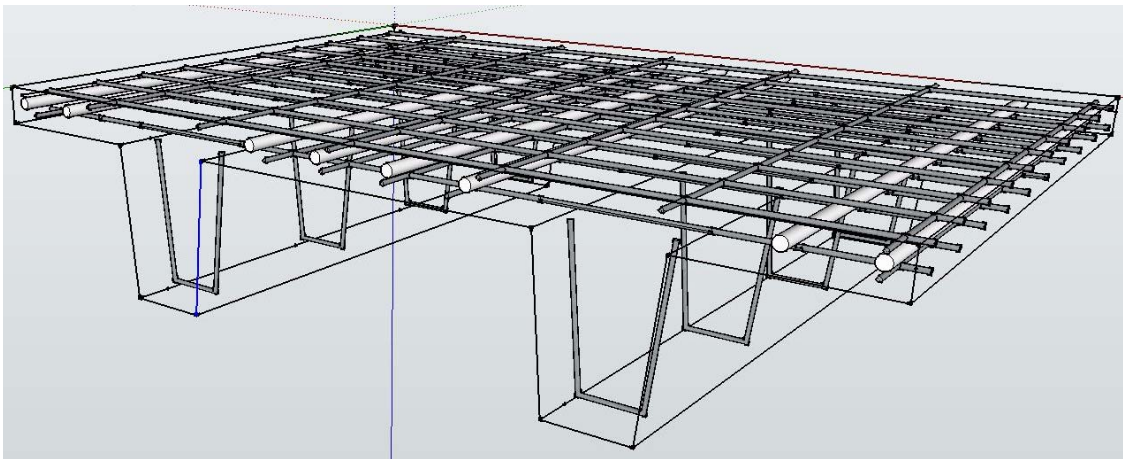

Figure 67 Consolidated 3D image of the floor element

5.4 Discussion field tests

The results of the GPR scan at Jungmansgatan 55 are very interesting as they show great similarities to chapter 2.10 in the state of the art. However it is hard to draw any conclusion if it is the chloride concentration, the corroded reinforcement or both together that causes the difference in signal intensity. Nonetheless the result show that the GPR can indicate areas where there might be problem with high chloride content or corroded rebar. To be more correct the GPR shows differences in conditions. If the entire scan area would have the exact same chloride concentration and the reinforcement would have the same degree of corrosion there are at the moment no reliable methods to show if these conditions are favorable or not with only GPR.

An important fact is that without the possibility of performing a 3D scan these differences in signal strength might not have been discovered. When only looking on the 2D scans of the same area, there are no indications that there is a difference in signal strength. This show that not only does 3D scans give a better view of the location of the reinforcement, but they also provide more information.

3D scans were also performed on the balconies at Ivargårdsgatan and in that case the concrete cover could have been performed with only 2D scan. The 3D scans may make it easier and timesaving to perform scenarios such as in Figure 56 and 57 where its shows which rebar are in the danger zone. But it is important to remember what the scan does not show. They show no existence of cracks or voids around the reinforcement, which may imply that even if there is an existence of corrosion, it might still be in the early stages.

Performing scans outdoors can sometimes be tricky due to the weather conditions. During the scans at Ivargårdsgatan the weather conditions where very wet and windy. If the surface that is being scanned is moist the apparatus might have a problem getting traction and data not being recorded or recorded at the wrong position. This might also occur if the surface is uneven and the wheels have to rotate more than the actual scanned distance.

The GPR also has limitations if the spacing between the rebar is too small. This can be seen in the scans performed at Lisa Sass Gata, Figure 64. If the spacing is smaller than one wavelength, 4,5cm, the apparatus cannot differentiate between the different rebar and they will appear as one large rebar.

However the GPR really shines during reinforcement mapping. It collects large amount of information very fast. The apparatus is so small that it can fit and be used in very tight conditions, although it cannot be used in angled connections between two concrete elements, When mapping the concrete elements at Lisa Sass Gata, the most time consuming part was to actually draw the element and the reinforcement.

6 Conclusions

The aim of this study was to evaluate Ground Penetrating Radar as a non-destructive investigation method. GPR radar shows great potential as an investigation method in concrete. It can perform very accurate scans and show the position and depth of embedded artefacts, if the object is homogenous and the dielectric constant is known. Although it cannot differ between different metal objects, such as rebar, pipe or rod, as all are shown as identical hyperbolas.

The StructurScan Mini HR is small in size and can be used in tight spaces. The interface of the apparatus is very user-friendly and the data can be processed post-scan both in the apparatus and in a PC-software.

The GPR is sensitive to high moisture content, as it can drastically reduce the penetration depth. The higher the moisture content the lower will the reflection strength from artifacts be. The moisture content also changes the shape of the hyperbola, low moisture content gives a rounder and wider hyperbola whilst higher moisture content will result in a more edgy and tighter shape hyperbola.

The position of voids and cracks can easily be detect, but not the size and volume.

The GPR provides the user with the possibilities of performing 2D scans for a fast onsite mapping of imbedded objects and 3D scan for a more detailed investigation in complex structures. 3D scans might also show conditions when there is a risk for high chloride concentration and corrosion.

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