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Methods and Equipment for Non Destructive Testing of Reinforced Concrete in Harbour Docks

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

FRANCISCO RIPOLL CANDEL

Department of Civil and Environmental Engineering
Division of GeoEngineering
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Rebars under the effect of the corrosion at the quay 710, Älvsborgshamnen, Port of Gothenburg.

Reproservice/ Department of Civil and Environmental Engineering
Göteborg, Sweden

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ABSTRACT

Nowadays, at the Port of Gothenburg a lot of works are being carried out to detect damages at the docks because of the corrosion at the bars in the reinforced concrete.

The methods to identify maintenance needed today are often destructive tests and selection of samples to ascertain the status of the concrete pier and the need for scheduled maintenance. This method is costly and does not always provide an accurate picture of the damage that needs attention.

The aim of this report is to research on the methods which are available at the moment for non-destructive testing (NDT) of the corrosion on the reinforced concrete structures at the harbour environment and the suitability of the handheld equipments to evaluate these damages. Taking into account the different characteristics of the equipments, the RapiCor was chosen.

The method to evaluate the accuracy of the equipment was testing, before the quays were destroyed during the maintenance program carried out by the Port of Gothenburg, and then, after that destruction, evaluating the accuracy studding the damages of the exposed rebars and comparing them with the results of the NDT equipment.

The result was that the RapiCor equipment was accurate detecting the corrosion damages and was also quicker. For achieve this accuracy different aspects, which are exposed at the report, should be borne in mind.

Finally, the conclusion is that using this NDT equipment, the detection of the corrosion damages is more efficient because time and money are going to be saved.

Key words: corrosion in reinforced concrete, non-destructive testing, marine environment, harbour docks.

Metoder och utrustning för icke-förstörande provning av armerad betong i hamn kajerna
Examensarbete inom geologiska och vattenteknik
FRANCISCO RIPOLL CANDEL
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SAMMANFATTNING

Göteborgs Hamn lägger ned mycket arbete på att upptäcka korrosionsskador i de stålarmerade betongkajerna. Idag används förstörande provningar för att upptäcka skador och göra urval av prover för att fastställa status och underhållsbehov. Detta är en kostsam och tidskrävande metod och den ger inte alltid en rättvisande bild av de skador som kräver åtgärder.

Detta examensarbete utreder alternativa icke-förstörande provmetoder med handhållen utrustning. Med hänsyn till tillgänglighet och egenskaper hos några olika utrusningar har RapiCor bedömts som mest lämplig.

Utvärdering av metodens tillförlitlighet har skett genom icke-förstörande prov inom tre testområden i Göteborgs Hamn och sedan efter destruktion av konstruktionen en bedömning av den frilagda betongen och armeringen.

Resultatet visade att utrustningen RapiCor var tillförlitlig vid detektering av korrosionsskador i hamnmiljö och också snabb och lätthanterlig. Rapporten diskuterar provningsförfarandet och ger rekommendationer för att säkerställa resultat med hög tillförlitlighet.

Nyckelord: korrosion i armerad betong, icke-förstörande provning, havsmiljö, hamn kajer.

Contents

Preface

This Master thesis has been carried out at Chalmers University of Technology, in the department of Civil and Environmental Engineering, division of Road and Traffic Group and at the Port of Gothenburg.

All the research of the information and the training with the equipments took place at the Department of Civil and Environmental Engineering and the concrete laboratory at Chalmers, the tests have been carried out at the Port of Gothenburg before and after the waterblasting process to compare the results during March and April 2010.

I would like to express my deepest gratitude to my teacher Gunnar Lannér for his attention, to the workers from the Svensk Water Blasting (Svensk Vatten Bilnings Teknik), specially Per Åke and his brothers for giving me a lot of information and their time, to the maintenance manager of the port, Stig Östfjord for providing me all I needed for carry out my works, and to the developer of the RapiCor equipment, Luping Tang for his valuable information and borrowing his equipment.

Göteborg May 2010

Francisco Ripoll

1 Introduction

1.1 Background

The main problem of the marine environment structures is the corrosion of the bars in the reinforced concrete. This environment is one of the most aggressive for this type of structures. The chloride ions attack the concrete and the steel is susceptible to be corroded.

Nowadays the procedure for the detection of these damages is breaking the surface of the docks without the knowledge of the real state of the structure. That is an expensive and time wasting procedure and not always provides an accurate picture of the damage that needs attention.

For knowing the state of the bars in the reinforced concrete without breaking it, different non-destructive testing methods and equipments are available at the moment; their properties are discussed at the following Chapters 4 and 5, respectively.

1.2 Aim

The aim of this study is to find out if these non-destructive testing equipments are providing advantages because their less consumption of time and money front to the destructive methods used nowadays. For achieving this purpose the accuracy of the NDT equipments should be proved.

1.3 Method

The method used to evaluate the accuracy of the equipment was testing, before the quays were destroyed during the maintenance program carried out by the Port of Gothenburg, and then, after that destruction, evaluating the accuracy studding the damages of the exposed rebars and comparing them with the results of the NDT equipment.

At the first part of the report, an inventory and evaluation of non-destructive tests that are currently in the market and providing a reliable result in concrete status is included.

Then the different full-scale tests are exposed explaining the remarks.

Finally, the results and the conclusions are presented and the suitability of using the non-destructive equipment is discussed.

2 The Port of Gothenburg

The Port was founded on 1621, it´s situated at the mouth of the Göta River and combines rive and seaport. This Port is the hub of Scandinavian maritime traffic and it´s the leading container harbour in the Nordic region.

Figure 2.1 Emplacement of the Port of Gothenburg in the northern Europe.

The Port of Gothenburg has many kilometres of concrete docks for the berthing of ocean vessels, specifically 12 kilometres in 151 berths.

The docks are rooted mainly in concrete piles. These docks are now in most cases over 40 years and when they are exposed to a difficult environment requires a major maintenance, primarily resulting corrosion of the reinforcement without any visible damage to the concrete surface.

The surfaces which have been tested are the slabs and the beams. The concrete piles are supposed to be in a good condition.

The first location of the tests is at the Ro/Ro terminal, the largest single port facility in Scandinavia for unitized cargo, Port of Göteborg (2009). The second and the third one are at different oil terminals, in concrete at the crude oil jetty the second one and in a bridge at the land side the third one. "In terms of tonnes, oil is the dominant cargo with 52 per cent of the total cargo turnover (22.8 million tonnes in 2008). Then come containers and trailers, forest products, steel and cars", Port of Göteborg (2009).

Figure 2.2 Emplacement of the Port in the city of Gothenburg.

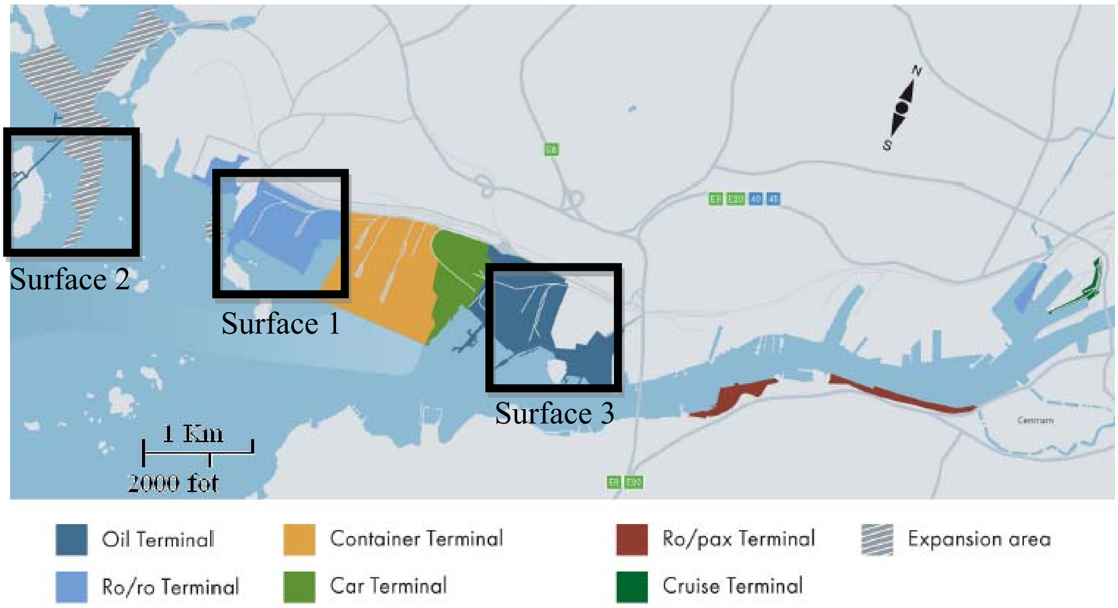


Figure 2.3 Emplacement of the different terminals in the Port and location of the tests.

3 Factors which facilitate the corrosion process

3.1 Corrosion induced by chloride ion

The composition of the seawater is 35‰ dissolved salts and the 55% of them are chlorine ions.

Those chlorine ions have the property of penetration into the reinforced concrete until the steel bars and then break the passive layer which is protecting the steel front the corrosion.

This passive layer is very dense and has a very high polarisation resistance, resulting in a very low corrosion rate, Tang (2002). The layer consists of iron oxide due to the alkalinity of pore solution it has a pH strongly basic (around 12.5).

When the passive layer is broken, the steel can be corroded (if O_2 are available) and the concrete can be delaminated. This area will be the anode and the nearby non-corroded area becomes the cathode. This chemical reaction is important to be understood because it´s the basis of the anodic protection.

3.2 Corrosion induced by carbonation

Unlike the corrosion due to chloride ion which is a local attack in the bars, the carbonation is a widespread attack.

The basic mechanism of carbonation is the penetration of CO_2 in the concrete. The protection of the steel is lost because of the reduction of the alkalinity of the concrete. This process occurs when the carbon dioxide, present in the atmosphere, reacts with calcium and magnesium hydroxides which are in the concrete.

The consumption of calcium hydroxide comes in a reduction of the pH to values lower than 9, which places the steel outside the passivity area. Therefore, the carbonation process should be avoided in the nearby area of the steel bars.

The final result is that the steel bars which were protected with the passive layer, now are exposed to the attacks of the atmosphere because the loss of chemical protection.

3.3 The thickness of cover layer of concrete

There is a direct relationship between the thickness and porosity of the coating of a reinforced concrete structure with the corrosion rate. The improvement in the construction designs with greater cover layer thicknesses and higher quality, lead to a higher protection to such structures.

3.4 Cracks

Perhaps one of the most eloquent signs in any damaged structure. Depending on its location, shape, history, evolution in time, environmental, etc., is easy in most cases, diagnose, or have a good starting point for further research. The fissures may be caused by mechanical actions, electro-chemical, physical and rheological.

4 Inventory of Methods for Non Destructive Testing of Reinforced Concrete

As the corrosion is an electrochemical process, most of the NDT methods for the field applications are based on electrochemical principles.

4.1 Linear Polarisation Method (LPM)

The Linear Polarisation is an electrochemical method that allows the knowledge of the corrosion rate. LPM can usually be done in less than 5 minutes. This is accomplished by applying a voltage signal to the sample which its potential value is very close to the corrosion potential E_{corr}. The values generally used are between -20 and 20 mV. The linear polarisation resistance is obtained from the slope of the graph of current versus potential.

The bigger is the value of the slope, the lower it is the value of the electrical resistivity.

The value of the slope is inversely proportional to the corrosion rate.

An advantage of linear polarisation resistance monitoring is that can provide a qualitative pitting tendency measurement.

The LPR monitoring can be carried out in two ways: potenciostatic (applying a variation in the potential and measuring the variation in the current) or galvanostatic (inversely).

$$R_p = \frac{\Delta V}{\Delta I} \tag{4.1}$$

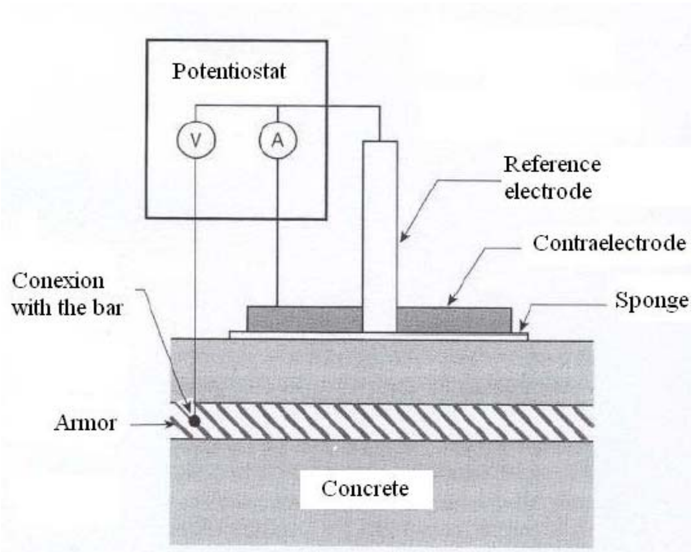


Figure 4.1 Measurement of linear polarisation resistance (three electrodes).

4.2 Pulse Technique (PT)

The technique is based on the same principle as LPR. The difference is that LPR measures responses under a stationary state and the pulse technique measures the responses under a transient state.

4.2.1 Galvanostatic Pulse Method (GPM)

In this method, the current applied is typically in the range of 10 to 100 µA and typical pulse duration is between 5-30 seconds. The small anodic current results in a change in potential of the reinforcement, which is recorded by a galvanostat.

4.2.2 Potentiostatic Pulse Method (PPM)

It´s difficult to apply a potentiostatic pulse in a steel-concrete system due to the unknown potential drop on the surface of counter electrodes, Tang, 2002.

4.3 Half Cell Potential (HCP)

This method consists of the estimation of the electrical half cell potential of the steel bars with the purpose of determine the corrosion activity of the steel in the armours. This technique is easy to apply but difficult to interpret.

The basis of the method is that, during the corrosion, the iron ions are moving from the bars to the nearby concrete, leaving electrons at the bar which give to the bar a negative charge. The HCP method is used to detect this negative charge and therefore give information about the corrosion activity. If the bar is corroded, the electrons tend to flow from the bar to the half cell. At the half cell, the electrons are consumed in a reduction reaction.

The electrochemical potential is a measurement of the availability of the transference of electrons between the metal and the surrounding environment, in this case, between the steel and the pores of the cement. As is not possible to measure the absolute value of the potential, it is necessary to measure the potential difference with a reference electrode.

This technique only gives a probability of corrosion, is not possible to know the real state of the rebars.

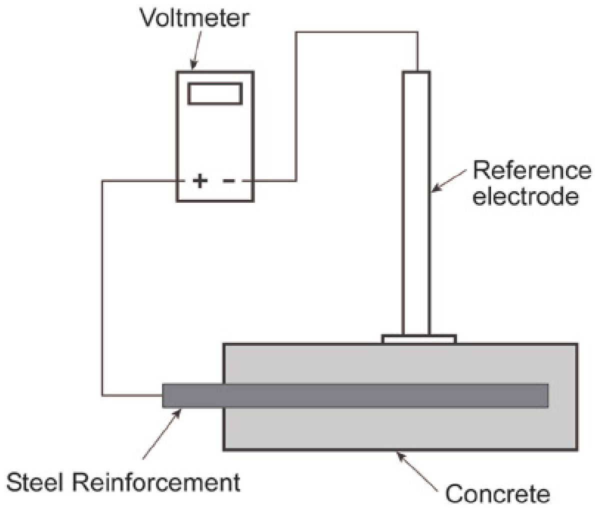


Figure 4.2 Measurement of the HCP

4.4 Resistivity of the concrete

The resistivity of the concrete layer is a measure of the capacity to act as an electrolyte and to conduct the corrosion currents. It´s based on the following assumption: the resistivity is proportional to the corrosion rate when the potential tests show that the corrosion could be possible, P. Schiessl, RILEM (1988).

The resistivity of the material is defined as the resistivity of a unit cube, of "L" centimetres length and "A" squared centimetres of section. The most simplified method for the measurement of the resistivity is using alternating current "I" across both parallel electrodes, separated "L" centimetres and with "A" squared centimetres of section. Then it´s possible to measure the resulting potential and the resistivity of the material is:

$$\rho = \frac{V * A}{I * L} \tag{4.2}$$

This method is only possible to use in new structures, because the electrodes are supposed to be inside the concrete.

To measure the resistivity in existing structures it is common to employ 4 Wenner probes (equidistant electrodes), BRE Centre for Concrete Construction (2000). The electrodes are placed line up, "x" centimetres spaced (less than the cover layer). An alternating current is applied between the extreme electrodes (usually sinusoidal with a frequency between 50 and 100 Hz) then the potential drop is measured with the intermediate electrodes obtaining the resistivity with the following equation:

$$\rho = \frac{2 * \Pi * x * V}{I} \tag{4.3}$$

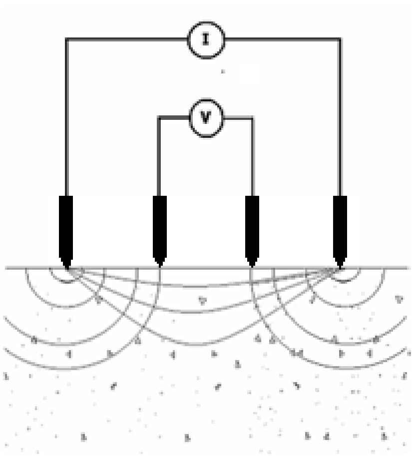


Figure 4.3 Measurement of the resistivity of the concrete.

Therefore, the measurements of the resistivity can be useful for the following aims, Polder, R. (2000):

- Evaluating the value of the concrete's resistivity for estimating the corrosion risk in case of depasivation.
- Allocate the more permeable structure areas for taking decisions about another investigations or protection actions.
- Allocate points with a higher water exposition or aggressive dissolved agents.
- Helping the developing of cathodic protection and other electrochemical treatments.
- Monitoring the quality of the concrete during the production.

Table 4.1 Corrosion risk assuming different resistivities.

Resistivity (KOhm.cm)	Corrosion risk
>20	Low
10-20	Intermediate
5-10	High
<5	Corrosion

4.5 Electrochemical Impedance Spectroscopy (EIS)

The EIS is a technique which uses alternating current. It´s based on applying a sinusoidal voltage of low amplitude to the work electrode (which remains at the corrosion potential thanks to a potentiometer) over a wide frequency range. The response current to each frequency is another sinusoidal current with other amplitude (ΔI) and a phase difference regarding the input signal, P. Schiessl, RILEM (1988). The impedance of the system, which depends on the frequency, is:

$$Z = \frac{\Delta E}{\Delta I} \tag{4.4}$$

This method is very attractive because it can determine polarization resistance and add extra information about the corrosion process. High frequency range can give information about dielectric properties of concrete, and low frequency range information about dielectric properties of passivity film on the steel, Bjegovic, Mikulic, Sekulic and Stirmer (2006).

The equipment for EIS measurement is very complicated and costly and is not available in the Nordic countries, Tang (2002b).

5 Inventory of Equipment for Non Destructive Testing of Reinforced Concrete

Nowadays a lot of hand-held equipments are available at the market. The following four have been chosen because their importance in the construction market or because a different technique has been developed.

5.1 GECOR

The device, GECOR, was patented in the 90s and since 1991 is a worldwide reference for the sector. It was the result of collaboration with the National Research Council, the Metallurgical Research, and the company Geocisa (ACS group) all of them in Spain. The equipment is made by a company in USA.

It´s based in the linear polarisation method (LPM). Measures the corrosion rate ($\mu A/cm^2$), half-cell measurements (mV) (corrosion potential), concrete resistivity (KΩ*cm), temperature and relative humidity measurements.

The last model developed is the GECOR 8. It has three different sensors. The sensor A is used for measurement in aerial structures and for measurement in structures with cathodic protection. The sensor B is employed for mapping of Corrosion Potential and Resistivity. Finally, the sensor C is used for measurements in submerged or very wet structures.

The grid points should be between 20 and 100 centimetres spaced.

GECOR has the following advantages:

- It´s possible to measure in submerged structures (should be proved).
- It´s possible to measure in structures with cathodic protection.
- It has noise level indicator.
- It has a user-friendly operator interface.
- Advanced software with the possibility to update it.

And the following disadvantages:

- The measurement takes around 5 minutes per location.
- The reference electrodes are Copper / Copper Sulphate ($Cu/CuSO_4$) with CuSO4 solution reservoirs. The maintenance of these electrodes it takes time because they need to be refilled.
- Three different sensors are needed.
- The corrosion rate meter weights 6 Kg and one of the sensors weights 1 Kg.

- It needs a battery pack, it´s not possible to use common batteries.
- The device should not be operated in temperatures below 0ºC.

Figure 5.1 GECOR equipment

Table 5.1 Equivalences between corrosion rate, corrosion level and time for visible corrosion used by GECOR.

Corrosion rate (μA/cm²)	Corrosion Level	Time for visible corrosion
<0,2	Passive	-
0,2-0,5	Low corrosion	>10 years
0,5-1	Moderate corrosion	3-10 years
>1	High corrosion	<2 years

5.2 GalvaPulse

It´s based in the Galvanostatic Pulse Measurement (GPM). GalvaPulse was developed at FORCE Technology in Copenhagen, Denmark. The Galvanostatic pulse method allows rapid measurements of polarisation resistance, ohmic resistance and open circuit potential (half-cell measurements).

This equipment is a rapid non-destructive device for determining the corrosion rate of reinforcement in concrete. The instrument measures the corrosion potential Ecorr by a reference electrode of type Ag/AgCl placed at the centre of the disc before applying a galvanostatic current to the counter electrode. Another current is applied to the guard ring to keep the potential difference between the counter electrode and guard ring close to zero. The device is equipped with software, which enables displaying the corrosion rate, electrical resistance and half-cell potential, together with the graphs of the galvanostatic pulse.

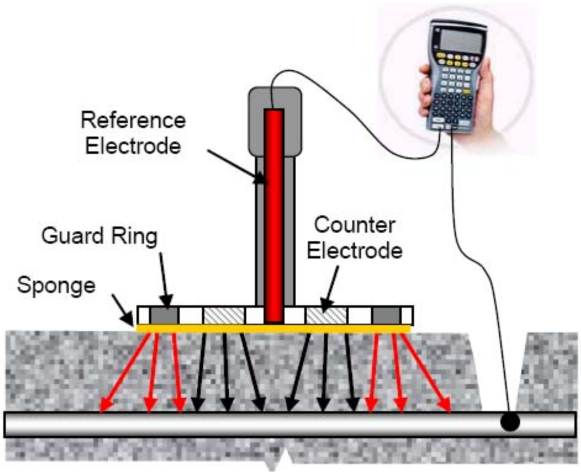


Figure 5.2 GalvaPulse´s outline.

The GalvaPulse handheld equipment has the following advantages:

- It´s possible to test on rough or curved surfaces.
- It takes only 5 to 10 seconds per test.
- It can store 20000 records.

The disadvantages are:

- It is not possible to estimate the actual loss of cross sectional area of the reinforcement from a single GPM measurement. If multiple GPM measurements are taken over a period of time, an average value can be estimated, Frølund, Klinghoffer and Sørensen (2003).
- The uncertainty of the area of the steel bar affected by the electrical signal from the counter and guard electrodes and non-uniform current distribution on the steel rebar can cause errors when calculating the corrosion rate of steel in concrete, Poursaee and Hansson (2008).

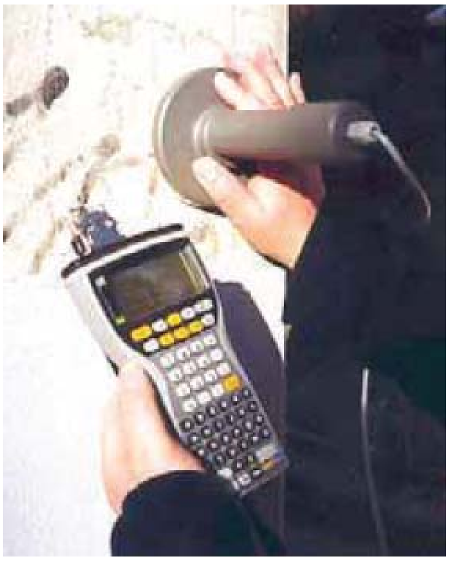


Figure 5.3 GalvaPulse equipment.

5.3 CorMap

The CorMap equipment is based on the Half-Cell Potential (HCP) theory. It´s distributed by an American company.

The corrosion in the bars of the concrete produces areas where is a larger concentration of negative ion in opposition which the areas with no corrosion.

This larger concentration of ions creates a small electric voltage potential. By measuring and mapping the voltage potential found in the concrete it´s possible to determine the presence of corroded steel reinforcement without costly and time consuming demolition of the concrete. This is done by recording the voltage between the rebar and a half cell, which is mapped across the surface of the concrete. Areas of rust with high corrosion will exhibit significantly lower voltages than areas without corrosion, thus areas of corroding steel reinforcing bar in concrete can be rapidly found. There is no need to know the exact position of the steel reinforcing bar or the amount of cover, the presence of the steel is all that is required. However, the voltmeter has to be connected to an exposed piece of the rebar network, and because the concrete is being tested, any material on the surface should be removed.

Advantages of CorMap equipment:

- A real-time colour plot is produced on the monitor screen during the scan. X and Y are position and Z is the potential (mV). See Figure 4.4.
- It has an automatic height sensor which ensures proximity while allowing a non-flat surface to be scanned.
- Economic method.

Disadvantages:

- It takes between 2 and 5 minutes per measurement.
- It can evaluate the probability of corrosion of the reinforcing steel but not the real state.
- The copper sulphate electrode needs maintenance.

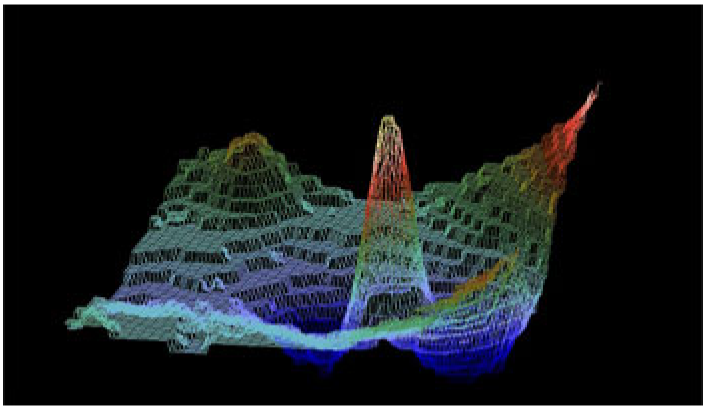


Figure 5.4 Colour plot. The z-axis is the potential.

Figure 5.5 The CorMap equipment

5.4 RapiCor

The RapiCor equipment is based in the Galvanostatic Pulse Method (GPM). It was developed by SP (Swedish National Testing and Research Institute), Borås, Sweden.

Figure 5.6 Suitcase with the devices needed to carry out the tests.

The instrument first measures the corrosion potential E_{corr} by the centre reference electrode and afterwards imposes galvanostatic currents I_{CE} and I_{GE} (see Figure 4.6) through the other electrodes towards the steel bar, Tang (2008).

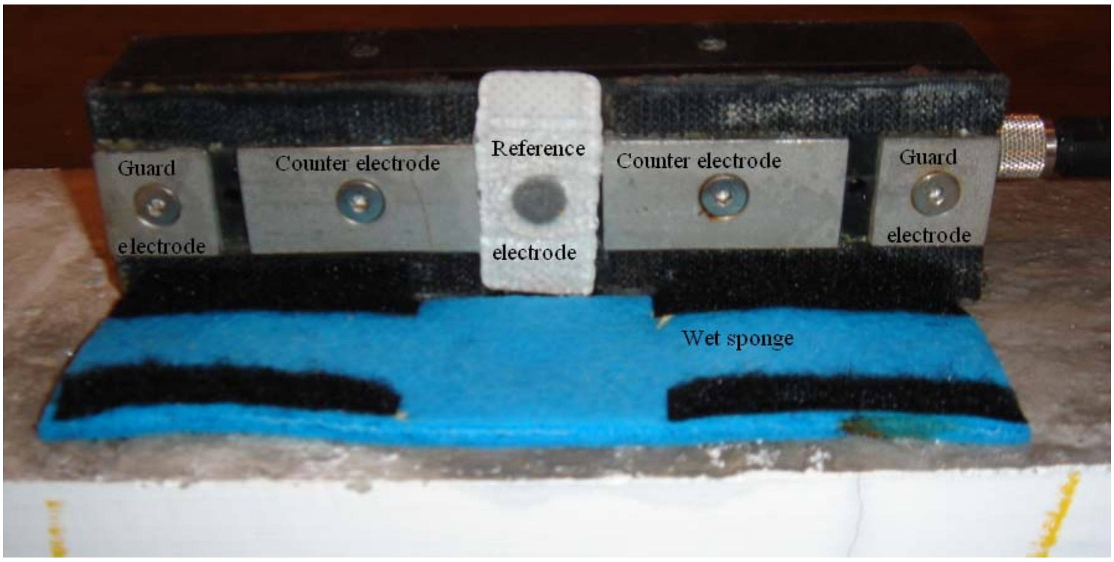


Figure 5.7 Sensor unit with the five different electrodes and the sponge.

The reference electrode (RE) consists of Ag/AgCl. This electrode is disposable and it doesn't need maintenance, when the tests are finished the electrode can be removed.

Positioned on each side of the RE is in points the counter electrodes (CE) which apply a short duration current pulse towards the reinforcement; and the guard electrodes (GE) which help to supply relatively homogeneous current density over the length of polarisation.

The wet sponge is used to improve the contact between the concrete and the electrodes.

The input data which are necessary to calculate the final results are the cover thickness of the concrete (mm) and the steel area affected by the electrical current (cm^2).

The results shown are the corrosion rate, the half-cell potential and the resistivity. With the combination of these measurements the corrosion level is obtained (see the table 5.2).

Table 5.2 Classification of corrosion index used by RapiCor

Corrosion level	**Corrosion rate** (μm/year)	**Half-cell potential** ($mV_{(CSE)}$)	**Resistivity** (ohm·m)
Negligible	<1 1 to 5	- > - 140	- > 10
Low	1 to 5 5 to 10	< - 140 > - 140	< 10 > 10
Moderate	5 to 10 >10	< - 140 > - 140	< 10 > 10
High	>10	< - 140	< 10

The advantages of RapiCor are:

- Short time per measurement (5-10 seconds).
- The electrodes don't need maintenance.
- The sensor and the handheld equipment are light and small comparing with the other equipment.
- Easy interface and software to interpret the data (Excel format).
- The potential-time curve is directly displayed on the computer screen.
- Available at Chalmers.

The disadvantages are:

- Not possible to use it in a rough surface (see Section 9.1.3).
- Not possible to use it in submerged structures.

6 Selection of the Equipment for Testing at the Port of Gothenburg

After the research of the different equipments which are available at the market for the evaluation of the corrosion, the equipment RapiCor was chosen.

Firstly the equipment CorMap was ruled out because it can evaluate the probability of corrosion of the reinforcing steel but not the real state which is the aim of this thesis.

Then the GalvaPulse was putted away because wasn´t available at Chalmers.

Finally the decision was between GECOR and RapiCor. The possibility of carry out the tests with both equipments, for was thought but after taking advice with different experts in this field the decision of choose only the RapiCor was taken.

Different reasons support this decision. The long time per measurement (around 2-5 minutes) makes not feasible this equipment for testing large surfaces (the tests were carried out at the Port). The need of maintenance of the electrodes is another reason. The acquisition and tweaking of the equipment was time and money consuming.

After consult the CBI (Swedish Cement and Concrete Research Institute) a report with the comparison between these two electrochemical methods was sent to me, Tang (2002b).

Then some conclusions from the report are given:

- The corrosion rates obtained by the 5 seconds short time galvanostatic pulse measurements (RapiCor) from the chloride introduced specimens are close to the true actual corrosion rate (mass loss divided by the corroded area of steel).

- The 5 seconds short time galvanostatic pulse measurements (RapiCor) overestimate the true mean corrosion rate, especially for the passive steel bars. When extrapolating the 5 seconds data to 100 seconds utilising the logarithmical relationship according to the equation (5.1), where the constants a and b are purely empiric, the corrosion rates measured by the galvanostatic pulse technique become closer to the true mean corrosion rate.

$$R_p = a * t^b \tag{5.1}$$

7 Procedure of the tests

7.1 Marking the grid

The first action for testing one surface is to indicate the test points drawing a grid. The results will be better if the test points are above the bars. The separation of the test points depend on the size of the area to be investigated.

The establishment of a reference system with some landmarks which certainly are not going to be removed is also important to recognize the test points after the destruction.

Figure 7.1 Marking the grid at the beam of the Surface 2 (Torshamnen).

7.2 Calculating the input data

These input data can be stored using the keyboard of the hand held equipment or after the tests at the laptop.

7.2.1 The cover thickness

To find out this first input value it´s possible to investigate the construction drawings but this method is not accurate because this cover thickness can oscillate because of the construction process.

The method used in this case was the utilization of a cover detector which calculates the cover thickness only placing the sensor over the concrete surface. This equipment can be used also as a rebar detector.

Figure 7.2 The cover detector PROFOMETER 3.

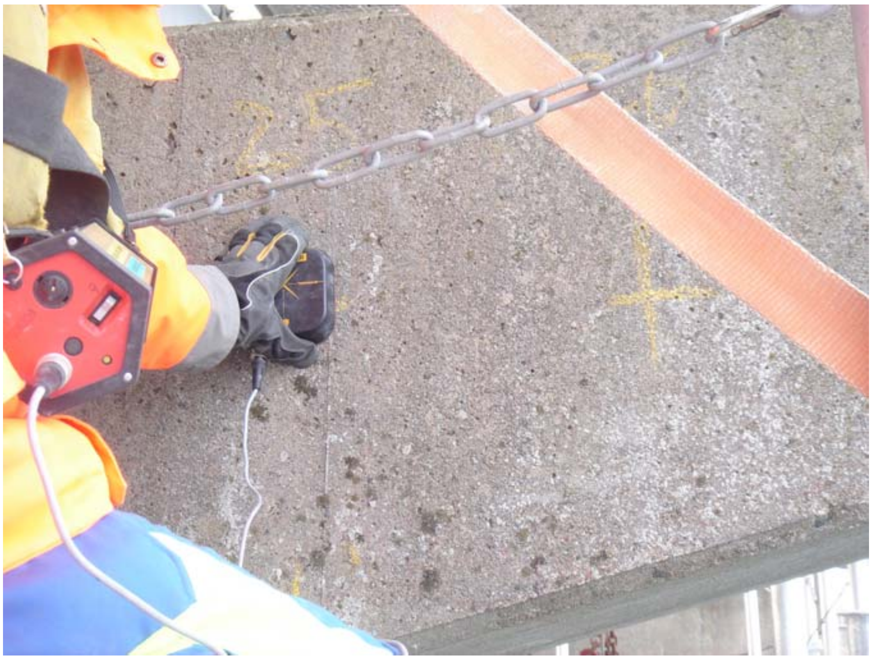


Figure 7.3 Using the cover detector on the beam at Torshamnen.

7.2.2 The steel area

For the calculation of the steel area is not necessary to use any equipment, investigating the construction drawings is possible to know the distribution of the steel bars and apply the equation (7.1), Tang (2008a).

$$A = L_P * \pi * \left[n_L * D_L \left(1 + \frac{\alpha * b_S}{d_L} + \right) n_T * D_T \frac{\beta * L_S}{d_T} \right] \tag{7.1}$$

where L_p=10.5 cm as the specified polarisation length, *n* is the number of steel bars that are bandaged together, *D* is the diameter of steel bars, *d* is the distance between the steel bars, b_S and L_S are the apparent wideness and length of the sensor, respectively, and α and β are the coefficients, whose values are dependent on the number of adjacent bars, the resistivities of concrete and surface film of steel. When only the number of adjacent bars is taken into account for the values of α and β, in most of cases α = β = 2. The subscript "L" and "T" denote longitudinal and transverse direction of steel bars, respectively, Tang (2008a).

7.3 Getting connection with the reinforcement

For carrying out the measurements it's necessary to get electrical connexion with the bars of the reinforcement.

First of all, using an accurate detector, it´s necessary to exactly detect the position of the bar.

Figure 7.4 Rebar locator used to detect the exactly position of the bars.

Then, with the driller, drill a hole to the rebar trying to surround it with a smaller diameter bit to get a better connection. With the help of a hammer install the bolt.

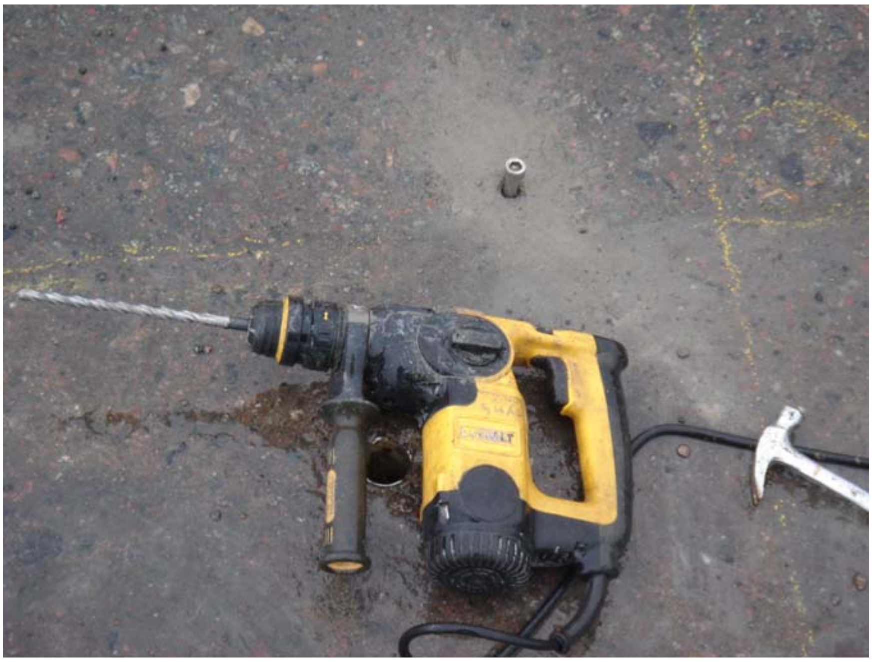


Figure 7.5 Volt installed.

After the bolt is installed it´s necessary to check the electrical connection. For this purpose a multimeter can be used. To ensure the good connectivity, the resistivity should be only a bit bigger than the resistivity of the cable drum.

Figure 7.6 Checking the connectivity of the beam at Torshamnen.

7.4 Carrying out the tests.

At this moment only remains to connect the cable with the hand held equipment and the sensor and it's possible to realize the tests.

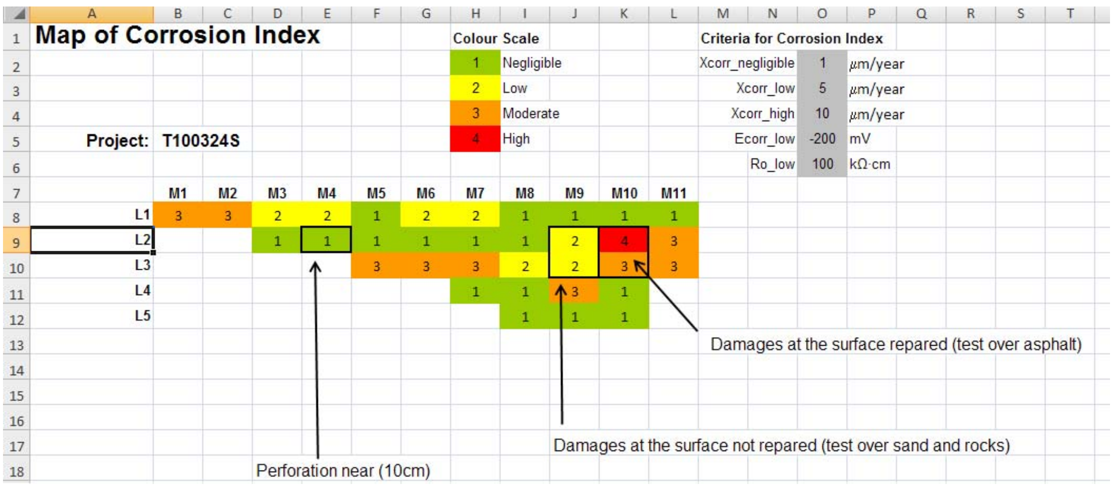
Figure 7.7　Testing with RapiCor at Skarvikshamnen.

These tests only take 10 seconds per measurement. After all the tests are done, the results can be copied to the laptop using the cable for data transfer.

7.5 Analyzing the data.

Once all the data are at the PC, it's possible to analyze them using the program which is in Excel format.

Because the Excel format it's possible to introduce comments in the file, it's also possible to modify the colour scale to clearly hierarchize the damages.



Map of Corrosion Index

Project: T100324S

Colour Scale	
1	Negligible
2	Low
3	Moderate
4	High

Criteria for Corrosion Index		
Xcorr_negligible	1	µm/year
Xcorr_low	5	µm/year
Xcorr_high	10	µm/year
Ecorr_low	-200	mV
Ro_low	100	kΩ·cm

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	3	3	2	2	1	2	2	1	1	1	1
L2			1	1	1	1	1	1	2	4	3
L3					3	3	3	2	2	3	3
L4							1	1	3	1	
L5								1	1	1	

Damages at the surface repared (test over asphalt)

Damages at the surface not repared (test over sand and rocks)

Perforation near (10cm)

Figure 7.8　Example of the worksheet "Corrosion Index".

The workbook obtained consists of five different worksheets:

- **RawData**: at this worksheet, all the values obtained are present with the input values which can be modified and recalculated using the macro.

- **Xcorr**: the values of corrosion rate obtained (μm/year) are represented as a matrix using the colour scale which can be modified.

- **Ecorr**: represents the values of corrosion potential, that is to say, the Half Cell Potential measurements, so with these measurements the probability of corrosion is obtained and can be combined with the rest of data. High negative values represent high possibility of corrosion (<-350 mV_{CSE}) and low negative values represent low possibility (>-200 mV_{CSE}).

- **Ro**: with the map of resistivity it's possible to find out the humidity present in the concrete. If the concrete is very moist (<100 KΩ*cm) the possibility of corrosion increases; contrary, if the concrete is very dry (>500 KΩ*cm) the possibility of corrosion increases.

- **CorrIndex**: at this worksheet all the previous values are aggregated in a unique final value (with its colour scale) which gives a clearly result of the corrosion damage. The final value is hierarchyzed in 4 steps: "1" as negligible, "2" as low, "3" as moderate and "4" as high corrosion damage.

8 Training with the Samples

The RapiCor equipment was used in three different locations but before, for the training, two different samples were also tested.

8.1 Training with the sample A

The sample A was tested during three weeks, it was more time than was expected but the cold winter advised against start before with the outside surfaces (the sample B was under the snow). This sample was a destroyed beam used at the Concrete Laboratory of Chalmers for the learning of the students.

With this beam was possible to train with the RapiCor, the rebar locator and the covermeter.

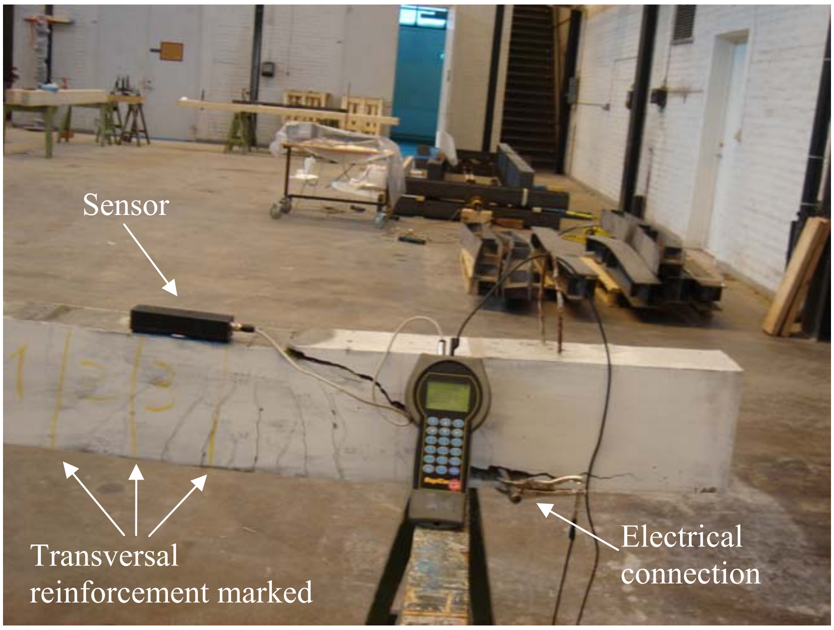


Figure 8.1 Testing the sample A with the RapiCor equipment at the Chalmers' laboratory.

As it's possible to see at the Figure 8.1, the electrical connection with the reinforcement was achieved through a crack which allowed introducing the bolt until the rebar so it wasn´t necessary to use the drill.

For the training with the rebar locator, the transversal reinforcement was marked.

Several measurements were carried out during these days, as follows there are some results obtained.

The surface tested was the vertical side which can be observed at the Figure 8.1.

8.1.1 Results from the sample A

Map of Corrosion Rate [µm/year]

Project: T100223

	M1	M2	M3	M4	M5	M6
L1	2,1	2,2	4,8	2	3,4	2,1
L2	8	7,1	9,1	11,6	9,6	7,6

Colour Scale

Xcorr <=	1	Negligible
<=	5	Low
<=	10	Moderate
	>10	High

Map of Corrosion potential [mV_{CSE}]

Project: T100223

	M1	M2	M3	M4	M5	M6
L1	-192	-187	-217	-213	-208	-208
L2	-229	-232	-219	-221	-217	-230

Colour Scale

Ecorr >=	-200	Low possibility
>=	-350	Uncertain
	<-350	High possibility

Map of Resistivity [kΩ·cm]

Project: T100223

	M1	M2	M3	M4	M5	M6
L1	131	128	32	35	47	39
L2	79	75	45	43	40	40

Colour Scale

Ro >=	500	Very dry
>=	100	Moderate dry
	<100	Very moist

Map of Corrosion Index

Project: T100223

	M1	M2	M3	M4	M5	M6
L1	1	1	2	2	2	2
L2	3	3	3	4	3	3

Colour Scale

1	Negligible
2	Low
3	Moderate
4	High

Figure 8.2 Results obtained from the sample A.

8.1.2 Discussion of the results from the sample A

Those results show that the longitudinal bar which is at the lower part of the beam is in a worse condition than the one which is at the upper part.

The map of resistivity indicates that the sample is, in most of cases, very moist. The reason is because the first tests indicated very low moisture (the beam was always inside the laboratory) then was necessary to contribute to get the moisture with spraying some water 10 minutes before the tests were carried out.

It’s necessary to clarify that to get a good electrical response the concrete is necessary to be moist.

The map of corrosion potential show a low possibility of corrosion (when the results are uncertain, those are very close to low possibility range). The reason is that the concrete is young so the passive layer is not affected by the ions and this layer can keep its alkalinity which prevents from the corrosion of the steel.

Testing the sample A, the following remarks were reached:

- The concrete which is indoor hasn´t moisture enough to transmit the electrical currents from the sensor until the rebars. It’s necessary to spray the surface 10 minutes before the tests.

- Testing the vertical surfaces, the measurement is very sensitive to the small movements. The polarization curves obtained per measurement should be a crescent graphics, so if any movement in the sensor is done, the curve is not continuous crescent and the tests must be repeated, see Figure 8.3.

- It’s not easy to achieve the moisture of the vertical surfaces because the water flows before can be absorbed by the concrete. Could be a good idea to use a wet rag fixed to the surface to achieve the moisture.

- It´s easier to detect the bars with the rebar locator than with the cover detector. With the first one it´s possible to detect the bars with more accuracy and with less time than with the second one.

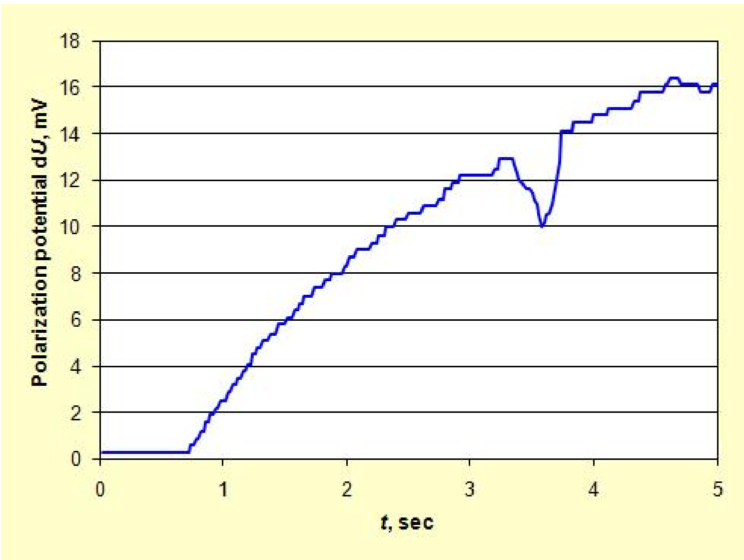


Figure 8.3 Abnormal polarization curve due to a movement in the sensor.

8.2 Training with the sample B

The sample B was a piece of a dock which was destroyed time ago. It was placed at the same place as the surface 1 (Älvsborgshamnen) for the training with the equipment. It was tested during three days.

This sample was a plate of 4x1x0.6 m.

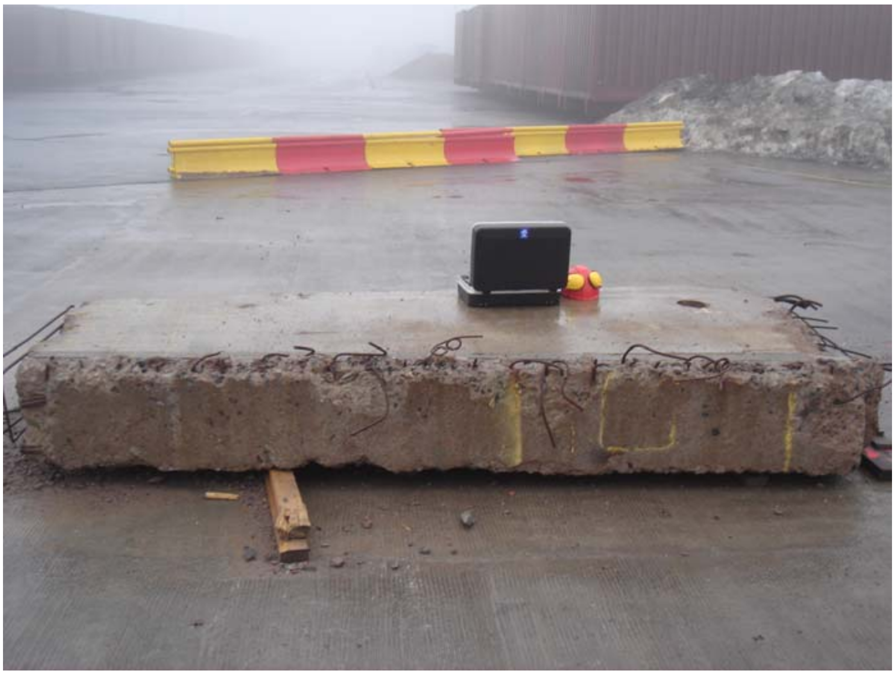
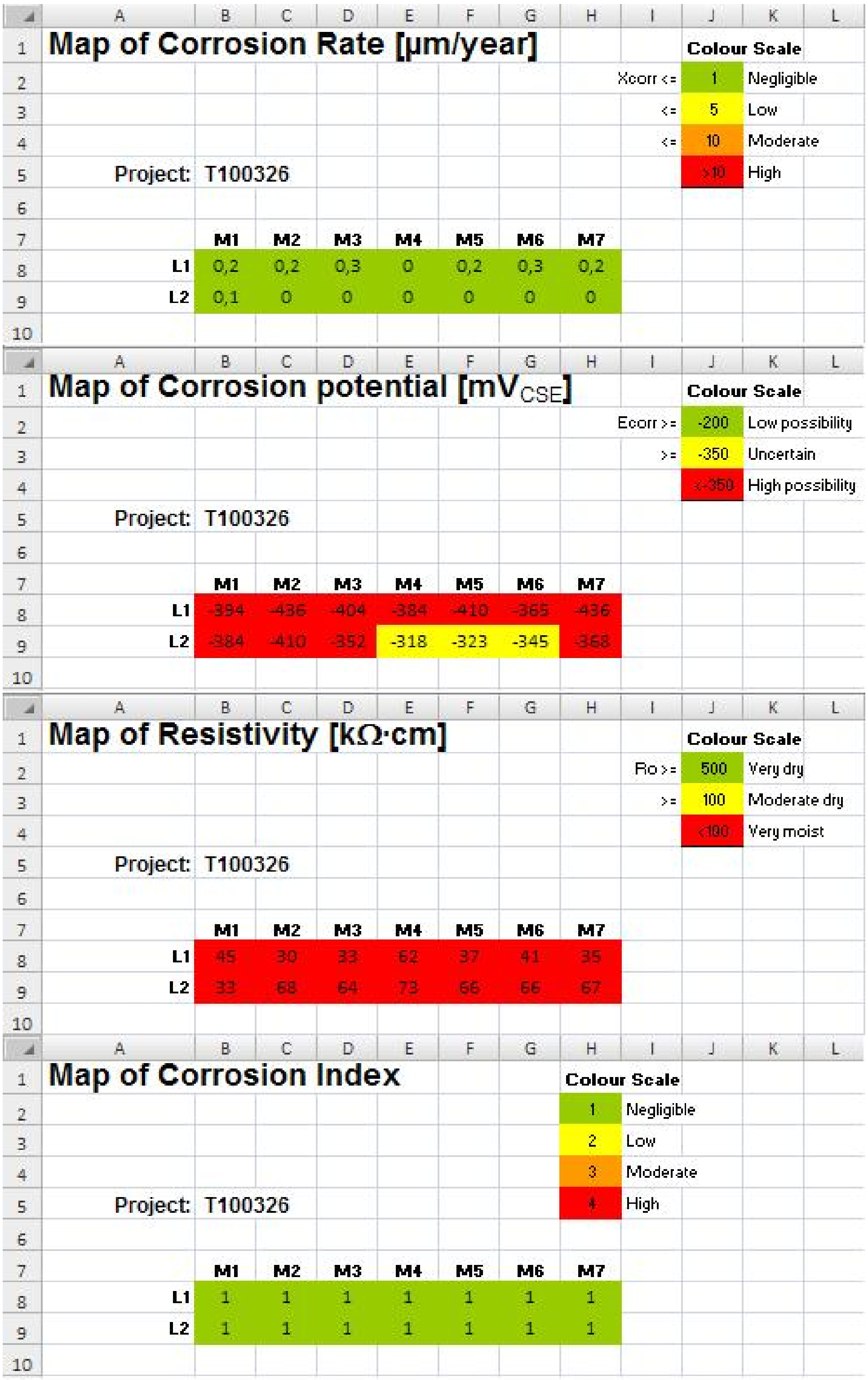


Figure 8.4 The sample B at Älvsborgshamnen.

The electrical connection was easily established using the rebars which were coming out of the concrete. Because they were corroded was necessary take out the rust to get the connection.

8.2.1 Results from the sample B

The upper surface of the sample was tested. The following worksheets are the results obtained:



Map of Corrosion Rate [µm/year]

Project: T100326

	M1	M2	M3	M4	M5	M6	M7
L1	0,2	0,2	0,3	0	0,2	0,3	0,2
L2	0,1	0	0	0	0	0	0

Colour Scale		
Xcorr <=	1	Negligible
<=	5	Low
<=	10	Moderate
	>10	High

Map of Corrosion potential [mV$_{CSE}$]

Project: T100326

	M1	M2	M3	M4	M5	M6	M7
L1	-394	-436	-404	-384	-410	-365	-436
L2	-384	-410	-352	-318	-323	-345	-368

Colour Scale		
Ecorr >=	-200	Low possibility
>=	-350	Uncertain
	<-350	High possibility

Map of Resistivity [kΩ·cm]

Project: T100326

	M1	M2	M3	M4	M5	M6	M7
L1	45	30	33	62	37	41	35
L2	33	68	64	73	66	66	67

Colour Scale		
Ro >=	500	Very dry
>=	100	Moderate dry
	<100	Very moist

Map of Corrosion Index

Project: T100326

	M1	M2	M3	M4	M5	M6	M7
L1	1	1	1	1	1	1	1
L2	1	1	1	1	1	1	1

Colour Scale	
1	Negligible
2	Low
3	Moderate
4	High

Figure 8.4 Results obtained from the sample B.

8.2.2 Discussion of the results from the sample B

Those results show that the sample is in a good condition in terms of corrosion; in fact, the bars which were coming out of the concrete confirm this theory because they didn't show section loss.

The map of resistivity indicates that the entire surface is very moist, but in this case is because natural reasons, because it was raining during 5 hours before the tests. With these values of moisture the electrical transference can be assured.

Contrary to the first sample, in this case all the measurements show high possibility of corrosion (when the results are uncertain, those are very close to high possibility range). The reason is that the sample is a piece of a dock, so provably it has high concentrations of chlorine ions which have the property of penetration into the reinforced concrete until the steel bars and then, break the passive layer which is protecting the steel front the corrosion.

Testing the sample B, the following remarks were reached:

- If the rebar which want be used for the electrical connection has rust, it's necessary to scrape it for take away the rust and ensure the connection.

- The surface tested was horizontal, for ensure the contact of the electrodes with the concrete through the wet sponge during the measurements, a small pressure was applied to the sensor in the vertical direction. It was observed that small variations in this pressure cause big variations in the polarization curve.

- The same measurements were carried out assuring first the contact with applying pressure and then testing removing the pressure and the results of the tests were equivalent.

- A bar which is corroded is not necessary to be losing mass. In fact, the film of rust which is surrounding the bar can work as a protection film against the moisture and aggressive agents.

9 Full - Scale Tests

Three different surfaces were tested and then destroyed through the waterblasting procedure to compare the results.

Going along the river the chlorine ions concentration varies. The Surface 2 which is placed downstream is subjected to a higher chlorine ions concentration than the Surface 3 which is upstream.

Figure 9.1 Location of the three surfaces tested at the Port of Gothenburg.

The areas tested are at Älvsborgshamnen (ro-ro terminal), the quay 710; at Torshamnen (oil terminal) the quay 800; and a road bridge at Skarvikshamnen (oil terminal).

The first surface was a triangle of 35 m^2 on the upper surface of the quay, the second one was a beam below a bridge over the seawater of 11 meters long and the third one was the deck of the road bridge over the pipelines at the crossroads of Bentylgatan with Oktangatan, 28m^2.

Figure 9.2 *Emplacement of the Surface 1 at the quay 710 (Älvsborgshamnen) where the tests were carried out.*

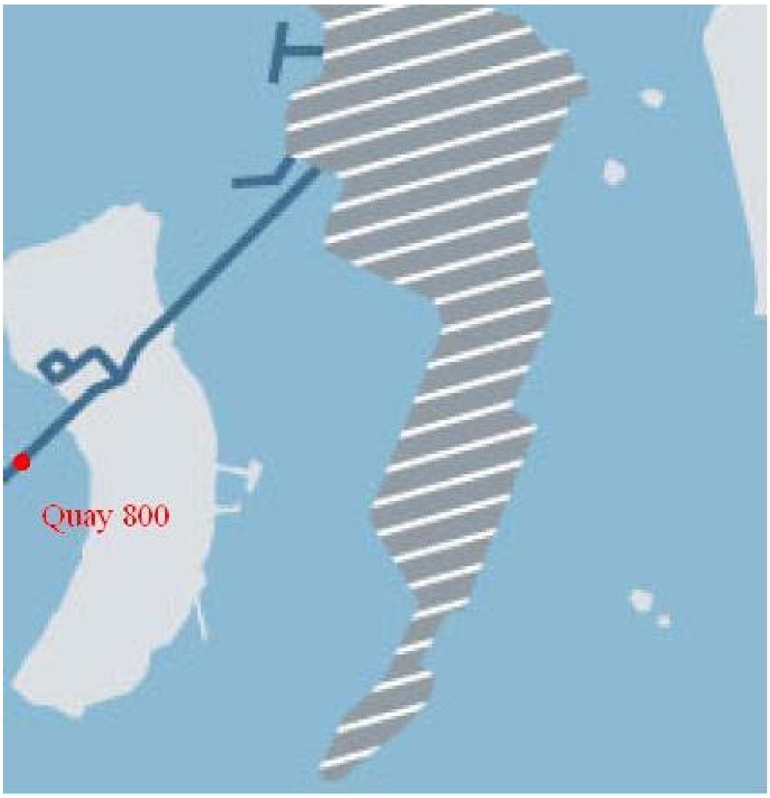


Figure 9.3 *Emplacement of the Surface 2 at the quay 800 (Torshamnen).*

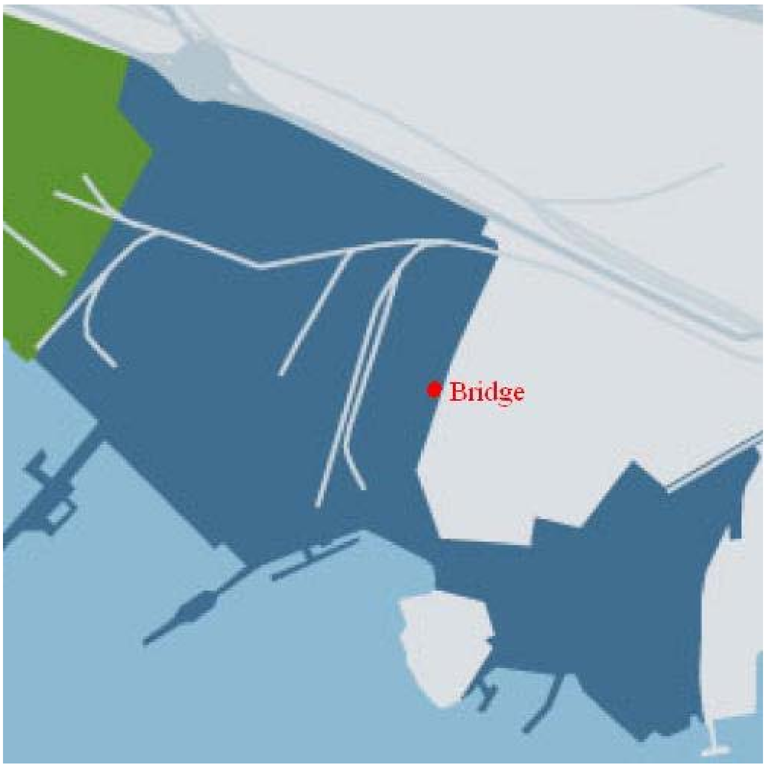


Figure 9.4 Emplacement of the Surface 3, a bridge at Skarvikshamnen.

9.1 Testing the Surface 1

The Surface 1 is placed at Älvsborgshamnen (ro-ro terminal), at the quay 710 of the Port of Gothenburg. It's a triangle of 35 m^2 on the upper surface of the quay near to the ramp where the goods are unloaded.

Because of its strategically position it's necessary to keep it in a good condition because all the tractor trailers should being driven over this surface.

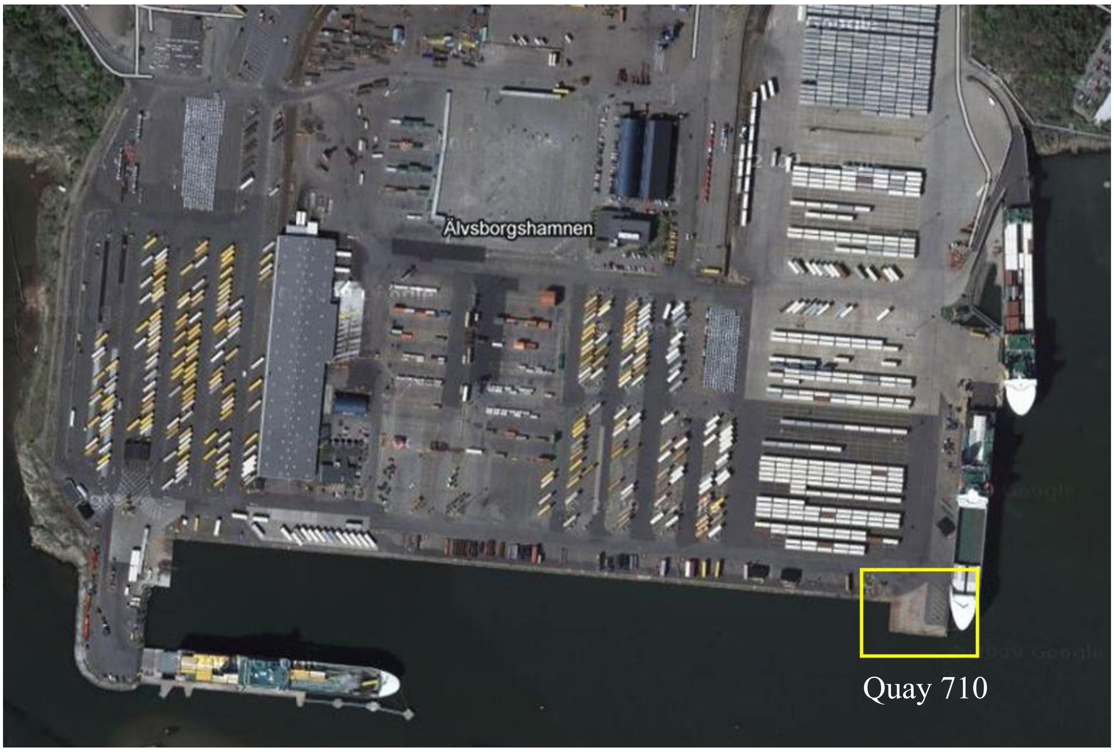


Figure 9.5 Älvsborgshamnen with the quay 710 marked.

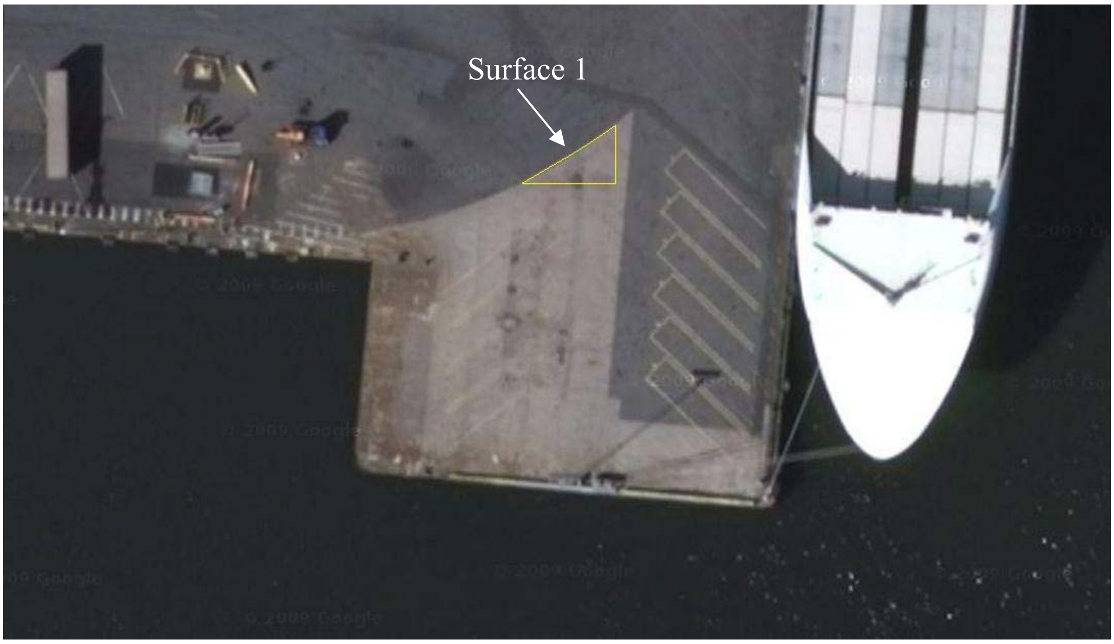


Figure 9.6 Quay 710 with the Surface 1 marked.

This Surface 1 can be divided in two different parts. One of them is a beam which forms the hypotenuse of the triangle. The raised view section can be considered constant. The other part is the rest of the Surface which is going to be called “main surface”.

Due to the differences expected in the reinforcing and in the orientation of the rebars, the tests were carried out separately, first the main surface and then the beam.

The electrical connection with the reinforcement was reached at the second attempt drilling a hole until the rebar. After the measurements were finished, it was difficult to take out the volt using the hammer and the Allen key because it was firmly fitted so it was necessary to use the drill to recover the bolt.

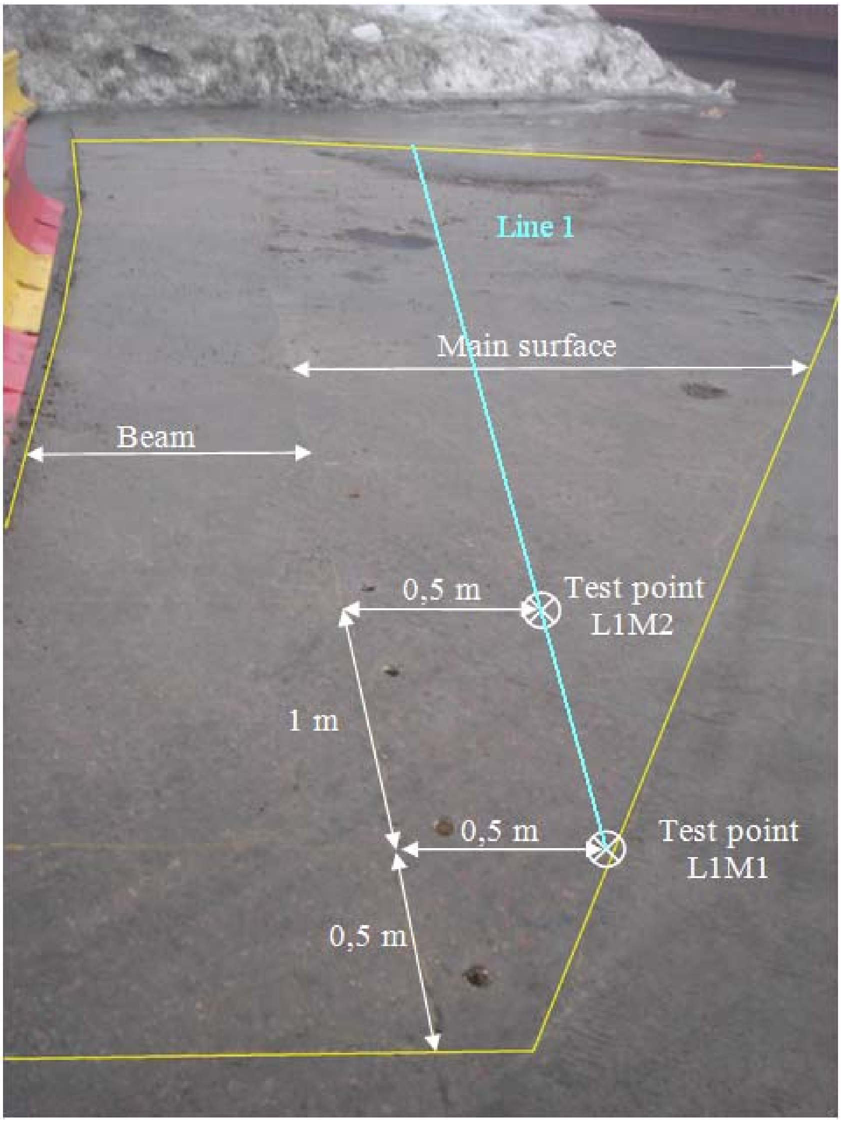


Figure 9.7 Detailed placement of the Surface 1. It´s possible to differentiate the beam, the main surface and the grid with two test points marked.

9.1.1 Testing the main surface

The first problem was to determine the most efficient test points' separation for the definition of the grid. Because of the area of this main surface (24 m^2) was thought that a of 1 meter side grid could be the best solution. The grid was started at 0,5 m to the borders of the surface.

For the detection of the test points after the waterblasting, a landmark was adopted.

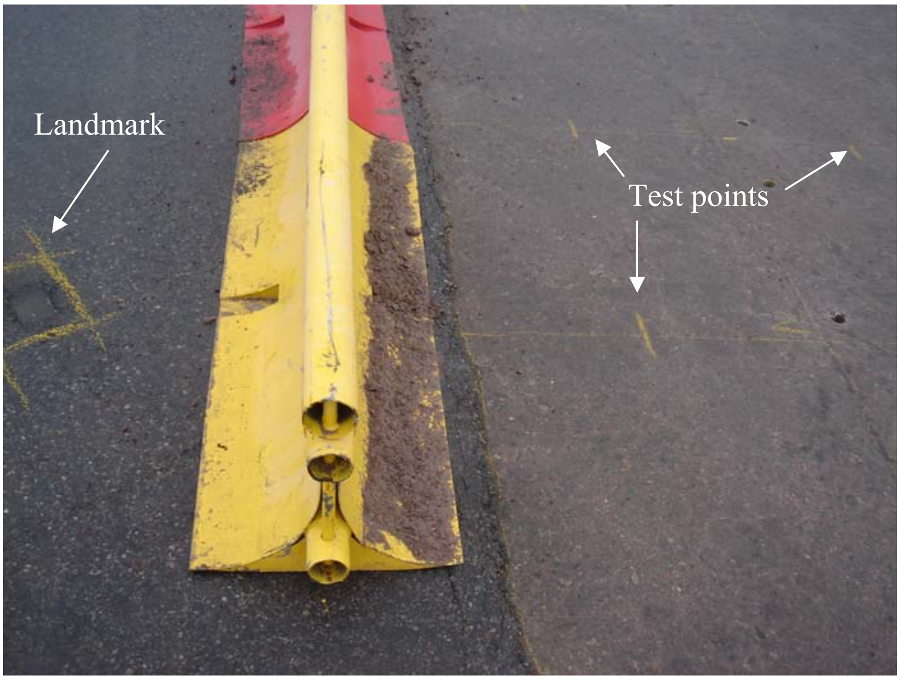


Figure 9.8 Landmark adopted for recognize the test points after the waterblasting process.

During the measurements, the destruction of a rectangular surface was carried out at the same quay. That was helpfully because of different reasons:

- During the establishment of the electrical connection was possible to ensure if the bolt was in contact with the rebars, establishing as a second point of connection the bars which were exposed at the waterblasted surface.

- It was also possible to ensure that all the reinforcement was electrically connected with the installed bolt because was connected with the reinforcement of the waterblasted surface which was placed 20 m far.

- The exposition of these bars allowed the acknowledgement of the direction of the bars so was possible to put the sensor in the same direction getting more reliable measurements.

- It was also used for the calculation of the steel density and as an example of the cover thickness. The steel density was calculated with the following parameters: longitudinal armor, Φ16 every 20 cm; transversal armor, Φ16 every 25 cm. Introducing these values in the Equation 7.1, the result is 137 cm^2.

9.1.1.1 Results from the main surface of the Surface 1

Therefore the results obtained from the main surface of the Surface 1 are the following (realize that the beam is not included in these results):

Map of Corrosion Rate [µm/year]

Project: T100324S

Colour Scale		
Xcorr <=	1	Negligible
<=	5	Low
<=	10	Moderate
	>10	High

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	5,1	5,1	2,2	1,2	0,8	1,2	1,8	0,8	0,8	0,3	0,6
L2			0,5	0,3	0,6	0,5	0,5	0,7	1,1	15,9	6,9
L3					8,3	7,8	5,2	4,1	4	5,5	7,5
L4							4,4	4,9	9	4,3	
L5								2,5	4,6	4,1	

Map of Corrosion potential [mV_{CSE}]

Project: T100324S

Colour Scale		
Ecorr >=	-200	Low possibility
>=	-350	Uncertain
	<-350	High possibility

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	-271	-398	-438	-426	-447	-491	-448	-420	-515	-459	-417
L2			-246	-275	-436	-419	-407	-385	-461	-435	-361
L3					-333	-380	-232	-256	-423	-290	-251
L4							-154	-164	-283	-136	
L5								-150	-177	10	

Map of Resistivity [kΩ·cm]

Project: T100324S

Colour Scale		
Ro >=	500	Very dry
>=	100	Moderate dry
	<100	Very moist

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	62	30	29	29	32	32	23	33	28	29	51
L2			33	35	26	41	39	32	6	21	36
L3					14	18	24	27	7	25	46
L4							16	19	16	52	
L5								20	49	51	

Map of Corrosion Index

Project: T100324S

Colour Scale	
1	Negligible
2	Low
3	Moderate
4	High

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	3	3	2	2	1	2	2	1	1	1	1
L2			1	1	1	1	1	1	2	4	3
L3					3	3	3	2	2	3	3
L4							1	1	3	1	
L5								1	1	1	

Perforation near (10cm)

Damages at the surface not repared
Test over sand and rocks

Damages at the surface repared
Test over asphalt

Figure 9.9 Results of the Surface 1 (realize that beam is not included).

9.1.1.2 Discussion of the results from the main surface of the Surface 1

As it's possible to see at the map of corrosion index, there are different test points which have singular properties. The test point L2M4 had a drain hole 10 cm away, that was thought that could affect the measurement because the variation of the cover thickness. The measurements L2M9 and L3M9 were carried out above sand and rocks because the concrete of the surface was much damaged when was raining this soil had a lot of moisture. The test points L2M10 and L3M10 were over an asphalt layer which was used for the reparation of the surface damaged.

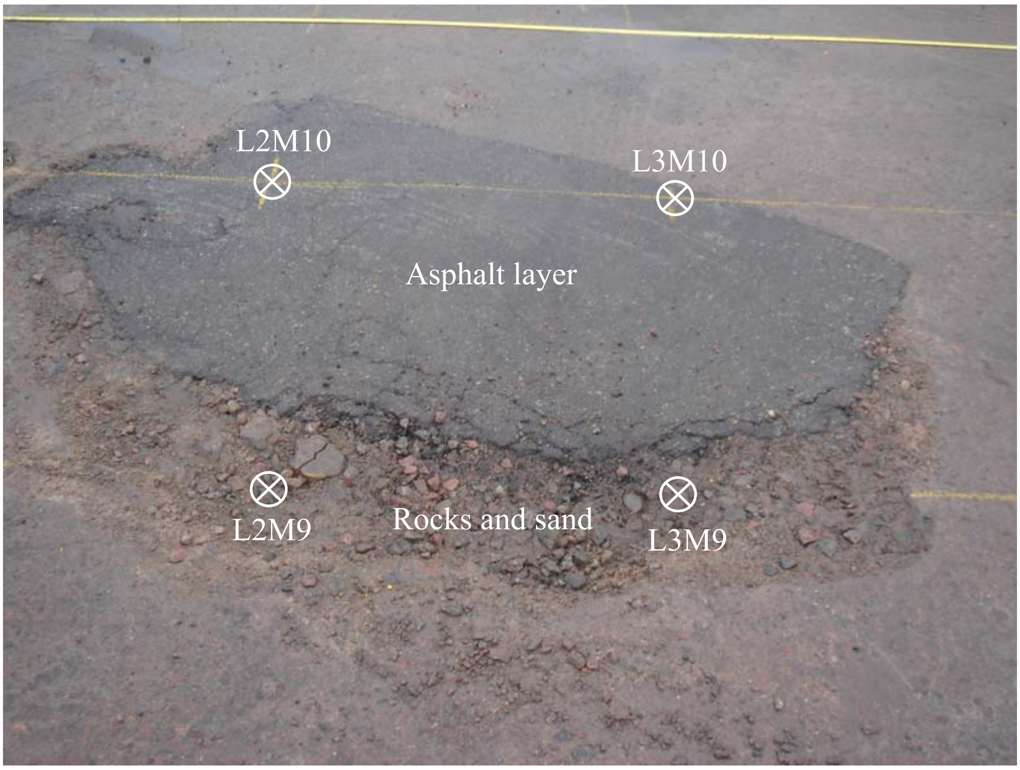


Figure 9.10 Damages where the test points were placed.

The map of resistivity shows that all the points were very moist, the reason is that was raining during the measurements' days.

The map of corrosion potential indicates the variation of this parameter when the test points are approaching to the line of the beam. When these points are near to this line (measurement line 1) the tests show a high possibility of corrosion. The reason of this variation is the slope which is located in this surface (in fact the drain holes are placed at this line, see Figure 9.7) so the chlorine ions presents in the water can be accumulated at this zone due to the accumulation of water which is not drained.

Regarding to the corrosion index, the tests show that the most important damages are under the points L2 from M9 to M11 and all the measurement line 3 and the points L4M9 and L1 from M1 to M2.

9.1.2 Testing the beam

The beam, without any construction drawings, was thought to have the same steel density than the main surface. The sensor was placed in the longitudinal direction of the beam.

The grid used was the same than in the main surface but placing the test points in the middle of the section of the beam.

9.1.2.1 Results from the beam of the Surface 1

The results obtained from the beam are the following:

Map of Corrosion Rate [µm/year]

Project: T100324B

Colour Scale: Xcorr <= 1 Negligible; <= 5 Low; <= 10 Moderate; >10 High

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	2,4	3,4	6,5	6,1	4,7	5,7	12,4	6,7	4,8	8,2	4,4

Map of Corrosion potential [mV_{CSE}]

Project: T100324B

Colour Scale: Ecorr >= -200 Low possibility; >= -350 Uncertain; <-350 High possibility

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	-96	-104	-81	-131	-101	-116	-158	-179	-148	-143	-217

Map of Resistivity [kΩ·cm]

Project: T100324B

Colour Scale: Ro >= 500 Very dry; >= 100 Moderate dry; <100 Very moist

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	69	88	89	84	89	86	56	52	37	48	47

Map of Corrosion Index

Project: T100324B

Colour Scale: 1 Negligible; 2 Low; 3 Moderate; 4 High

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
L1	1	1	2	2	1	2	3	2	1	2	2

Figure 9.11 Results of the beam of the Surface 1.

9.1.2.2 Discussion of the results from the beam of the Surface 1

As in the main surface, the tests show that the surface is very moist. The corrosion potential show in most of cases that the possibility of corrosion is low, that could be because the previous reason (no water accumulation at this section) or because the concrete is in a better condition so the chlorine ions can't penetrate into the reinforced concrete until the steel bars breaking the passive layer which is protecting the steel front the corrosion.

Finally the corrosion index is less than the expected studying the corrosion rate because the application of the corrosion potential (which is low). These tests only represent important damages around the measurement 7.

9.1.3 Testing the Surface 1 after the first process of waterblasting

After the tests were carried out, the Surface 1 was waterblasted going down around 30 mm (see Figure 9.12)

Figure 9.12 Checking the depth after the first waterblasting.

After the waterblasting the surface was cleaned and dried with a water pump.

Figure 9.13 Cleaning the Surface 1 taking away the rubble.

After this process the waterblasted surface was tested with the RapiCor. A lot of doubts about the good working of the equipment at this rough surface came up in this moment because the developer of the RapiCor told that the sensor should be placed in a flat surface for a good measurement.

For this reason the first part of the surface tested was the beam because after the waterblasting was less rough than the rest of the surface (see Figure 9.14).

One conclusion reached about the waterblasting process is that is not easy to arrive until 4 cm over the concrete in the destruction process, because in some areas, the concrete is in a worse condition and big blocks of concrete emerge leaving the steel in the surface and doing impossible the realization of the tests (a cover layer of concrete is necessary to achieve the polarization of the steel).

After this first waterblasting was possible to assure that the concrete in the beam was in a better condition because applying the same pressure the depth reached was less than in the main surface. If the concrete is in a better condition, is supposed to be more impermeable to the chlorine intrusion what is a good quality for the protection front the corrosion.

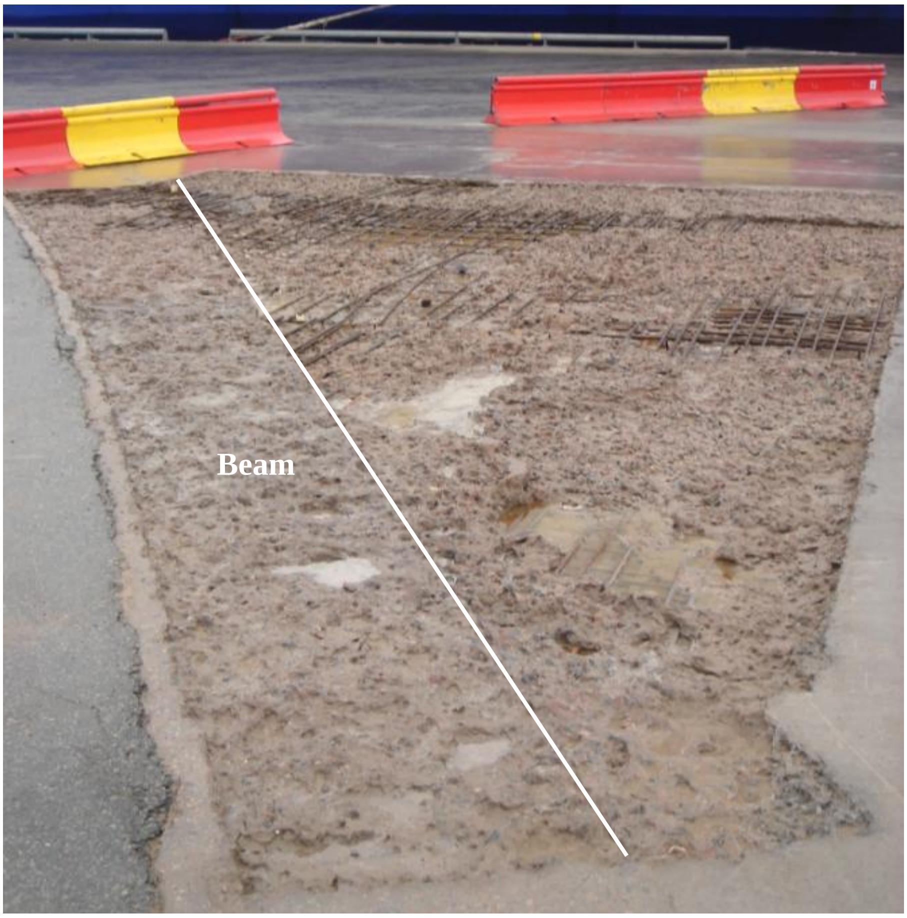


Figure 9.14 Surface 1 after the first waterblasting.

9.1.3.1 Results from the beam of the Surface 1 after the first process of waterblasting

The results obtained for these measurements are the following:

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Map of Corrosion Rate [µm/year]									Colour Scale			
2									Xcorr <=	1	Negligible		
3									<=	5	Low		
4									<=	10	Moderate		
5	Project:	T100408B								>10	High		
6													
7		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	
8	L1	0,8	0	0	0	0	0	0	0	0	0	0,1	
9													

Figure 9.15 Results of corrosion rate obtained after the waterblasting of the beam of the Surface 1.

9.1.3.2 Discussion of the results from the beam of the Surface 1 after the first process of waterblasting

Because the wrong measurements of corrosion rate obtained, the tests were stopped arriving to the conclusion that is not possible to test at the waterblasted surfaces because the impossibility of achieve a good polarization curve.

Different solutions were consulted for achieve a surface smooth enough:

- The first one was to prepare a grout of cement + sand with the proportion 1 : 3 for achieving a flat surface. This solution was discarded because the time to takes to prepare the grout (10 minutes) and waiting the hardening (around 10 hours).

- The second one was to use a strong sander to making smooth the surface. This solution was also discarded because this device was not available.

For all this reasons the possibility of testing in the rough surface was discarded and the results obtained in the upper surface were adopted as definitive.

9.1.4 Discussion of the results after the second waterblasting of Surface 1

After the Surface 1 was finally destroyed arriving until the underneath part of the bars, the grid was drawn another time (now using a yellow cord).

Figure 9.16 Grid at the Surface 1 waterblasted with one pile marked.

With the grill drawn was possible to evaluate the accuracy of the tests reaching to the following conclusions:

- The prediction of corrosion damages obtained by RapiCor was accurate in most of cases but some errors were detected because different reasons (which are as follows).

- It's very difficult to place all the test points over the bars if an homogeneous grid want be reached. Some of the test points are not with a bar just below, Figure 9.17. This fact can modify the steel density affected by the polarization current.

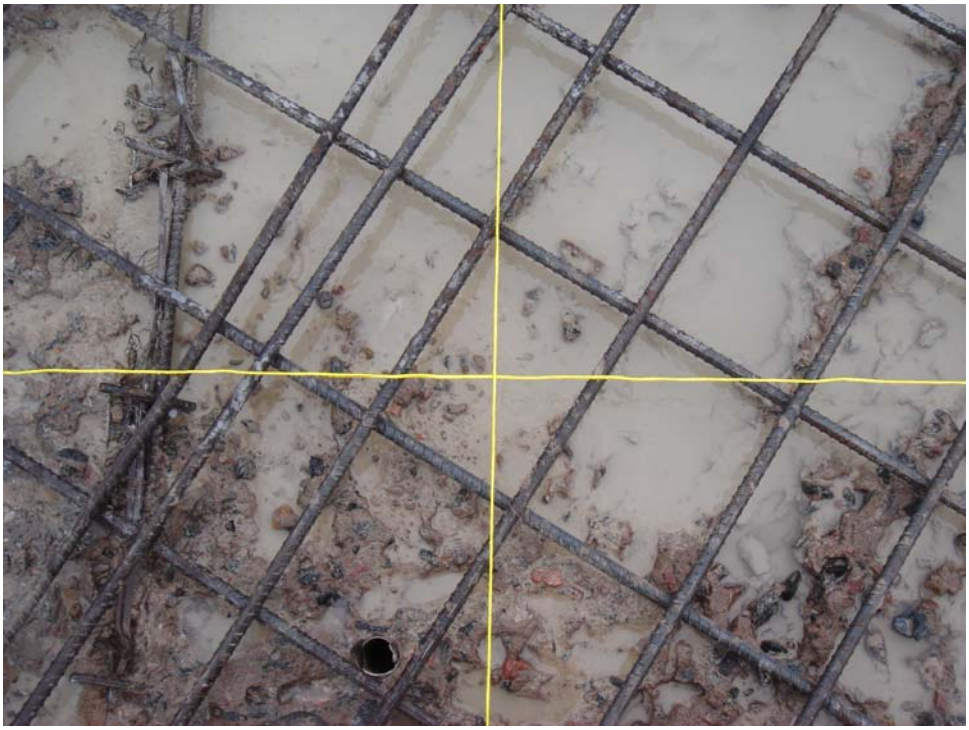


Figure 9.17 Test point L1M4 of the main surface without a rebar below.

- The grid of 1 squared meter is too big for the detection of isolated damages. The test point of the main surface was classified as a "negligible" regarding its corrosion index. As it's possible to see at the Figure 9.18 there is damage next to the point which was not detected.

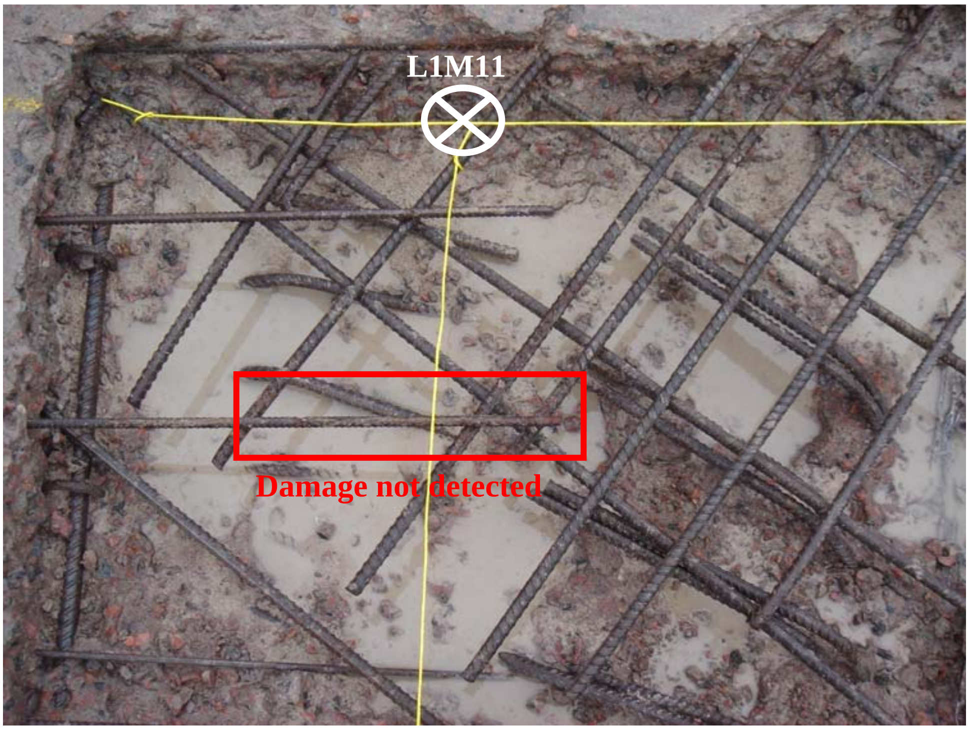


Figure 9.18 Test point L1M11 of the main surface and the corrosion damage.

- The variations in the steel density produced by the reinforcement of the piles (which can be seen at the Figure 9.16) modify the corrosion rate leading to wrong corrosion indexes. These variations are very difficult to calculate because the bars are in different depths and it's hard to know until where the polarization current is arriving. Increasing the steel density the corrosion rate decreases and vice versa.

- The waterblasting process use pressures around 800 bars, besides taking away the concrete also moves some bars which came loose. For this reason sometimes it's difficult to evaluate the accuracy.

Figure 9.19 Surface 1 with some bars removed because the waterblasting process.

- The direction of the reinforcement is not the same than the beam, in fact, it's in the same direction that in the main surface. This fact not seems to affect in a certain extent to the final results.

- The measurement point L1M7 of the beam was classified as a "Moderate" (Figure 8.9). Observing the bars under this point no damage can be detected. This error may be due to the decreasing steel density which is affected by the polarization current since there's no any bar is just under this point, Figure 9.20.

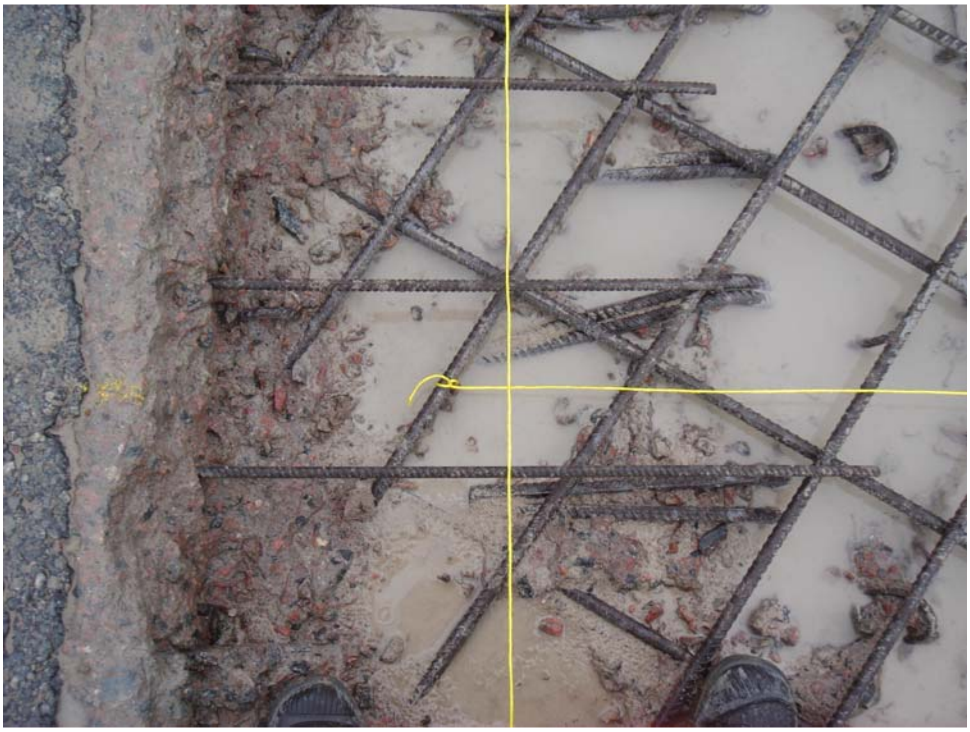


Figure 9.20 Test point L1M7 of the beam. No corrosion damages detected.

9.2 Testing the Surface 2

The Surface 2 is placed at Torshamnen (oil terminal), at the quay 800 of the Port of Gothenburg. It's the beam 19 (PortGot's nomenclature). This beam is placed under the bridge which supports the pipelines and the service road from the landside to the quay 800; see Figures 9.21, 9.22, 9.23.

The beam has a trapezium shape with 11.20 meters long and 1.20 meters depth.

For testing the sample a scaffolding was installed. The beam was tested during eight days.

Because the emplacement of this testing site, at the mouth of the Göta River, the place is very windy, and the predominating wind is coming from the sea so, in these beams, a lot of problems with the chloride content are being obtained.

Because the quay is an oil terminal, during the berthing of the oil vessels, no works are allowed at the end area of the bridge. The beam studied was outside this area.

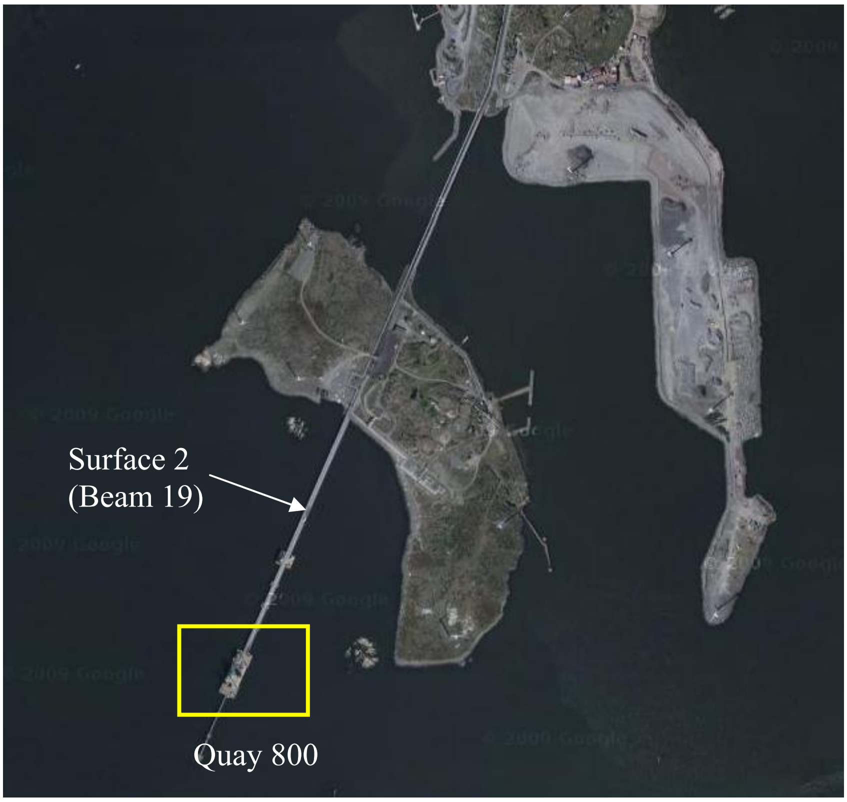


Figure 9.21 Emplacement of the Quay 800 and the Beam 19 tested.

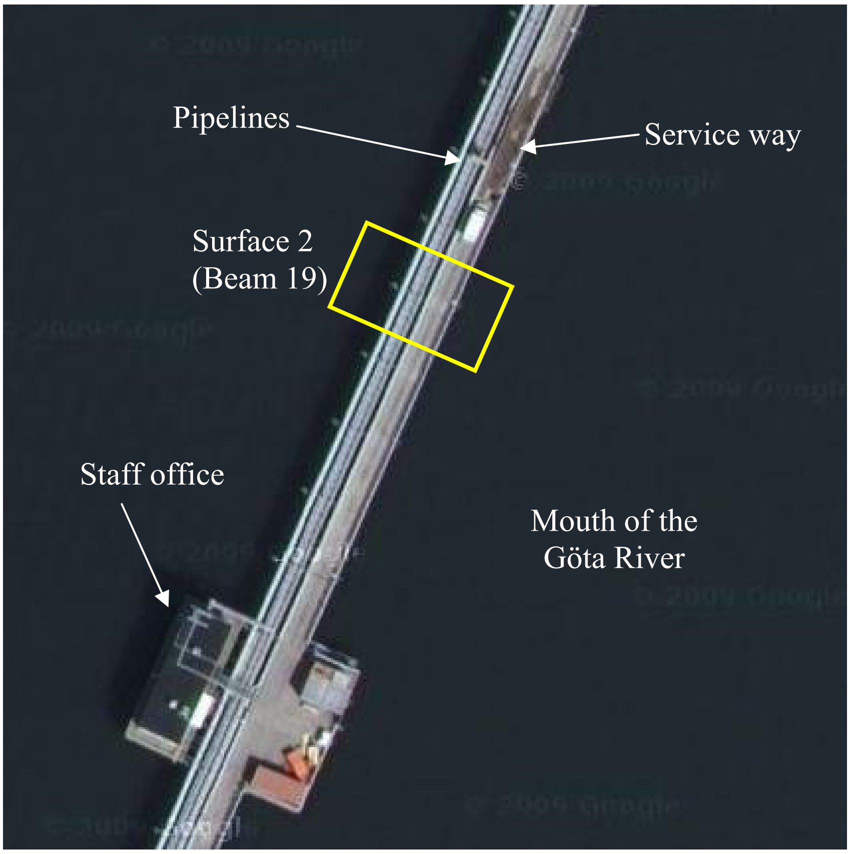


Figure 9.22 Detailed emplacement of the Surface 2.

Figure 9.23 Position of the Surface 2 in the bridge.

This Surface 2, for its testing, was divided in three different sides. The side A was the frontal view of the beam which was oriented to the land side. The side B was the opposite of the A, it means, oriented to the sea side. Finally, the side C was the upper surface of the beam. The bottom part of the beam was not possible to be tested because of the position of the scaffolding.

For test all the sides, one electrical connection point was established at the side B, reaching it at the first attempt. The connection was checked using the multimeter and the rebars exposed in an extraction test (Figure 7.6). Like in the Surface 1, the bolt was firmly fitted and was difficult to take it out. Using a lever the bolt was knock out of position.

9.2.1 Testing the side A of the Surface 2

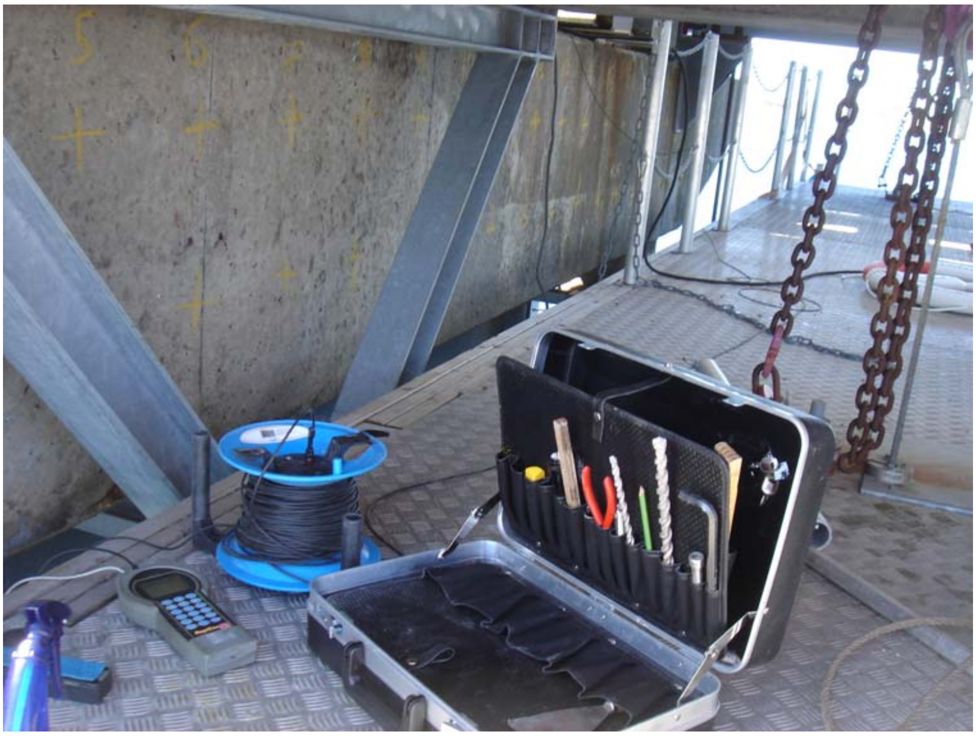


Figure 9.24 Scaffolding which allowed carrying out the tests. It´s also possible appreciate the grid in the side A.

9.2.1.1 Results from the side A of the Surface 2

The first side tested was the A, for these measurements a grid of 2 lines per 27 measurements was chosen. The grid squares were 0.4 meters side.

The results obtained from this side A are the following:

Map of Corrosion Rate [µm/year]

Colour Scale		
Xcorr <=	1	Negligible
<=	5	Low
<=	10	Moderate
	>10	High

Project: T100414

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27
L1	>500	>500	0	0	0	0	0,1	0,2	0,3	0,3	2,4	3,9	1,7	0,2	2,7	4,1	0,2	2,7	0	0,5	0	0	0	0	0	0	0
L2	>500	>500	0	0	0	2,4	0	0,3	1,3	0,1	0,5	0,8	1,3	0,7	1,4	0,6	0	3,2	0,9	0,3	0	0	0	0,1	3,6		

Map of Corrosion potential [mV_{CSE}]

Colour Scale		
Ecorr >=	-200	Low possibility
>=	-350	Uncertain
	<-350	High possibility

Project: T100414

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27
L1	-188	-218	-278	-285	-291	-278	-279	-271	-277	-291	-291	-315	-340	-336	-327	-290	-276	-269	-275	-264	-316	-313	-318	-278	-229	-233	-269
L2	-153	-159	-336	-322	-348	-329	-269	-269	-291	-321	-340	-352	-342	-309	-349	-326	-281	-143	-219	-153	-249	-265	-278	-257	-190		

Map of Resistivity [kΩ·cm]

Colour Scale		
Ro >=	500	Very dry
>=	100	Moderate dry
	<100	Very moist

Project: T100414

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27
L1	253	292	312	121	175	111	62	40	45	109	79	123	83	115	107	126	147	140	304	249	323	198	99	155	170	194	244
L2	304	200	257	124	78	25	71	39	36	77	82	80	95	99	114	137	265	178	183	201	345	286	118	141	314		

Map of Corrosion Index

Colour Scale	
1	Negligible
2	Low
3	Moderate
4	High

Criteria for Corrosion Index		
Xcorr_negligible	1	µm/year
Xcorr_low	5	µm/year
Xcorr_high	10	µm/year
Ecorr_low	-200	mV
Ro_low	100	kΩ·cm

Project: T100414

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27
L1	3	3	1	1	1	1	1	1	1	1	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
L2	3	3	1	1	1	2	1	1	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1		

Figure 9.25 Results of the Surface 2, side A.

9.2.1.2 Discussion of the results from the side A of the Surface 2

The measurement line 2 finish at the measurement 25 because of the trapezium shape of the beam.

The measurements categorized as “>500” at the map of corrosion are interpreted as invalids because no current response has been registered, and should be repeated. These values appear at the final results at the points L1M1, L1M2, L2M1 and L2M2 because they were repeated 6 times each and the result obtained was always the same in all of them.

In the rest of the points very low values for the corrosion rate were obtained and in most of cases with the “0” value.

The rest of maps show a moderate dry surface and an uncertainly corrosion potential.

The polarization curves of these results always started in the 2nd second of the 5 seconds’ polarization period. For this reason and because the results show a very low range of corrosion damage, the measurements were suspicious not to be truthful.

9.2.2 Testing the side B of the Surface 2

For the determination of these aspects the side B was tested. Observing the construction drawings (Figure 9.31) another grid was drawn to ensure that the tests points were over the steel bars. The grid used in this case was made up of three measurement lines matching up with the longitudinal bars in order to avoid the doubts about bad polarization not to make the tests over the bars.

9.2.2.1 Results from the side B of the Surface 2

Testing the side B the following results were obtained:

Map of Corrosion Rate [µm/year]

Colour Scale: Xcorr <= 1 Negligible; <= 5 Low; <= 10 Moderate; >10 High

Project: T100415 and T100420R

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23
L1	>500	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0,6	1	0,2
L2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3,2	0	0	>500	0	0,5
L3				0	0	0	0	0	0	0	>500	0	>500	0	0	0	0	0	0	0	0	0	0,5

Map of Corrosion potential [mV_{CSE}]

Colour Scale: Ecorr >= -200 Low possibility; >= -350 Uncertain; <-350 High possibility

Project: T100415 and T100420R

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23
L1	-264	-224	-297	-291	-312	-310	-285		-290	-259	-352	-308	-393	-224	-269	-210	-198	-159	-171	-183	-145	-167	-179
L2	-223	-281	-214	-216	-206	-239	-205	-257	-261	-270	-272	-261	-289	-249	-284	-261	-227	-184	-163	-152	-178	-219	-212
L3				-187	-188	-193	-215	-286	-194	-269	-288	-347	-319	-238	-218	-274	-217	-194	-150	-169	-150	-219	-238

Map of Resistivity [kΩ·cm]

Colour Scale: Ro >= 500 Very dry; >= 100 Moderate dry; <100 Very moist

Project: T100415 and T100420R

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23
L1	29	129	77	107	99	201	297		273	300	311	225	222	236	237	231	313	200	173	194	63	96	167
L2	175	204	274	244	202	264	275	396	481	373	448	302	347	297	226	248	245	65	200	186	57	216	109
L3				217	231	510	432	430	506	567	209	347	150	300	444	470	431	569	606	460	609	568	188

Map of Corrosion Index

Colour Scale: 1 Negligible; 2 Low; 3 Moderate; 4 High

Criteria for Corrosion Index: Xcorr_negligible 1 µm/year; Xcorr_low 5 µm/year; Xcorr_high 10 µm/year; Ecorr_low -200 mV; Ro_low 100 kΩ·cm

Project: T100415 and T100420R

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23
L1	4	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
L2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1
L3				1	1	1	1	1	1	1	3	1	3	1	1	1	1	1	1	1	1	1	1

Figure 9.26 Results of the Surface 2, side B.

9.2.2.2 Discussion of the results from the side B of the Surface 2

There are no values at the line 1 measurements 1 to 3 because the trapezium shape of the beam and the test point L1M8 was also impossible to be tested because one support of the scaffolding was there.

The tests at this side are considered invalids because in most of them the results obtained for the corrosion rate are ">500" or "0". For this reason the test procedure was aborted and the developer of the equipment was consulted to discuss the results which had being obtained.

The conclusion was that the equipment couldn’t achieve a good polarization curve because different possible reasons:

- The steel bars are in a deeper position which can’t be reached by the polarization curve. This reason was discarded because the data of cover depth was delimited between 47 and 80 mm being the average value 56 mm. These cover depths were worked at the Surface 1 without any problem (in fact, the average at the Surface 1 was 75 mm).

- The concrete wasn’t wet enough to transmit the polarization current. To rule out this hypothesis the concrete was thoroughly wetted. Firstly with a sponge 10 minutes before the measurements and secondly 1 minute before each test with the spray bottle. The difficulty consists in the vertically position of the side which prevent the water to wet more the concrete because it flows before penetration. Another reason regarding the difficult to maintain the concrete moist enough is the heavy wind present at the area which eliminate quickly the water on the concrete’s surface. With all of these handicaps the results presented are with the higher levels of moisture which could be obtained.

Figure 9.27 Wetting more the concrete with the sponge and the spray bottle.

- The third hypothesis and provably the main reason of the bad polarization response obtained was the delamination (peeling) due to the corrosion of the concrete layer. To find this possible delamination, the surface of the concrete was hit using a hammer and listening the rebound sound. The delamination was found in several areas of the beam. This delamination is caused because the increase in the volume of the steel when is corroded. This effect leads to an heterogeneous concrete layer which interferes in the good transmission of the currents.

Figure 9.28   Hitting with the hammer to find the possible delamination.

9.2.3 Testing the side C of the Surface 2

After the two vertical sides were tested, it was the turn of the horizontal side C. A lot of test points were not possible to be tested because all the supports of the pipelines, the piles and the slab of the service way.

The grid used was the same of the other sides longitudinally and three lines in the transversal direction matching up with the longitudinal bars which are represented at the Figure 9.31 and 9.32.

Figure 9.29 Testing the side C. The supports of the pipelines prevent some tests.

9.2.3.1 Results from the side C of the Surface 2

The results from the side C are the following:

Map of Corrosion Rate [µm/year]

Colour Scale: Xcorr <= 1 Negligible; <= 5 Low; <= 10 Moderate; >10 High

Project: T100420

	M1	M2	M3	M4	M5	M6	M7	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M20	M21	M22	M23	M26	M27
L1	1,4	0,3	0,3	0,3	0,5	0,1	0,1	0,1	0,1	0,2	0,2	0,4	0,2	0,2	0,3	0,4	0,3	0,7	0,3	0,5	0,4	0,8	0,7
L2	1,9														1	0,6	0,4		1,1	1,3	0,2	0,3	0,8
L3	0,6	0,6	0,2	0,6	0,3	0,2	0,1	0,1	0,1	0,1	0,1	0,1	0,2	0,5	0,2	0,7	0,4	0,1	0,1	0	0,1	0,4	0,2

Map of Corrosion potential [mV_{CSE}]

Colour Scale: Ecorr >= -200 Low possibility; >= -350 Uncertain; <-350 High possibility

Project: T100420

	M1	M2	M3	M4	M5	M6	M7	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M20	M21	M22	M23	M26	M27
L1	-288	-239	-229	-236	-195	-245	-245	-255	-346	-317	-341	-275	-309	-320	-261	-134	-173	-275	-269	-245	-264	-53	-48
L2	-313														-304	-170	-194		-217	-249	-260	-37	-14
L3	-213	-141	-180	-195	-112	-151	-154	-213	-208	-218	-217	-232	-247	-235	-208	-39	-74	-156	-156	-157	-168	13	5

Map of Resistivity [kΩ·cm]

Colour Scale: Ro >= 500 Very dry; >= 100 Moderate dry; <100 Very moist

Project: T100420

	M1	M2	M3	M4	M5	M6	M7	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M20	M21	M22	M23	M26	M27
L1	177	310	174	238	230	538	439	454	643	375	435	330	277	280	292	212	263	102	75	91	118	162	96
L2	45														206	193	195		116	58	214	196	114
L3	95	113	166	118	209	212	495	559	377	393	398	309	178	225	269	180	197	188	135	357	284	250	142

Map of Corrosion Index

Colour Scale: 1 Negligible; 2 Low; 3 Moderate; 4 High

Criteria for Corrosion Index: Xcorr_negligible 1 µm/year; Xcorr_low 5 µm/year; Xcorr_high 10 µm/year; Ecorr_low -200 mV; Ro_low 100 kΩ·cm

Project: T100420

	M1	M2	M3	M4	M5	M6	M7	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M20	M21	M22	M23	M26	M27
L1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
L2	2														1	1	1		1	2	1	1	1
L3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 9.30 Results of the Surface 2, side C.

9.2.3.2 Discussion of the results from the side C of the Surface 2

In this case was easier to increase the moisture of the beam because the surface was in the horizontal position (see the map of resistivity). The results of corrosion rate are very low so according to these results the steel at the upper part of the beam should be in a good condition. The corrosion potential shows in most of cases uncertain or low possibility of corrosion.

The measurements of the Surface 2 allow the tester to reach to the following conclusions:

- It’s not easy to calculate the steel density using the following drawings:

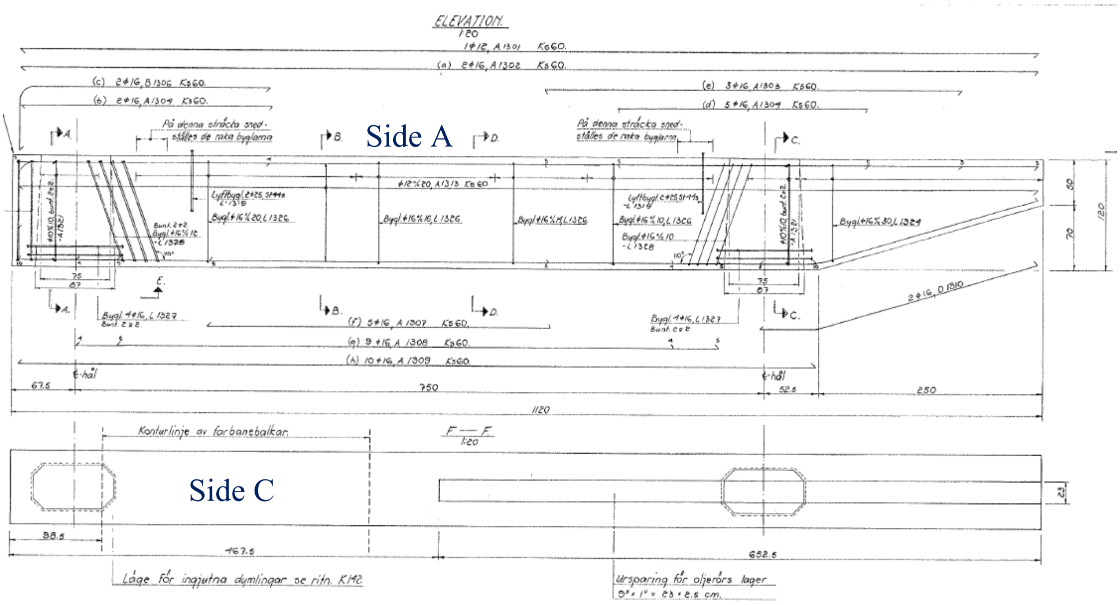


Figure 9.31 Construction drawings of the Surface 2. It's possible to differentiate the sides A and C. The side B is the opposite of the A.

- It´s difficult to know which bars are affected by the polarization current to include them in the steel density equation:

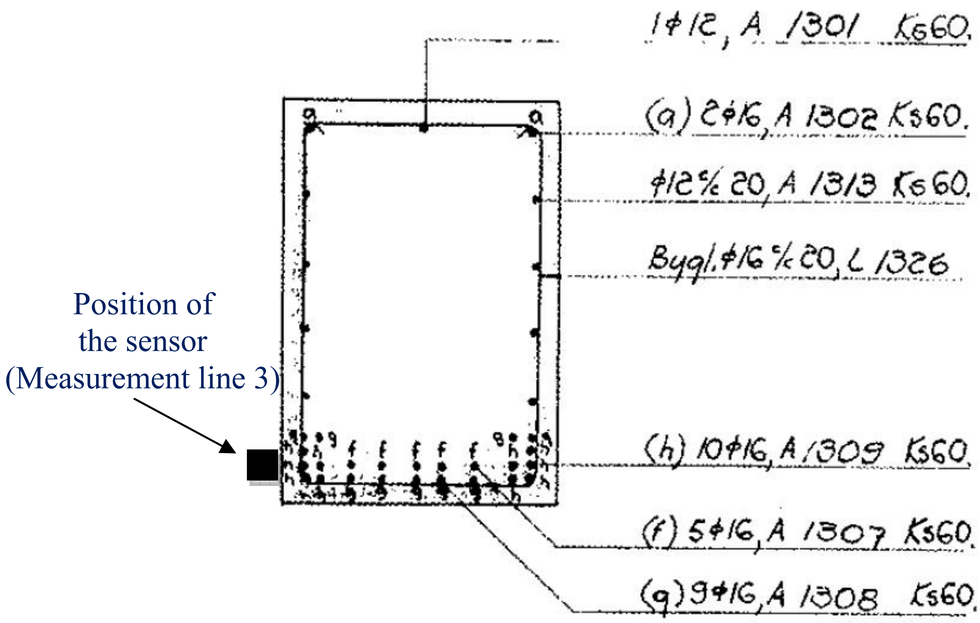


Figure 9.32 Position of the sensor when the line 3 was tested.

- When the position of the tester is not so much comfortable, the surface tested is in a vertical position and it's heavy windy, reach a good polarization curve without any external movement is a hard job.

- Is not possible to test in surfaces affected by delamination.

- The steel structures which are around the surface tested interfere in the measurements of the cover meter (see Figure 9.29). For this reason the cover depth of the test points at the side C were calculated using the construction drawings (Figure 9.31).

9.3 Testing the Surface 3

The Surface 3 is placed at Skarvikshamnen (oil terminal), at the crossroads of Bentylgatan with Oktangatan. It's the deck of a bridge over the pipelines.

It was tested during three days.

The bridge has a slope in the west direction so the bars in this side are expected to be in a worse condition because the accumulation of the de-icing salts in this area.

Figure 9.33 Skarvikshamnen with the emplacement of the bridge marked.

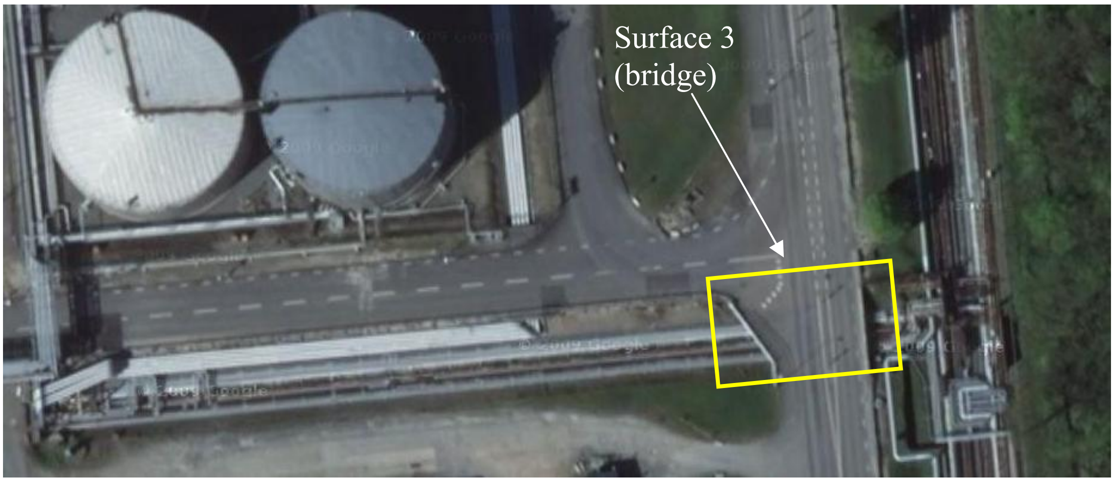


Figure 9.34 Detailed emplacement of the Surface 3.

The main surface tested (side A) was $28m^2$ and the two sides (B at the landside and C at the seaside) were 5 and 4 m^2 respectively.

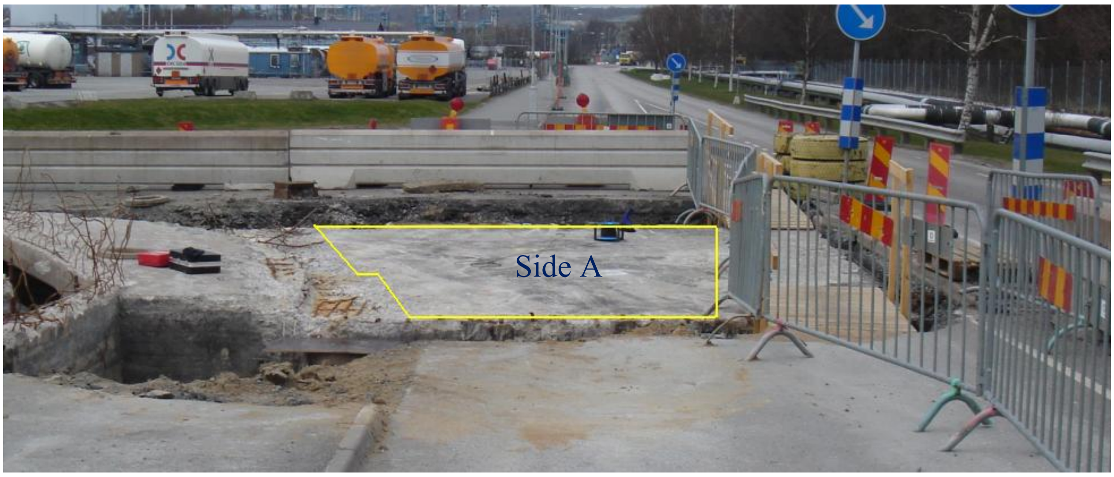


Figure 9.35 Surface 3 with the side A marked.

It wasn't necessary to drill a hole to achieve the electrical connection because different destructive tests were present at the area and was possible to establish directly the connection with the pliers.

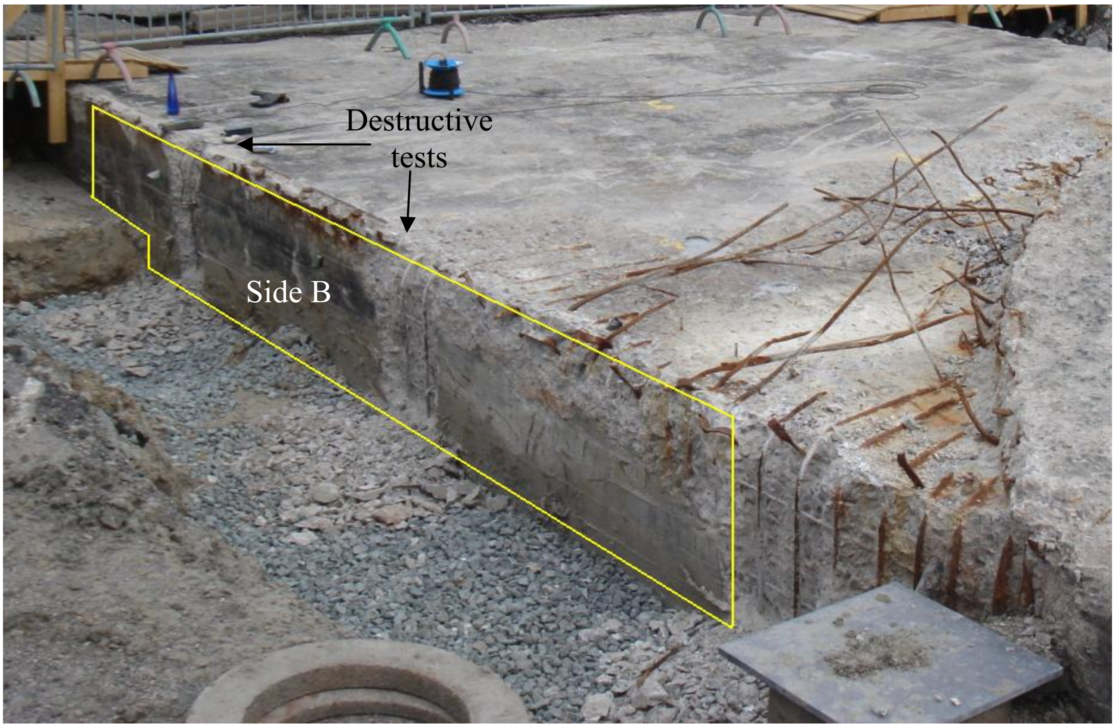


Figure 9.36 Side B. It's possible to appreciate the destructive tests inside this side.

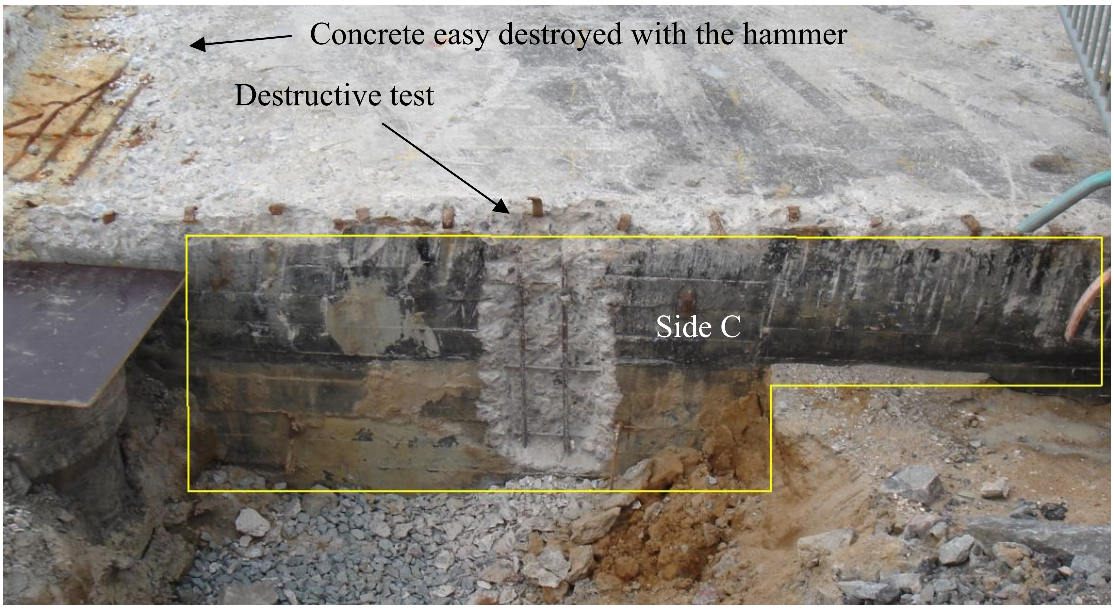


Figure 9.37 Side C. It's possible to appreciate the destructive test inside this side.

As it's possible to see for example at the Figure 9.37, the destroyed concrete was white and was easy to break it using a hammer. For these reasons the concrete was probably under the effect of the carbonation.

9.3.1 Testing the side A of the Surface 3

9.3.1.1 Results from the side A of the Surface 3

The results of the tests at the side A (horizontal) are the following. For the establishment of a visual hierarchy, the colour scale for the corrosion index was modified in all the tests of the Surface 3:

Map of Corrosion Rate [µm/year]

Colour Scale

Xcorr <=	0,5	Negligible
<=	1	Low
<=	4	Moderate
	>4	High

Project: T100426

N

Slope

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
L1	0	0	0	0,1	0	0	0	0	1,1	0,1	0	0,1	1,4	0,8
L2	0,1	0	0	0	0	1,5	0	0	2,7	0	>500	>500	0	0
L3	0	0	0	0	0	0	0	0	0	0	0	0	0	0,1
L4	0	0	0,3	0,7	0	0,1	0	0	0	0	0	0,1	0,5	0,3
L5	0,1	0,1	0,6	0,1	0	0,3	0	0,2	0,1	1	0,2	0,4	0,5	0,4
L6	0,7	0,1	0,1	0,6	1,7	0,7	0,1	0,1	1,3	2,1	0,6	0,6	8,5	7,9
L7	1,1	2,8	8,9	2	0,5	0,5	1,9	0,3	0,7	1,2	0,5			
L8	1,2	0,6	1,4	2	0,9	0,6	1,3	0,7						

Map of Corrosion potential [mV_{CSE}]

Colour Scale

Ecorr >=	-200	Low possibility
>=	-350	Uncertain
	<-350	High possibility

Project: T100426

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
L1	-153	-163	-131	-106	-84	-61	-117	-127	-75	-87	-102	-102	-155	-159
L2	-115	-104	-4	-17	-3	-1	-19	-29	-30	-24	-50	-51	-48	-123
L3	-103	-71	-59	-63	-82	-72	-74	-87	-95	-98	-128	-144	-178	-187
L4	-155	-153	-130	-110	-75	-98	-63	-46	-84	-112	-165	-136	-177	-151
L5	-175	-154	-130	-100	-82	-103	-88	-134	-168	-161	-156	-150	-152	-142
L6	-213	-207	-163	-140	-136	-150	-154	-161	-191	-202	-134	-121	-155	-139
L7	-210	-222	-193	-174	-152	-133	-148	-137	-122	-144	-98			
L8	-199	-200	-189	-155	-121	-82	-80	-93						

Map of Resistivity [kΩ·cm]

Colour Scale

Ro >=	500	Very dry
>=	100	Moderate dry
	<100	Very moist

Project: T100426

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
L1	133	148	121	67	159	67	48	82	55	63	126	53	24	35
L2	246	268	142	165	171	63	100	187	70	174	26	21	136	103
L3	142	163	94	108	101	91	100	96	77	136	95	85	77	50
L4	60	73	24	17	73	46	64	89	86	112	108	39	32	46
L5	48	51	35	47	110	32	122	52	31	23	34	29	30	52
L6	33	50	49	39	36	35	68	62	16	27	31	43	71	113
L7	24	21	10	18	45	30	42	32	42	45	58			
L8	31	30	22	17	24	26	37	34						

Map of Corrosion Index

Colour Scale

1	Negligible
2	Low
3	Moderate
4	High

Criteria for Corrosion Index

Xcorr_negligible	0,5	µm/year
Xcorr_low	1	µm/year
Xcorr_high	4	µm/year
Ecorr_low	-200	mV
Ro_low	100	kΩ·cm

Project: T100426

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
L1	1	1	1	1	1	1	1	1	2	1	1	1	2	1
L2	1	1	1	1	1	2	1	1	2	1	3	3	1	1
L3	1	1	1	1	1	1	1	1	1	1	1	1	1	1
L4	1	1	1	1	1	1	1	1	1	1	1	1	1	1
L5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
L6	2	1	1	1	2	1	1	1	2	3	1	1	3	3
L7	3	3	3	2	1	1	2	1	1	2	1			
L8	2	1	2	2	1	1	2	1						

Figure 9.38 Results Surface 3, side A. Criteria for corrosion index modified.

9.3.1.2 Discussion of the results from the side A of the Surface 3

As it's shown at the Figure 9.38 at the map of corrosion rate, the hypothesis commented before about the effect of the slope can be proved. The points which are at the lower part of the surface have a higher corrosion rate value. The measurements L2M11 and L2M12 can be classified like as invalid because the value is ">500".

As the results indicate, the most important problems regarding the corrosion are at the lower points but especially near the two sides (B and C).

The results of the corrosion index are minimized because the effect of a low possibility of corrosion obtained at the map of corrosion potential.

At the map of resistivity can be checked that the moisture is enough.

Looking the destructive tests made before the RapiCor measurements, it's possible to appreciate that the bars near the line 8 are corroded. For this reason the results of this line 8 should be at least classified as "Low" but at some points the classification is "Negligible". Changing the cover depth to 50 mm the results change very much, the average of the cover depth measured was 70mm. So, if the cover meter were measuring deeper than the reality, the results would change a lot, see Figure 9.39:

Map of Corrosion Rate [μm/year]

Project: T100426

Colour Scale		
Xcorr <=	0,5	Negligible
<=	1	Low
<=	4	Moderate
	>4	High

N

Slope

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
L1	0	0	0	0,2	0	0	0	0	2,9	0,2	0	0,3	2,7	1,3
L2	0,1	0	0	0	0	3,8	0	0	6,4	0	>500	>500	0	0
L3	0	0	0	0	0	0	0	0	0	0	0	0	0	0,1
L4	0,1	0	0,8	1,9	0	0,4	0	0	0	0	0	0,3	0,8	0,4
L5	0,1	0,2	1	0,3	0	0,8	0	0,5	0,5	2	0,4	0,7	0,8	0,6
L6	1,4	0,2	0,3	1,4	3,9	1,7	0,3	0,2	3,9	4,6	1,8	1,3	14,3	12,7
L7	2,2	5,5	20,8	5	1,1	1,7	5	1	1,9	2,1	1,1			
L8	2,2	1,1	2,7	4	1,8	1,4	3	1,7						

Map of Corrosion potential [mV_{CSE}]

Project: T100426

Colour Scale		
Ecorr >=	-200	Low possibility
>=	-350	Uncertain
	<-350	High possibility

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
L1	-153	-163	-131	-106	-84	-61	-117	-127	-75	-87	-102	-102	-155	-159
L2	-115	-104	-4	-17	-3	-1	-19	-29	-30	-24	-50	-51	-48	-123
L3	-103	-71	-59	-63	-82	-72	-74	-87	-95	-98	-128	-144	-178	-187
L4	-155	-153	-130	-110	-75	-98	-63	-46	-84	-112	-165	-136	-177	-151
L5	-175	-154	-130	-100	-82	-103	-88	-134	-168	-161	-156	-150	-152	-142
L6	-213	-207	-163	-140	-136	-150	-154	-161	-191	-202	-134	-121	-155	-139
L7	-210	-222	-193	-174	-152	-133	-148	-137	-122	-144	-98			
L8	-199	-200	-189	-155	-121	-82	-80	-93						

Map of Resistivity [kΩ·cm]

Project: T100426

Colour Scale		
Ro >=	500	Very dry
>=	100	Moderate dry
	<100	Very moist

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
L1	75	83	58	41	113	86	65	95	51	41	106	36	15	20
L2	110	151	120	129	129	60	114	155	63	128	23	17	75	47
L3	85	101	106	110	102	114	119	106	104	109	88	75	57	31
L4	35	43	17	13	76	32	98	110	107	82	80	24	18	23
L5	29	32	22	30	97	24	121	40	20	16	22	18	17	28
L6	23	31	34	31	30	29	46	42	14	21	27	32	38	49
L7	16	14	9	15	34	26	41	25	37	25	39			
L8	21	20	15	11	17	19	30	28						

Map of Corrosion Index

Project: T100426

Colour Scale	
1	Negligible
2	Low
3	Moderate
4	High

Criteria for Corrosion Index		
Xcorr_negligible	0,5	μm/year
Xcorr_low	1	μm/year
Xcorr_high	4	μm/year
Ecorr_low	-200	mV
Ro_low	100	kΩ·cm

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
L1	1	1	1	1	1	1	1	1	2	1	1	1	2	2
L2	1	1	1	1	1	2	1	1	3	1	3	3	1	1
L3	1	1	1	1	1	1	1	1	1	1	1	1	1	1
L4	1	1	1	2	1	1	1	1	1	1	1	1	1	1
L5	1	1	1	1	1	1	1	1	1	2	1	1	1	1
L6	3	1	1	2	2	2	1	1	2	4	2	2	3	3
L7	3	4	3	3	2	2	3	1	2	2	2			
L8	2	2	2	2	2	2	2	2						

Figure 9.39 Results Surface 3 side A with the input data modified. Criteria for corrosion index modified.

9.3.2 Testing the side B of the Surface 3

9.3.2.1 Results from the side B of the Surface 3

After testing the side A, the side B was tested obtaining the following results:

Map of Corrosion Rate [µm/year]

Project: T100427A

Colour Scale		
Xcorr <=	0,5	Negligible
<=	1	Low
<=	4	Moderate
	>4	High

	M1	M2	M3	M5	M6	M7	M8	M10	M11
L1	0	0	0	0	0,3	0	0	>500	0,6
L2	0	0	0	0	0	0	0	2,2	0

Map of Corrosion potential [mV_{CSE}]

Project: T100427A

Colour Scale		
Ecorr >=	-200	Low possibility
>=	-350	Uncertain
	<-350	High possibility

	M1	M2	M3	M5	M6	M7	M8	M10	M11
L1	-35	18	7	-45	-24	-28	-101	-119	-65
L2	13	18	70	57	-5	-28	-79	-80	-66

Map of Resistivity [kΩ·cm]

Project: T100427A

Colour Scale		
Ro >=	500	Very dry
>=	100	Moderate dry
	<100	Very moist

	M1	M2	M3	M5	M6	M7	M8	M10	M11
L1	137	121	131	134	53	106	139	60	69
L2	142	92	161	156	134	149	117	40	133

Map of Corrosion Index

Project: T100427A

Colour Scale	
1	Negligible
2	Low
3	Moderate
4	High

Criteria for Corrosion Index		
Xcorr_negligible	0,5	µm/year
Xcorr_low	1	µm/year
Xcorr_high	4	µm/year
Ecorr_low	-200	mV
Ro_low	100	kΩ·cm

	M1	M2	M3	M5	M6	M7	M8	M10	M11
L1	1	1	1	1	1	1	1	3	1
L2	1	1	1	1	1	1	1	1	1

Figure 9.40 Results Surface 3, side B. Criteria for corrosion index modified.

9.3.2.2 Discussion of the results from the side B of the Surface 3

All these tests show that only appear problems after the measurement 10 (the lower test points) and like happened before, they are minimized because the corrosion potential.

9.3.3 Testing the side C of the Surface 3

9.3.3.1 Results from the side C of the Surface 3

Following the results of the side C are exposed. It's important to clarify that now the lower points are at the measurements 1 and 2.

Map of Corrosion Rate [µm/year]

Project: T100427B

	M1	M2	M4	M5	M6
L1	0,1	0	0,4	0,1	0
L2	0	0	0,2	0,6	2,2
L3	0	0	0,1		

Colour Scale

Xcorr <=	0,5	Negligible
<=	1	Low
<=	4	Moderate
	>4	High

Map of Corrosion potential [mV_{CSE}]

Project: T100427B

	M1	M2	M4	M5	M6
L1	-17	13	0	-13	-5
L2	-59	-3	18	15	-17
L3	-46	-10	-25		

Colour Scale

Ecorr >=	-200	Low possibility
>=	-350	Uncertain
	<-350	High possibility

Map of Resistivity [kΩ·cm]

Project: T100427B

	M1	M2	M4	M5	M6
L1	72	83	43	74	119
L2	192	220	81	48	51
L3	168	128	58		

Colour Scale

Ro >=	500	Very dry
>=	100	Moderate dry
	<100	Very moist

Map of Corrosion Index

Project: T100427B

	M1	M2	M4	M5	M6
L1	1	1	1	1	1
L2	1	1	1	1	2
L3	1	1	1		

Colour Scale

1	Negligible
2	Low
3	Moderate
4	High

Criteria for Corrosion Index

Xcorr_negligible	0,5	µm/year
Xcorr_low	1	µm/year
Xcorr_high	4	µm/year
Ecorr_low	-200	mV
Ro_low	100	kΩ·cm

Figure 9.41 Results Surface 3, side C. Criteria for corrosion index modified.

9.3.3.2 Discussion of the results from the side C of the Surface 3

No problems of corrosion appear at this side. Only at the L2M6 a value of corrosion appears. The empty test points were impossible to be tested because the presence of earth which could not be removed.

9.3.4 Discussion of the results after waterblasting of Surface 3

Unlike other surfaces which were totally waterblasted, this one was only waterblasted until below the bars in some zones, only until measurement line 5 (included).

Because the good condition of the bars expected at the upper lines wasn’t necessary to replace them. During the waterblasting, a bad quality concrete was removed, in fact, a pressure of only 600 bars was needed while the pressure used for example at the Surface 1 was around 800 bars.

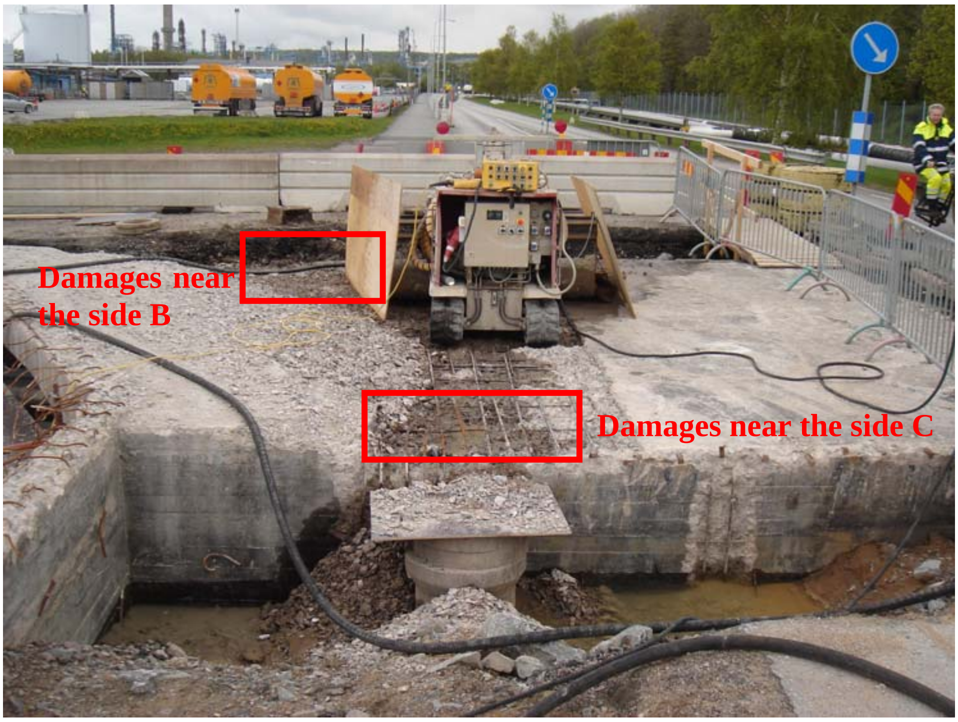


Figure 9.42 Waterblasting the Surface 3, side A. With the zones of corrosion damages marked.

The marked zones were placed at the lower lines measurements (regarding the slope mentioned before). The bars were more corroded near these sides because there were both stone cornices (parapets) where the water was accumulated causing cracks because of the ice expansion in the freezing and defreezing processes and increasing the chloride concentration.

Figure 9.43 Detail of the damages at the side A test points L6M13 and L6M14.

As can be seen at the previous image and with the results showed at the Figures 9.38 and 9.39 these damages were classified as “Moderate”.

Figure 9.44 Detail of the damages at the side A test points L7M1 and L8M1.

The damages at the horizontal surface near the landside are lower as can be seen at the Figure 9.44. These damages were classified as “Lower” and “Moderate” at the Figures 9.38 and 9.39.

After the damages could be seen the following conclusions were reached:

- The slope of the bridge affects largely the corrosion rate of the reinforcement due to two main reasons: the water is accumulated at this are causing cracks during the winter because of the freezing and defreezing processes and because of the accumulation of the de-icing salts which increase the chloride content and help the process of depassivation of the cover layer of concrete.

- The parapets also affect to the accumulation of the water causing the same effects than the slope.

- The waterblasting process showed that the concrete quality is bad because the pressure to take it away was less than the pressure used in the other surfaces. Probably the bad quality of the concrete is due to the carbonation detected by the tests which the Port was carrying out.

- There is a suspicion about the Profometer measurements because is thought that was showing more depth than was in the reality. That could be because of the carbonation of the concrete. If the input parameter cover depth is increased, the corrosion rate is being underestimated. This aspect was discussed with the Figures 9.38 and 9.39.

10 Final Conclusions

The prediction of corrosion damages obtained by RapiCor was accurate in most of cases but some errors were detected because different reasons (which are as follows).

It's important to wet the surface five minutes before the tests and immediately before. Despite these surfaces are next to the sea, the heavy wind can dry the surface. The concrete must be moist enough to be able to carry the polarization current to the reinforcement. To achieve high moisture in vertical surfaces, could be interesting the study of some gels which viscosity allow to remain more time wetting the test points.

It´s difficult to know which part of the reinforced steel is affected by the polarization current for the calculation of the steel density.

It´s also difficult to clean the hole of powder to install the bolt and achieve a good electrical connection. This powder causes problems to extract the bolt when the tests are finished because it's hardened.

The input data can be stored using the keyboard of the hand held equipment or after the tests at the laptop. It´s better to do it at the laptop.

Testing the vertical surfaces can be difficult. When the position of the tester is not so much comfortable, the surface tested is in a vertical position and if it's heavy windy, reach a good polarization curve without any external movement is a hard job.

It's not possible to test in surfaces affected by delamination.

It is not possible to use the RapiCor equipment in a waterblasted surface.

It is possible to test in a surface made of asphalt or sand and rocks even if it's wet.

If there is ice in the surface of the concrete, it should be removed.

The most effective grid is 50 x 50 cm trying to match up with the bars.

The waterblasting process is a destructive method which can determinate the quality of the concrete measuring the variation on the depth achieved maintaining constant the pressure and the feed rate.

There are steel density variations when for example a pile is under the surface. These variations affect to the results.

For all these reasons, some simple modifications could improve the equipment:

- It could be a good idea start improving the connexion of the 3-ways cable because during the use, there were problems of disconnections.

- Another easy modification is to give more embossed shape to the buttons, because it´s difficult to press them when the operator is using gloves.

- If it’s possible, could be interesting include a cover detector to carry out these measurements just before of the polarization method. This modification could save even more time.

- For the measurements on vertical surfaces, add to the sensor some kind of anchor bolts to firmly fix the sensor to the sample, could facilitate the achievement of a good polarization current curve.

- Extending the cable which joins the handheld equipment with the sensor, better measurements could be reached because the position of the tester is going to be more comfortable.

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