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Rapid Assessment of Reinforcement Corrosion in Concrete Bridges

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Contents

Abstract

This report presents the results from the research project “Rapid assessment of reinforcement corrosion in concrete bridges”. In this project the effect of moisture in concrete on the measurement of corrosion by the RapiCor was studied in the laboratory. The RapiCor technique was used on over 20 real bridge concrete structures in order to evaluate its applicability for assessment of corrosion conditions of reinforcement steel in real bridge concrete structures. The results measured by the RapiCor from 13 bridge structures are presented in this report. From the laboratory study conclusions can be drawn that wetting-drying cycles apparently affect the resistivity of concrete and half-cell potential of steel, but not significantly affect the corrosion rate, if the corrosion rate is in the range of moderate to high corrosion. From the field evaluation the conclusions include that the RapiCor can in general be effectively used in assessment of corrosion conditions of reinforcement steel in bridge concrete structures with satisfactory precision, and that the weather will not significantly affect the assessment of corrosion conditions by the RapiCor technique. Based on the conclusions some suggestions are given for proper use of the RapiCor technique in assessment of corrosion conditions of reinforcement steel in the bridge concrete structures.

1 Introduction

Reinforcement corrosion is one of the most serious problems causing deterioration of reinforced concrete structures. In Sweden there are over ten thousands road bridges that are exposed to deicing salt or marine environment and are periodically inspected. So far routine inspection of concrete bridges is mainly based on ocular examinations, from which potential risks of ongoing corrosion cannot be detected. The condition assessment of concrete bridges is to a great extent dependent on the personal experience of an inspector. In the past years a rapid non-destructive technique has been developed at SP for measurement of corrosion of steel in concrete. The technique has been verified in the laboratory on both small and large reinforced concrete specimens, but only applied to a limited number of real structures. To utilise this rapid method for bridge inspection further investigation is needed to evaluate its applicability and the interpretation of the measurement results for safer assessments. With the safe assessment of reinforcement corrosion the need for maintenance can be more safely estimated and more optimal bridge maintenance can be realised.

In this project the rapid technique will be further developed to adapt to practical bridge inspections. The project includes the following activities:

Activity 1 – Laboratory study. In this activity the effect of humidity on the measurement of corrosion including corrosion rate, half-cell potential and resistivity were studied. Both new and old concrete specimens with embedded steel bars were used in the study. The work from this activity is summarised in Chapter 3.

Activity 2 – Further development of the instrument. In this work five pieces of hand-held prototype instrument were manufactured and three of them were sent to potential inspectors for field measurement. A short course was held to train inspectors to use the instrument as well as to be able to properly collect measurements and other important information. The work is summarised in Chapter 4.

Activity 3 – Field evaluation. In this part of work over 20 real bridge concrete structures were inspected by three individual groups, that is, KFS in Stockholm, CBI in Stockholm and students of Linköping University with the help of Vägverket Region Mälardalen. The results measured by the RapiCor were compared with either chloride content near reinforcement steel or visual examination on the exposed reinforcement steel bars after removal of concrete by water-jetting. The measurement results from 13 bridge concrete structures containing various parts of structure are presented in Chapter 5.

Activity 4 – Scientific and technical supplement. In this work the scientific basis of appropriate criteria for evaluation of reinforcement corrosion was summarized. Furthermore, the methodology is technically completed in accordance with scientific development and feedback from the field evaluation to be adapted to the complex reality. The instrument was upgraded with the function of project view in which the map of corrosion index can be seen directly after the measurement so as to be able to make a quick "Go / No-Go" assessment of reinforcement condition, i.e. "No corrosion" or "Corrosion in progress". The work involved in this activity is summarised partly in Chapter 4 and partly in the guidelines for proper use of the instrument.

As the final activity, in Chapter 6 the conclusions based on the above activities are drawn and suggestions are given.

2 New technique for rapid assessment of corrosion

In the past years, through a number of research projects Tang (2002a; 2002b; 2002c) developed a new method based on the galvanostatic pulse technique in consideration of the time-dependent behaviour of polarisation and with the help of mathematical modelling for estimation of current distribution. This technique was further developed by Tang & Fu (2006) and implemented as a handheld instrument, called RapiCor, for application to the real structures for rapid mapping corrosion of steel. The measurement principle is illustrated in Figure 2.1. This new technique has been verified with both small and large specimens exposed in the laboratory as well as the field exposure sites [Tang, 2002b; Tang & Utgenannt, 2007].

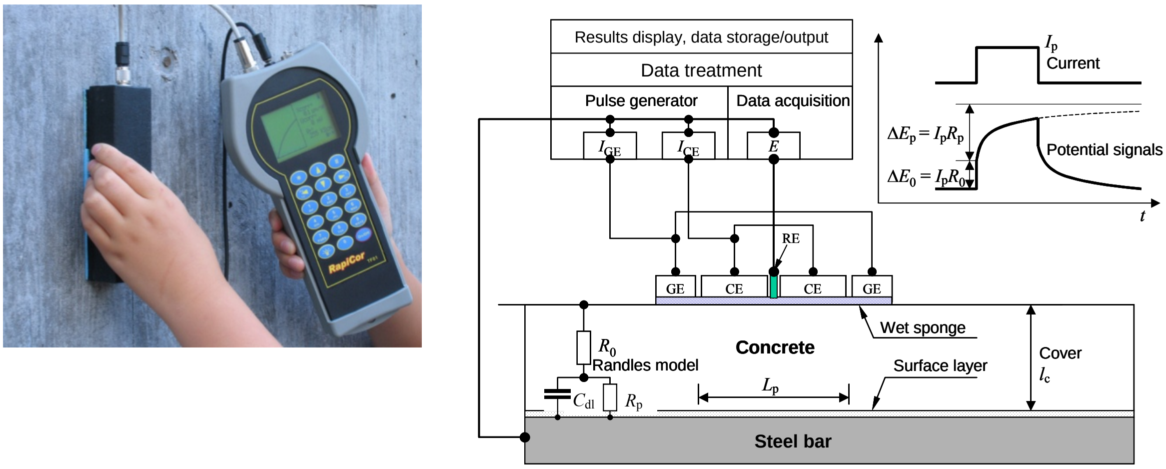


Figure 2.1 Handheld instrument RapiCor (left) and it measurement principle (right)

The advantages of this new instrument include

- *Rapidity*: It takes only 5-10 seconds for measurement of three parameters, i.e. corrosion rate, half-cell potential and resistivity of concrete.
- *Simplicity*: For general engineering applications, it does not need an ordinary user to set some complicated parameters that may confuse the user or result in different measurement values.
- *Reliability*: As a polarization technique, the polarization curve is clearly visible in order to give the user information to judge if the measurement has been properly carried out or anything wrong in the measurement, so as to be able to correct any mistake in situ.
- *Safety*: To reach the rapidity, the storage of measurement data must be very safe. The data should not be destroyed or disappeared due to any interruption of battery. Therefore, the DataFlash memory chip was used in the instrument for rapid and safe storage of the data.
- *Practicality*: For more practical uses, the instrument was designed as
  - tight enclosure that should fulfil protection class IP65 (DIN40050/IEC529, protection from dust and a jet of water), in order to be used in the environments with splash water;
  - low power consumption for long time measurement (about 100 hr continuous use with 4 pieces of ordinary R6 battery); and
  - small sensor unit with a stable gel type of Ag/AgCl reference electrode for easy use and maintenance/replacement.

The basic equation for calculation of corrosion rate, X_{corr}, from a polarisation measurement is as follows:

$$X_{\mathrm{corr}} = \frac{BM}{\rho z F} \cdot \frac{I_{\mathrm{p}}}{A \cdot \Delta E_{\mathrm{p}}} = C \cdot \frac{I_{\mathrm{p}}}{A \cdot \Delta E_{\mathrm{p}}} \tag{2.1}$$

where

B:	constant which is often assumed as 26 mV [Andrade & González, 1978],
M:	molecular weight of metal (M = 56 g/mol for Fe),
ρ:	specific density of metal (ρ = 7.85 g/cm^3 for Fe),
z:	number of ionic charges (z = 2 for Fe),
F:	Faraday constant (F = 96480 C/mol or A·s/mol),
I_{p}:	polarisation current, often in μA,
A:	polarisation area, often in cm^2, and
ΔE_{p}:	polarisation potential, often in mV.

All the above constants can be replaced with a new constant C = 302 [(μm/yr)·(mV·cm^2/μA)], resulting in a dimension of μm/yr for X_{corr}, if the values of polarisation current I_{p}, polarisation area A and polarisation potential ΔE_{p}, have the dimensions μA, cm^2 and mV, respectively.

In this new technique, the effective polarisation current I_{p} is calculated from the imposed galvanostatic current and the mathematic modelling for a single steel bar, and the polarisation potential ΔE_{p} is obtained from the polarisation curve [Tang, 2002c]. In real reinforced concrete structures the reinforcement bars are, however, connected each other. When the electrical current is imposed to the sensor (electrodes unit), which is placed on the concrete surface above the localised bar, the current will not only flow to the localised bar, but also partly flow through the concrete to the adjacent steel bars. Although it is difficult to exactly quantify how much amount of current flowing to the adjacent bars, it is reasonable to assume that this "bypassed" current is related to the size of sensor, conductivity of concrete, corrosion condition and distance between steel bars. Thus for a reinforcement network as shown in Figure 2.2, the following equation was proposed for calculating the effective area of reinforcement, A, to which the polarisation current has flowed:

$$A = L_{\mathrm{p}} \cdot \pi \cdot \left[n_{\mathrm{L}} D_{\mathrm{L}} \left(1 + \frac{\alpha b_{\mathrm{s}}}{d_{\mathrm{L}}} \right) + n_{\mathrm{T}} D_{\mathrm{T}} \frac{\beta L_{\mathrm{s}}}{d_{\mathrm{T}}} \right] \tag{2.2}$$

where L_{p} is 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 steel bars, b_{s} and L_{s} are the apparent wideness and length of the sensor, respectively, and α and β are coefficients, whose values are dependent on the number of adjacent bars, the conductivities of concrete and surface film of steel. In most cases $\alpha = \beta = 2$. The subscript "L" and "T" denote longitudinal and transverse direction of steel bars, respectively.

Since the ohmic resistance, R_{Ω}, can also be obtained from the galvanostatic pulse, the resistivity of concrete cover can be estimated by the following equation:

$$\rho_{\mathrm{c}} = R_{\Omega} \cdot \frac{(A_{\mathrm{sp}} + A)}{2 l_{\mathrm{c}}} \tag{2.3}$$

where A_{sp} is the area of moist sponge in connection between the sensor and the concrete surface and l_c is the thickness of concrete cover.

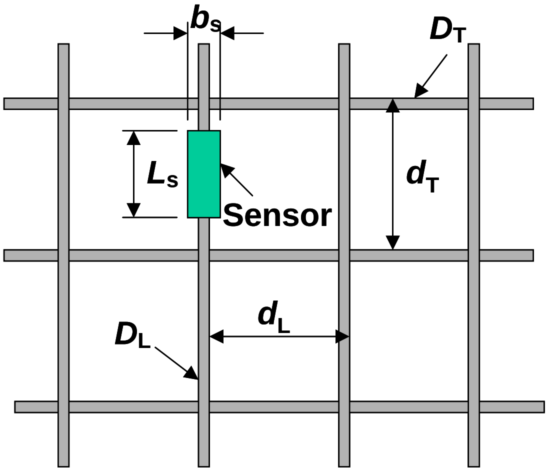


Figure 2.2: Illustration of reinforcement network in a real concrete structure

3 Effect of moisture on the corrosion measurement

3.1 Concrete slabs embedded with steel bars

Concrete slabs of size 250 × 250 × 70 mm with w/c 0.5 and with different chloride introductions (0%, 1.5%, 3% and 6 % by mass of cement), were used in the study. Each slab was embedded with two cool-drawn carbon steel bars of diameter 10 mm, in parallel positioned in the centre portion of each slab at the mid-height (about 35 mm), with a space of 100 mm between each other, as shown in Figure 3.1.

The concrete slabs were manufactured in 2001 for a Nordtest project [Tang, 2002b] and a previous SNRA (Vägverket) project [Tang, 2002c]. Some of concrete slabs with 0% chloride introduction were subjected to the chloride migration test under the external electrical field in order to initiate corrosion. Most of the slabs were stored in plastic boxes with water, while some of them were, however, exposed to the indoor air with occasional wetting. Some slabs have only a half part with one steel bar left while another half part was sawn away for the other uses (education, exhibition, destructive test, etc.).

In order to keep the similar conditions for the measurements, all the slabs were dried in the indoor climate for about two month. Afterwards they were subject to wetting-drying cycles at different intervals (3 days and 6 days).

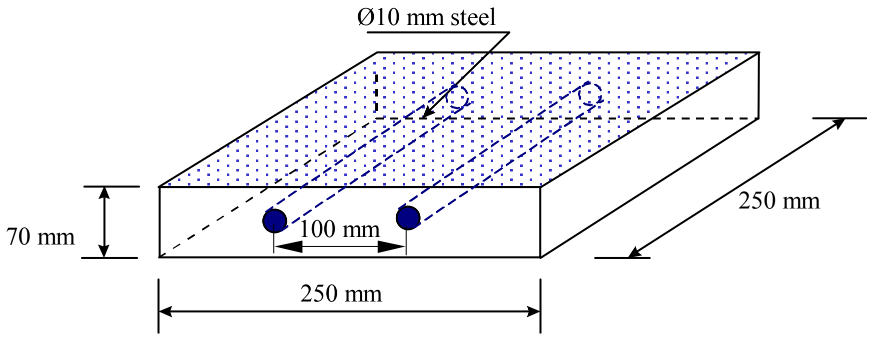


Figure 3.1 Illustration of concrete slabs with two embedded steel bars.

3.2 Corrosion measurement

The corrosion conditions in each steel bar were measured using the RapiCor handheld instrument, which records three parameters, that is, corrosion rate, half-cell potential and resistivity. Detailed measurement procedures were in accordance with the instruction manual (Appendix A). An example of the measurement is shown in Figure 3.2.

Figure 3.2 Example of the corrosion measurement on the concrete slab.

3.3 Classic resistivity measurement

In order to compare the resistivity measured by the RapiCor, a classic method with two plates as shown in Figure 3.3 was employed. The resistivity was calculated from equation (1):

$$\rho = \frac{A}{L} \cdot \left(\frac{U_2}{U_1} - \frac{U_{20}}{U_{10}} \right) \cdot R_{\mathrm{ref}} \tag{3.1}$$

where:

ρ: resistivity of concrete, in kΩ·cm,
A: Test area of the specimen, in cm²,
L: thickness of the specimen, in cm;
R_{ref}: reference resistor, $R_{ref} = 0.100$ kΩ in this study,
U_1, U_2: absolute value of the potential drop across the reference resistor and the specimen (including sponges), respectively, in mV, and
U_{10}, U_{20}: absolute value of the potential drop across the reference resistor and the sponges (without the specimen), respectively, in mV.

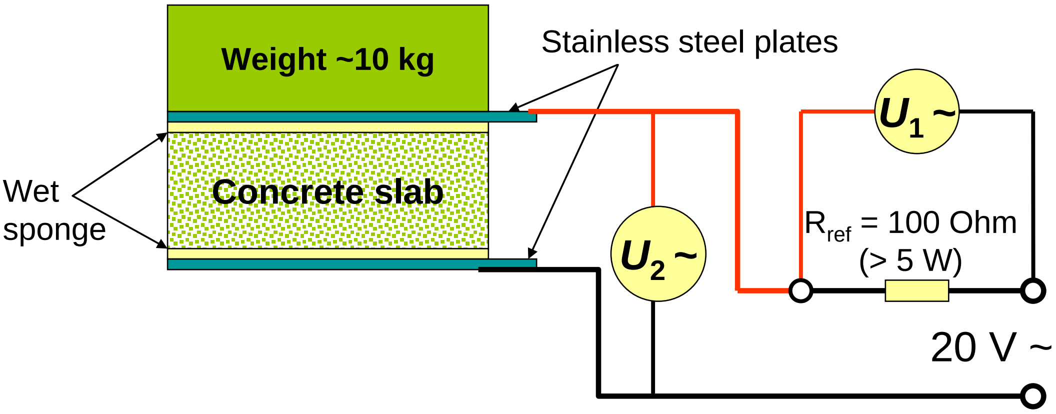


Figure 3.3 Illustration of the classic resistivity measurement.

3.4 A non-invasive measurement of resistivity

The corrosion measurement by the RapiCor at the present requires the connection with the reinforcement network, implying that at least one hole in the concrete structure should be drilled in order to connect to the reinforcement bar. Although there are some commercially available instruments for non-invasive resistivity measurement based on the Wenner four-point method, it is more practical for an inspector to use the same apparatus if a non-invasive technique can be incorporated in the RapiCor instrument for the measurement of resistivity as a preliminary assessment of corrosion risk. Owing to the structural limitation, it is difficult to use the Wenner four-point principle in the RapiCor. Therefore, a three-point method was considered as shown in Figure 3.4. The RapiCor sends a pulse of galvanostatic current I to the concrete from the electrode A to the electrode B. The reference electrode RE at the centre measures the initial potential of response. This potential should be related to the resistivity of concrete in the near surface zone, as expressed in equation (3.2).

$$\rho = k \cdot \frac{U}{I} \qquad (3.2)$$

where:

k: correlation factor,
U: initial potential measured by the reference electrode RE, and
I: galvanostatic current.

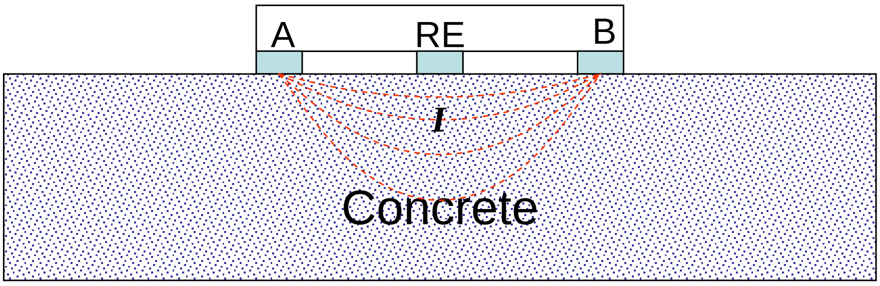


Figure 3.4 Illustration of the three-point resistivity measurement.

3.5 Results from the corrosion measurement

The results from the corrosion measurement are summarised in Figures 3.5.1 to 3.5.9. It can be seen from Figures 3.5.2 - 3.5.3, 3.5.5 - 3.5.6 and 3.5.8 - 3.5.9 that the resistivity of concrete and half-cell potential of steel were apparently changed with the wetting-drying cycles, while the changes in corrosion rate (Figures 3.5.1, 3.5.4 and 3.5.7) seem not exactly to follow the wetting-drying cycles. When the corrosion rate is in the moderate level (5~10 µm/year) to the high level (>10 µm/year), the wetting-drying cycles will not result in the change in corrosion level.

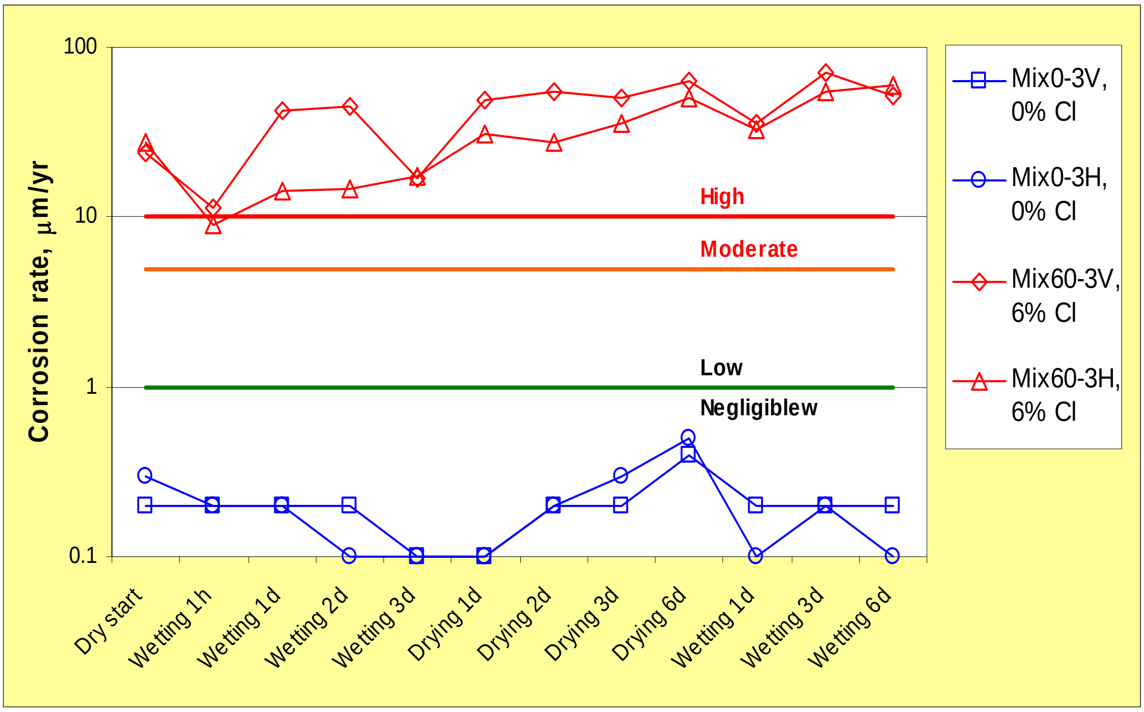


Figure 3.5.1 Corrosion rate of steel bars in concrete without chloride (0%) and with 6% introduced chlorides.

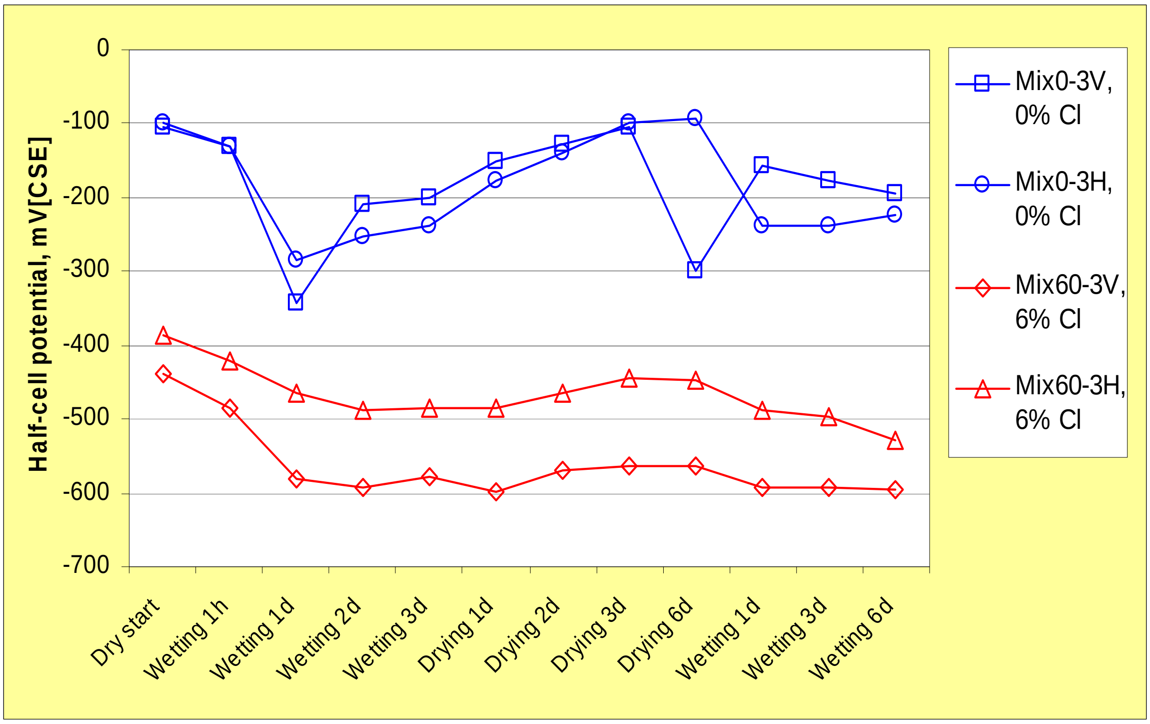


Figure 3.5.2 Half-cell potential of steel bars in concrete without chloride (0%) and with 6% introduced chlorides.

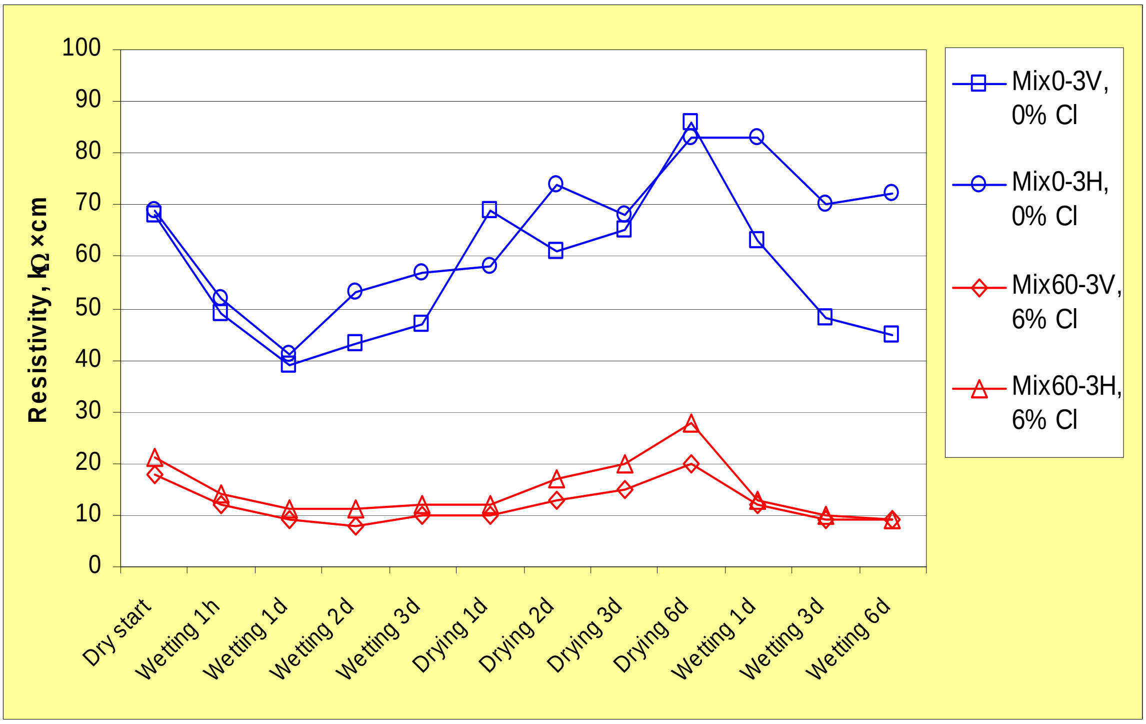


Figure 3.5.3 Resistivity of concrete without chloride (0%) and with 6% introduced chlorides (measured by the RapiCor).

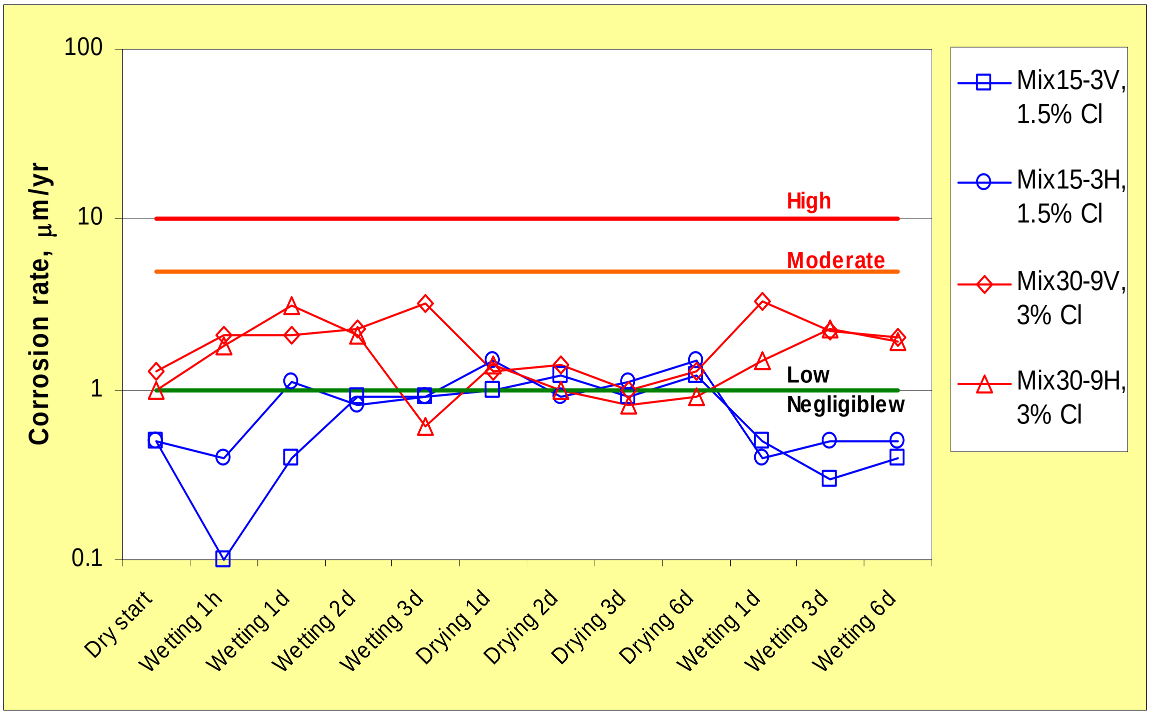


Figure 3.5.4 Corrosion rate of steel bars in concrete with 1.5% and 6% introduced chlorides, respectively.

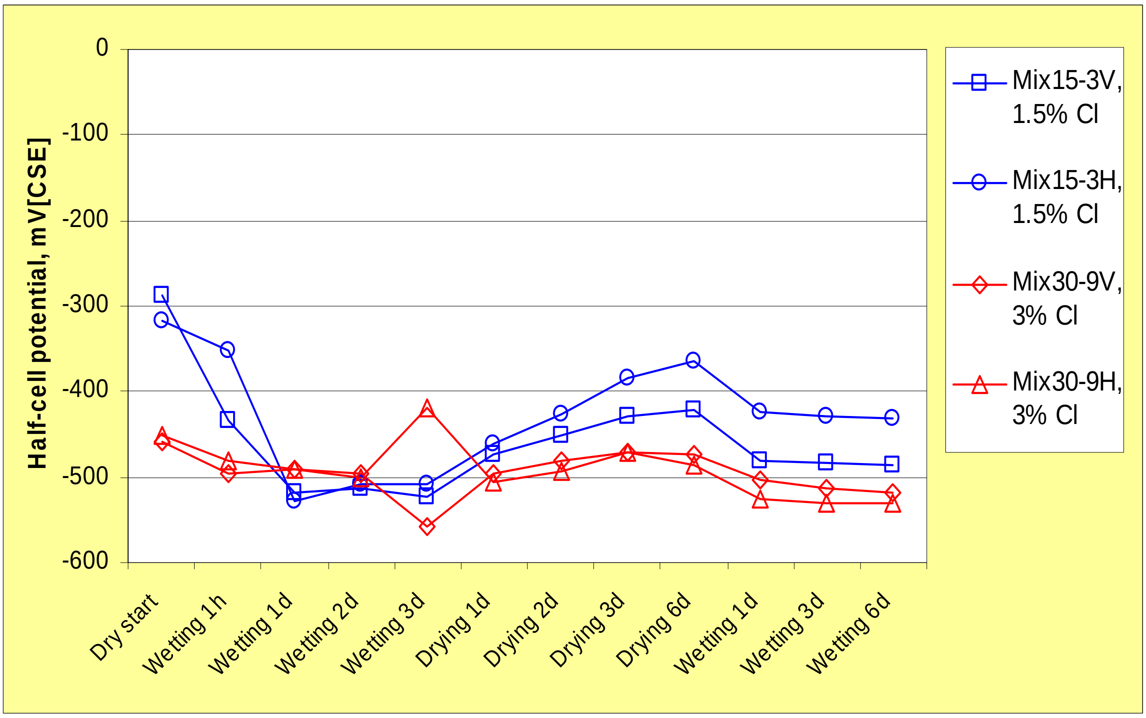


Figure 3.5.5 Half-cell potential of steel bars in concrete with 1.5% and 6% introduced chlorides, respectively.

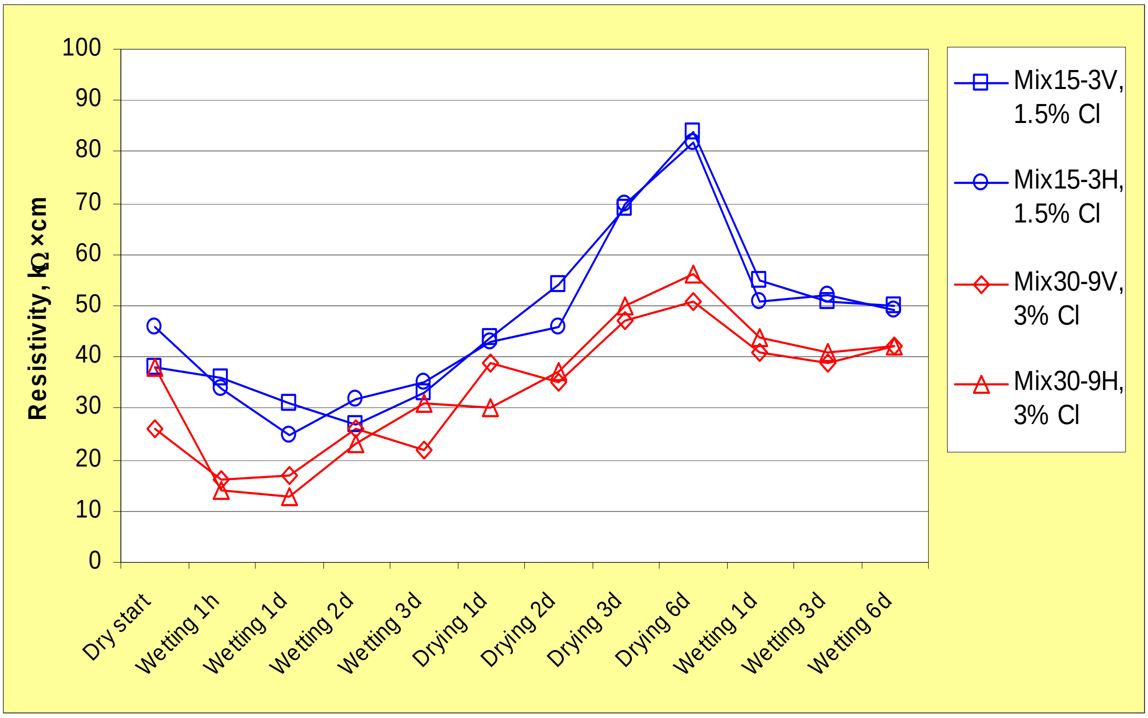


Figure 3.5.6 Resistivity of concrete with 1.5% and 6% introduced chlorides, respectively (measured by the RapiCor).

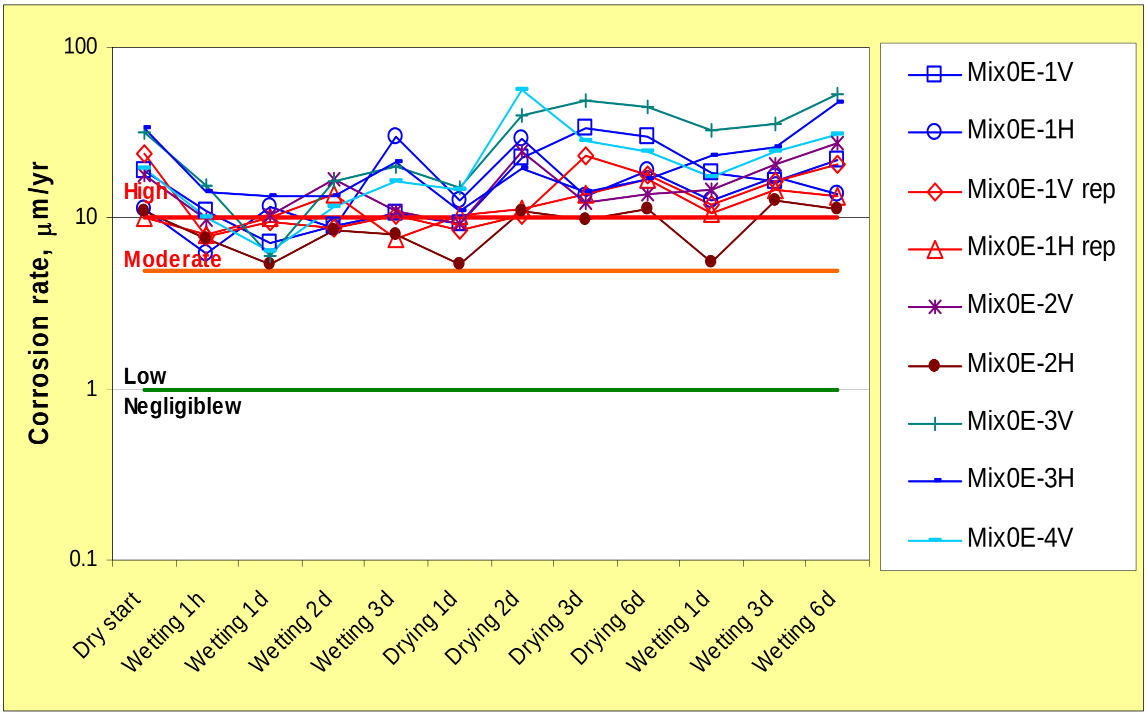


Figure 3.5.7 Corrosion rate of steel bars in concrete with initiated corrosion by chloride migration test.

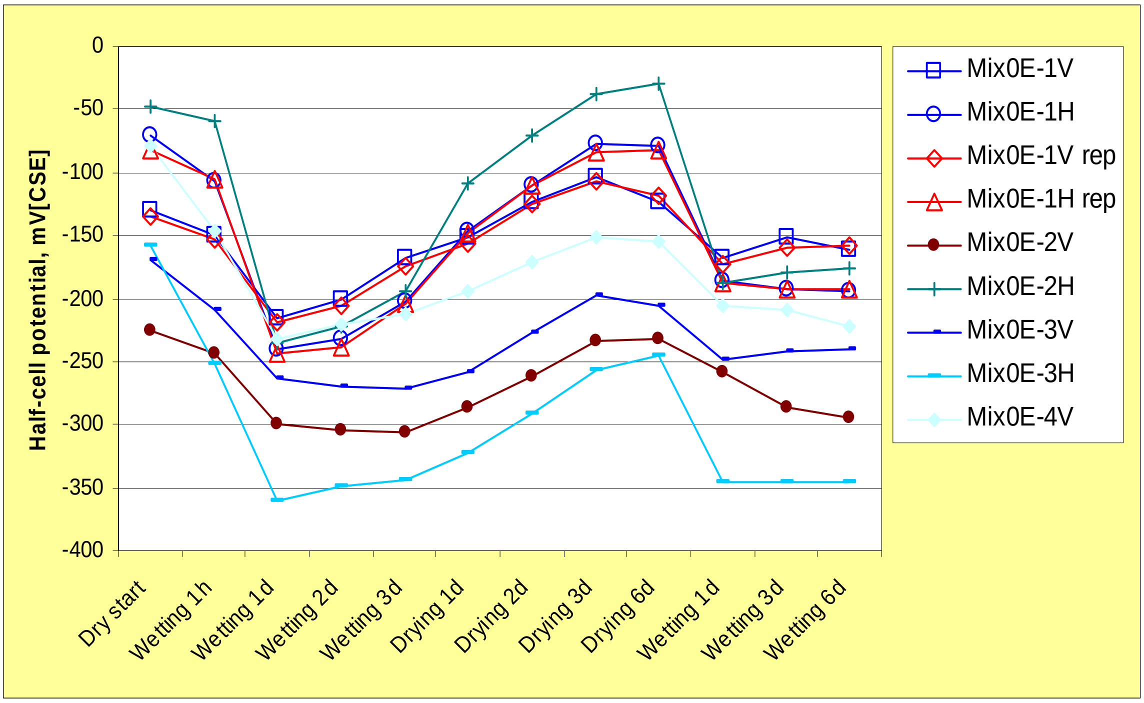


Figure 3.5.8 Half-cell potential of steel bars in concrete with initiated corrosion by chloride migration test.

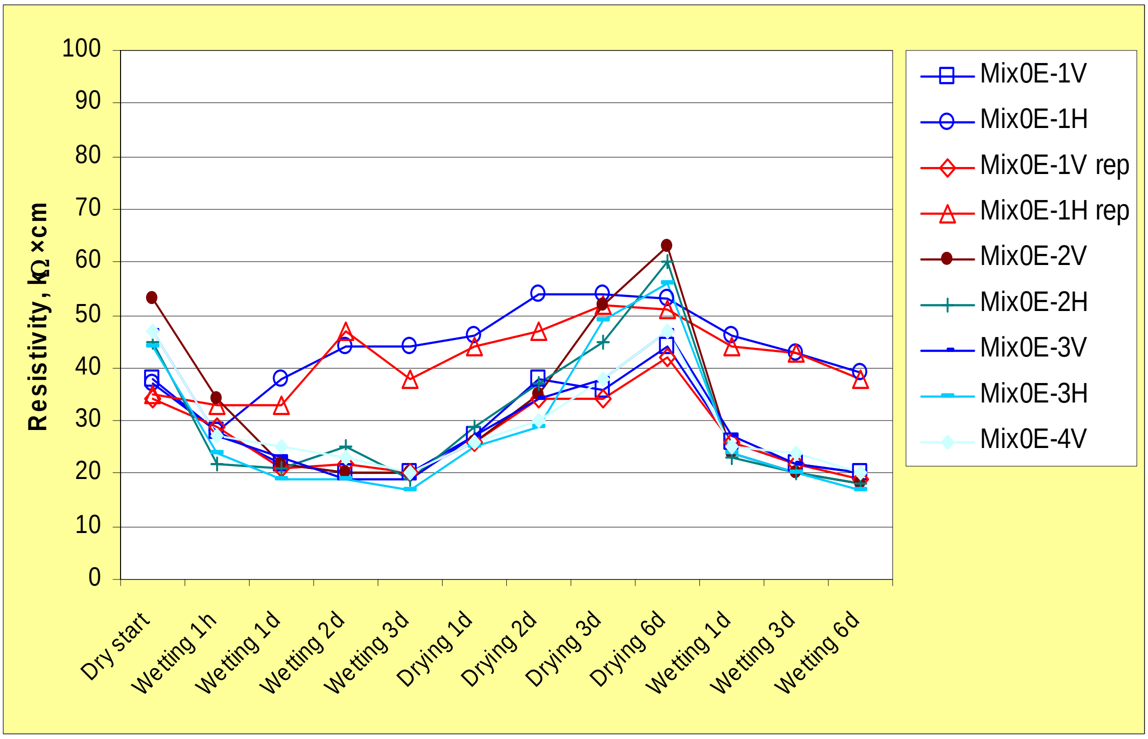


Figure 3.5.9 Resistivity of concrete with initiated corrosion by chloride migration test (measured by the RapiCor).

3.6 Results from different resistivity methods

Figure 3.6.1 shows the comparison between the resistivities measured by the RapiCor and the classic method, indicating that the resistivity measured by the RapiCor is reasonably comparable with the classic method.

In calculation of the resistivity by the three-point method, the constant $k = 2\pi$ was adopted as the first trial. Figure 3.6.2 shows the comparison between the resistivities measured by the RapiCor and the three-point method. When a constant current of 10 mA was used, the slope is 1.085, implying that the actual k value should be a little smaller than 2π. While when a constant current of 50 mA was used, the slope is 0.995, very close to 1, implying that the actual k value is close to 2π. Probably a larger current gave a higher potential response, resulting in a better correlation to the resistivity measured by the RapiCor.

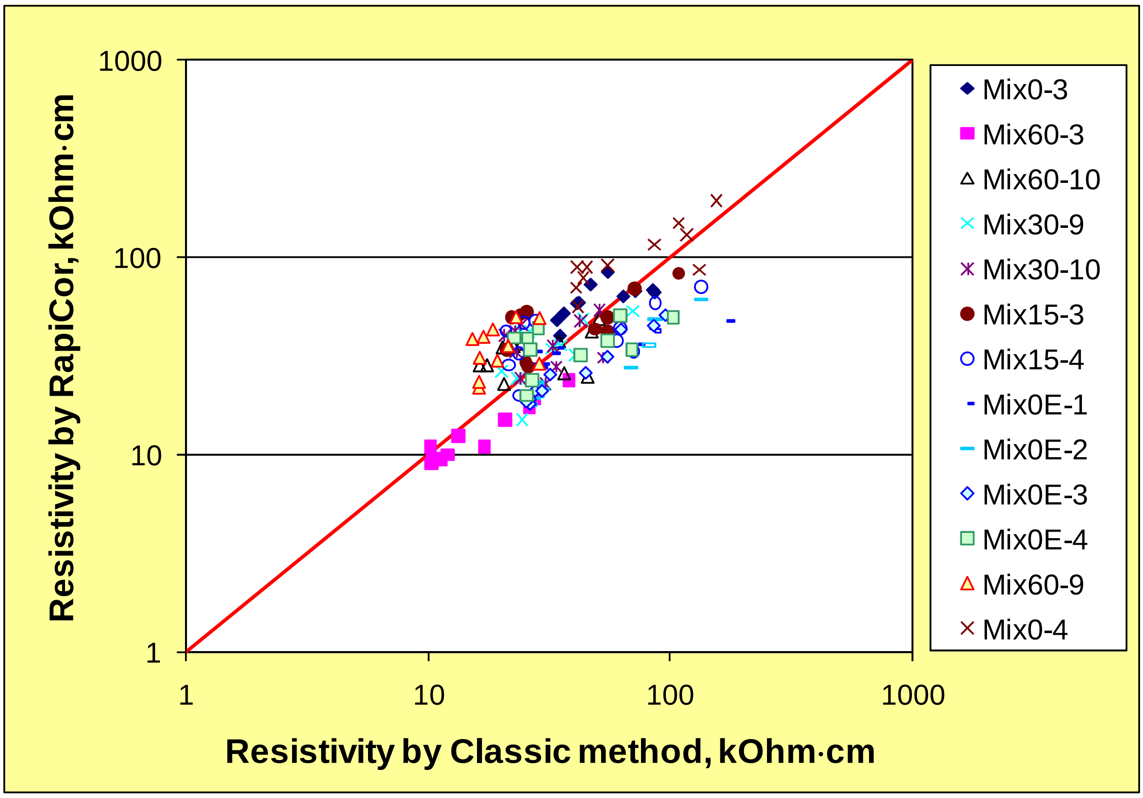


Figure 3.6.1 Comparison between resistivities measured by the classic method and the RapiCor.

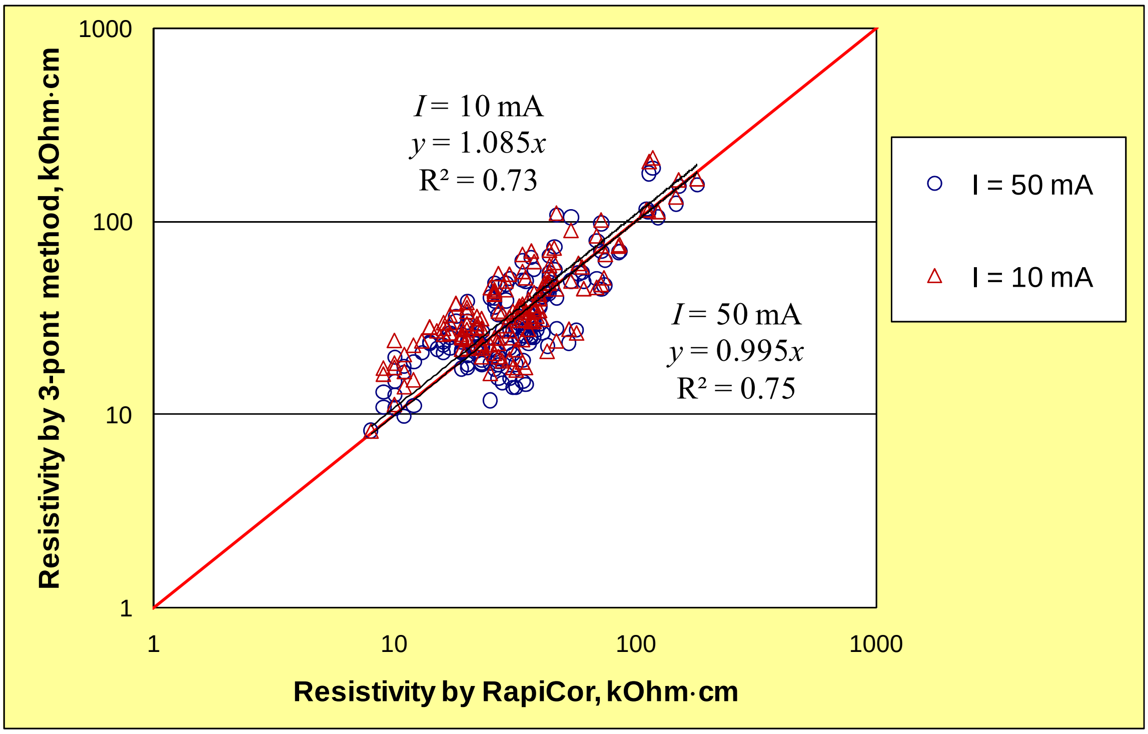


Figure 3.6.2 Comparison between resistivities measured by the three-point method and the RapiCor.

3.7 Relationship between corrosion rate and resistivity

Figure 3.7.1 shows the relationship between corrosion rate and resistivity measured by the RapiCor and the three-point method. It can be seen that when the measured resistivity is higher than 80-120 kOhm·cm, the corrosion rate is under 1 µm/year (negligible level). On the other hand, a low resistivity does not always mean a high corrosion rate, because the steel bar in a wet concrete with low resistivity may not necessarily have corrosion if there is no chloride around the bar. This means that the resistivity can only be used as a supplementary parameter, but cannot be directly used for assessment of corrosion. Therefore, the resistivity of 100 kOhm·cm in the assessment of corrosion level is a reasonable criterion.

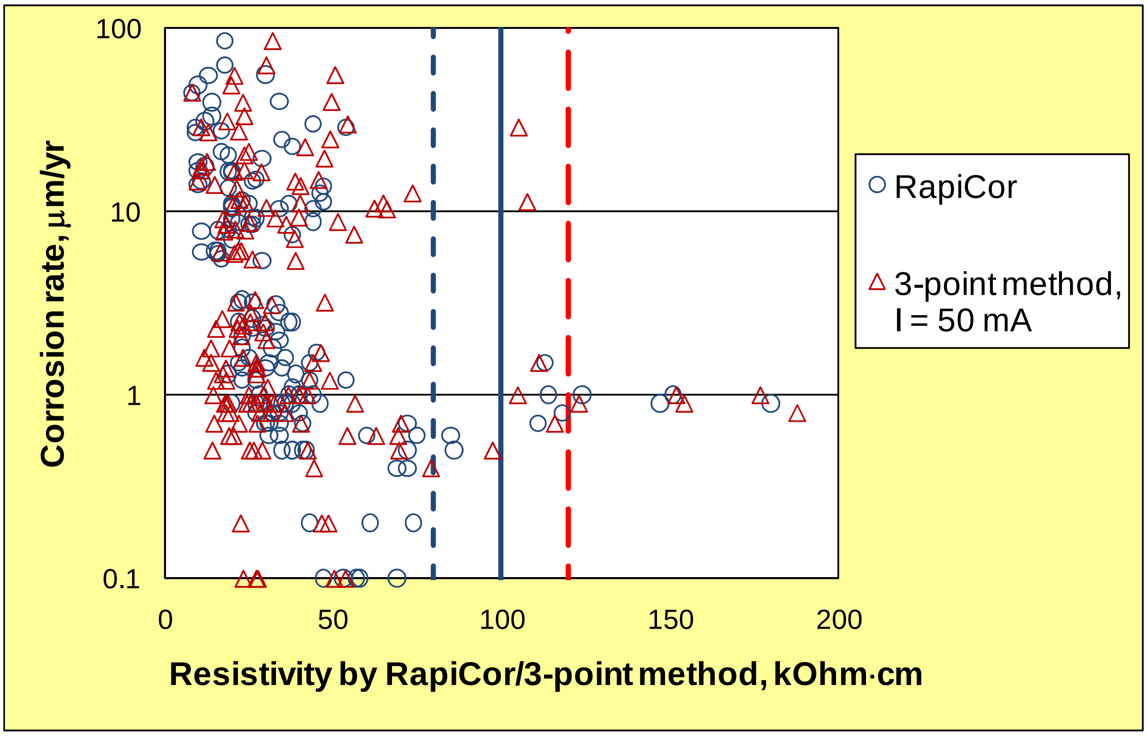


Figure 3.7.1 Relationship between corrosion rate and resistivity measured by the the RapiCor and the three-point method.

4 Preparation for the field application by the potential users

4.1 Further development of the instrument

From the experience after several cases of application of the previous prototype of the handheld instrument, it was realised that further development of the instrument was needed in order to manufacture new prototypes of the instrument for use in this project. In the new prototypes the following improvements were made:

- **New design of the electrodes units** with the possibility to use either simple or more accurate reference electrode. The previous RapiCor used a simple reference electrode only. From the experience it was found that the simple reference electrode is not so stable and can change 20 to 50 mV during the use. This potential shift is a slow process and, therefore, does not affect the corrosion rate measurement (in a few seconds) but will affect the value of half-cell potential. Therefore, it needs frequent calibration in order to assure the accuracy of the half-cell potential measurement. With the new design, the more stable gel type of reference electrode can be used in the measurement. Thus the measurement quality can be improved. Two types of the electrodes unit are shown in Figure 4.1.
- **New design of PCB** (printed Circuit Board) taking into account shielding of signal wires in order to improve signal-noise ratio. It was found that the electrical noise in the previous apparatus is not ideally low, probably due to the interference of the electrical-magnetic field around the wires receiving and amplifying the signals.
- **Software improvement and debugging** in order to find the possible problems in the previous software for handling the signals. It was found that in some special cases the polarisation curve from the previous apparatus looks strange. Sometimes part of the initial curve is cut off, while sometimes there is a sudden lift at the initial point, the

former will result in underestimation of corrosion rate while the latter overestimation of corrosion rate. Possible reasons might be the inhomogeneous resistivity of concrete and non-ideal depolarisation of steel bars, which shifted the compensation potential based on the ideal model. A solution has been found and the improvement of software was made taking into account the non-ideal reality.

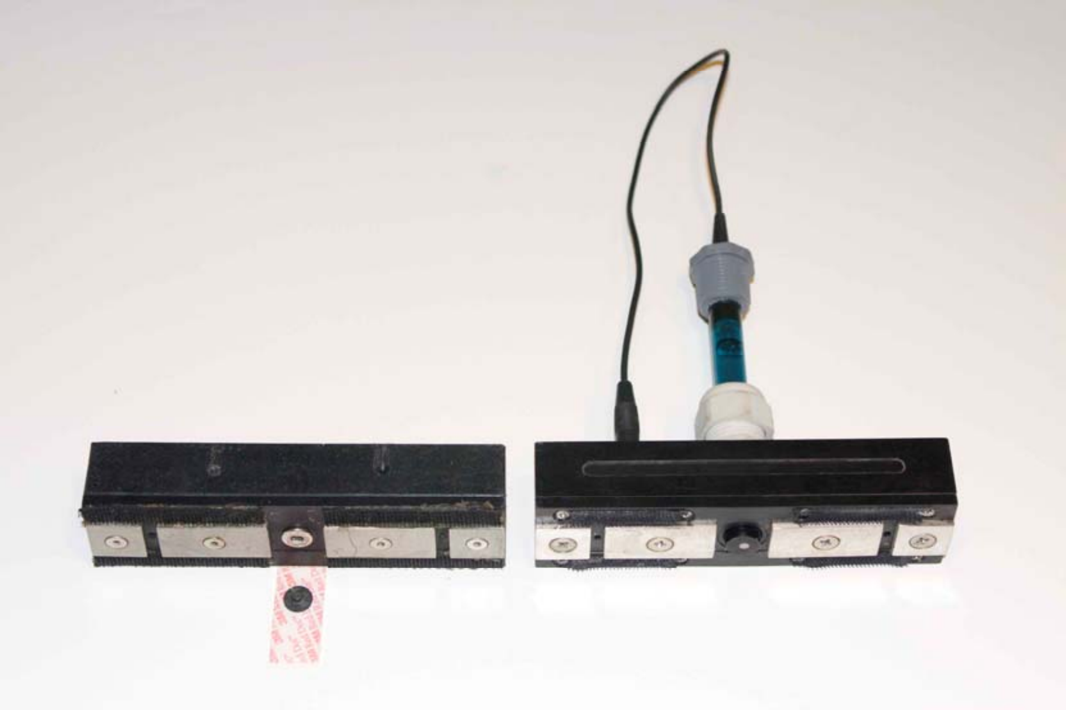


Figure 4.1 Type S (left, previous) and Type R (right, new) electrodes unit.

4.2 Training of the potential users for bridge inspections

In order to train the potential users of the RapiCor instrument for application in the bridge inspections, a two-half-day course was arranged at the CBI in Stockholm 2-3 June 2008. 10 persons including six from the Vägverkt Regions of Southeast, Mälardalen, Middle and Stockholm, and 4 from the CBI Stockholm. A reinforced concrete beam of 2400×30×30 mm was used as an example of a real size concrete structure. Local corrosion on the steel bars in the beam was induced in advance, by drilling a hole close to the steel bars and filling concentrated NaCl solution in it. The course included three parts: fundamental theory of steel corrosion in concrete, techniques of corrosion measurement with focus on the RapiCor, and practical operation of the instrument.

4.3 Delivery of the RapiCor instrument

In July-September 2008, three copies of the RapiCor instrument were delivered to three potential users including Vägverket Region Mälardalen in Eskilstuna, Vägverket Region Southeast in Linköping, and KFS Anläggnings Konstruktörer AB in Stockholm. CBI kept two copies for its own use and further development.

For those who did not participate the course given in June 2008, a short training was arranged in the field to help the users in starting the use of the instrument.

5 Field evaluation of the RapiCor

5.1 Assessment of corrosion level

From the previous investigations it has been shown that, among the three parameters measured by the RapiCor, the corrosion rate correlates best to the actual chloride content in concrete near reinforcement steel, as reported by Tang & Malmberg (2005) and Tang & Utgenannt (2007). It has, therefore, been suggested to take corrosion rate as main parameter, and take half-cell potential and resistivity as complementary parameters in the assessment of corrosion level. The criteria of each parameter, especially resistivity, may be dependent on the type of concrete structures, the surface treatment and the weather when the measurement is carried out. An example of criteria is shown in Table 5.1.1.

Table 5.1.1 Example of criteria for classification of corrosion level

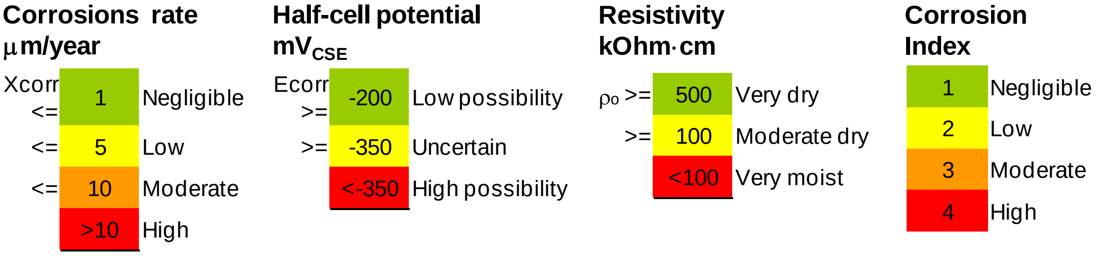
Corrosion level		Corrosion rate [µm/yr]	Half-cell potential [mV$_{(CSE)}$]	Resistivity [kOhm·cm]	Criteria
1	Negligible	$< X_L$	-	-	$X_L = 1$ µm/yr $X_M = 3 \sim 5$ µm/yr* $X_H = 10$ µm/yr $E_{cr} = -200$ mV$_{(CSE)}$ $\rho_{cr} = 100 \sim 120$ kOhm·cm†
		$X_L \sim X_M$	$\geq E_{cr}$	$\geq \rho_{cr}$	
2	Low	$X_L \sim X_M$	$< E_{cr}$	$< \rho_{cr}$	
		$X_M \sim X_H$	$\geq E_{cr}$	$\geq \rho_{cr}$	
3	Moderate	$X_M \sim X_H$	$< E_{cr}$	$< \rho_{cr}$	
		$> X_H$	$\geq E_{cr}$	$\geq \rho_{cr}$	
4	High	$> X_H$	$< E_{cr}$	$< \rho_{cr}$	

* 3 for average measurement and 5 for single measurement.

† depending on the type of concrete, surface treatment, weather, etc.

According to Table 5.1.1, the parameter corrosion rate is used for primary classification. If the two complementary parameters are not lower than the criteria for possible corrosion, the corrosion condition will be classified as one level lower. For example, if the corrosion rate is >10 µm/yr corresponding to “high”, but the half-cell potential is higher than -200 mV CSE or the resistivity is larger than 100 kOhm·cm, the corrosion level will be classified as “moderate”. In this way the assessment would be safer than that based on only one parameter, considering the complication of reinforcement corrosion in the real structures.

In the field evaluation in this project, the above criteria were primarily used by taking $X_M = 5$ µm/yr (as for single measurement) and $\rho_{cr} = 100$ kOhm·cm. In such a way, a colour scale for each parameter can been shown in a cell of the MS Excel worksheet with the measurement value, as shown in Figure 5.1.1 as an example.



Corrosions rate µm/year

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

Half-cell potential mV$_{CSE}$

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

Resistivity kOhm·cm

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

Corrosion Index

1	Negligible
2	Low
3	Moderate
4	High

Figure 5.1.1 Colour scale of each parameter with various criteria.

In the following sections the results from field evaluation reported by KFS, CBI in Stockholm and Vägverket Region Mälardalen are presented. Although a prototype of the RapiCor instrument has been delivered to Vägverket Region Southeast, due to the lack of personnel, there is no any evaluation nor report from it.

5.2 Evaluation by KFS

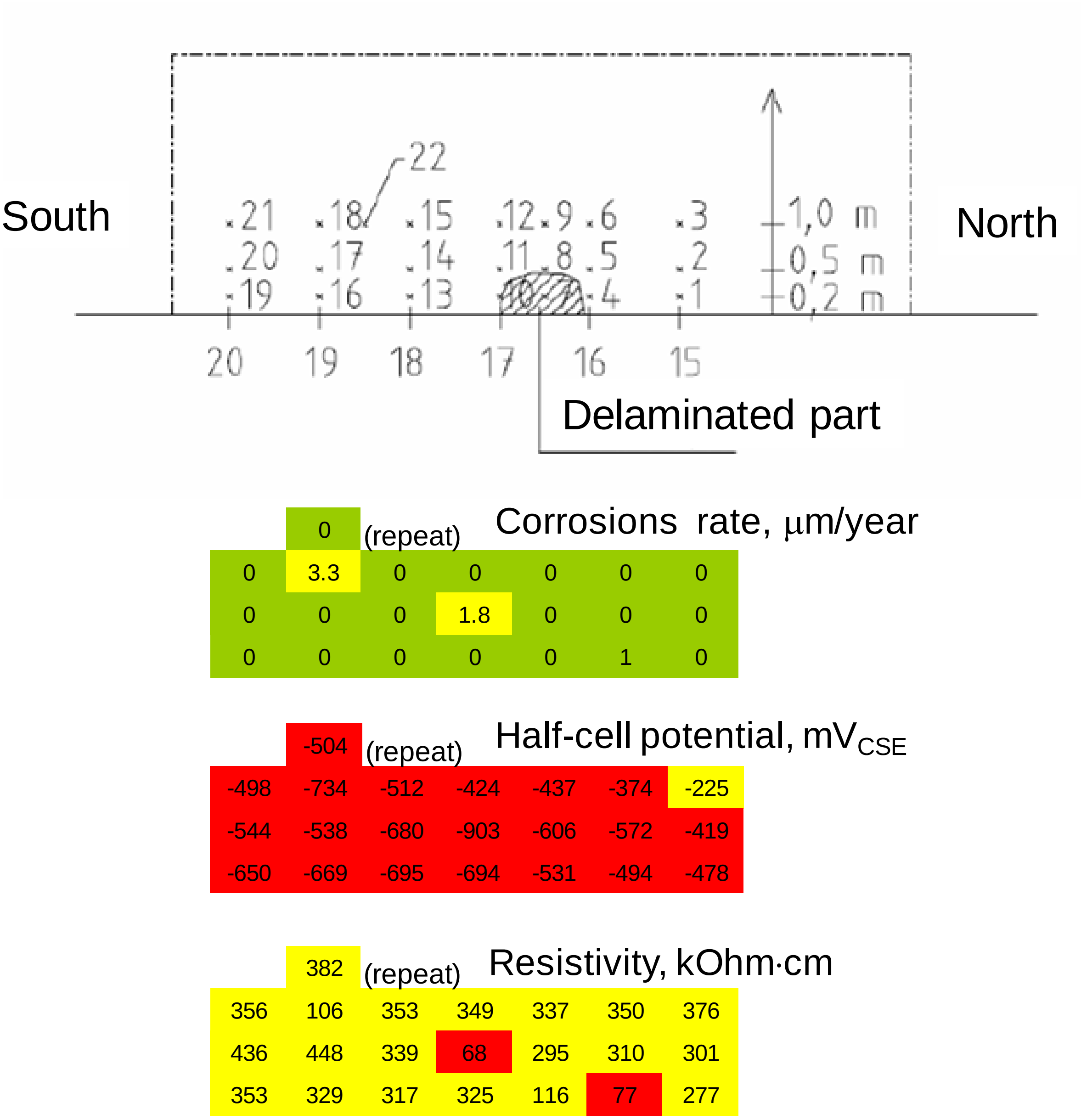
KFS conducted a survey on two concrete bridges, one over Boo-Stranväg at Gustavsvik, numbered as 2-583-1, and another over the local road south Vikdalen in Nacka, numbered as 2-723-1. In the later case the measurement was carried out twice.

Bridge 2-583-1

A view of Bridge 2-583-1 is shown in Figure 5.2.1. The bridge was built in 1978 with a span of 13 m and wideness of about 28 m. The measurement was carried out on the west front wall between 15 and 20 m from the north end, at the height of 0.2, 0.5 and 1 m from the ground. The measurement positions and results are shown in Figure 5.2.2.

It can be seen from the results that the values of half-cell potential are in general very negative, implying very high possibility of active corrosion, but the values of resistivity are in general very high and the values of corrosion rate are almost zero, implying dry concrete without corrosion. The results of half-cell potential are contradictory to those of the other two parameters. Possible reason is the poor connection of the black cable to the reinforcement steel network.

Figure 5.2.1 View of Bridge 2-583-1 from the north.



Corrosions rate, µm/year

	0	(repeat)				
0	3.3	0	0	0	0	0
0	0	0	1.8	0	0	0
0	0	0	0	0	1	0

Half-cell potential, mV_{CSE}

	-504	(repeat)				
-498	-734	-512	-424	-437	-374	-225
-544	-538	-680	-903	-606	-572	-419
-650	-669	-695	-694	-531	-494	-478

Resistivity, kOhm·cm

	382	(repeat)				
356	106	353	349	337	350	376
436	448	339	68	295	310	301
353	329	317	325	116	77	277

Figure 5.2.2 Measurement positions and results from Bridge 2-583-1.

Because of problems in connecting the black cable to the rebar only one of the three measurements, reasonable results (see Figure 1 and 2). CPMP has expressed some views on the kit packaging. of equipment for while the other two measurements.

Bridge 2-723-1
A view of Bridge 2-723-1 is shown in Figure 5.2.3. The bridge was built in 1967 with a span of 12 m and wideness of about 38 m. The space under the bridge has been used for storage of sand containing de-icing slat and some delaminations were found on the lower part of the front wall from the ground up to about 0.5 to 1 m.

The measurement was carried out twice at the same positions on the west front wall (Figure 5.2.4) from the north end to a length of 18 m at an interval of 2 m, at the height of 1 and 2 m from the ground. In the first measurement the black cable was connected to an exposed steel bar as shown in Figure 5.2.5 and in the second measurement the black cable was connected to the bolt which was supposed to be in contact with the steel network through a drilling hole (Figure 5.2.6). The measurement results are shown in Figures 5.2.7 and 5.2.8.

Figure 5.2.3 View of Bridge 2-723-1 from the north.

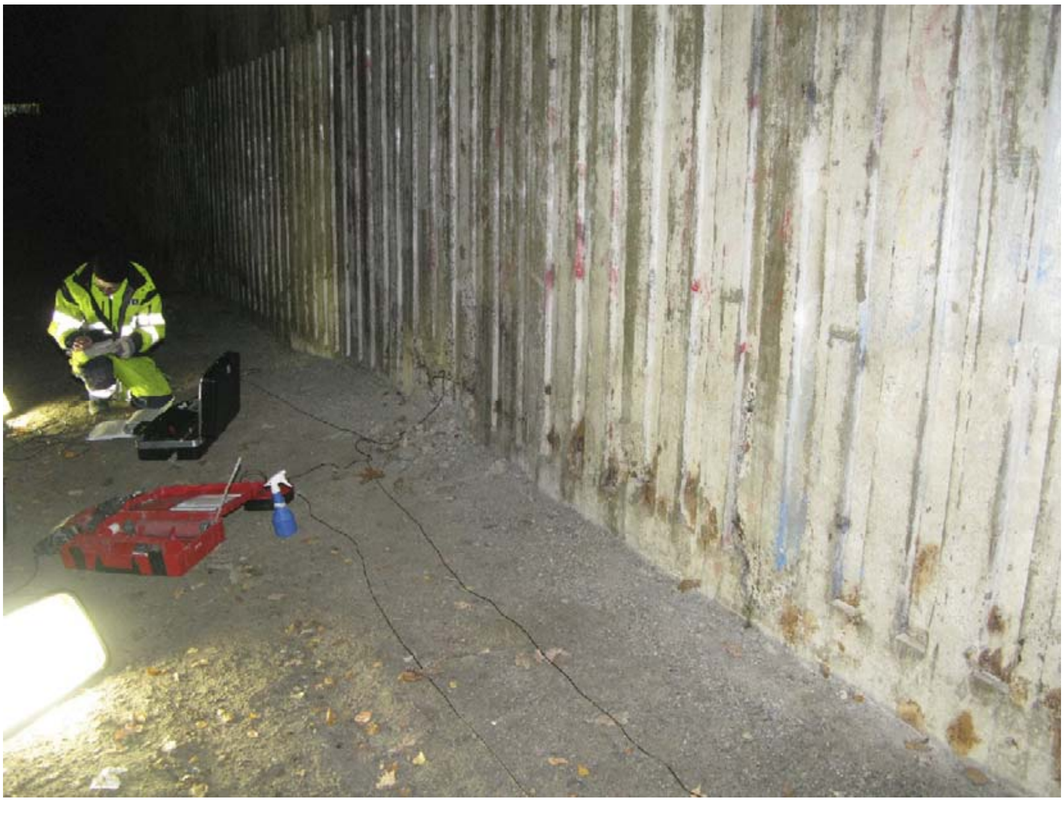
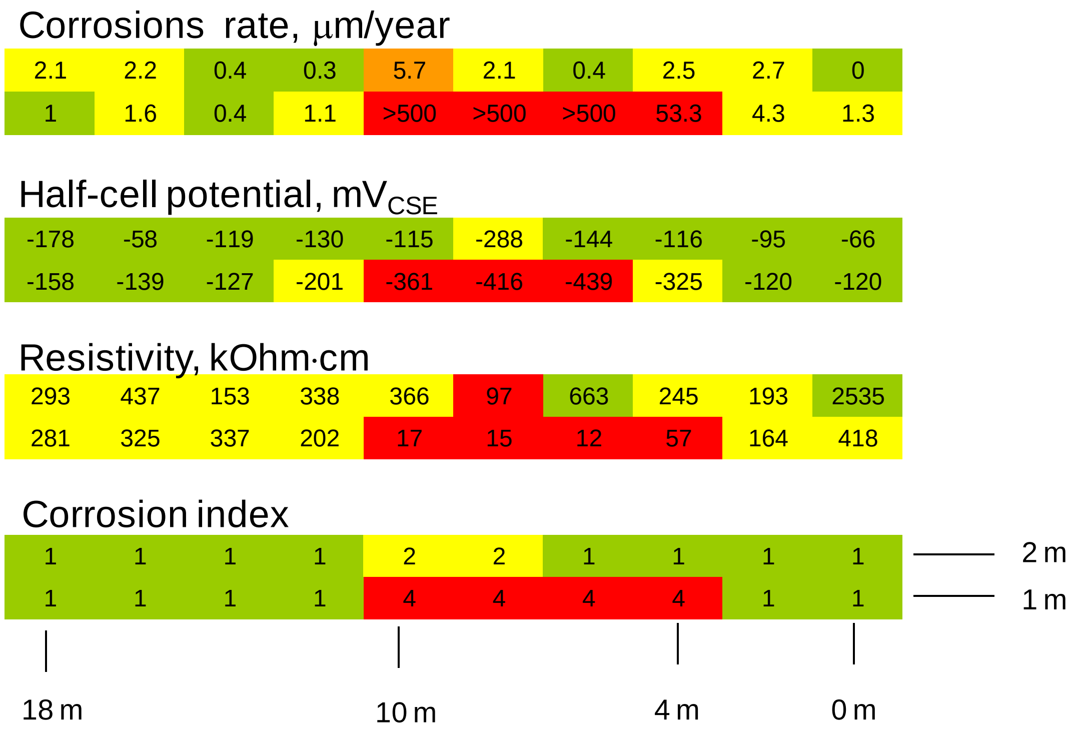


Figure 5.2.4 Corrosion measurement on the west front wall of Bridge 2-723-1.

Figure 5.2.5 Black cable connection in the first measurement.

Figure 5.2.6 Black cable connection in the second measurement.



Corrosions rate, µm/year

2.1	2.2	0.4	0.3	5.7	2.1	0.4	2.5	2.7	0
1	1.6	0.4	1.1	>500	>500	>500	53.3	4.3	1.3

Half-cell potential, mV$_{CSE}$

-178	-58	-119	-130	-115	-288	-144	-116	-95	-66
-158	-139	-127	-201	-361	-416	-439	-325	-120	-120

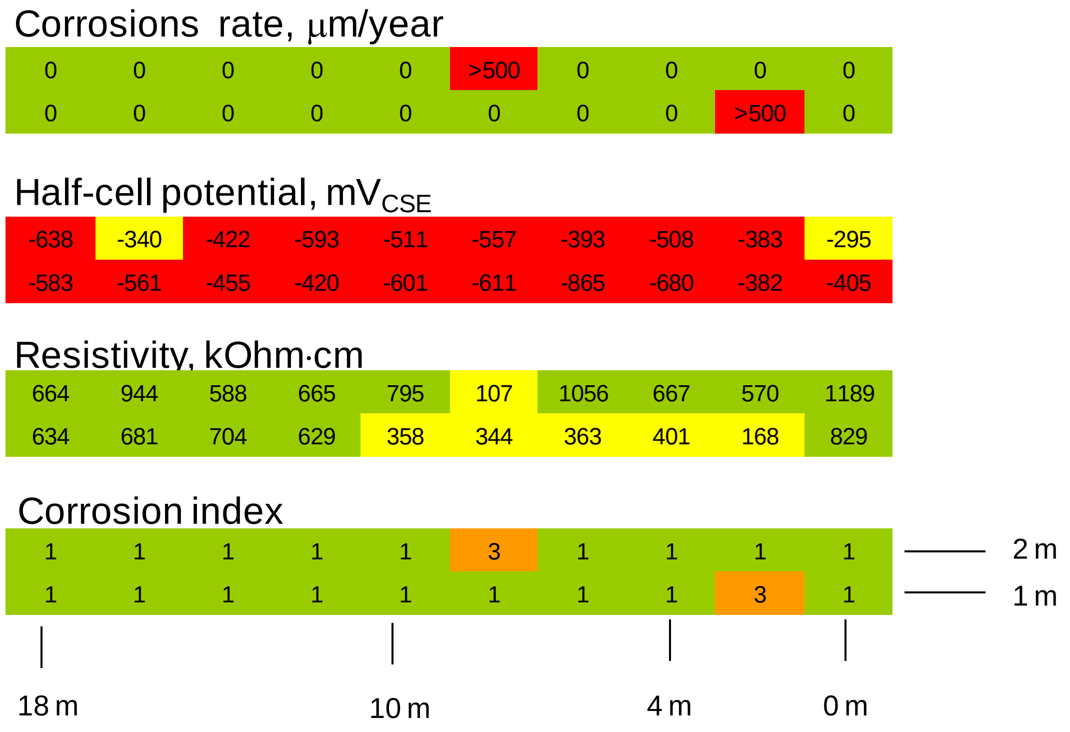
Resistivity, kOhm·cm

293	437	153	338	366	97	663	245	193	2535
281	325	337	202	17	15	12	57	164	418

Corrosion index

1	1	1	1	2	2	1	1	1	1
1	1	1	1	4	4	4	4	1	1

Figure 5.2.7 Results from the first measurement on the front wall of Bridge 2-723-1.



Corrosions rate, µm/year

0	0	0	0	0	>500	0	0	0	0
0	0	0	0	0	0	0	0	>500	0

Half-cell potential, mV$_{CSE}$

-638	-340	-422	-593	-511	-557	-393	-508	-383	-295
-583	-561	-455	-420	-601	-611	-865	-680	-382	-405

Resistivity, kOhm·cm

664	944	588	665	795	107	1056	667	570	1189
634	681	704	629	358	344	363	401	168	829

Corrosion index

1	1	1	1	1	3	1	1	1	1
1	1	1	1	1	1	1	1	3	1

Figure 5.2.8 Results from the second measurement on the front wall of Bridge 2-723-1.

It can be seen that the results from the two measurement are not comparable. In the second measurement the values of half-cell potential were generally low and the values of resistivity were generally high, while the values of corrosion rate were in most cases close to zero, very similar to what happened in Figure 5.2.2. Possible poor contact between the bolt and the steel network could be an explanation. The experience from the above measurements pointed out the importance of a good contact between the bolt and the steel network. This can be achieved by checking the ohmic resistance between two bolts as suggested in the instruction manual, or in the above case, checking the ohmic resistance between the bolt and any of the exposed steel bars.

Nevertheless the results in Figure 5.2.7 revealed a reasonable map of the corrosion condition on the west front wall. The delamination was observed near the measurement position 10 m at the height of 1 m, where the corrosion index is 4 (high corrosion) as shown in Figure 5.2.7.

5.3 Evaluation by CBI Stockholm

Under the period of this project, SP Concrete and Materials group became merged with previous CBI and formed a new CBI Betonginstitutet in 2008. Although the staff at CBI Stockholm and CBI Borås (previous SP Concrete and Materials group) nowadays belongs to the same research institute, the persons at CBI Stockholm who carried out the field evaluation have the similar knowledge of the RapiCor as the other users. Therefore, their field evaluation can be also representative as ordinary bridge inspectors.

5.3.1 Description of the structures inspected

Totally 7 bridges around Stockholm region were inspected, as listed in Table 5.3.1. The information about concrete used in each structure was taken from available drawings or documents. After the corrosion measurement by the RapiCor some cores of diameter 50-80 mm, depending on the size of reinforcement, were taken from each structure inside the measurement area at the positions with different corrosion levels were detected by the RapiCor. It was planed that, when sampling the cores, at least one of the cores from each structure should contain reinforcement steel. These cores were used in the laboratory for analysis of chloride content at the depth where the reinforcement steel lay and also for measurement of carbonation depth. The steel bars taken from the cores was visually examined for their actual corrosion condition. It should be noticed that the visual examination on the steel bars taken from the cores can only be conditionally used for verification of the results measured by the RapiCor. Depending on the size of grid in the corrosion measurement, the point measured by the RapiCor represents the corrosion condition in the area around the measurement point. This means that the area of size at least similar to the measurement grid should be exposed for visual examination in order to make a reliable verification. With a single core, if the visual corrosion is found in the steel bar taken from the core this observation can be used for verification of the result measured by the RapiCor, while if no corrosion is found in the steel bar taken from the core this observation may be used for verification of passive results, but not for verification of depassive results measured by the RapiCor.

In the examination of the measurement results it was found that the results from Bridges 1 and 4 were more or less similar to those in Figures 5.2.2 and 5.2.8, that is, zero corrosion rate, very negative half-cell potential and very high resistivity, implying possible poor connection of the black cable to the reinforcement steel network. Therefore, the results from these two bridges are not presented in the following sections.

Table 5.3.1 Bridge structures inspected by CBI Stockholm

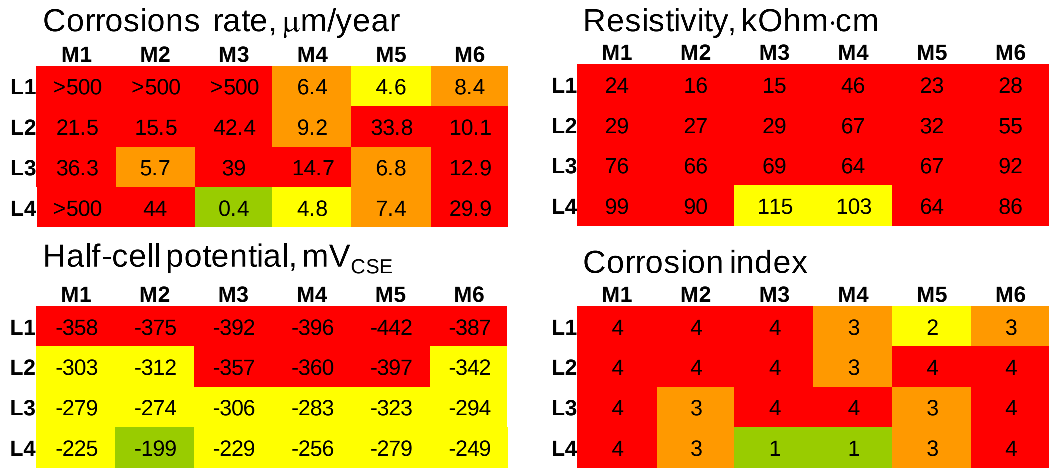
Bridge 1	Bridge 1-189-1
Structure part	Southeast retaining wall
Built year	1969
Concrete	Class I STD, K350, consistence T, water tight, entrained air 4-6%, reinforcement Ks40
Observations	Vertical crack though the wall about 2 m in the measurement area
Carbonation depth	≈ 5 mm
Bridge 2	Bridge over local road Lilla Frescativägen
Structure part	Abutment
Built year	1970
Concrete	Class I STD, K300, consistence T, entrained air 4-6%, reinforcement Ks40
Observations	Surface treated by impregnation, possibly some type of graffiti-protection, no damage observed
Carbonation depth	≈ 5 mm
Bridge 3	Bridge over pedestrian/bicycle road about 1 km from Ulriksdals Slott in Solna
Structure part	Wing wall
Built year	1967
Concrete	Class II STD, K300, consistence T, water tight, reinforcement Ks40
Observations	None
Carbonation depth	≈ 10 mm
Bridge 4	Bridge over pedestrian/bicycle road and traffic lines at meeting place Ulriksdal in Solna
Structure part	Wing wall
Built year	1969
Concrete	Reinforcement Ks40
Observations	None
Carbonation depth	≈ 8 mm
Bridge 5	Bridge over Ålkist channel by Ålkistan Lake
Structure part	Edge beam
Built year	1967
Concrete	Class I STD, K300, consistence P, water tight, entrained air 3.5%, reinforcement Ks40
Observations	Delaminations on vertical side
Carbonation depth	≈ 3 mm
Bridge 6	East bridge of the Gröndal bridge
Structure part	Abutment
Built year	1967
Concrete	-
Observations	Local delamination/spalling, part of surface treated by impregnation/graffiti-protection
Carbonation depth	≈ 10 mm
Bridge 7	Bridge over pedestrian/bicycle road at meeting place Fredhäll
Structure part	Wing wall
Built year	1966
Concrete	-
Observations	Local spalling, part of surface treated by impregnation/graffiti-protection
Carbonation depth	≈ 3 mm

5.3.2 Results of corrosion measurement by the RapiCor

Bridge 2 – Abutment of the bridge over local road Lilla Frescativägen

A view of the measurement area on the abutment of Bridge 2 is shown in Figure 5.3.1 and the measured results are shown in Figure 5.3.2. It can be seen that the reinforcement steel in the structure is under the condition of high corrosion. Three cores were taken from positions L1M4, L1M5 and L1M6. Only one steel bar was found from the core taken from L1M4. According to the results from the chloride analysis (see section 5.3.7) the chloride content at the depth of steel bar is 0.63-1.0 % mass of cement. Although no corrosion was found on the steel bar in one of the drilled cores and no damage was observed in the real structure, the high chloride content is in agreement with the results from the RapiCor measurement, that is, the steel in the concrete is at the high risk of corrosion.

Figure 5.3.1 View of the measurement area on the abutment of Bridge 2.



Corrosions rate, μm/year

	M1	M2	M3	M4	M5	M6
L1	>500	>500	>500	6.4	4.6	8.4
L2	21.5	15.5	42.4	9.2	33.8	10.1
L3	36.3	5.7	39	14.7	6.8	12.9
L4	>500	44	0.4	4.8	7.4	29.9

Resistivity, kOhm·cm

	M1	M2	M3	M4	M5	M6
L1	24	16	15	46	23	28
L2	29	27	29	67	32	55
L3	76	66	69	64	67	92
L4	99	90	115	103	64	86

Half-cell potential, mV_{CSE}

	M1	M2	M3	M4	M5	M6
L1	-358	-375	-392	-396	-442	-387
L2	-303	-312	-357	-360	-397	-342
L3	-279	-274	-306	-283	-323	-294
L4	-225	-199	-229	-256	-279	-249

Corrosion index

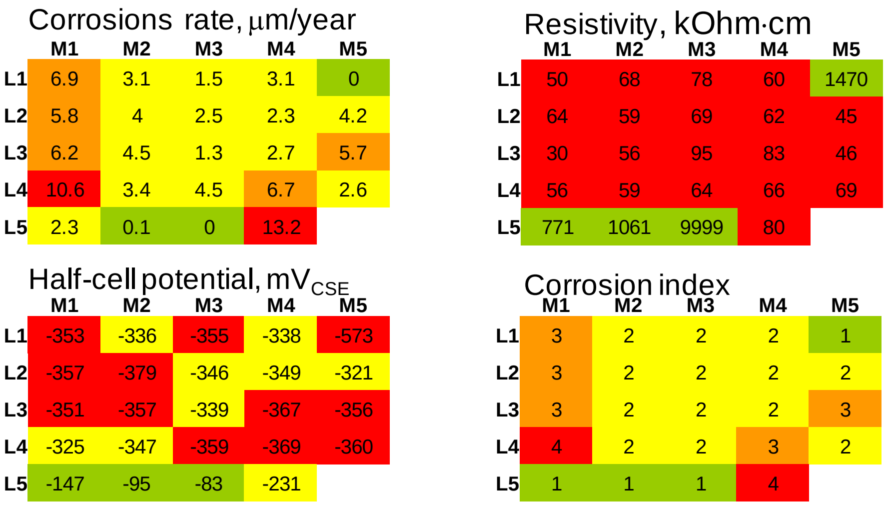
	M1	M2	M3	M4	M5	M6
L1	4	4	4	3	2	3
L2	4	4	4	3	4	4
L3	4	3	4	4	3	4
L4	4	3	1	1	3	4

Figure 5.3.2 Results from the RapiCor measurement on the abutment of Bridge 2.

Bridge 3 – Wing wall of the bridge over pedestrian/bicycle road about 1 km from Ulriksdals Slott in Solna

A view of the measurement area on the wing wall of Bridge 3 is shown in Figure 5.3.3 and the measured results are shown in Figure 5.3.4. It can be seen that the reinforcement steel in the structure is generally under the condition of low corrosion, with a few measurement point showing moderate to high corrosion. Three cores were taken from positions L1M1, L3M1 and L3M2. The chloride content at the depth of steel bar is 0.19-0.42 % mass of cement. No corrosion was found on the steel bars in two of the drilled cores and no significant damage was observed in the measurement area of the real structure. The chloride content is close to the threshold value (if 0.4 % mass of cement is assumed) for depassivation of steel in concrete. This is reasonably in agreement with the results from the RapiCor measurement.

Figure 5.3.3 View of the measurement area on the wing wall of Bridge 3.



Corrosions rate, µm/year

	M1	M2	M3	M4	M5
L1	6.9	3.1	1.5	3.1	0
L2	5.8	4	2.5	2.3	4.2
L3	6.2	4.5	1.3	2.7	5.7
L4	10.6	3.4	4.5	6.7	2.6
L5	2.3	0.1	0	13.2	

Resistivity, kOhm·cm

	M1	M2	M3	M4	M5
L1	50	68	78	60	1470
L2	64	59	69	62	45
L3	30	56	95	83	46
L4	56	59	64	66	69
L5	771	1061	9999	80	

Half-cell potential, mV$_{CSE}$

	M1	M2	M3	M4	M5
L1	-353	-336	-355	-338	-573
L2	-357	-379	-346	-349	-321
L3	-351	-357	-339	-367	-356
L4	-325	-347	-359	-369	-360
L5	-147	-95	-83	-231	

Corrosion index

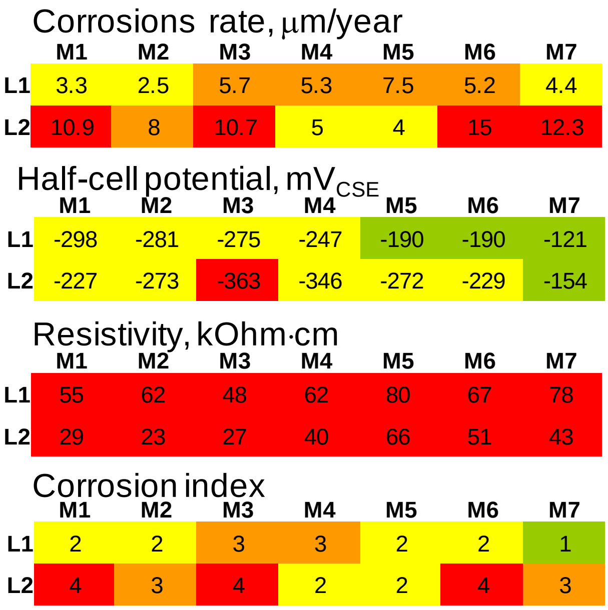
	M1	M2	M3	M4	M5
L1	3	2	2	2	1
L2	3	2	2	2	2
L3	3	2	2	2	3
L4	4	2	2	3	2
L5	1	1	1	4	

Figure 5.3.4 Results from the RapiCor measurement on the wing wall of Bridge 3.

Bridge 5 – Edge beam of the bridge over Ålkist channel by Ålkistan Lake

A view of the measurement area on the wing wall of Bridge 5 is shown in Figure 5.3.5 and the measured results are shown in Figure 5.3.6. It can be seen that the reinforcement steel in the lower part of the beam is under the condition of higher corrosion than that in the upper part. Three cores were taken from positions L1M3, L2M2 and L2M4. The chloride content at the depth of steel bar in the cores taken from the lower part is 0.81-1.1 % mass of cement and in the core taken from the upper part is 0.32 % mass of cement. Superficial to severe corrosion was found on the steel bars in all the three drilled cores (Figure 5.3.7) and delamination damage was observed in the real structure. This means that the results from the RapiCor measurement is in good agreement with the reality.

Figure 5.3.5 View of the measurement area on the edge beam of Bridge 5.



Corrosions rate, µm/year

	M1	M2	M3	M4	M5	M6	M7
L1	3.3	2.5	5.7	5.3	7.5	5.2	4.4
L2	10.9	8	10.7	5	4	15	12.3

Half-cell potential, mV_{CSE}

	M1	M2	M3	M4	M5	M6	M7
L1	-298	-281	-275	-247	-190	-190	-121
L2	-227	-273	-363	-346	-272	-229	-154

Resistivity, kOhm·cm

	M1	M2	M3	M4	M5	M6	M7
L1	55	62	48	62	80	67	78
L2	29	23	27	40	66	51	43

Corrosion index

	M1	M2	M3	M4	M5	M6	M7
L1	2	2	3	3	2	2	1
L2	4	3	4	2	2	4	3

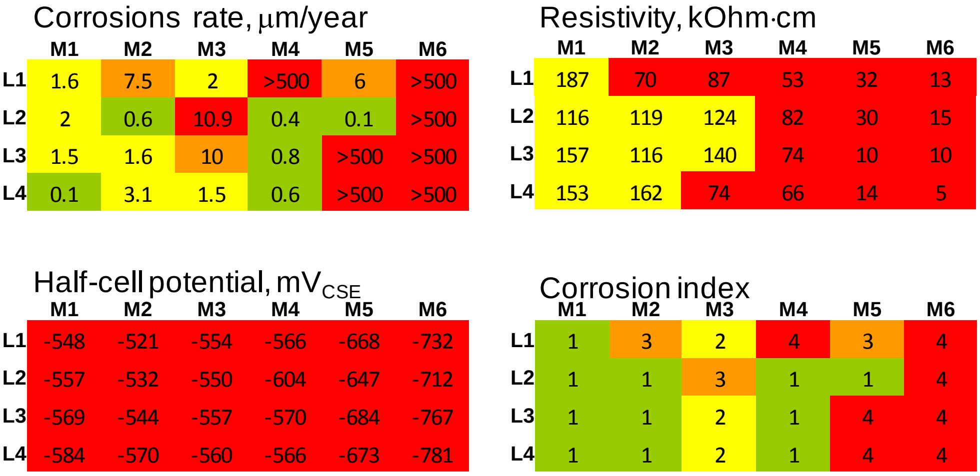
Figure 5.3.6 Results from the RapiCor measurement on the edge beam of Bridge 5.

Figure 5.3.7 Corrosion on the steel bars in cores L2M2 and L2M4 drilled from Bridge 5.

Bridge 6 – Abutment of the east bridge of the Gröndal bridge

A view of the measurement area on the abutment of Bridge 6 is shown in Figure 5.3.8 and the measured results are shown in Figure 5.3.9. It can be seen that the reinforcement steel in the right part of the structure is under the condition of high corrosion but not in the left part. In this structure two cores were taken from the right part (positions L1M5 and L4M6) and two from the left part (positions L1M2 and L3M3). The chloride content at the depth of steel bar in the cores taken from the right part is 0.80-2.18 % mass of cement, while in the cores taken from the left part is 0.16-0.32 % mass of cement. Superficial to moderate corrosion was found on the steel bars in the cores drilled from the right part but no corrosion was found on the steel bars in the cores drilled from the left part (Figure 5.3.10). Delamination damage was observed in the real structure. This again verifies that the results from the RapiCor measurement is in good agreement with the reality.

Figure 5.3.8 View of the measurement area on the abutment of Bridge 6.



Corrosions rate, µm/year

	M1	M2	M3	M4	M5	M6
L1	1.6	7.5	2	>500	6	>500
L2	2	0.6	10.9	0.4	0.1	>500
L3	1.5	1.6	10	0.8	>500	>500
L4	0.1	3.1	1.5	0.6	>500	>500

Resistivity, kOhm·cm

	M1	M2	M3	M4	M5	M6
L1	187	70	87	53	32	13
L2	116	119	124	82	30	15
L3	157	116	140	74	10	10
L4	153	162	74	66	14	5

Half-cell potential, mV$_{CSE}$

	M1	M2	M3	M4	M5	M6
L1	-548	-521	-554	-566	-668	-732
L2	-557	-532	-550	-604	-647	-712
L3	-569	-544	-557	-570	-684	-767
L4	-584	-570	-560	-566	-673	-781

Corrosion index

	M1	M2	M3	M4	M5	M6
L1	1	3	2	4	3	4
L2	1	1	3	1	1	4
L3	1	1	2	1	4	4
L4	1	1	2	1	4	4

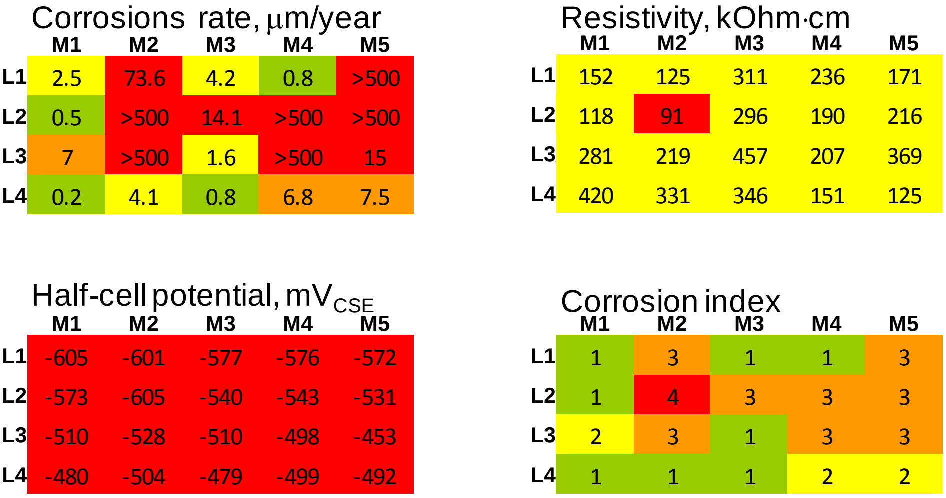
Figure 5.3.9 Results from the RapiCor measurement on the abutment of Bridge 6.

Figure 5.3.10 Corrosion on the steel bars in cores L1M5 and L4M6 drilled from Bridge 6.

Bridge 7 – Wing wall of the bridge over pedestrian/bicycle road at meeting place Fredhäll

A view of the measurement area on the wing wall of Bridge 7 is shown in Figure 5.3.11 and the measured results are shown in Figure 5.3.12. In this structure four cores were taken from positions L2M1, L3M1, L3M3 and L4M4, where no or little corrosion (index 1-2) was detected by the RapiCor. Very superficial corrosion was found on the steel bar in the core taken from L4M4 (corrosion index 2), while no corrosion could be observed on the steel bars from the other cores (Figure 5.3.13). No visible damage was observed in the measurement area although there was some local spalling on the upper part of the structure, as can be seen in Figure 5.3.11.

Figure 5.3.11 View of the measurement area on the wing wall of Bridge 7.



Corrosions rate, µm/year

	M1	M2	M3	M4	M5
L1	2.5	73.6	4.2	0.8	>500
L2	0.5	>500	14.1	>500	>500
L3	7	>500	1.6	>500	15
L4	0.2	4.1	0.8	6.8	7.5

Resistivity, kOhm·cm

	M1	M2	M3	M4	M5
L1	152	125	311	236	171
L2	118	91	296	190	216
L3	281	219	457	207	369
L4	420	331	346	151	125

Half-cell potential, mV_{CSE}

	M1	M2	M3	M4	M5
L1	-605	-601	-577	-576	-572
L2	-573	-605	-540	-543	-531
L3	-510	-528	-510	-498	-453
L4	-480	-504	-479	-499	-492

Corrosion index

	M1	M2	M3	M4	M5
L1	1	3	1	1	3
L2	1	4	3	3	3
L3	2	3	1	3	3
L4	1	1	1	2	2

Figure 5.3.12 Results from the RapiCor measurement on the wing wall of Bridge 7.

Figure 5.3.13 Superficial corrosion on the steel bar in core L4M4 drilled from Bridge 7.

5.3.3 Summary of the results from the cores taken from the structures

The cores taken from the structures were transported to the CBI laboratory in Stockholm for analysis of chloride content, measurement of carbonation depth and visual examination of steel bars in the core for their actual corrosion condition.

Chloride analysis
Approximately 5 mm thick disc was cut from each core at the depth as shown in Figure 5.3.14. The discs were dried at 105 °C and ground to powder. The chloride content and calcium content in each powder sample were determined by a well-established method at CBI Stockholm. The cement content in the sample was estimated from the calcium content assuming 65 % CaO in cement.

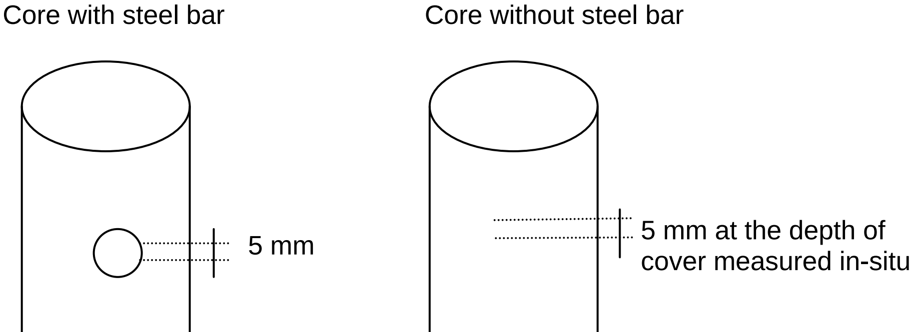


Figure 5.3.14 Schematic of sampling position for chloride analysis.

Carbonation depth

The carbonation depth in each core was measured in accordance with EN 12690-2.

Degree of corrosion in the visual examination

In the visual examination the corrosion condition of steel bar was classified by an index called “degree of corrosion”, as exampled in Table 5.3.2.

Table 5.3.2 Classification of the degree of corrosion

Degree of corrosion	Example	Remarks
R0		No visible corrosion
R1		Small rust spots on the ribs, superficial corrosion, or only yellow colour on the reinforcement surface
R2		Significant rust spots on the ribs and reinforcement surface, < 1 mm severe rust spots, or general corrosion with poor bond
R3		Disappeared ribs due to corrosion, or severe rust spots about 1 mm deep on half or entire curved surface
R4		Disappeared ribs due to corrosion and severe rust spots deeper than 1 mm on half or entire curved surface

Summary of the results

The results of chloride content, carbonation depth and degree of corrosion from each core are summarised in Table 5.3.3, where the corrosion index measured by the RapiCor is also listed for comparison. As a comparison, the relationship between corrosion index and chloride content is shown in Figure 5.3.15. It can be seen that, in the most of positions where the RapiCor detected corrosion (index ≥ 2), the chloride content was higher than the critical value (0.4 % mass of cement).

Table 5.3.3 Summary of the results from each core

Bridge	**Position**	**Corrosion index**	**Cl^- % of cement**	**Carbonation depth (mm)**	**Degree of corrosion**	**Cover (mm)**
Bridge 1	L1M1	*	0.60	5	R3	30
Bridge 1	L1M3	*	0.10	5	R0	30
Bridge 1	L1M4	*	0.16	5	R0	32
Bridge 1	L2M2	*	0.08	5	R0	29
Bridge 2	L1M4	3	0.63	5	R0	50
Bridge 2	L1M5	2	1.00	5	-	
Bridge 2	L1M6	3	0.67	5	-	
Bridge 3	L1M1	3	0.20	10	R0	50
Bridge 3	L3M1	3	0.42	10	R0	25
Bridge 3	L3M2	2	0.19	10	R0	19
Bridge 4	L1M1	*	0.08	8	R0	43
Bridge 4	L1M2	*	0.21	8	R0	45
Bridge 4	L3M1	*	0.47	8	R0	43
Bridge 5	L1M3	3	0.32	3	R1	50
Bridge 5	L2M2	3	1.10	3	R1	20
Bridge 5	L2M4	2	0.81	3	R3	20
Bridge 6	L1M2	3	0.30	10	R0	25
Bridge 6	L1M5	3	0.80	10	R1	25
Bridge 6	L3M3	2	0.16	10	R0	30
Bridge 6	L4M6	4	2.18	10	R2	32
Bridge 7	L3M1	2	n.d.	3	R0	20
Bridge 7	L3M3	1	n.d.	3	R0	38
Bridge 7	L4M4	2	n.d.	3	R1	30

* Not relevant due to possible poor connection
n.d. – not determined

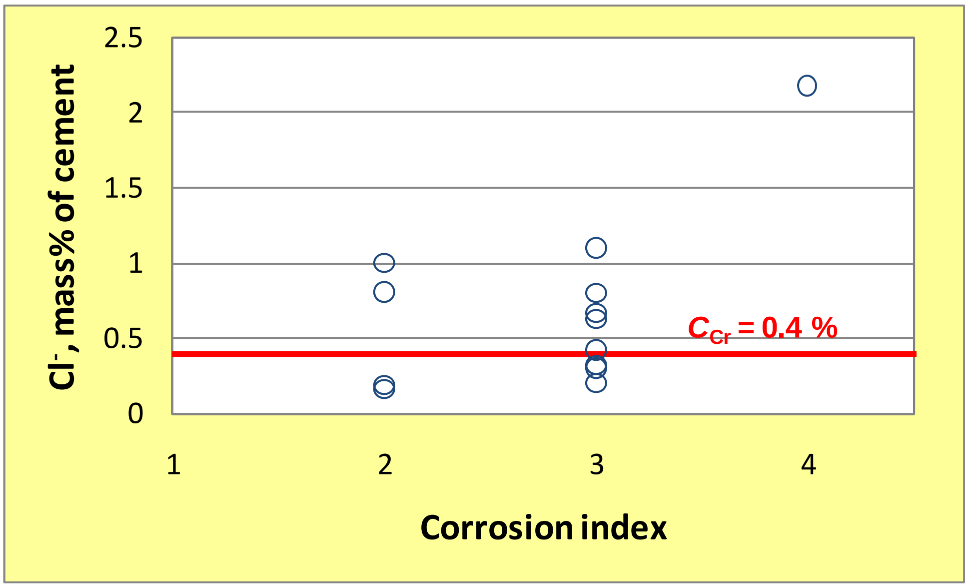


Figure 5.3.15 Relationship between corrosion index by the RapiCor and chloride content in concrete

5.4 Evaluation By Vägverket Region Mälardalen

Two students at Linköping University carried out the field evaluation through their examination work with Vägverket Region Mälardalen in Eskilstuna [Lind & Wikslund, 2010]. In the beginning of their work, a special training was arranged for them to learn the fundamental knowledge and proper use of the RapiCor instrument. The importance of good connection between the black cable and steel network has been emphasised in order to avoid the poor connections as happened in the previous cases.

They inspected 12 bridge structures in this region and four of them were selected for presentation in their bachelor thesis. The following sections are based on their thesis [Lind & Wikslund, 2010].

5.4.1 Measurement on the southern bearing seat of Bridge 19-388-1

The bearing seat is on the southern side of Bridge 19-388-1 in Köping. During the inspection it was discovered that the transition structure between the roadway and bridge deck is broken. Consequently dirt and salt water was leaked down on the bearing seat, initiating severe corrosion of reinforcement steel in the concrete and resulting spalling, as can be seen in Figure 5.4.1. In order to determine the extent of reinforcement corrosion inside the concrete from the visible damage, a mapping was carried out using the RapiCor.

Figure 5.4.1 Spalling on the southern bearing seat of Bridge 19-388-1 [Lind & Wikslund, 2010]

Measurement

The measurement was carried out on the wall of the bearing seat with a line (L) of measurement every meter from east to west. The leak is positioned between Lines 9 and 11. The first measurement was made to locate approximately where the corrosion started, then a more precise measurement was made on each vertical reinforcement bar between Lines 7 and 12 as lined in the first measurement.

Weather conditions

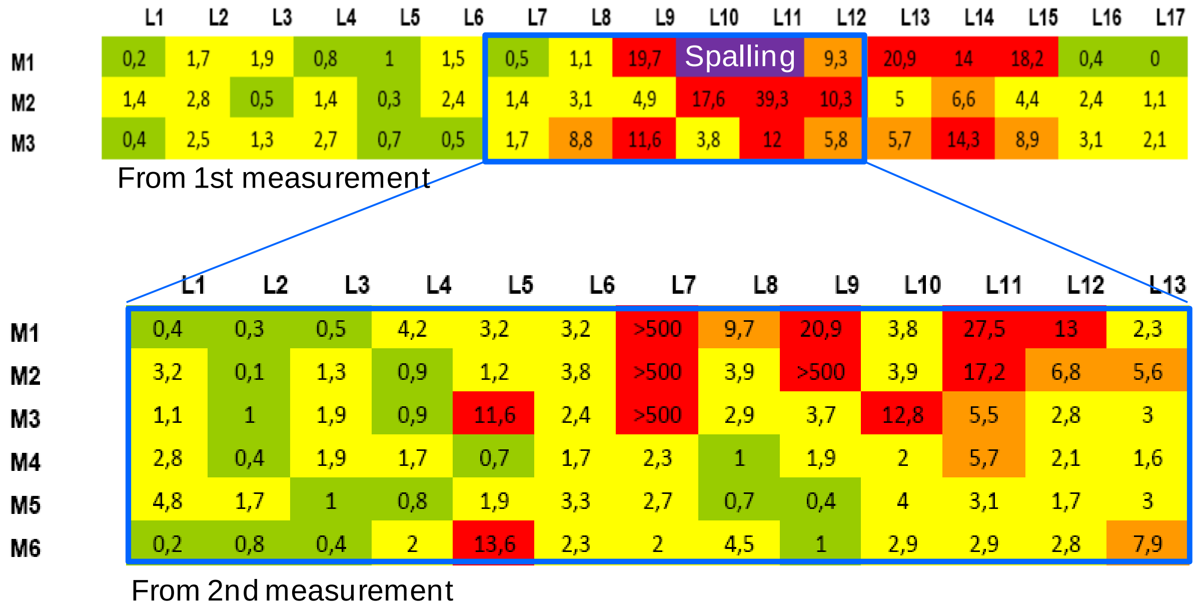
Under the first measurement (20th April, 2010): Relative humidity about 20 %, temperature about 10 °C, no raining days before the measurement

Under the second measurement (30th April, 2010): Relative humidity about 50 %, temperature about 16 °C, twice shower of rain of 1-1.5 mm during the two days before the measurement

Measurement results

A wide view of measurement area is shown in Figure 5.4.2 and the measured results are shown in Figures 5.4.3 to 5.4.6.

Figure 5.4.2 A wide view of the measurement area on the southern bearing seat of Bridge 19-388-1 [Lind & Wikslund, 2010] (Stora= Lines in the 1st measurement; Lilla = Lines in the 2nd measurement)



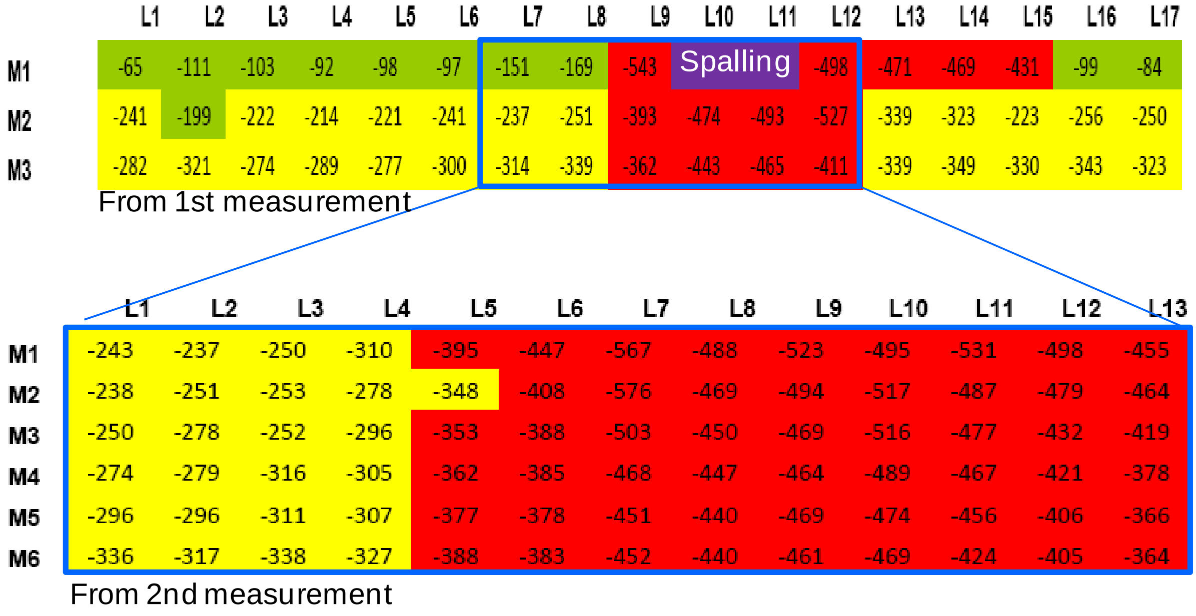
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17
M1	0,2	1,7	1,9	0,8	1	1,5	0,5	1,1	19,7	Spalling		9,3	20,9	14	18,2	0,4	0
M2	1,4	2,8	0,5	1,4	0,3	2,4	1,4	3,1	4,9	17,6	39,3	10,3	5	6,6	4,4	2,4	1,1
M3	0,4	2,5	1,3	2,7	0,7	0,5	1,7	8,8	11,6	3,8	12	5,8	5,7	14,3	8,9	3,1	2,1

From 1st measurement

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
M1	0,4	0,3	0,5	4,2	3,2	3,2	>500	9,7	20,9	3,8	27,5	13	2,3
M2	3,2	0,1	1,3	0,9	1,2	3,8	>500	3,9	>500	3,9	17,2	6,8	5,6
M3	1,1	1	1,9	0,9	11,6	2,4	>500	2,9	3,7	12,8	5,5	2,8	3
M4	2,8	0,4	1,9	1,7	0,7	1,7	2,3	1	1,9	2	5,7	2,1	1,6
M5	4,8	1,7	1	0,8	1,9	3,3	2,7	0,7	0,4	4	3,1	1,7	3
M6	0,2	0,8	0,4	2	13,6	2,3	2	4,5	1	2,9	2,9	2,8	7,9

From 2nd measurement

Figure 5.4.3 Map of corrosion rate [µm/year] on the southern bearing seat of Bridge 19-388-1, based on [Lind & Wikslund, 2010]



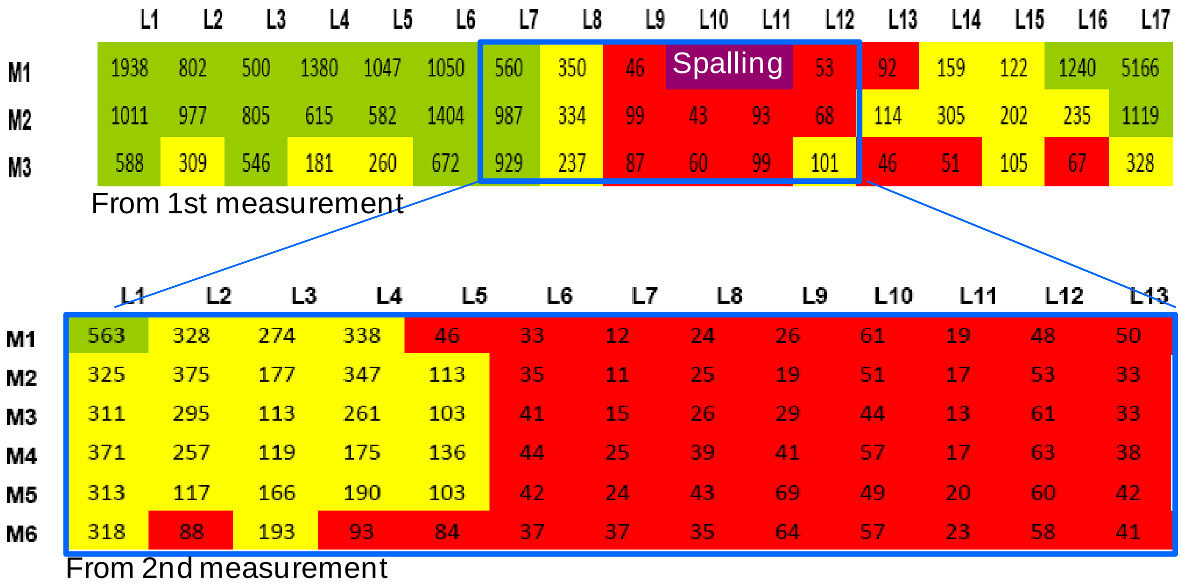
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17
M1	-65	-111	-103	-92	-98	-97	-151	-169	-543	Spalling		-498	-471	-469	-431	-99	-84
M2	-241	-199	-222	-214	-221	-241	-237	-251	-393	-474	-493	-527	-339	-323	-223	-256	-250
M3	-282	-321	-274	-289	-277	-300	-314	-339	-362	-443	-465	-411	-339	-349	-330	-343	-323

From 1st measurement

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
M1	-243	-237	-250	-310	-395	-447	-567	-488	-523	-495	-531	-498	-455
M2	-238	-251	-253	-278	-348	-408	-576	-469	-494	-517	-487	-479	-464
M3	-250	-278	-252	-296	-353	-388	-503	-450	-469	-516	-477	-432	-419
M4	-274	-279	-316	-305	-362	-385	-468	-447	-464	-489	-467	-421	-378
M5	-296	-296	-311	-307	-377	-378	-451	-440	-469	-474	-456	-406	-366
M6	-336	-317	-338	-327	-388	-383	-452	-440	-461	-469	-424	-405	-364

From 2nd measurement

Figure 5.4.4 Map of half-cell potential [mV$_{CSE}$] on the southern bearing seat of Bridge 19-388-1, based on [Lind & Wikslund, 2010]



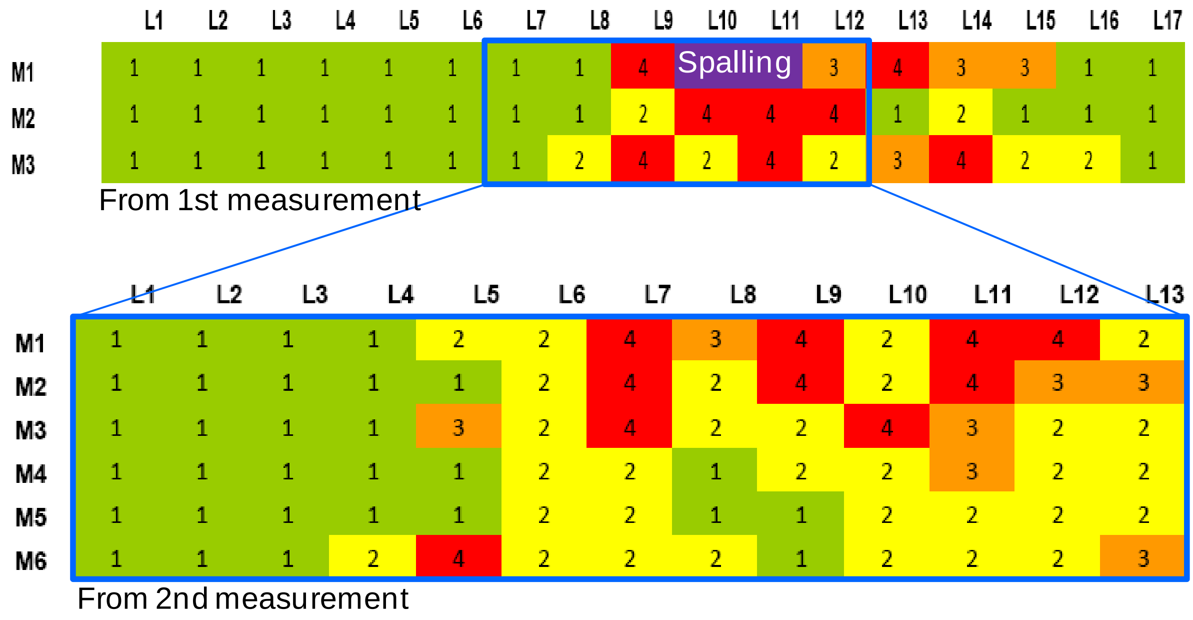
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17
M1	1938	802	500	1380	1047	1050	560	350	46	Spalling		53	92	159	122	1240	5166
M2	1011	977	805	615	582	1404	987	334	99	43	93	68	114	305	202	235	1119
M3	588	309	546	181	260	672	929	237	87	60	99	101	46	51	105	67	328

From 1st measurement

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
M1	563	328	274	338	46	33	12	24	26	61	19	48	50
M2	325	375	177	347	113	35	11	25	19	51	17	53	33
M3	311	295	113	261	103	41	15	26	29	44	13	61	33
M4	371	257	119	175	136	44	25	39	41	57	17	63	38
M5	313	117	166	190	103	42	24	43	69	49	20	60	42
M6	318	88	193	93	84	37	37	35	64	57	23	58	41

From 2nd measurement

Figure 5.4.5 Map of resistivity [kOhm·cm] on the southern bearing seat of Bridge 19-388-1, based on [Lind & Wikslund, 2010]



	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17
M1	1	1	1	1	1	1	1	1	4	Spalling		3	4	3	3	1	1
M2	1	1	1	1	1	1	1	1	2	4	4	4	1	2	1	1	1
M3	1	1	1	1	1	1	1	2	4	2	4	2	3	4	2	2	1

From 1st measurement

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
M1	1	1	1	1	2	2	4	3	4	2	4	4	2
M2	1	1	1	1	1	2	4	2	4	2	4	3	3
M3	1	1	1	1	3	2	4	2	2	4	3	2	2
M4	1	1	1	1	1	2	2	1	2	2	3	2	2
M5	1	1	1	1	1	2	2	1	1	2	2	2	2
M6	1	1	1	2	4	2	2	2	1	2	2	2	3

From 2nd measurement

Figure 5.4.6 Map of corrosion index on the southern bearing seat of Bridge 19-388-1, based on [Lind & Wikslund, 2010]

Comments

It can be seen from the above figures that the results measured on two different days are fairly comparable. From these two measurements, a rough one to see trends and then a more elaborated one, it appears a clear border in the maps, where the corrosion is ongoing in the concrete structure, that is, at L9 of the first measurement and between L5-6 of the second measurement, about one meter west of the drainage pipe.

The weather seem to have significant influence on the values of half-cell potential and resistivity (Figures 5.4.4 and 5.4.5), but not much on the values of corrosion rate (Figure 5.4.3), nor on the assessment of areas of ongoing corrosion (Figure 5.4.6). This is in agreement with the results presented in section 3.5.

5.4.2 Measurement on the eastern front wall of Bridge 19-380-1

From previous inspections by Vägverket corrosion damages were found on the eastern front wall of Bridge 19-380-1 on Highway E18 over local road 691 by the traffic place Brånsta outside Hallstahammar. To investigate the reasons to the corrosion damages chloride contents in concrete were measured on the three lines and at three heights, i.e. 0.1 m, 0.5-0.8 m and 1.5 m above the ground (see Figure 5.4.7 for the sampling positions). From these measured chloride contents it revealed that the chloride contents at the lower two heights, i.e. 0.1 m and 0.5-0.8 m, exceeded the limit value of 3 % mass of cement as specified by Vägverket. Therefore, there exists risk or even high risk of corrosion. With this background the RapiCor was used on this front wall to see if it is in agreement with the results from chloride measurement.

Measurement

The measurement was carried out over the whole front wall on every other steel bars, that is, with about 50 cm between each line. On each line 7 points were measured at heights 3.0 m, 2.3 m, 1.8 m, 1.5 m, 1.1 m, 0.7 m and 0.2m above the ground (M1 as the upmost and M7 as the lowest) in the direction of north to south. The previous sampling positions for chloride measurement are near positions L3M4 (9), L3M6 (8), L3M7 (7), L15M4 (6), L15M6 (5), L15M7 (4), L26M4 (3), L26M6 (2), L26M7 (1).

Weather conditions

The measurement day (6th May, 2010): Relative humidity about 40-50 %, temperature about 10 °C, no raining days before the measurement

Measurement results

A view of measurement area is shown in Figure 5.4.7 and the measured results are shown in Figures 5.4.8 to 5.4.11, where previous sampling holes for chloride measurement are marked with thick black square or rectangular and delamination areas are marked with blue ellipse.

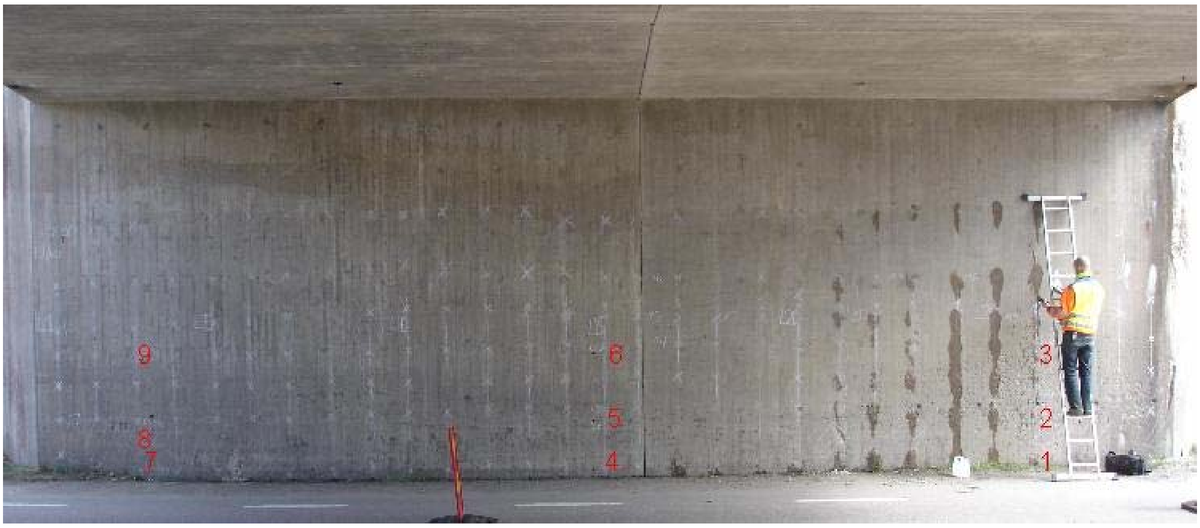
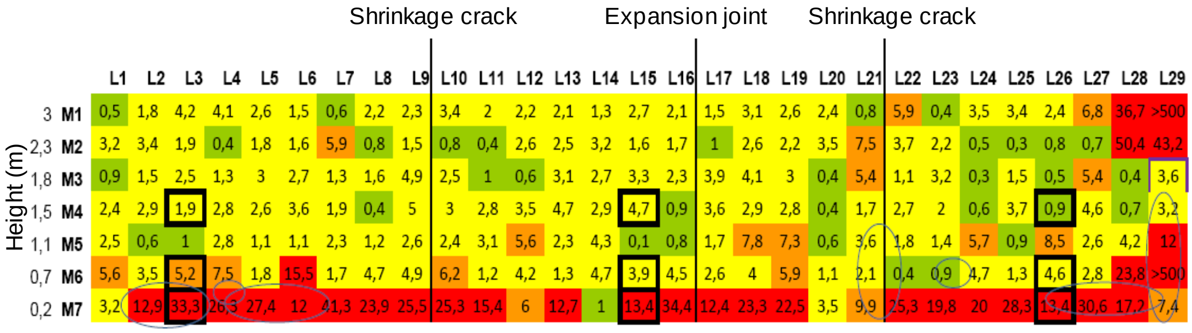
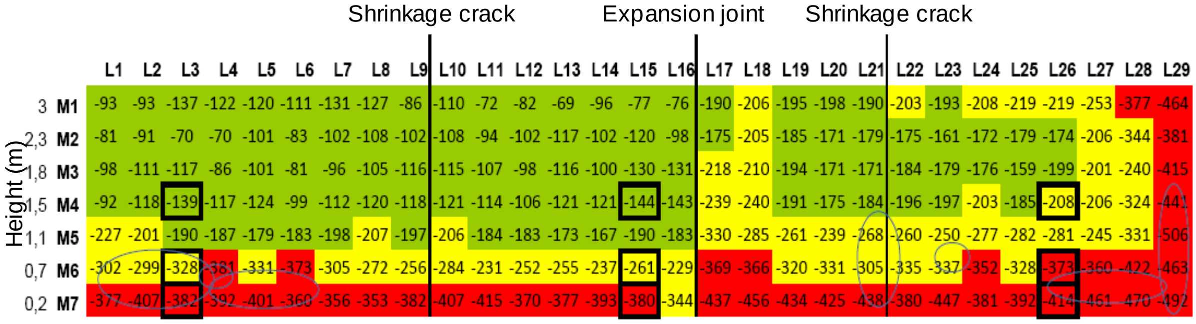


Figure 5.4.7 A view of the measurement area on the eastern front wall of Bridge 19-380-1 [Lind & Wikslund, 2010]



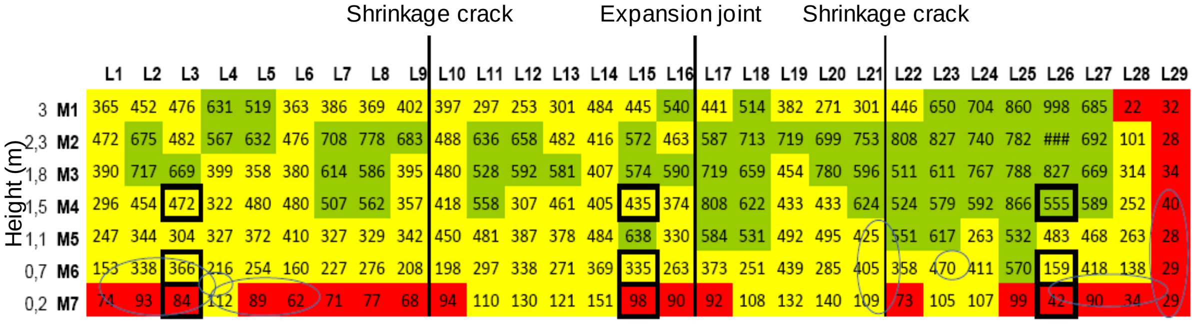
Height (m)		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21	L22	L23	L24	L25	L26	L27	L28	L29
3	**M1**	0,5	1,8	4,2	4,1	2,6	1,5	0,6	2,2	2,3	3,4	2	2,2	2,1	1,3	2,7	2,1	1,5	3,1	2,6	2,4	0,8	5,9	0,4	3,5	3,4	2,4	6,8	36,7	>500
2,3	**M2**	3,2	3,4	1,9	0,4	1,8	1,6	5,9	0,8	1,5	0,8	0,4	2,6	2,5	3,2	1,6	1,7	1	2,6	2,2	3,5	7,5	3,7	2,2	0,5	0,3	0,8	0,7	50,4	43,2
1,8	**M3**	0,9	1,5	2,5	1,3	3	2,7	1,3	1,6	4,9	2,5	1	0,6	3,1	2,7	3,3	2,3	3,9	4,1	3	0,4	5,4	1,1	3,2	0,3	1,5	0,5	5,4	0,4	3,6
1,5	**M4**	2,4	2,9	1,9	2,8	2,6	3,6	1,9	0,4	5	3	2,8	3,5	4,7	2,9	4,7	0,9	3,6	2,9	2,8	0,4	1,7	2,7	2	0,6	3,7	0,9	4,6	0,7	3,2
1,1	**M5**	2,5	0,6	1	2,8	1,1	1,1	2,3	1,2	2,6	2,4	3,1	5,6	2,3	4,3	0,1	0,8	1,7	7,8	7,3	0,6	3,6	1,8	1,4	5,7	0,9	8,5	2,6	4,2	12
0,7	**M6**	5,6	3,5	5,2	7,5	1,8	15,5	1,7	4,7	4,9	6,2	1,2	4,2	1,3	4,7	3,9	4,5	2,6	4	5,9	1,1	2,1	0,4	0,9	4,7	1,3	4,6	2,8	23,8	>500
0,2	**M7**	3,2	12,9	33,3	26,3	27,4	12	41,3	23,9	25,5	25,3	15,4	6	12,7	1	13,4	34,4	12,4	23,3	22,5	3,5	9,9	25,3	19,8	20	28,3	13,4	30,6	17,2	7,4

Figure 5.4.8 Map of corrosion rate [μm/year] on the eastern front wall of Bridge 19-380-1 [Lind & Wikslund, 2010].



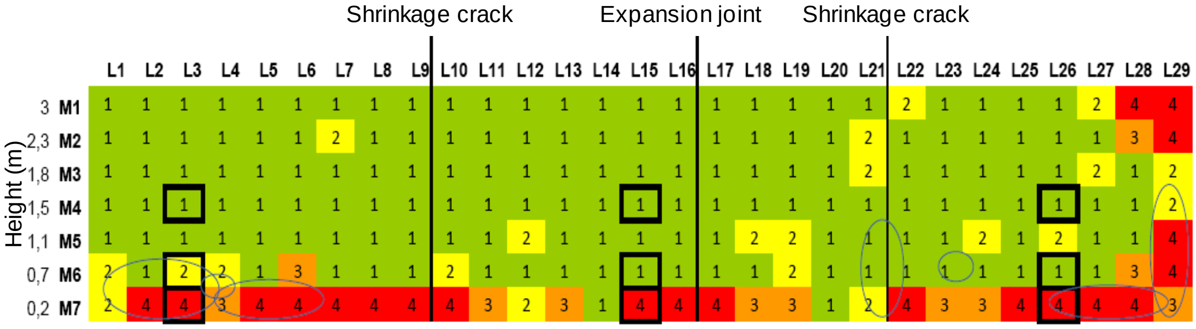
Height (m)		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21	L22	L23	L24	L25	L26	L27	L28	L29
3	M1	-93	-93	-137	-122	-120	-111	-131	-127	-86	-110	-72	-82	-69	-96	-77	-76	-190	-206	-195	-198	-190	-203	-193	-208	-219	-219	-253	-377	-464
2,3	M2	-81	-91	-70	-70	-101	-83	-102	-108	-102	-108	-94	-102	-117	-102	-120	-98	-175	-205	-185	-171	-179	-175	-161	-172	-179	-174	-206	-344	-381
1,8	M3	-98	-111	-117	-86	-101	-81	-96	-105	-116	-115	-107	-98	-116	-100	-130	-131	-218	-210	-194	-171	-171	-184	-179	-176	-159	-199	-201	-240	-415
1,5	M4	-92	-118	-139	-117	-124	-99	-112	-120	-118	-121	-114	-106	-121	-121	-144	-143	-239	-240	-191	-175	-184	-196	-197	-203	-185	-208	-206	-324	-441
1,1	M5	-227	-201	-190	-187	-179	-183	-198	-207	-197	-206	-184	-183	-173	-167	-190	-183	-330	-285	-261	-239	-268	-260	-250	-277	-282	-281	-245	-331	-506
0,7	M6	-302	-299	-328	-381	-331	-373	-305	-272	-256	-284	-231	-252	-255	-237	-261	-229	-369	-366	-320	-331	-305	-335	-337	-352	-328	-373	-360	-422	-463
0,2	M7	-377	-407	-382	-392	-401	-360	-356	-353	-382	-407	-415	-370	-377	-393	-380	-344	-437	-456	-434	-425	-438	-380	-447	-381	-392	-414	-461	-470	-492

Figure 5.4.9 Map of half-cell potential [mV$_{CSE}$] on the eastern front wall of Bridge 19-380-1 [Lind & Wikslund, 2010].



Height (m)		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21	L22	L23	L24	L25	L26	L27	L28	L29
3	M1	365	452	476	631	519	363	386	369	402	397	297	253	301	484	445	540	441	514	382	271	301	446	650	704	860	998	685	22	32
2,3	M2	472	675	482	567	632	476	708	778	683	488	636	658	482	416	572	463	587	713	719	699	753	808	827	740	782	###	692	101	28
1,8	M3	390	717	669	399	358	380	614	586	395	480	528	592	581	407	574	590	719	659	454	780	596	511	611	767	788	827	669	314	34
1,5	M4	296	454	472	322	480	480	507	562	357	418	558	307	461	405	435	374	808	622	433	433	624	524	579	592	866	555	589	252	40
1,1	M5	247	344	304	327	372	410	327	329	342	450	481	387	378	484	638	330	584	531	492	495	425	551	617	263	532	483	468	263	28
0,7	M6	153	338	366	216	254	160	227	276	208	198	297	338	271	369	335	263	373	251	439	285	405	358	470	411	570	159	418	138	29
0,2	M7	74	93	84	112	89	62	71	77	68	94	110	130	121	151	98	90	92	108	132	140	109	73	105	107	99	42	90	34	29

Figure 5.4.10 Map of resistivity [kOhm·cm] on the eastern front wall of Bridge 19-380-1 [Lind & Wikslund, 2010]



Height (m)		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21	L22	L23	L24	L25	L26	L27	L28	L29
3	M1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	2	4	4
2,3	M2	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	3	4
1,8	M3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	2	1	2
1,5	M4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
1,1	M5	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	2	2	1	1	1	1	2	1	2	1	1	4
0,7	M6	2	1	2	2	1	3	1	1	1	2	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	3	4
0,2	M7	2	4	4	3	4	4	4	4	4	4	3	2	3	1	4	4	4	3	3	1	2	4	3	3	4	4	4	4	3

Figure 5.4.11 Map of corrosion index on the eastern front wall of Bridge 19-380-1 [Lind & Wikslund, 2010]

Comments and concluding remarks

The results measured by the RapiCor are compared with the previously measured chloride contents, as listed in Table 5.4.1. It appears that the assessments from these two techniques (The RapiCor and the chloride analysis) are in quite good agreement.

Table 5.4.1 Comparison between the RapiCor results and the chloride content, based on [Lind & Wikslund, 2010]

Sample No.	**Half-cell potential, mV**	**Risk for corrosion**	**Cl^- % mass of cement**	**Comment**
1 (near L26M7)	-414mV, Red	High risk	1.013% Red	In good agreement
2 (near L26M6)	-373mV, Red	High risk	0.812% Red	In good agreement
3 (near L26M4)	-208mV, Yellow	Low risk	0.163% Yellow	In fair agreement
4 (near L15M7)	-380mV, Red	High risk	0.887% Red	In good agreement
5 (near L15M6)	-261mV, Yellow	Risk	0.400% Pink	In good agreement
6 (near L15M4)	-144mV, Green	Low risk	0.163% Yellow	In good agreement
7 (near L3M7)	-382mV, Red	Moderate-high risk	0.595% Pink	In agreement
8 (near L3M6)	-328mV, Yellow	Low risk	0.777% Red	Not in agreement*
9 (near L3M4)	-139mV, Green	Low risk	0.140% Green	In good agreement

* *The actual chloride sampling was taken in the middle of positions L3M6 and L3M7. Therefore, the comparison at this point may not be very reliable.*

It can be concluded from the corrosion map that, up to and including 0.5 m height of the front wall is under a condition of rather severe corrosion. From Table 5.4.1 we can assume that this is caused by road salt that splashed up on the front wall.

From the mapping results we can also see that high corrosion was detected by the RapiCor specially near the southern opening (right side in the figures) of the front wall, where the salt water from the highway above has run through drainage channels down to the concrete, which caused severe corrosion on the entire front wall from the opening to about 2 m inward. To confirm this, a visual examination was arranged by water-jetting away the cover concrete for exposure of reinforcement, as shown in Figure 5.4.12, where corrosion attack on the reinforcement bars can be clearly seen. This is in good agreement with the results measured by the RapiCor.

Figure 5.4.12 Reinforcement bars after removal of concrete at the southern opening of the eastern front wall of Bridge 19-380-1 [Lind & Wikslund, 2010]

5.4.3 Measurement on the underside of the slab of Bridge 19-117-1

The bridge structure inspected is shown in Figure 5.4.13. In the previous inspections some lime precipitations have been found on the underside of concrete slab of Bridge 19-117-1 in Högbyn, V Surahammar. Besides these lime precipitations, no big damage was observed except that some concrete was dropped off from the underside of the slab with a small area in the southeastern corner. The bridge was built in 1937 and situated along a road with low traffic where sand is used as the anti-slipping material. The RapiCor was used to determine if the lime precipitation was due to leakage in the watertight membrane, and to find out if there was corrosion due to possible leakage in the slab.

Figure 5.4.13 Concrete bridge 19-117-1 [Lind & Wikslund, 2010] (Left: a view from side; Right: Lime precipitations underside the bridge slab).

Measurement

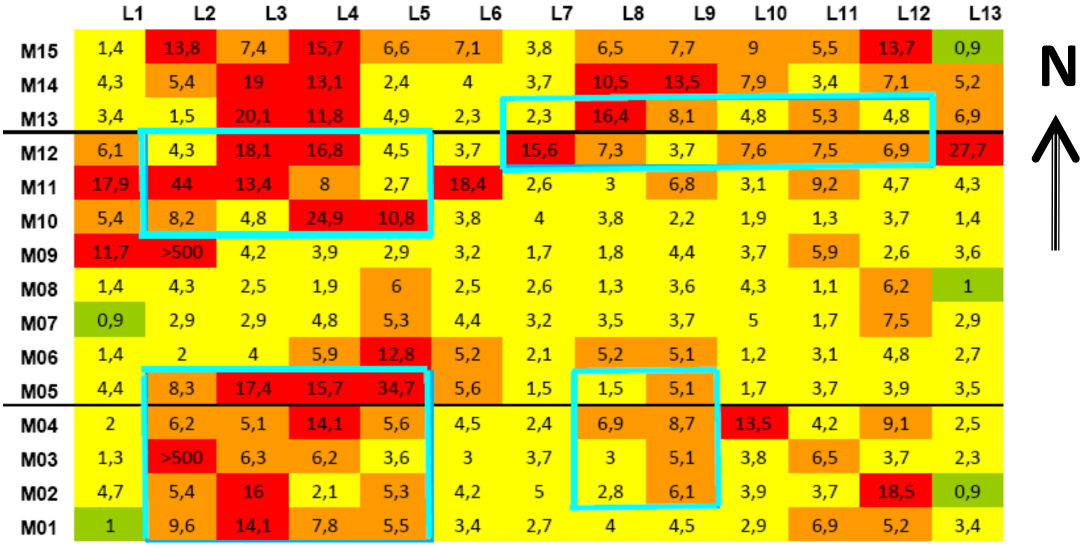
To carry out the measurement a bridge lift was required because there is a river under the bridge. It was remarkable during the measurement that the there was abundance of lime precipitations, especially in the northern half part from M10 towards the northern abutment widespread from L1-L13. Other areas with large amount of lime precipitations are between L1-L5 and M1-M5, and between L9-L10 and M1-M4, on the southern side. At points M4-M5 on line 7 concrete was released away. At position L8M12 there was a small superficial delamination.

Weather conditions

The measurement day (4th May, 2010): Relative humidity about 20 % and temperature about 10 °C, no raining days before the measurement

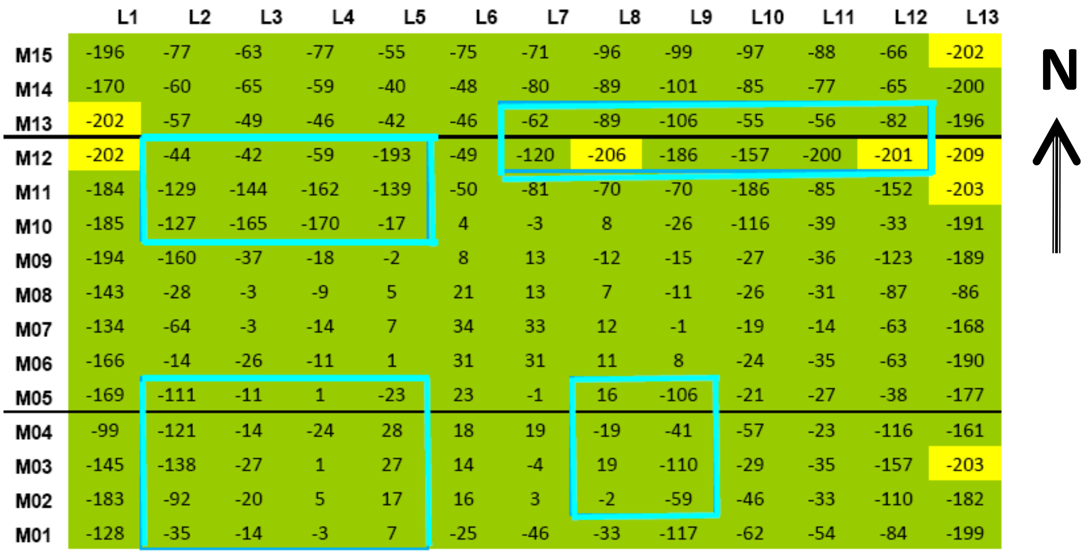
Measurement results

The measured results are shown in Figures 5.4.14 to 5.4.17, where the areas of lime precipitations are marked with thick blue rectangular or square. It can be seen that the areas of relatively high corrosion risk are related to the areas of lime precipitations. The relatively positive values of half-cell potential in Figure 5.4.15 may indicate that the corrosion is possibly induced by carbonation rather than chloride ions. This will be further discussed later. The low values of resistivity in Figure 5.4.16 indicates that the concrete with lime precipitations is relatively moist. The map of corrosion index in Figure 5.4.17 indicates no high risk of corrosion on the reinforcement steel in most part of the slab, but low to moderate risk in and around the areas of lime precipitations. This should be reasonable for carbonation induced corrosion, which is a general type of corrosion without pitting.



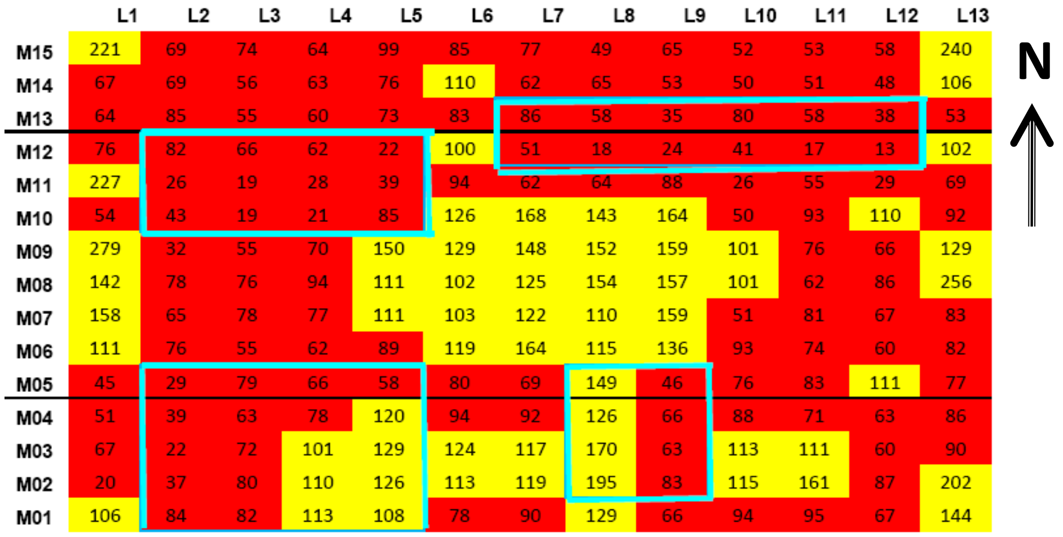
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
M15	1,4	13,8	7,4	15,7	6,6	7,1	3,8	6,5	7,7	9	5,5	13,7	0,9
M14	4,3	5,4	19	13,1	2,4	4	3,7	10,5	13,5	7,9	3,4	7,1	5,2
M13	3,4	1,5	20,1	11,8	4,9	2,3	2,3	16,4	8,1	4,8	5,3	4,8	6,9
M12	6,1	4,3	18,1	16,8	4,5	3,7	15,6	7,3	3,7	7,6	7,5	6,9	27,7
M11	17,9	44	13,4	8	2,7	18,4	2,6	3	6,8	3,1	9,2	4,7	4,3
M10	5,4	8,2	4,8	24,9	10,8	3,8	4	3,8	2,2	1,9	1,3	3,7	1,4
M09	11,7	>500	4,2	3,9	2,9	3,2	1,7	1,8	4,4	3,7	5,9	2,6	3,6
M08	1,4	4,3	2,5	1,9	6	2,5	2,6	1,3	3,6	4,3	1,1	6,2	1
M07	0,9	2,9	2,9	4,8	5,3	4,4	3,2	3,5	3,7	5	1,7	7,5	2,9
M06	1,4	2	4	5,9	12,8	5,2	2,1	5,2	5,1	1,2	3,1	4,8	2,7
M05	4,4	8,3	17,4	15,7	34,7	5,6	1,5	1,5	5,1	1,7	3,7	3,9	3,5
M04	2	6,2	5,1	14,1	5,6	4,5	2,4	6,9	8,7	13,5	4,2	9,1	2,5
M03	1,3	>500	6,3	6,2	3,6	3	3,7	3	5,1	3,8	6,5	3,7	2,3
M02	4,7	5,4	16	2,1	5,3	4,2	5	2,8	6,1	3,9	3,7	18,5	0,9
M01	1	9,6	14,1	7,8	5,5	3,4	2,7	4	4,5	2,9	6,9	5,2	3,4

Figure 5.4.14 Map of corrosion rate [µm/year] on the underside of concrete slab of Bridge 19-117-1 [Lind & Wikslund, 2010].



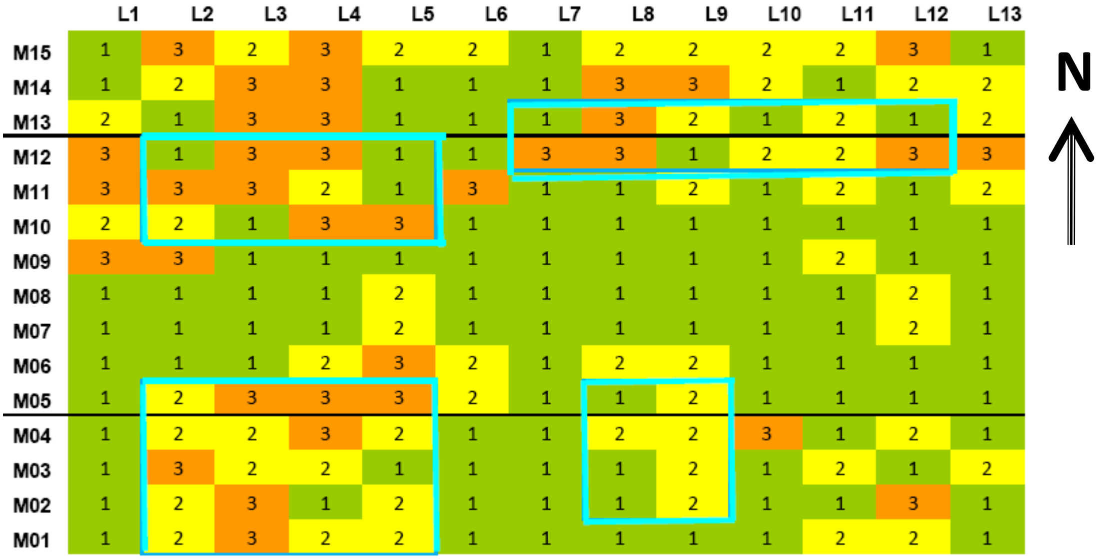
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
M15	-196	-77	-63	-77	-55	-75	-71	-96	-99	-97	-88	-66	-202
M14	-170	-60	-65	-59	-40	-48	-80	-89	-101	-85	-77	-65	-200
M13	-202	-57	-49	-46	-42	-46	-62	-89	-106	-55	-56	-82	-196
M12	-202	-44	-42	-59	-193	-49	-120	-206	-186	-157	-200	-201	-209
M11	-184	-129	-144	-162	-139	-50	-81	-70	-70	-186	-85	-152	-203
M10	-185	-127	-165	-170	-17	4	-3	8	-26	-116	-39	-33	-191
M09	-194	-160	-37	-18	-2	8	13	-12	-15	-27	-36	-123	-189
M08	-143	-28	-3	-9	5	21	13	7	-11	-26	-31	-87	-86
M07	-134	-64	-3	-14	7	34	33	12	-1	-19	-14	-63	-168
M06	-166	-14	-26	-11	1	31	31	11	8	-24	-35	-63	-190
M05	-169	-111	-11	1	-23	23	-1	16	-106	-21	-27	-38	-177
M04	-99	-121	-14	-24	28	18	19	-19	-41	-57	-23	-116	-161
M03	-145	-138	-27	1	27	14	-4	19	-110	-29	-35	-157	-203
M02	-183	-92	-20	5	17	16	3	-2	-59	-46	-33	-110	-182
M01	-128	-35	-14	-3	7	-25	-46	-33	-117	-62	-54	-84	-199

Figure 5.4.15 Map of half-cell potential [mV_{CSE}] on the underside of concrete slab of Bridge 19-117-1 [Lind & Wikslund, 2010].



	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
M15	221	69	74	64	99	85	77	49	65	52	53	58	240
M14	67	69	56	63	76	110	62	65	53	50	51	48	106
M13	64	85	55	60	73	83	86	58	35	80	58	38	53
M12	76	82	66	62	22	100	51	18	24	41	17	13	102
M11	227	26	19	28	39	94	62	64	88	26	55	29	69
M10	54	43	19	21	85	126	168	143	164	50	93	110	92
M09	279	32	55	70	150	129	148	152	159	101	76	66	129
M08	142	78	76	94	111	102	125	154	157	101	62	86	256
M07	158	65	78	77	111	103	122	110	159	51	81	67	83
M06	111	76	55	62	89	119	164	115	136	93	74	60	82
M05	45	29	79	66	58	80	69	149	46	76	83	111	77
M04	51	39	63	78	120	94	92	126	66	88	71	63	86
M03	67	22	72	101	129	124	117	170	63	113	111	60	90
M02	20	37	80	110	126	113	119	195	83	115	161	87	202
M01	106	84	82	113	108	78	90	129	66	94	95	67	144

Figure 5.4.16 Map of resistivity [kOhm·cm] on the underside of concrete slab of Bridge 19-117-1 [Lind & Wikslund, 2010].



	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
M15	1	3	2	3	2	2	1	2	2	2	2	3	1
M14	1	2	3	3	1	1	1	3	3	2	1	2	2
M13	2	1	3	3	1	1	1	3	2	1	2	1	2
M12	3	1	3	3	1	1	3	3	1	2	2	3	3
M11	3	3	3	2	1	3	1	1	2	1	2	1	2
M10	2	2	1	3	3	1	1	1	1	1	1	1	1
M09	3	3	1	1	1	1	1	1	1	1	2	1	1
M08	1	1	1	1	2	1	1	1	1	1	1	2	1
M07	1	1	1	1	2	1	1	1	1	1	1	2	1
M06	1	1	1	2	3	2	1	2	2	1	1	1	1
M05	1	2	3	3	3	2	1	1	2	1	1	1	1
M04	1	2	2	3	2	1	1	2	2	3	1	2	1
M03	1	3	2	2	1	1	1	1	2	1	2	1	2
M02	1	2	3	1	2	1	1	1	2	1	1	3	1
M01	1	2	3	2	2	1	1	1	1	1	2	2	1

Figure 5.4.17 Map of corrosion index on the underside of concrete slab of Bridge 19-117-1 [Lind & Wikslund, 2010].

Comments and concluding remarks

By analyzing the different parameters related to corrosion, we can see that all parameters follow the lime precipitations to some extent. The half-cell potential is positive in the middle of the bridge, but more negative (still with 90 % probability of no corrosion according to ASTM C876) in the edges. Considering the bridge is 73 years old, carbonation can be a reason to the generally positive half-cell potential in the central area where it is under the sheltered condition and the concrete is relatively dry, as also indicated by the map of resistivity in Figure 5.4.16.

Another possible reason why the half-cell potential was so positive, despite the moderate to high corrosion rate, could be the micro-cell corrosion on the steel bars in the upper layer, while we measured the half-cell potential of the steel bars in the lower layer, which functioned as the cathode in the circuit of macro-cell corrosion. However, this possibility of macro-cell corrosion should be very low if there is no chlorides in the concrete, because the upper layer of concrete cannot be more carbonated than the lower layer and the steel bars in the upper layer should be protected by the alkaline environment.

In order to make sure no chloride in the concrete and the corrosion is induced by carbonation, measurement of carbonation depth and chloride content in one or two cores can be performed.

5.4.4 Measurement on the edge beams of Bridge 19-386-1

Bridge 19-386-1 on Highway E18 in Västerås (Figure 5.4.18) was built in 1961 and widened in 1974 when the road was upgraded to highway. The southern edge beam was originally built and found significantly damaged due to corrosion. The northern edge beam is 13 years younger than the south and looks, on the other hand, completely undamaged. To see how much difference between these two edge beams from different ages, their corrosion conditions were investigated by the RapiCor. An important difference between these edge beams is that the northern edge beam descends toward the roadway. Except for this difference the two edge beams were, from the structural view of point, designed in a similar manner with similar reinforcement in terms of size, number and density of stirrup.

Figure 5.4.18 A view of Bridge 19-386-1 from the south side [Lind & Wikslund, 2010].

Measurement

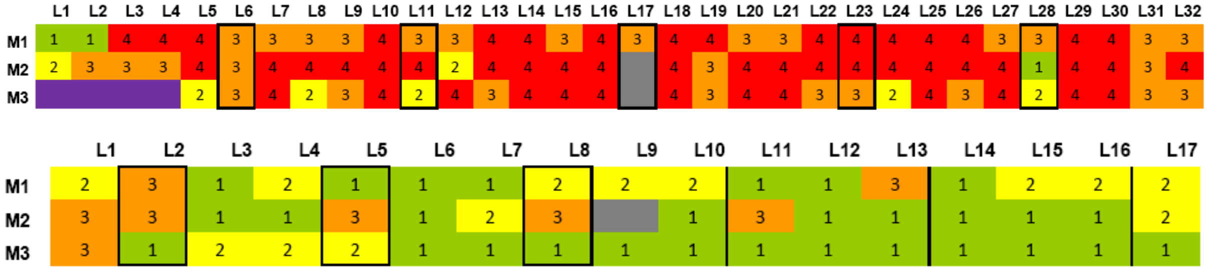
The southern edge beam was significantly damaged hence the measurement was carried out on all the unexposed steel bars between every stirrups. The Northern edge beam looks much better. Thus the measurement points were taken between every other stirrups, as shown in Figure 5.4.19.

Figure 5.4.19 Measurement grids on the southern edge beam (left) and the northern edge beam (right) of Bridge 19-386-1 [Lind & Wikslund, 2010].

Weather conditions

The measurement day (3rd May, 2010): Relative humidity about 15 % and temperature about 14 °C, no raining days before the measurement

Measurement results
The measured results (corrosion index only) are shown in Figure 5.4.20. The results show that there is much more severe corrosion in the southern edge beam.



	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21	L22	L23	L24	L25	L26	L27	L28	L29	L30	L31	L32
M1	1	1	4	4	4	3	3	3	3	4	3	3	4	4	3	4	3	4	4	3	3	4	4	4	4	4	3	3	4	4	3	3
M2	2	3	3	3	4	3	4	4	4	4	4	2	4	4	4	4		4	3	4	4	4	4	4	4	4	4	1	4	4	3	4
M3					2	3	4	2	3	4	2	4	3	4	4	4		4	3	4	4	3	3	2	4	3	4	2	4	4	3	3

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17
M1	2	3	1	2	1	1	1	2	2	2	1	1	3	1	2	2	2
M2	3	3	1	1	3	1	2	3		1	3	1	1	1	1	1	2
M3	3	1	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1

Figure 5.4.20 Map of corrosion index on the southern edge beam (upper) and the northern edge beam (lower) of Bridge 19-386-1 [Lind & Wikslund, 2010]. (purple color = exposed steel due to spalling of concrete; gray = attachment for road signs. The black boxes mark the position of guardrail post down into the edge beam).

Comments and concluding remarks
According to the measurement results it can be concluded that the southern edge beam is in poor condition, and the northern edge beam is generally in good condition. The 13 years younger age is one of the reasons to their difference in corrosion conditions. Another reason could be the fact that the southern edge beam is more exposed to the freezing-thawing climate, which enhanced the salt water uptake due to freeze-thaw cycles. A big reason why the northern edge beam is in good condition could be its inward descent which hindered the deicing salt water from running out through the concrete beam.

6 Conclusions and recommendations

6.1 Conclusions

From the laboratory study presented I n Chapter 3 the following two conclusions can be drawn:

- Wetting-drying cycles apparently affect the resistivity of concrete and half-cell potential of steel. Care must be taken in interpreting the values of resistivity and half-cell potential related to corrosion conditions.
- The corrosion rate measurement seems not significantly affected by wetting-drying cycles, especially when corrosion is at the moderate or high level, which is more important for the bridge inspection.
- The RapiCor instrument can be used for the bridge inspection under various weathers without big problem in the assessment of corrosion conditions.

The results reported by Lind & Wikslund (2010) from Bridge 19-388-1 (measured under the dry and moist weather) also verified the above conclusions.

From the field evaluation presented in Chapter 5 the following conclusions can be drawn:

- The RapiCor can in general be effectively used in assessment of corrosion conditions of reinforcement steel in bridge concrete structures with satisfactory precision.
- Good connection between the instrument cable and the steel network must be assured in order to carry out the reliable measurement.

- There is a reasonably good correlation between the corrosion index and the chloride content near the reinforcement steel.
- Carbonated concrete may result in a relatively positive half-cell potential.

6.2 Suggestions

- Although the RapiCor is a rapid method for assessment of corrosion conditions in the real structures, it still takes much longer time than the conventional visual inspection. If the budget for bridge inspection is limited to the nowadays level for conventional visual inspection, it is not possible to include the RapiCor in such a cheap inspection. Therefore, it is suggested to increase the budget of ordinary inspection in order to make use of the RapiCor for a more reliable inspection.
- The mapping procedure should be optimised in order to reduce the inspection time.
- The electrodes unit should be designed in such a way that a telescope may be used for reaching a height of 2-3 m so that the inspection can be carried out by one operator.

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Appendix A Operation manual of the RapiCor

(32 pages including this page)

RapiCor

TF01

Operation Manual

July 2008

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Contents

1 Introduction

Thank you for choosing RapiCor as your assistant for non-destructive corrosion mapping. The instrument helps you to assess reinforcement corrosion by means of the corrosion rate stating how much steel is being dissolved in µm/year (10^{-3} mm/year). In addition, the half-cell potentials of the reinforcement and the resistivity of the cover layer are simultaneously measured and used as complementary information.

1.1 Principle

The measurement principle is illustrated in Fig. 1.

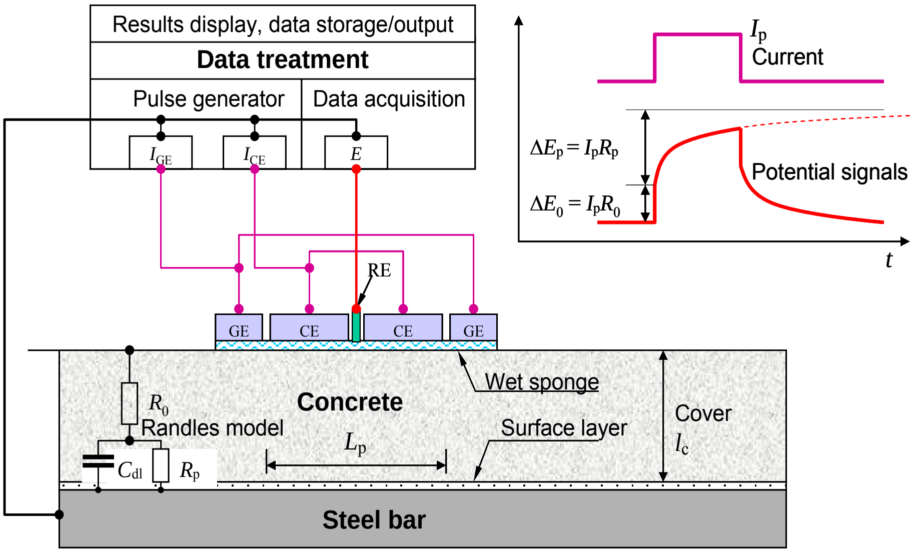


Fig. 1 – Measurement principle.

The electrode consists of a centre reference Ag/AgCl electrode (RE). Positioned on each side of the reference electrode is in points the counter electrodes (CE) and the guard electrodes (GE). With the counter electrodes (CE) a short duration current pulse is applied towards the reinforcement. The two guard electrodes (GE) help to supply relatively homogeneous current density over a length of L_p of the steel bar.

All electrodes are positioned in a handheld, rectangular shaped handle, 15 cm long and 4×3 cm in cross-section, to be placed on the concrete surface, for accurate readings right above the embedded steel bar as illustrated above.

A wet sponge is placed on the concrete surface to improve the contact between the concrete and the electrodes.

The instrument first measures the corrosion potential E_{corr} by the center reference electrode and afterwards imposes galvanostatic currents I_{CE} and I_{GE} through the other electrodes towards the steel bar. The potential response ΔE is recorded at 0.02 seconds time intervals for 5 full seconds. The recorded potential-time curve is directly displayed on the screen of the instrument and is used for calculation of the various parameters, the resistivity of the concrete cover layer and the corrosion rate of the steel bar below.

The special feature of the RapiCorr is that, based on numerical 2-D FEM modeling of the current distribution, the effective polarization current I_p is obtained by integrating the current distribution curve through the specified polarization length L_p. In addition, the currents applied from the electrode system are kept constant in order to obtain the transient potential curve as a response of the total current.

The corrosion rate, X_{corr}, in (µm/year) is calculated using the equation:

$$X_{corr} = C \cdot \frac{I_p}{A \cdot \Delta E_p}$$

"C" being a constant, 302 (µm/year)·(mV·cm^2/µA), "I_p" the effective polarization current in µA, "A" the confined polarization area of the steel bar and ΔE_p the steady-state polarization potential.

The resistivity of the concrete, ρ_c, is calculated as well, using the equation:

$$\rho_c = R_\Omega \cdot \frac{(A_{sp} + A)}{2 l_c}$$

"R_Ω" being the true concrete resistance, "A_{sp}" the electrode sponge area, "A" the confined steel area and l_c the depth to the steel bar.

1.2 Classification and accuracy

The corrosion condition can be classified according to Table 1.

Table 1 – Example of classification of corrosion index

Corrosion Index		Corrosion rate (µm/year)	Half-cell potential (mV $_{(CSE)}$)	Resistivity (kOhm·cm)
1	Negligible	<1 1~5	- > - 200	- > 100
2	Low	1~5 5~10	< - 200 > - 200	< 100 > 100
3	Moderate	5~10 >10	< - 200 > - 200	< 100 > 100
4	High	>10	< - 200	< 100

The primary evaluation parameter, the corrosion rate, is supplemented by the half-cell potential and the resistivity for classifying the state of corrosion. If these two complementary parameters are not in consistence with the corrosion rate, the corrosion level will be classified as one level lower.

For example, if the corrosion rate is in the range of 5~10 µm/year corresponding to "moderate" corrosion level, while the half-cell potential is higher than –200 mV CSE and the resistivity is larger than 100 kOhm·cm, the corrosion level will be classified as "low".

The classification of the corrosion rate is in the same order as experienced earlier by other test systems (e.g. GalvaPulse, K. Clear Instrument & Gecor). The corrosion rate measured by the RapiCor has been calibrated with actual weight loss measurements, ref. [2] & [3], and found reasonably comparable.

2 RapiCor Instrument

2.1 Equipment Kits

The equipment comes in an attaché case (see Fig. 2) containing:

1. RapiCor handheld instrument (1 ps)
2. Electrode unit Type R (1 ps)
3. Electrode unit Type S (1 ps, optional)
4. Check box (1 ps)
5. Rebar locator including a 6LF22 battery and operating instructions (1 ps)
6. 3-ways cable for connecting the instrument the electrodes unit or check box (1 ps)
7. Banana cable for connecting the instrument to the cable drum or the rebar (1 ps)
8. Cable for data transfer to PC (1 ps)
9. Crocodile clip (2 ps)
10. AA LR6 battery for the instrument (4 ps)

In the lids of the suitcase:

11. Adjustable clamping pliers (1 ps)
12. Gel type of Ag/AgCl reference electrode (1 ps)
13. Simple Ag/AgCl electrodes (10 ps, optional)
14. Sponges for the electrodes unit (5 ps)
15. Scissors (1 ps, optional)
16. Rebar adapting bolt (2 ps)
17. Allen key (1 ps)
18. Hammer (1 ps)
19. Operation manual
20. Program CD

Additional delivery:

21. Cable drum, 30 meters
22. Spray bottle (1 ps)

Fig. 2 – Example of the equipment kit.

2.2 The handheld instrument

Figures 3 to 5 show various parts of the instrument.

Fig. 3 – Front panel.

Fig. 4 – Battery cover and box.

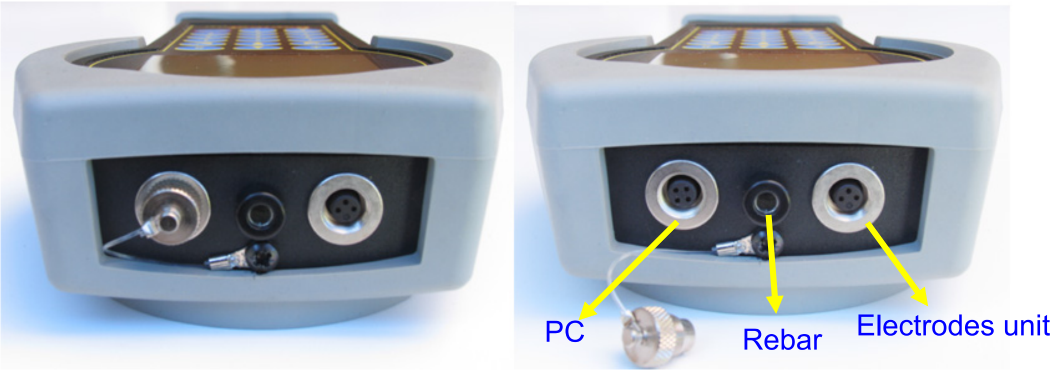


Fig. 5 – Sockets; a) with protection cap on, and b) with protection cap unscrewed.

2.3 Function of the keys

On/Off Turn on or off the instrument by pressing and holding it a few seconds until the screen displays the menu or the content on the screen disappears.

▲ Move upwards the cursor or the selection arrow.

▼ Move downwards the cursor or the selection arrow.

Pg Up ◀ Move leftwards the cursor or a page up if there are many items in a list.

▶ Pg Dn Move rightwards the cursor or a page down if there are many items in a list.

* Go to the previous step or repeat the polarization process if the polarization curve is abnormal under a measurement.

\# Go to the next step, accept the selected operation or accept the polarization curve under a measurement.

💡	Enlighten the background of the screen. Notice that enlightening consumes power and should not be used under the polarization process.
1 del	Input number “1” by one short press or delete the content under the cursor by two short presses.
2 ABC	Input number “2” by one short press, letter “A” by two short presses, “B” by three short presses, or “C” by four short presses.

Similarly, for the rest of numerical keys one short press input the number, two short presses input the first letter, three short presses for the second letter, and so on.

3 Operation Instruction

3.1 Getting started

3.1.1 Installing batteries

- Unscrew (if any) and open the battery cover on the back of the instrument (see Fig. 3).
- Insert four AA LR6 batteries and make sure that the polarities (+ and -) are aligned correctly.
- Replace and press (or screw) tight the battery cover.

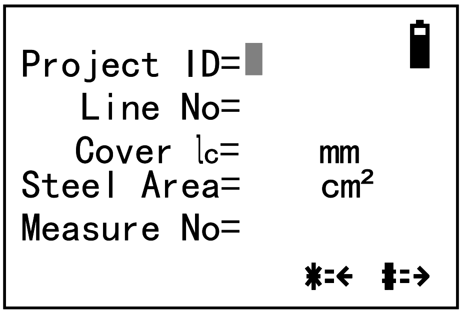
3.1.2 Controlling the instrument

- Connect the instrument to Check Box with the 3-ways cable and the single black cable (see Fig. 6).
- Turn on the instrument and select “Measurement” (default).
- Press “#” key so that the screen shows the input parameters (see Fig. 7).
- Name any Project ID and input any Line No.
- Input Cover 50 mm and Steel Area 50 cm^2.
- Input any Measure No.
- Put the position in Check Box at “A” (simulating passive steel in a moderate dry concrete), “B” or “C” (see Table 2 for the simulation of each position).
- Press “#” key so that the screen shows a confirmation of the input parameters.
- Press “*” to go back to the previous display if any correction/modification of the input parameter is needed.
- If the input parameters are correct, press “#” to start the measurement. The screen shows the development of a polarization curve (NOTE 1) and, when the polarization process is finished, the keys “*” and “#” appear.
- Press “#” to display the measurement results or press “*” to repeat the polarization if the polarization curve is abnormal (e.g. very fluctuation or decreasingly development).
- Disconnect the instrument and Check Box if the results are in the range as listed in Table 2, indicating that the instrument works correctly, or otherwise repeat the measurements to make sure if the instrument is out of function (NOTE 2).
- Turn off the instrument by pressing “On/Off” key and holding it a few seconds until the display on the screen disappears.

NOTE 1: At position “C” the second polarization curve appears immediately after the first one due to the low value of the first polarization.

NOTE 2: Please contact the dealer if the instrument is out of function.

Fig. 6 – Connection to Check Box.



```
Project ID=█
   Line No=
   Cover lc=     mm
Steel Area=     cm²
Measure No=
               *=←  #=→
```

Fig. 7 – Display of input parameters.

Table 2 – Approximate values of Check Box.

Position and its simulation		X_{corr} [µm/year]	U_{corr}* [mV]	ρ_c [kOhm·cm]
A	Passive steel in moderate dry concrete	< 0.3	0 ± 5	220~280
B	Passive steel in wet concrete	< 0.3		20~40
C	Depassive steel in wet concrete	22~28		18~24

* No simulation of half-cell potential.

3.1.3 Zero-setting the reference potential

Before using the electrodes unit Type R, the following procedure is needed to set the reference potential close to zero:

- Connect the instrument with the check box as shown in Fig. 6.
- Turn on the instrument and select “Calibration” using ↑ or ↓ keys.
- Press “#” key so that the screen shows the sub-menu (see Fig. 8).
- Select “New Calibr” and press “#” key to start calibration. The new value (NOTES 1) on the right side of the same row will appear after a second.
- Repeat the above procedure until the new value is stable.
- Select “Upgrade” and press “#” key to store the new value in the memory. The old value on the right side of “Last calibr” will be replaced by the new value.
- Press “*” key to quit the calibration.

NOTE 1: Under the connection as shown in Fig. 6, the value should be close to 0 ± 5 mV.

.

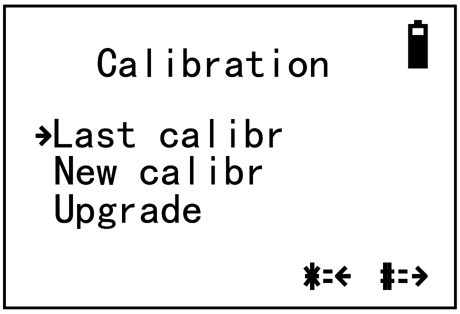


Fig. 8 – Sub-menu for calibration the reference electrode.

3.1.4 Preparing the electrodes unit Type R

This unit is designed for using a gel type of Ag/AgCl reference electrode (RE) to achieve a high precision of half-cell potential measurement.

- Take away the plastic cup from the electrode tip and keep the cup in a safe place.
- Install the RE onto the holder at the center of the unit as shown in Fig. 9.
- Let the tip of the RE slightly (about 1 mm) protrude the counter electrodes (CE) so as to assure its contact with the sponge.
- Put the wet sponge or absorbent cloth (NOTE 1) onto the unit as shown in Fig. 9.
- Connect the electrodes unit with the 3-ways cable to the 3-ways socket (see Fig. 5).

NOTE 1: The sponge can easily be made by cutting a piece of 15×4 cm cellulose based material, e.g. kitchen clothe of about 3 mm thickness (under moist condition), and gluing with contact adhesive a strip of female touching band of size about 50×8 mm on each corner (see Fig. 9).

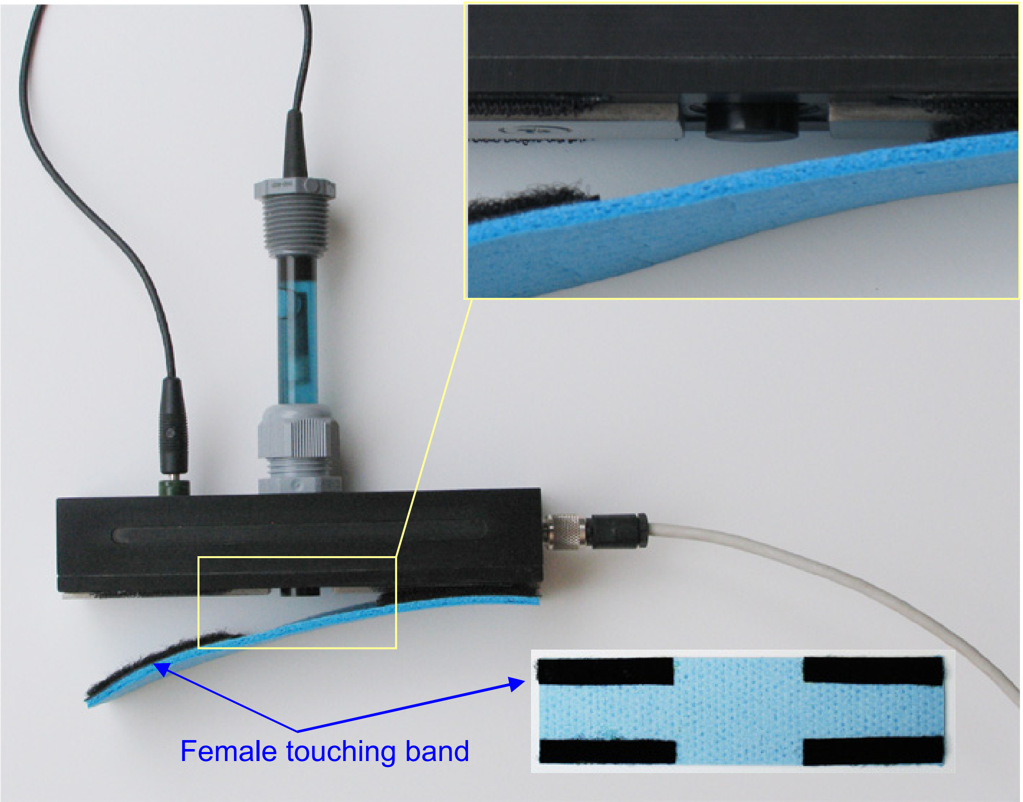


Fig. 9 – Install the gel type of reference electrode onto the electrodes unit Type R.

3.1.5 Preparing the electrodes unit Type S (optional)

This unit is designed for using a simple type of Ag/AgCl electrode and can be used when the accuracy of half-cell potential is not crucial or when the measurement space is limited for placement of the electrodes unit Type R.

- Cut the simple Ag/AgCl electrode (NOTE 1) to a wideness of 18~20 mm if necessary (see Fig. 10).
- Install the simple electrode onto the holder at the center of the unit (see Fig. 11).
- Take away the protection film from the simple electrode.
- Put the wet sponge or absorbent cloth onto the unit (see Fig. 12).
- Connect the electrodes unit with the 3-ways cable to the 3-ways socket (see Fig. 5).

NOTE 1: The potential of this simple type of Ag/AgCl may slowly shift due to the contaminations of various ions from concrete. Since the shifting process is very slow, it does not affect the corrosion rate or resistivity measurement, but may result in a shifted half-cell potential after many measurements. Therefore, it is recommended to calibrate (see 3.1.6) this type of electrode frequently (e.g. every 30 measurements) against the better stable gel type of Ag/AgCl reference electrode if a high accuracy of half-cell potential is required. When the calibration value is more negative than -110 mV, the simple electrode must be replaced.

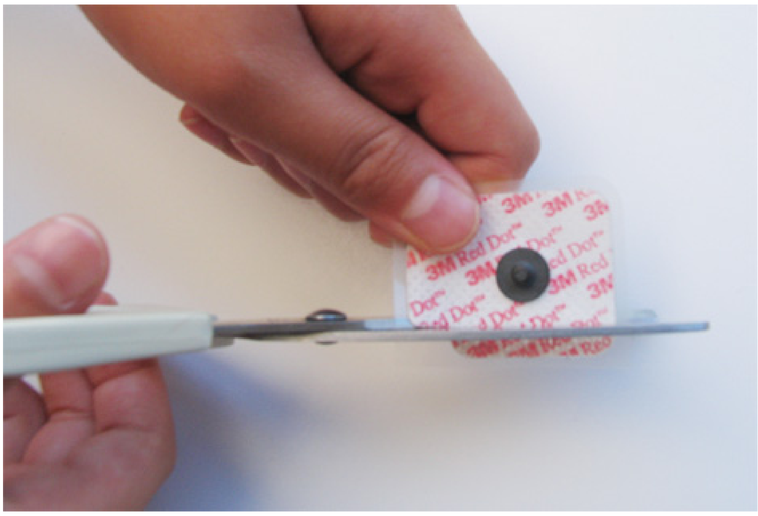


Fig. 10 – Cutting a simple Ag/AgCl electrode.

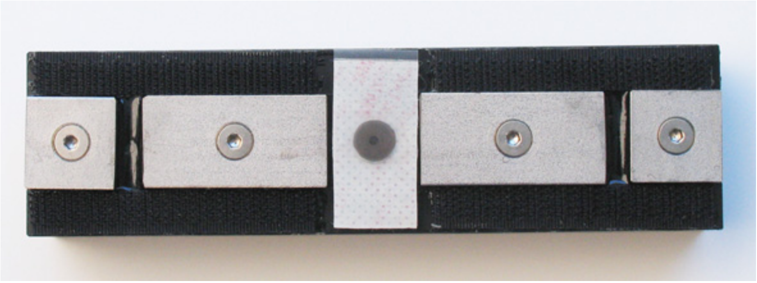


Fig. 11 – Install a simple Ag/AgCl electrode.

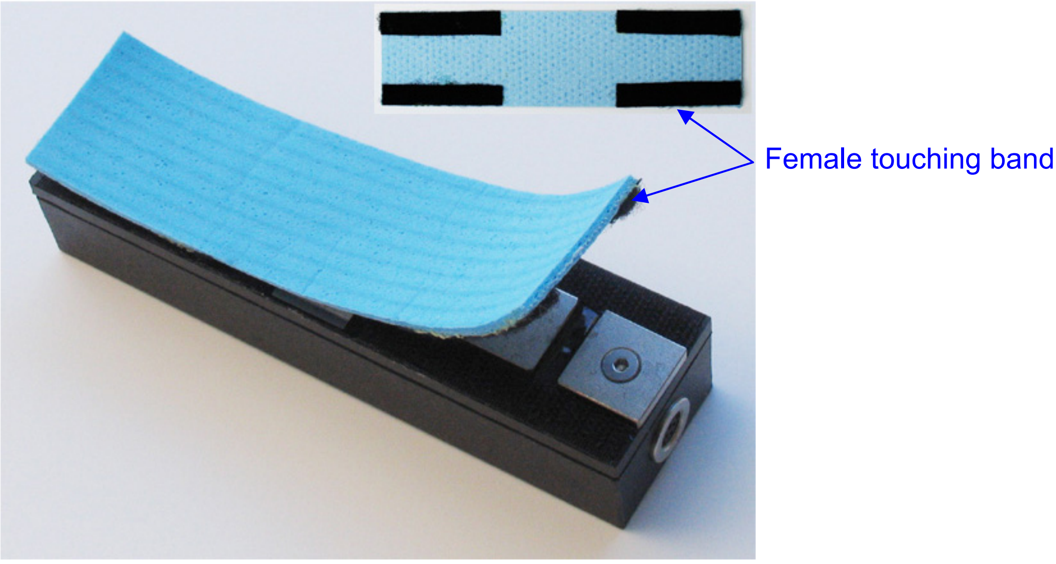


Fig. 12 – Placing a sponge on the electrodes.

3.1.6 Calibrating the simple Ag/AgCl electrode (optional)

- Connect the gel type of Ag/AgCl reference electrode to the single black socket in the front of the instrument (see Fig. 5).
- Place the electrodes unit on a wet sponge.
- Place the gel type of Ag/AgCl reference electrode closely beside the central electrode (see Fig. 13).
- Turn on the instrument and select "Calibration" using ↑ or ↓ keys.
- Press "#" key so that the screen shows the sub-menu (see Fig. 8).
- Select "New Calibr" and press "#" key to start calibration. The new value (NOTE 1) on the right side of the same row will appear after a second.
- Repeat the above procedure until the new value is stable.
- Select "Upgrade" and press "#" key to store the new value in the memory. The old value on the right side of "Last calibr" will be replaced by the new value.
- Press "*" key to quit the calibration.

NOTE 1: If any of the reference electrodes is disconnected, the value will be very negative (-2000 ~ -3300 mV depending on the environment). In this case please check the connection.

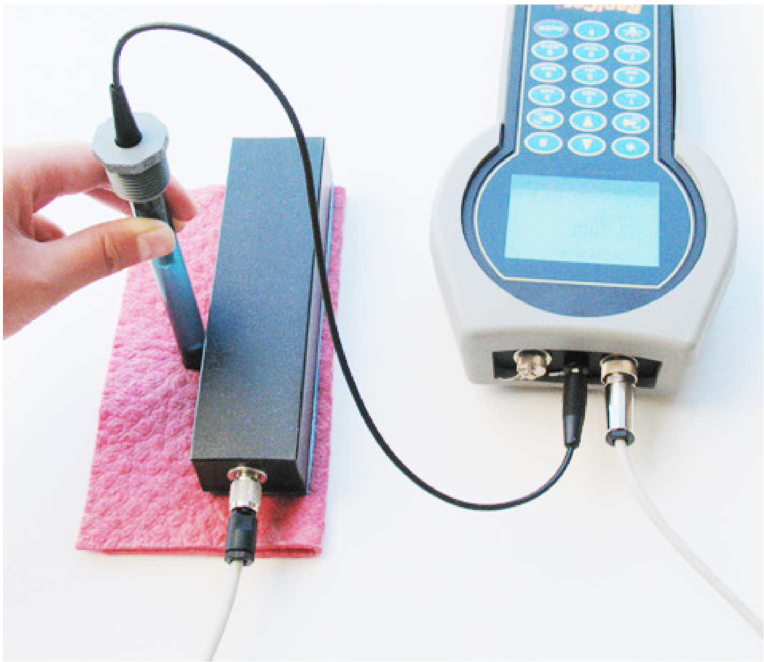


Fig. 13 – Calibration of the simple Ag/AgCl electrode.

3.2 Preparing the measurement

3.2.1 Getting connection to reinforcement

- Locate the reinforcement using the rebar locator (see the separate operation manual).
- Drill a hole of ∅18~20 mm to the rebar, on the centerline, and continue drill with a 10 mm drill bit sideward so that the drill bit is in touch with the rebar (see Fig. 14).
- Blow the hole free from dust and insert the rebar adapting bolt with the help of a hammer into the hole with the sloping edge of the bolt resting against the rebar.

- Turn the bolt firmly with the 10 mm Allen key for the threads of the bolt to cut into the rebar.

Afterwards the reinforcement can be connected with the help of the adjustable clamping pliers, crocodile clips, cable drum and/or banana cable to the single black socket in the front of the instrument (see Fig. 5).

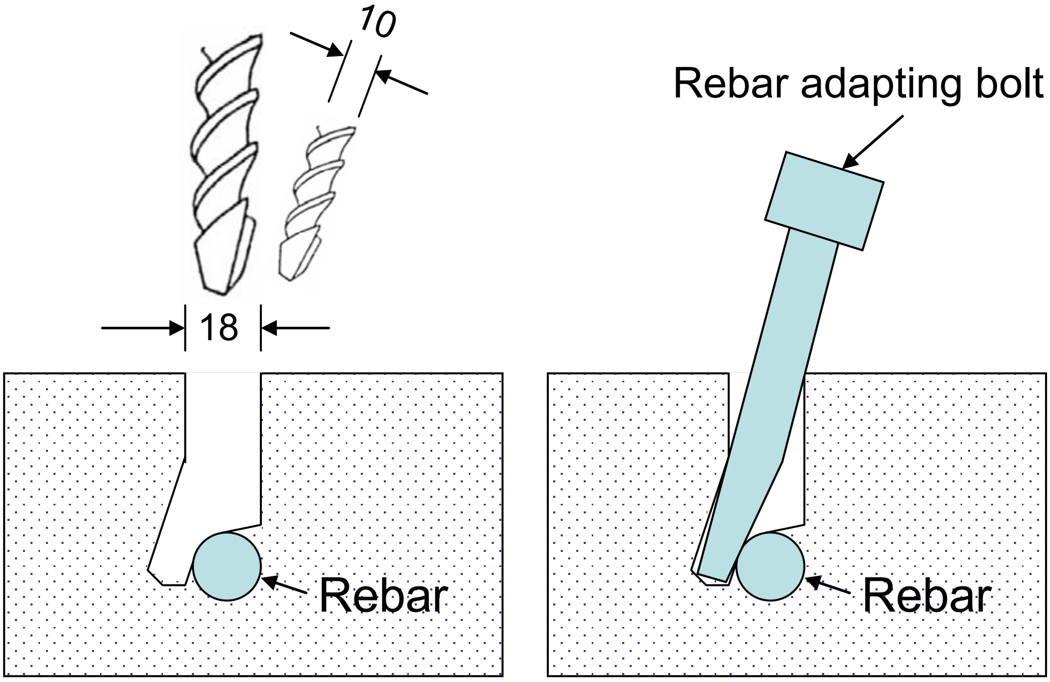


Fig. 14 – Connecting to reinforcement.

3.2.2 Checking connectivity of the reinforcement

The reinforcement bars in concrete should be electrically connected. If uncertain, two positions covering the measurement area have to be connected following 3.2.1. Two ways can be used to check the connectivity: using a multimeter to measure the ohmic resistance (it should be less than a few ohms with good connectivity) between two positions; or using the following way:

- Connect one of the exposed bars through one of the adapter bolts by means of clamping pliers, crocodile clips and a banana cable or the drum cable to the banana socket in the instrument (see Fig. 15).
- Similarly, connect another exposed bar to the banana socket in Check Box.
- Carry out the test as described in 3.1.2 “Controlling the instrument”.

If the values from the test are close to those listed in Table 2, the connectivity is good. Otherwise it is poor, either caused by lack of reinforcement connection or poor connection between the adapter bolt and the bar.

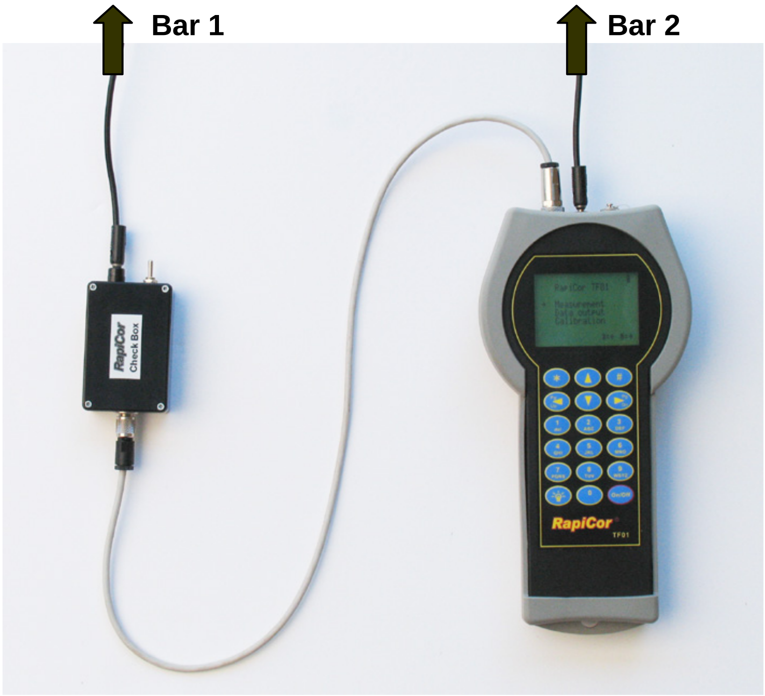


Fig. 15 – Checking connectivity.

3.2.3 Marking grid

A grid may be small or large depending on the type of structures and the size of area to be investigated. It is preferable to mark a grid as a multiple unit of the bar spacing so that the measurement position is above the rebar.

3.2.4 Wetting the concrete surface

The concrete must be moist enough to be able to carry the polarization current to the reinforcement. Therefore, the concrete surface at the measurement position should be sufficiently wetted before measuring. The similar procedure for wetting described in ASTM C876 can be followed.

3.2.5 Estimating the cover thickness

The cover thickness can be estimated in the following ways:

- By means of an accurate cover detector;
- By measurement through the drilled holes; or
- By investigating the structural drawings.

3.2.6 Estimating the steel area

In the real structures, for instance, bearing walls in a tunnel, the reinforcement bars are connected each other and placed in two perpendicular directions, as shown in Fig. 16. When the electrical current is imposed to the electrodes unit (sensor in Fig. 16) the current will not only flow to the underneath bar, but also partly flow through the concrete to the adjacent steel bars. Although it is difficult to exactly quantify how much amount of current flowing to the adjacent bars, it is reasonable to assume that this “bypassed” current is related to the sizes of the electrodes unit, distance between steel bars, resistivity of concrete and corrosion conditions. The following equation is suggested for calculating the effective area of reinforcement, A, to which the polarization current, I_p, has flowed [Ref 2]:

$$A = L_p \cdot \pi \cdot \left[n_L D_L \left(1 + \frac{\alpha b_s}{d_L} \right) + n_T D_T \frac{\beta L_s}{d_T} \right]$$

where L_p = 10.5 cm as the specified polarization length, n is the number of steel bars that are bandaged together, D is the diameter of steel bars, d is the distance between steel bars, b_s and L_s are the apparent wideness and length of the sensor, respectively, and α and β are 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 cases $\alpha = \beta = 2$. The subscript "L" and "T" denote longitudinal and transverse direction of steel bars, respectively.

The information about steel bars in concrete can be obtained by investigating the structural drawings or by actual measurement of an exposed area.

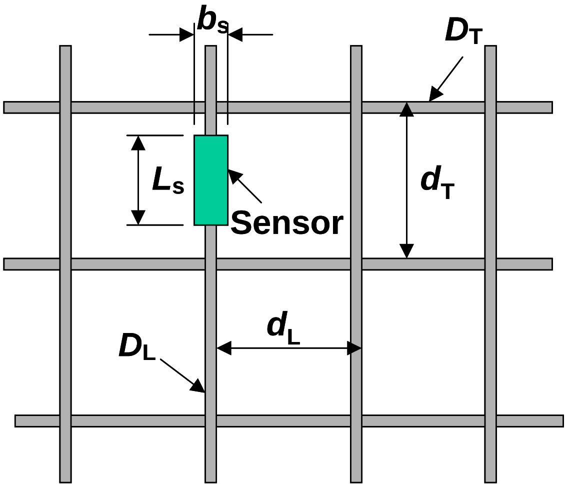


Fig. 16 – Illustration of reinforcement network in a real concrete structure.

3.3 Carrying measurements

- Connect one of the exposed bars through one of the adapter bolts by means of clamping pliers and a banana cable or the drum cable to the banana socket in the instrument (see Fig. 5).
- Place the electrodes unit with wet sponge on the wet concrete surface where the underneath reinforcement is to be measured.
- Turn on the instrument and select "Measurement" (default).
- Press "#" key so that the screen shows the input parameters (NOTE 1).
- Name or rename Project ID (max. 8 letters or numbers).
- Input Line No (range from 1 to max. 60).
- Input Cover thickness (range from 1 to max. 254 mm).
- Input Steel Area (range from 1 to max. 999 cm^2).
- Input Measure No (range from 1 to max. 30).
- Press "#" key so that the screen shows a confirmation of the input parameters.
- Press "*" to go back to the previous display if any correction/modification of the input parameter is needed.

- If the input parameters are correct, firmly hold the electrodes unit in place and press “#” to start the measurement. The screen shows the development of a polarization curve (NOTE 2) and, when the polarization process is finished, the keys “*” and “#” appear.
- Press “#” to display the measurement results, which are automatically stored in the internal memory for later retrieval, or press “*” to repeat the polarization if the polarization curve is abnormal (e.g. very fluctuation or decreasingly development, see Appendix for some examples).
- Move the electrodes unit to the next measurement position and repeat the above procedures (NOTE 3).
- If the results from a measurement position are in doubt, the measurement can be repeated by inputting the corresponding Line No. and Measure No. [NOTE 4]

NOTE 1: The instrument automatically remembers and retrieves the latest input parameters.

NOTE 2: If the value of the first polarization curve is too low, the instrument automatically increases the current and measures the second polarization curve.

NOTE 3: The instrument automatically increases one Line No. after each measurement.

NOTE 4: Only the results from the latest measurement with the corresponding Project ID, Line No. and Measure No. are stored in the memory, implying that the previous data at the corresponding Project ID, Line No. and Measure No. will be deleted. If the previous data will be kept, Project ID must be renamed.

3.4 Transferring the data to a computer

- Unscrew the protection cap [NOTE 1] on the 4-ways socket and connect the 4-ways plug of the data cable to the socket and the 9-pins plug to a serial port in the computer (see Fig. 17) [NOTE 2].
- Start program “RapiCor Data Acquisitioner” (see Chapter 4 for detailed information about the program).
- Turn on the instrument and select “Data output”.
- Press “#” key so that the screen shows the sub-menu (see Fig. 18).
- Select “PC2RapiCor” (default) and press “#” so as to make the instrument ready for data output, as shown Fig. 19.
- Start the acquisition by clicking the title box or pressing Ctrl+d (= simultaneously pressing both “Ctrl” and “d” keys) on the computer.
- When a window appears, select the correspondent serial port number.
- Click “List Project” so that the button becomes disabled a while for retrieving the project IDs from the instrument. With a proper established communication, the project IDs will be shown in the list box in a few seconds. Otherwise please check the connection and serial port number. Sometimes restart the instrument can help the establishment of communication between the computer and the instrument.
- Select the desired project ID [NOTE 3] and click “Download” so that the message box appears informing the downloading is ongoing (be patient because the downloading process is slow – approximately at a rate of 20 measurement results per second).
- If any endless running of the program occurs, press Ctrl+Break to terminate it.
- After successful transfer of data, a new Excel workbook containing transferred data and a message box appear. If no further transfer is needed, click “No” to terminate the transfer.
- Save the data in the Excel workbook as a desired file name.

- Turn off the instrument, disconnect the cable and replace the protection cap on the socket.

NOTE 1: The protection cap or plug should be tightly screwed on the socket to protect the instrument from splashing water.

NOTE 2: If it is lack of serial port on a portable computer, a USB-RS232 adapter can be used for create a USB based serial port. Read the user manual of the adapter to install its software and identify the port number after the connection of the adapter.

NOTE 3: The instrument stores the last polarization curve as Project ID "||last||". Select this for downloading the polarization curve.

Fig. 17 – Connecting to a serial port.

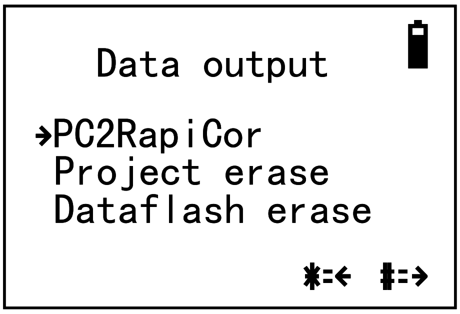


Fig. 18 – Sub-menu of Data output.

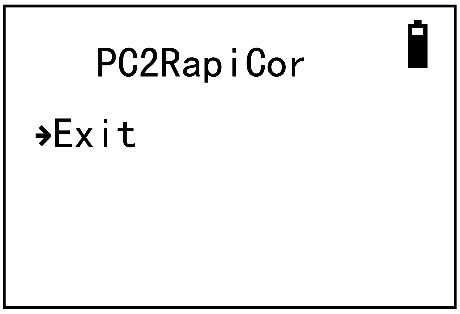


Fig. 19 – Ready for data output.

3.5 Erasing data from the memory

The instrument can store maximum 40 projects, each of which can contain a matrix of maximum 60 lines and maximum 30 measure numbers. To avoid data loses due to overflow or other damages of the memory, it is recommended to transfer the data to a computer as soon the measurements of a project are completed. Afterwards the project data in the memory may be erased to leave places for new projects.

To erase individual project data:

- Turn on the instrument and select “Data output”.
- Press “#” key so that the screen shows the sub-menu.
- Select “Project erase” and press “#” key so that the screen shows the project list.
- Select the project to be erased using ↑ or ↓ keys, or “Pg Up” or “Pg Dn” keys when appreciated.
- Press “#” key so that the screen shows the confirmation message.
- Select “Yes” and press “#” key again to erase the selected project [NOTE 1].

To erase all the projects in the memory:

- Turn on the instrument and select “Data output”.
- Press “#” key so that the screen shows the sub-menu.
- Select “Dataflash erase” and press “#” key so that the screen shows the confirmation message.
- Select “Yes” and press “#” key again to erase all the projects [NOTE 2].

NOTE 1: The erased data are unrecoverable! Make sure that the selected data can be erased before this operation.

NOTE 2: The instrument refreshes all the memory spaces for 40 projects, no matter if there are data or not. So it will take 30~40 seconds to complete the operation.

4 Program for Data Transfer and Presentation

4.1 Installation

- Insert the program CD in a CD-ROM driver of the computer.
- If the installation does not start automatically, click “Start” in Microsoft Windows and select “This computer” [NOTE 1].
- In “This computer” window click the CD-ROM driver containing the program CD.
- Find the file “Setup” and double click it.
- Follow the instruction on the screen until the installation is completed.

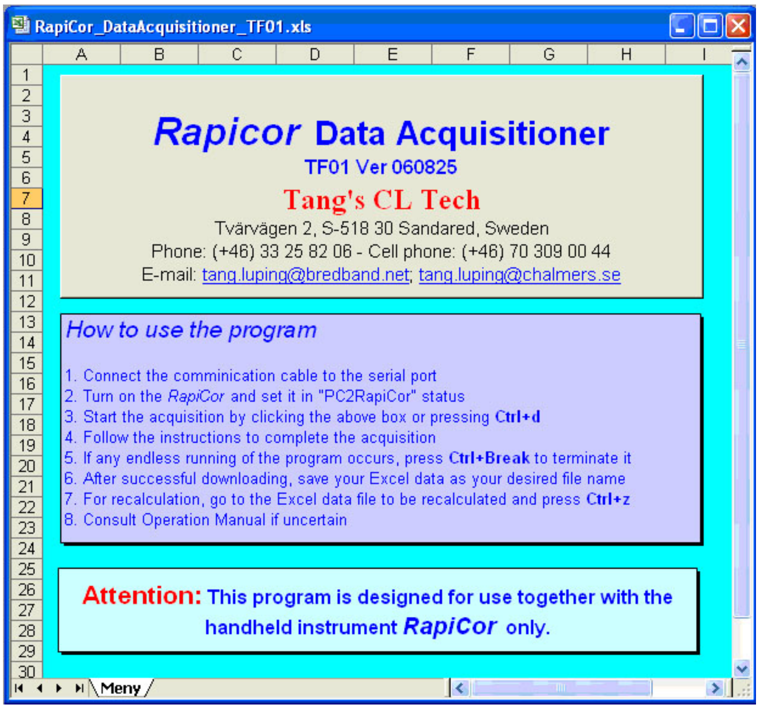
After the installation, the program named “RapiCor Data Acquisitioner” can be found in the directory “C:\Program files\RapiCor\”.

NOTE 1: Alternatively, click “Start” and select “Run”. In “Run” box type “D:\setup”, where “D” is the label of the CD-ROM driver containing the program CD. It could be any other letter depending on the computer settings.

4.2 Starting the program

Different ways can be used to start the program. A classic way is to click “Start” in Microsoft Windows, then click “All program”, “RapiCor” and “RapiCor Data Acquisitioner”. A simple way is to create a shortcut of the program on the desktop. Consult your computer administrator for how to create a shortcut.

After start of the program, a window will appear (see Fig. 20). Follow the instruction in the window for data transfer or recalculation.



Rapicor **Data Acquisitioner**

TF01 Ver 060825

Tang's CL Tech

Tvärvägen 2, S-518 30 Sandared, Sweden

Phone: (+46) 33 25 82 06 - Cell phone: (+46) 70 309 00 44

E-mail: tang.luping@bredband.net; tang.luping@chalmers.se

How to use the program

1. Connect the comminication cable to the serial port
2. Turn on the *RapiCor* and set it in "PC2RapiCor" status
3. Start the acquisition by clicking the above box or pressing **Ctrl+d**
4. Follow the instructions to complete the acquisition
5. If any endless running of the program occurs, press **Ctrl+Break** to terminate it
6. After successful downloading, save your Excel data as your desired file name
7. For recalculation, go to the Excel data file to be recalculated and press **Ctrl+z**
8. Consult Operation Manual if uncertain

Attention: This program is designed for use together with the handheld instrument ***RapiCor*** only.

Fig. 20 – Program for data transfer.

4.3 Data transfer from RapiCor to computer

See 3.4 “Transferring the data to a computer” for detailed procedures. In this section some examples will be given.

By clicking the title box or pressing Ctrl+d (= simultaneously pressing both “Ctrl” and “d” keys) on the computer, a new window appears. Again, follow the instruction in the window to list the projects stored in the instrument (see Fig. 21). Afterwards select the project and click “Download” to start data transfer. After successful transfer of data, a new Excel workbook containing transferred data and a message box appear. Select “Yes” for another transfer or “No” if no further transfer is needed. , click “No” to terminate the transfer.

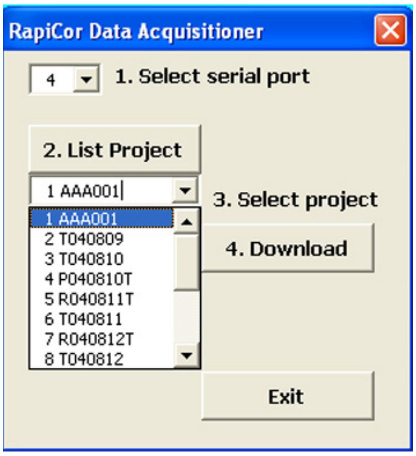
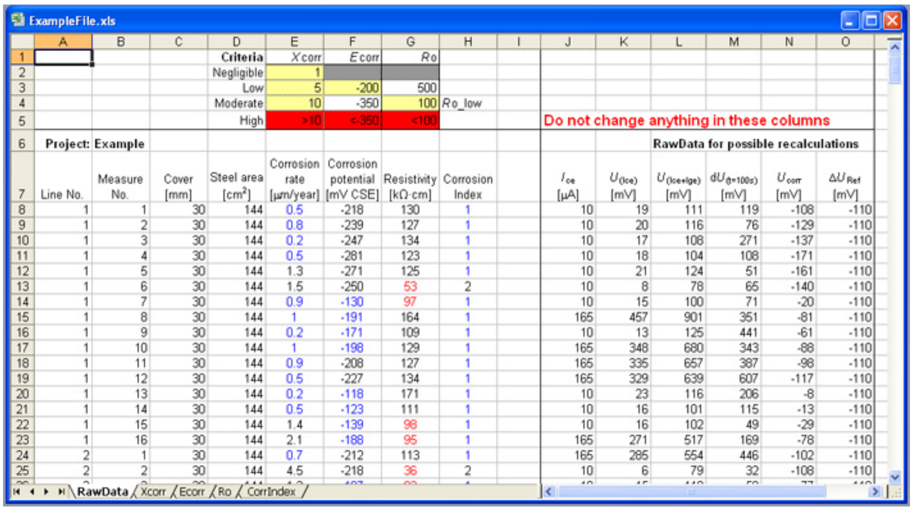


Fig. 21 – Example of the download window.

As a project download, the Excel workbook contains five worksheets, that is, “RawData”, “Xcorr”, “Ecorr”, “Ro” and “CorrIndex”. Do not change any cell position or sheet name if a recalculation of the data is needed. A copy of the workbook or individual worksheet can be made if an individual format is needed.

Worksheet “RawData” (see Fig. 22) contains not only the basic input parameters and the calculated results, but also the raw measured values (under columns “RawData for possible recalculation”), which are not related to the input parameters. Therefore, **these data should not be changed or modified** except the last column for calibrated values of the reference electrode, ΔU_{Ref}, if it involved any systematic error in the calibration.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1				**Criteria**	*Xcorr*	*Ecorr*	*Ro*								
2				Negligible	1										
3				Low	5	-200	500								
4				Moderate	10	-350	100	*Ro_low*							
5				High	>10	<-350	<100			Do not change anything in these columns					
6	**Project:**	**Example**										**RawData for possible recalculations**			
7	Line No.	Measure No.	Cover [mm]	Steel area [cm^2]	Corrosion rate [µm/year]	Corrosion potential [mV CSE]	Resistivity [kΩ·cm]	Corrosion Index		I_{ce} [µA]	$U_{(Ice)}$ [mV]	$U_{(Ice+Ige)}$ [mV]	$dU_{(t=100s)}$ [mV]	U_{corr} [mV]	ΔU_{Ref} [mV]
8	1	1	30	144	0.5	-218	130	1		10	19	111	119	-108	-110
9	1	2	30	144	0.8	-239	127	1		10	20	116	76	-129	-110
10	1	3	30	144	0.2	-247	134	1		10	17	108	271	-137	-110
11	1	4	30	144	0.5	-281	123	1		10	18	104	108	-171	-110
12	1	5	30	144	1.3	-271	125	1		10	21	124	51	-161	-110
13	1	6	30	144	1.5	-250	53	2		10	8	78	65	-140	-110
14	1	7	30	144	0.9	-130	97	1		10	15	100	71	-20	-110
15	1	8	30	144	1	-191	164	1		165	457	901	351	-81	-110
16	1	9	30	144	0.2	-171	109	1		10	13	125	441	-61	-110
17	1	10	30	144	1	-198	129	1		165	348	680	343	-88	-110
18	1	11	30	144	0.9	-208	127	1		165	335	657	387	-98	-110
19	1	12	30	144	0.5	-227	134	1		165	329	639	607	-117	-110
20	1	13	30	144	0.2	-118	171	1		10	23	116	206	-8	-110
21	1	14	30	144	0.5	-123	111	1		10	16	101	115	-13	-110
22	1	15	30	144	1.4	-139	98	1		10	16	102	49	-29	-110
23	1	16	30	144	2.1	-188	95	1		165	271	517	169	-78	-110
24	2	1	30	144	0.7	-212	113	1		165	285	554	446	-102	-110
25	2	2	30	144	4.5	-218	36	2		10	6	79	32	-108	-110

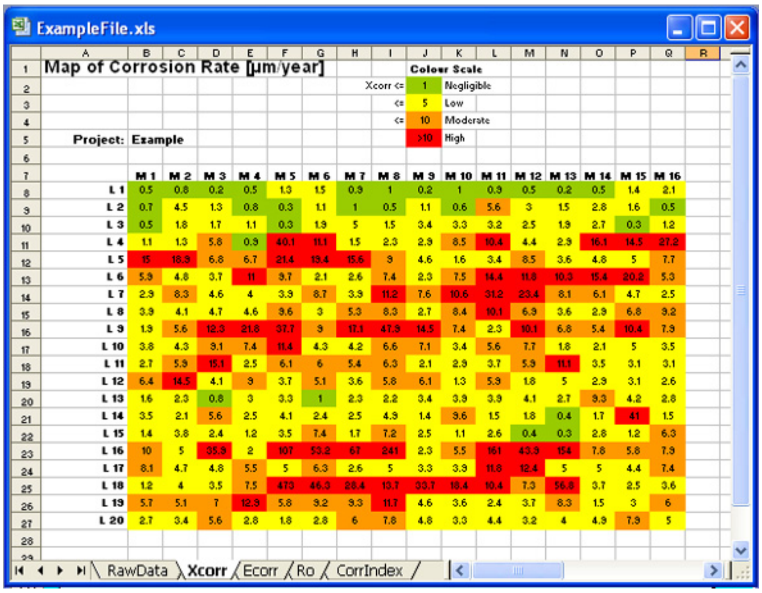
Fig. 22 – Example of the worksheet “RawData”.

The raw measured values include:

I_{ce}:	Imposed current from the central electrode
$U_{\text{(Ice)}}$:	First response of potential at the current I_{ce}
$U_{\text{(Ice+Ige)}}$:	First response of potential at both the current I_{ce} and I_{ge}
$\mathrm{d}U_{\text{(t=100s)}}$:	Extrapolated polarization potential at 100 seconds
U_{corr}:	Half-cell potential

ΔU_{Ref}: Potential difference under calibration of the simple reference electrode against the gel type of reference electrode. When the electrodes unit type R is used, $\Delta U_{\mathrm{Ref}} \approx -110$ mV

The rest of worksheets present the results in the grid matrix with Line No. as row and Measure No. as column (see Figs. 23 to 26). In the matrix, each cell represents a measurement. Its color is dependent on the criteria under “Color scale”, which can be modified by desire.



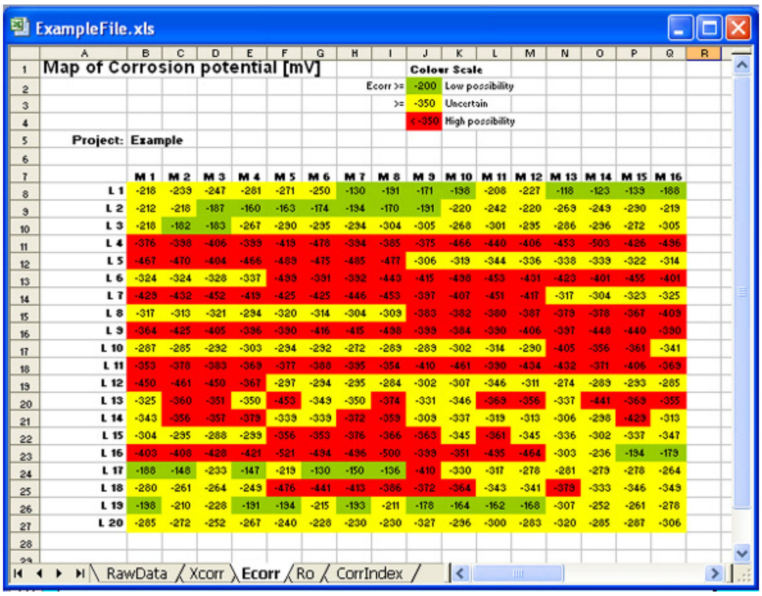
Map of Corrosion Rate [µm/year]

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

Project: Example

	M 1	M 2	M 3	M 4	M 5	M 6	M 7	M 8	M 9	M 10	M 11	M 12	M 13	M 14	M 15	M 16
L 1	0.5	0.8	0.2	0.5	1.3	1.5	0.9	1	0.2	1	0.9	0.5	0.2	0.5	1.4	2.1
L 2	0.7	4.5	1.3	0.8	0.3	1.1	1	0.5	1.1	0.6	5.6	3	1.5	2.8	1.6	0.5
L 3	0.5	1.8	1.7	1.1	0.3	1.9	5	1.5	3.4	3.3	3.2	2.5	1.9	2.7	0.3	1.2
L 4	1.1	1.3	5.8	0.9	40.1	11.1	1.5	2.3	2.9	8.5	10.4	4.4	2.9	16.1	14.5	27.2
L 5	15	18.9	6.8	6.7	21.4	19.4	15.6	9	4.6	1.6	3.4	8.5	3.6	4.8	5	7.7
L 6	5.9	4.8	3.7	11	9.7	2.1	2.6	7.4	2.3	7.5	14.4	11.8	10.3	15.4	20.2	5.3
L 7	2.9	8.3	4.6	4	3.9	8.7	3.9	11.2	7.6	10.6	31.2	23.4	8.1	6.1	4.7	2.5
L 8	3.9	4.1	4.7	4.6	9.6	3	5.3	8.3	2.7	8.4	10.1	6.9	3.6	2.9	6.8	9.2
L 9	1.9	5.6	12.3	21.8	37.7	9	17.1	47.9	14.5	7.4	2.3	10.1	6.8	5.4	10.4	7.9
L 10	3.8	4.3	9.1	7.4	11.4	4.3	4.2	6.6	7.1	3.4	5.6	7.7	1.8	2.1	5	3.5
L 11	2.7	5.9	15.1	2.5	6.1	6	5.4	6.3	2.1	2.9	3.7	5.9	11.1	3.5	3.1	3.1
L 12	6.4	14.5	4.1	9	3.7	5.1	3.6	5.8	6.1	1.3	5.9	1.8	5	2.9	3.1	2.6
L 13	1.6	2.3	0.8	3	3.3	1	2.3	2.2	3.4	3.9	3.9	4.1	2.7	9.3	4.2	2.8
L 14	3.5	2.1	5.6	2.5	4.1	2.4	2.5	4.9	1.4	9.6	1.5	1.8	0.4	1.7	41	1.5
L 15	1.4	3.8	2.4	1.2	3.5	7.4	1.7	7.2	2.5	1.1	2.6	0.4	0.3	2.8	1.2	6.3
L 16	10	5	35.9	2	107	53.2	67	241	2.3	5.5	161	43.9	154	7.8	5.8	7.9
L 17	8.1	4.7	4.8	5.5	5	6.3	2.6	5	3.3	3.9	11.8	12.4	5	5	4.4	7.4
L 18	1.2	4	3.5	7.5	473	46.3	28.4	13.7	33.7	18.4	10.4	7.3	56.8	3.7	2.5	3.6
L 19	5.7	5.1	7	12.9	5.8	9.2	9.3	11.7	4.6	3.6	2.4	3.7	8.3	1.5	3	6
L 20	2.7	3.4	5.6	2.8	1.8	2.8	6	7.8	4.8	3.3	4.4	3.2	4	4.9	7.9	5

Fig. 23 – Example of the worksheet “Xcorr” (map of corrosion rate).



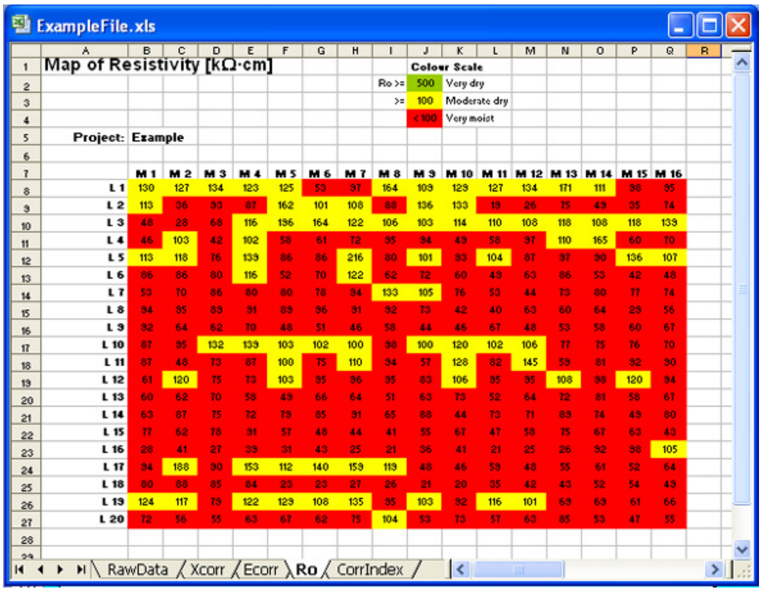
Map of Corrosion potential [mV]

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

Project: Example

	M 1	M 2	M 3	M 4	M 5	M 6	M 7	M 8	M 9	M 10	M 11	M 12	M 13	M 14	M 15	M 16
L 1	-218	-239	-247	-281	-271	-250	-130	-191	-171	-198	-208	-227	-118	-123	-139	-188
L 2	-212	-218	-187	-160	-163	-174	-194	-170	-191	-220	-242	-220	-269	-249	-290	-219
L 3	-218	-182	-183	-267	-290	-295	-294	-304	-305	-268	-301	-295	-286	-296	-272	-305
L 4	-376	-398	-406	-399	-419	-478	-394	-385	-375	-466	-440	-406	-453	-503	-426	-496
L 5	-467	-470	-404	-466	-489	-475	-485	-477	-306	-319	-344	-336	-338	-339	-322	-314
L 6	-324	-324	-328	-337	-499	-391	-392	-443	-415	-498	-453	-431	-423	-401	-455	-401
L 7	-429	-432	-452	-419	-425	-425	-446	-453	-397	-407	-451	-417	-317	-304	-323	-325
L 8	-317	-313	-321	-294	-320	-314	-304	-309	-383	-382	-380	-387	-379	-378	-367	-409
L 9	-364	-425	-405	-396	-390	-416	-415	-498	-399	-384	-390	-406	-397	-448	-440	-390
L 10	-287	-285	-292	-303	-294	-292	-272	-289	-289	-302	-314	-290	-405	-356	-361	-341
L 11	-353	-378	-383	-369	-377	-388	-395	-354	-410	-461	-390	-434	-432	-371	-406	-369
L 12	-450	-461	-450	-367	-297	-294	-295	-284	-302	-307	-346	-311	-274	-289	-293	-285
L 13	-325	-360	-351	-350	-453	-349	-350	-374	-331	-346	-369	-356	-337	-441	-369	-355
L 14	-343	-356	-357	-379	-339	-339	-372	-359	-309	-337	-319	-313	-306	-298	-429	-313
L 15	-304	-295	-288	-299	-356	-353	-376	-366	-363	-345	-361	-345	-336	-302	-337	-347
L 16	-403	-408	-428	-421	-521	-494	-496	-500	-399	-351	-495	-464	-303	-236	-194	-179
L 17	-188	-148	-233	-147	-219	-130	-150	-136	-410	-330	-317	-278	-281	-279	-278	-264
L 18	-280	-261	-264	-249	-476	-441	-413	-386	-372	-364	-343	-341	-379	-333	-346	-349
L 19	-198	-210	-228	-191	-194	-215	-193	-211	-178	-164	-162	-168	-307	-252	-261	-278
L 20	-285	-272	-252	-267	-240	-228	-230	-230	-327	-296	-300	-283	-320	-285	-287	-306

Fig. 24 – Example of the worksheet “Ecorr” (map of half-cell potential).



Map of Resistivity [kΩ·cm]

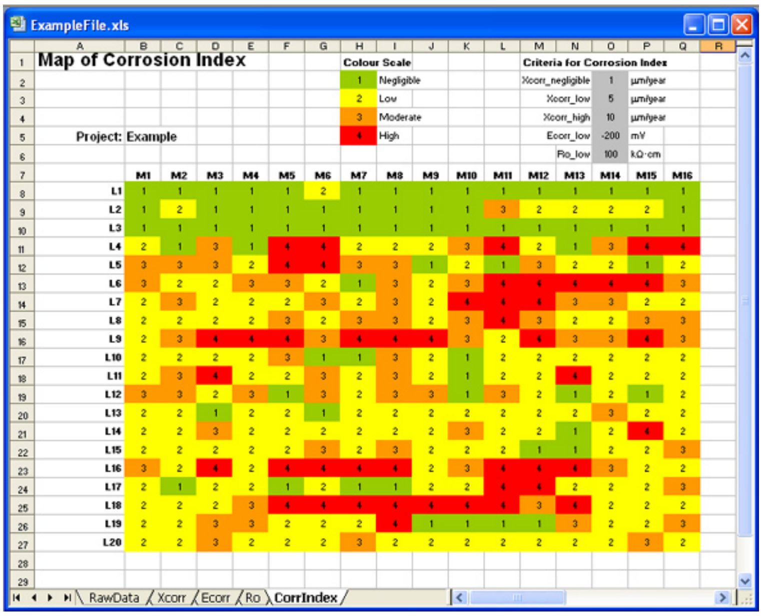
Colour Scale

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

Project: Example

	M 1	M 2	M 3	M 4	M 5	M 6	M 7	M 8	M 9	M 10	M 11	M 12	M 13	M 14	M 15	M 16
L 1	130	127	134	123	125	53	97	164	109	129	127	134	171	111	98	95
L 2	113	36	93	87	162	101	108	88	136	133	19	26	75	49	35	74
L 3	48	28	68	116	196	164	122	106	103	114	110	108	118	108	118	139
L 4	46	103	42	102	58	61	72	95	94	49	58	97	110	165	60	70
L 5	113	118	76	139	86	86	216	80	101	93	104	87	97	90	136	107
L 6	86	86	80	116	52	70	122	62	72	60	49	63	86	53	42	48
L 7	53	70	86	80	80	78	94	133	105	76	53	44	73	80	77	74
L 8	94	95	89	91	89	96	91	92	73	42	40	63	60	64	29	56
L 9	92	64	62	70	48	51	46	58	44	46	67	48	53	58	60	67
L 10	87	95	132	139	103	102	100	98	100	120	102	106	77	75	76	70
L 11	87	48	73	87	100	75	110	94	57	128	82	145	59	81	92	90
L 12	61	120	75	73	103	95	96	95	83	106	95	95	108	98	120	94
L 13	60	62	70	58	49	66	64	51	63	73	52	64	72	81	58	67
L 14	63	87	75	72	79	85	91	65	88	44	73	71	89	74	49	80
L 15	77	62	78	91	57	48	44	41	55	67	47	58	75	67	63	43
L 16	28	41	27	39	31	43	25	21	36	41	21	25	26	32	98	105
L 17	94	188	90	153	112	140	159	119	48	46	59	48	55	61	52	64
L 18	80	88	85	84	23	23	27	26	21	20	35	42	43	52	54	49
L 19	124	117	79	122	129	108	135	95	103	92	116	101	69	69	61	66
L 20	72	56	55	63	67	62	75	104	53	73	57	63	85	53	47	55

Fig. 25 – Example of the worksheet “Ro” (map of resistivity).



Map of Corrosion Index

Colour Scale

1	Negligible
2	Low
3	Moderate
4	High

Criteria for Corrosion Index

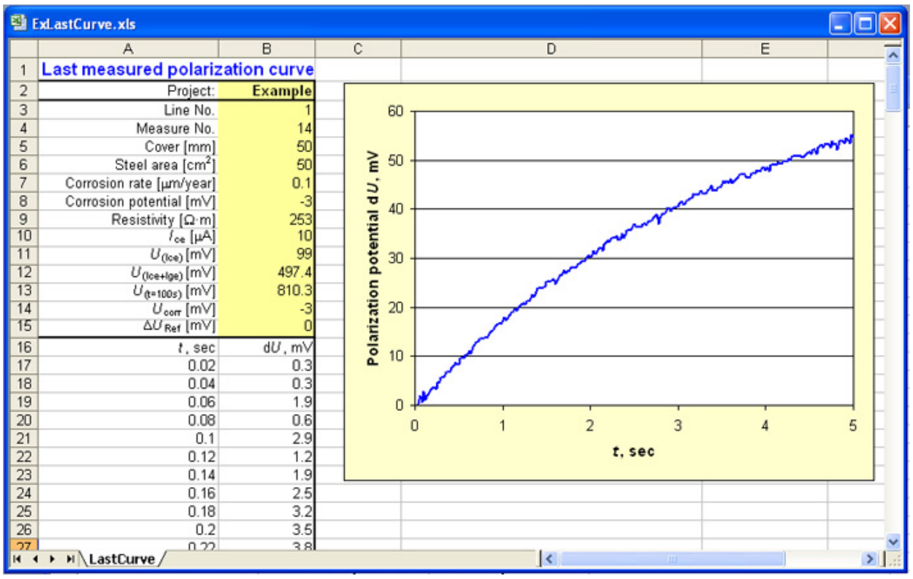
Xcorr_negligible	1	µm/year
Xcorr_low	5	µm/year
Xcorr_high	10	µm/year
Ecorr_low	-200	mV
Ro_low	100	kΩ·cm

Project: Example

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16
L1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1
L2	1	2	1	1	1	1	1	1	1	1	3	2	2	2	2	1
L3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
L4	2	1	3	1	4	4	2	2	2	3	4	2	1	3	4	4
L5	3	3	3	2	4	4	3	3	1	2	1	3	2	2	1	2
L6	3	2	2	3	3	2	1	3	2	3	4	4	4	4	4	3
L7	2	3	2	2	2	3	2	3	2	4	4	4	3	3	2	2
L8	2	2	2	2	3	2	3	3	2	3	4	3	2	2	3	3
L9	2	3	4	4	4	3	4	4	4	3	2	4	3	3	4	3
L10	2	2	2	2	3	1	1	3	2	1	2	2	2	2	2	2
L11	2	3	4	2	2	3	2	3	2	1	2	2	4	2	2	2
L12	3	3	2	3	1	3	2	3	3	1	3	2	1	2	1	2
L13	2	2	1	2	2	1	2	2	2	2	2	2	2	3	2	2
L14	2	2	3	2	2	2	2	2	2	3	2	2	1	2	4	2
L15	2	2	2	2	2	3	2	3	2	2	2	1	1	2	2	3
L16	3	2	4	2	4	4	4	4	2	3	4	4	4	3	2	2
L17	2	1	2	2	1	2	1	1	2	2	4	4	2	2	2	3
L18	2	2	2	3	4	4	4	4	4	4	4	3	4	2	2	2
L19	2	2	3	3	2	2	2	4	1	1	1	1	3	2	2	3
L20	2	2	3	2	2	2	3	2	2	2	2	2	2	2	3	2

Fig. 26 – Example of the worksheet “CorrIndex” (map of corrosion index).

When downloading “||last||”, the Excel workbook contains only one worksheet with the raw data and a diagram of last polarization curve (see Fig. 27).


ExLastCurve.xls

	A	B
1	Last measured polarization curve	
2	Project:	Example
3	Line No.	1
4	Measure No.	14
5	Cover [mm]	50
6	Steel area [cm^2]	50
7	Corrosion rate [μm/year]	0.1
8	Corrosion potential [mV]	-3
9	Resistivity [Ω·m]	253
10	I_{ce} [μA]	10
11	$U_{(Ice)}$ [mV]	99
12	$U_{(Ice+Ige)}$ [mV]	497.4
13	$U_{(t=100s)}$ [mV]	810.3
14	U_{corr} [mV]	-3
15	ΔU_{Ref} [mV]	0
16	t, sec	dU, mV
17	0.02	0.3
18	0.04	0.3
19	0.06	1.9
20	0.08	0.6
21	0.1	2.9
22	0.12	1.2
23	0.14	1.9
24	0.16	2.5
25	0.18	3.2
26	0.2	3.5
27	0.22	3.8

Fig. 27 – Example of the worksheet for the last polarization curve.

4.4 Data recalculation

With the need of correction or modification of the input parameters, such as cover thickness, steel area, or the criteria for corrosion, one can recalculate the results directly in the workbook to be recalculated by pressing Ctrl+z [NOTE 1]. After the recalculation, all the five worksheets in the workbook are modified with the new calculated values.

NOTE 1: The main program must be started in order to start the recalculation.

5 Maintenance

5.1 Electrodes unit

After the measurements the following care should be taken:

- Remove the sponge from the electrodes unit.
- Remove the reference electrode from the central holder.
- With the plug tightly screwed on the socket, rinse the electrodes and the central holder with tap water so as to get rid of any chlorides and other corrosive substances.
- After wiping off the exceed water disconnect the cable and keep both the electrodes unit and the cable in the suitcase.
- If the sponge is in a good condition for further use, clean it with tap water, squeeze out exceed water and keep it in a plastic bag for a short storage. For a long-term storage, let it slowly dry and keep it in a place convenient for the next use.
- For the gel type of reference electrode, thoroughly rinse the electrode tip with distilled or demineralized water and place the cap back on the electrode tip [NOTE 1].
- For the simple type of reference electrode (optional), if it is relatively fresh, keep it in a plastic bag for a short storage. It should be noticed that this simple type of

reference electrode cannot be kept for a long time. It should be replaced frequently.

NOTE 1: The cup should be filled with saturated KCl solution.

5.2 Handheld instrument

If the display window becomes dirty, gently rinse it with tap water and wipe the exceed water with a soft cloth. Do not use any chemical agent and rough material on it.

The instrument is designed for resistance against spry water, provided that the sockets are tightly screwed with the plugs or protection caps. Therefore, when clean the instrument with tap water, care should be taken to avoid the water spraying to the unscrewed socket.

5.3 Changing batteries

When the battery indicator on the upright corner of the screen becomes empty or the display becomes weak, it is an indication that the batteries must be replaced. In this case follow the instruction in 3.1.1to change the batteries.

If the instrument is not in use for a long term, take out batteries from the battery box to avoid leakage of battery liquid, which is very corrosive and can damage the instrument.

6 Technical specifications

Pulse current:

The first pulse 50 µA ($I_{CE} + I_{GE}$), precision 2% (±1µA)
The second pulse 330 µA ($I_{CE} + I_{GE}$), precision 1.5% (±5µA)

Potential measurement:

Range 0 – 330 mV (DC), sensitivity 0.3 mV, precision 0.3% (±1 mV)
Range 330 – 3300 mV (DC), sensitivity 3 mV, precision 0.3% (±10 mV)

Data storage:

72000 measurement results in total (40 projects, 60 lines per project, 30 measurement points per line, and each measurement includes three important parameters, i.e. corrosion rate, half-cell potential & resistivity), and the last measurement curve of polarisation potential versus time (for e.g. research purpose).

Operation power:

4× AA LR6 batteries

Power consumption:

A set of new batteries (4× AA LR6) can normally be used for about 100 hours under “Turn-On” status and for a significantly longer time under “Turn-Off” status [NOTE 1].

NOTE 1: Based on the information from DURACELL MN1500 battery. The use of enlightening can significantly reduce the service life of batteries.

References

[1] Tang L. and Fu Y. (2006), "A rapid technique using handheld instrument for mapping corrosion of steel in reinforced concrete", Restoration of Buildings and Monuments, Vol. 12(5-6), pp. 387-400, 2006.

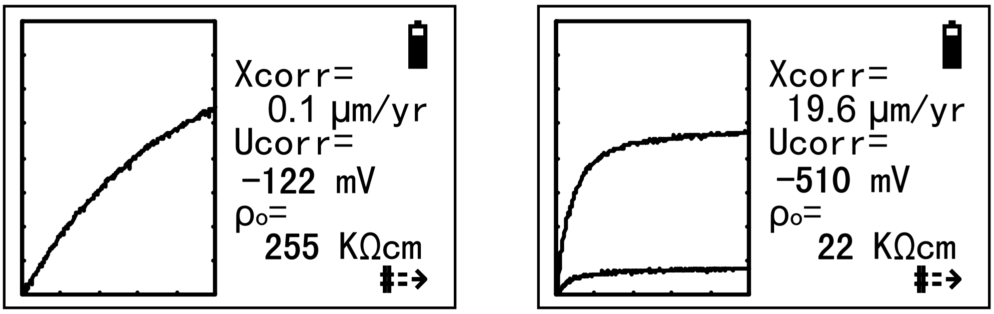
[2] Tang, L., "Mapping Corrosion of Steel in Reinforced Concrete Structures". SP Report, 2002:32, Borås: SP Swedish National Testing and Research Institute

[3] Tang, L., "Calibration of the Electrochemical Methods for the Corrosion Rate Measurement of Steel in Concrete – Nordtest project No. 1531-01". SP Report 2002:25, Borås: SP Swedish National Testing and Research Institute

[4] Tang, L. & Malmberg, B., "Assessment of Reinforcement Corrosion in Concrete Highway Tunnel Structures", accepted for publication in Proceedings of International Conference on Concrete Repair, Rehabilitation and Retrofitting, Cape Town, South Africa, 21-23 November 2005, pp. 409-414.

[5] Tang, L. and Utgenannt, P., "Verification of a rapid technique for corrosion measurement using reinforced concrete slabs after long-term field exposure", in "Concrete Platform 2007", Proceedings of an International Conference, Belfast, April 2007, (Queen's University of Belfast) 219-228.

Appendix: Some example of polarization curves



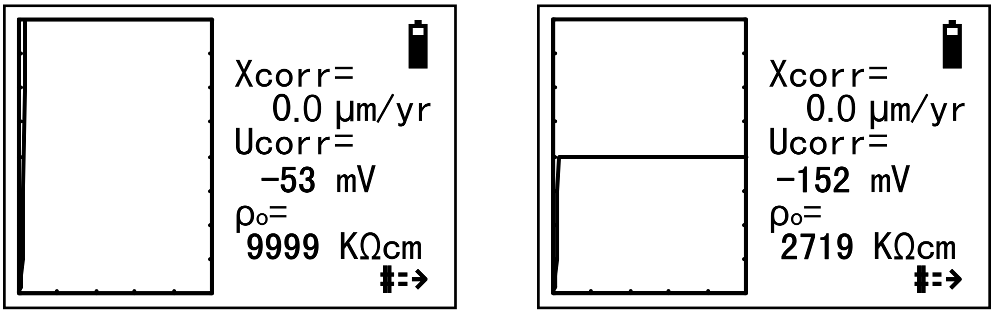
Xcorr=
0.1 µm/yr
Ucorr=
-122 mV
ρo=
255 KΩcm

Xcorr=
19.6 µm/yr
Ucorr=
-510 mV
ρo=
22 KΩcm

a) passive

b) corroding

Example 1 – Normal polarization with clear curves.



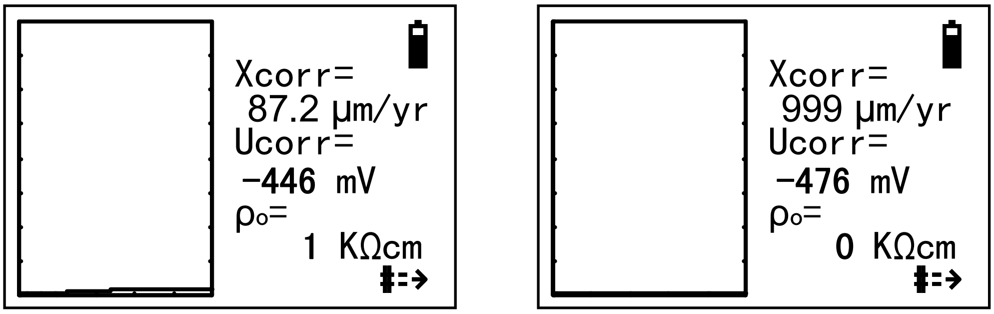
Xcorr=
0.0 µm/yr
Ucorr=
-53 mV
ρo=
9999 KΩcm

Xcorr=
0.0 µm/yr
Ucorr=
-152 mV
ρo=
2719 KΩcm

a) extremely high ohmic resistance

b) high ohmic or polarization resistance

Example 2 – Responses out of the measurement range due to very high ohmic or polarization resistance (implying negligible corrosion in both cases).



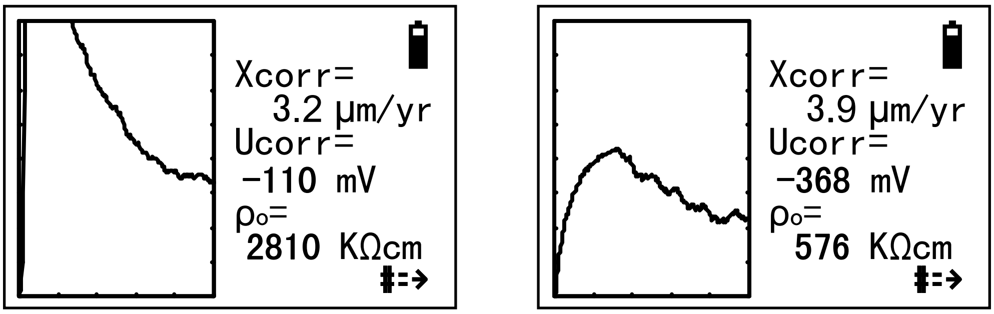
Xcorr=
87.2 µm/yr
Ucorr=
-446 mV
ρo=
1 KΩcm

Xcorr=
999 µm/yr
Ucorr=
-476 mV
ρo=
0 KΩcm

a) high corroding

b) extremely high corroding or short connection

Example 3 – Normal polarization with unclear curves.

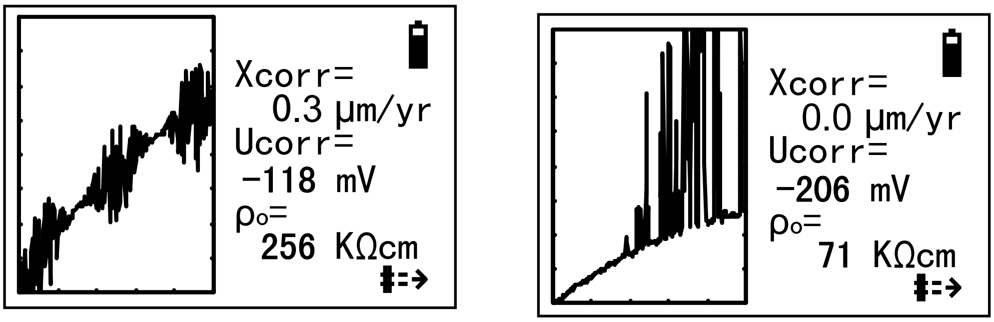


Xcorr=
3.2 µm/yr
Ucorr=
−110 mV
ρ_o=
2810 KΩcm

Xcorr=
3.9 µm/yr
Ucorr=
−368 mV
ρ_o=
576 KΩcm

a) X_{corr} value has no sense　　b) X_{corr} value may have meaning

Example 4 –Abnormal polarization curves due to very dry concrete.



Xcorr=
0.3 µm/yr
Ucorr=
−118 mV
ρ_o=
256 KΩcm

Xcorr=
0.0 µm/yr
Ucorr=
−206 mV
ρ_o=
71 KΩcm

a) external electrical field　　b) poor connectivity

Example 5 – Abnormal polarization curves due to some disturbances.

Appendix B Guidelines for using the RapiCor in the bridge inspection (in Swedish)

Vad krävs för att mäta med RapiCor?
– En Steg för steg guide

Preliminärt av Christian Lind och Martin Wikslund, Linköping Universitet

- **Före avresa till mätobjekt:**
    - Rätt temperatur ute, helst inte mindre än 5 grader i luft och betongkonstruktionen.
    - Väderleken, ej för torrt väder gärna regn någon eller några dagar innan. Förvattning av konstruktionen under 2 dagar är även ett alternativ.
    - Eventuella tillstånd, avspärrningar, TA-planer, kranbil etc.
    - Fungerande och kalibrerad utrustning. Kan även kalibreras på plats.
    - Eventuell tillgång till armeringsritningar för beräkning av polarisationsareor.
    - Eventuella överblicksbilder och skadebilder.
- **Utrustningslista**
    - RapiCor med tillbehörsväska
    - Profometer 5 – kompletterande armeringslokaliseringsinstrument
    - Förlängningssladd till RapiCor
    - En rejäl slagborrmaskin med 10mm respektive 20mm borr samt extra batteri
    - Vattenspruta och minst 5 liter extra vatten
    - Asfaltskritor
    - Tumstock
    - Kamera
    - Eventuell stege
    - Cement med tillbehör för lagning av borrhål

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Denna rapport får endast återges i sin helhet, om inte CBI i förväg skriftligen godkänt annat.
CBI Uppdragsrapport

  - Skyddsutrustning
  - Penna och papper för mätningsplatsbeskrivning och övriga noteringar
- **Ankomst till mätobjekt**
  - Säker parkering.
  - Rundvandring och övergripande inspektion på armslängds avstånd.
  - Urlastning och etablering.
  - Montera och iordningsställande av RapiCor, Profometer och borrmaskin.
  - Lokalisering och uppmärkning av minst 2 stycken inkopplingsjärn.
  - Borrning med 20mm borr till järn sedan med 10mm borr snett intill järn.
  - Blås rent hålen och kontrollera kontakten mellan järnen med multimetern.
  - Montera rostfri bult i ett av hålen med hjälp av hammare och insexnyckel, bulten skall sitta stumt.
  - Kontrollera kontakten mellan bulten och det andra järnet med multimeter, motståndet bör vara ca 2-3 ohm eller mindre.
  - Koppla på förlängningskabeln och anslut till RapiCor.
  - Markera upp lämpliga mätpunkter med hjälp av armeringslokalisationsinstrumenten, här kan ritningarna och tumstocken vara användbara som komplement.
  - Skriv in projektnummer, konstruktionsdel, orientering, startriktning, ungefärligt täckskiktsdjup samt polarisationsarea i RapiCor.
  - Börja förblöta mätpunkter, om det är torrt får man blöta upprepade gånger innan mätning.
  - Tag foto samt notera orientering och avstånd etc. på papper.
- **Mätstart och mätning**
  - Se till att svampen på sensorn är blöt och referenselektroden sitter fast med rätt utstick, ca 0,5-1mm.
  - Placera sensorn rakt ovanför och längs med det järn som skall mätas och om möjligt mellan korsande armering, när järnen ligger tätt spelar det mindre roll då polarisationsarean är stor medan det spelar en större roll vid gles armering.
  - Håll sensorn med ett fast, stadigt och jämnt tryck mot betongytan. Tag gärna stöd med fingrarna och den nedre delen av handflatan mot väggen.

  - Starta mätning, försök att vara så stilla som möjligt då minsta rörelse av sensorn kan störa polarisationskurvan och mätningen måste göras om.

  - Vid minsta tvivel på kurvans utseende, gör om mätningen men vänta 2-3 sekunder innan omstart p.g.a. att metallen fortfarande är något polariserad.

  - Dubbla låga kurvor kan tyda på korrosion men också att strömmen sprids ut om det finns mycket järn i närheten.

  - Uppenbara felkurvor och extrema värden bör mätas om och sensorn bör flyttas något (max 2cm utanför järnet och gärna mindre än 4cm längs järnet). Vid upprepade tveksamma värden, blöt mätpunkten ytterligare. Mät igen om ingen skillnad efter 3-4 ommätningar notera och gå vidare.

  - Mät nästa punkt tills linjen är klar. Ändra därefter linje samt mätpunktsnummer och gå vidare till nästa linje.

  - Notera eventuellt bomknack, sprickor och avspjälkning vid och i närheten av mätpunkter.

- **Efterarbete**

  - För över mätresultaten till dator så snart som möjligt då RapiCor har begränsad lagringskapacitet, 40 projekt, 60 linjer/projekt och 30 mätpunkter/linje.

  - Kontrollera att polarisationsarean och täckskiktsdjupet stämmer i dataprogrammet. Om en area/täckskikt har använts trots att mätobjektet har olika areor/täckskikt, ändra och uppdatera rådatabladet.

  - Vänd färgkartorna efter önskemål och notera gärna orientering, avstånd mellan mätpunkter och linjer, eventuella kalkutfällningar, bomknacksområden, avspjälkningar och sprickor.

  - Namnge bilder från mätningen som hjälp för vidare analys av resultaten.

  - Skriv en liten rapport om iakttagelser och resultat.

- **Felkällor**

  - Torr betong ger hög en resistivitet. Det kan då vara svårare att få till bra kurvor vilket kan leda till många ommätningar samt intetsägande resultat. Exempelvis om mätning sker på konstruktionsdelar som har tydliga korrosionsskador, såsom avspjälkningar, bomknack och rostutfällningar, ger ett resultat som inte överensstämmer med verkligheten. Detta på grund av att betongen är för torr och därmed saknar möjlighet att bära strömmen mellan järn och sensor samt att korrosionsprocessen avstannar vid brist på elektrolyt.

  - Vid oförväntade och extrema värden som inte överensstämmer med tendensen i övrigt kan det bero på att sensorn placerats över en stor sten i ballasten. Ett exempel kan vara om resistiviteten legat omkring 100-400 för att i en mätpunkt överstiga 1000 kΩ*cm. Stenen försvårar för strömmen att nå järnet. Genom att flytta sensorn någon centimeter i sidled eller längsled kan ett bättre mätresultat fås.

- Vid mätning över och nära sprickor kan vattnet som sprutats på betongen få direktkontakt med armeringen. Det blir då kortslutning och instrumentet indikerar 999,9µm/år i korrosionshastighet.
- Om man vid mätning är instabil på handen eller skakar till kan kurvan få en dipp eller en höjning. Eftersom instrumentet gör en så kallad regretionsanalys av mätkurvan på 5 separata mätpunkter vid varje hel sekund. Den anpassar en linje till dessa 5 mätpunkter för att kunna extrapolera mätningen upp till 100 sekunder och därefter presentera en specifik korrosionshastighet.
- Instrumentet gör mätning på 5 till 10 sekunder beroende på om den skickar ut en eller två strömpulser. Om kurvan då vid en av dessa punkter är inkorrekt på grund av att man varit instabil, blir extrapolationen felaktig och den slutliga korrosionshastigheten stämmer inte.
- Grovt felaktigt inmatad polarisationsarea ger stora felaktigheter i korrosionshastighet. Exempelvis om den sanna polarisationsarean är 150cm^2 och korrosionshastigheten är 10µm/år men den inmatade arean är 75 cm^2. Instrumentet ger då 20µm/år i korrosionshastighet. Är den inmatade polarisationsarean 300 cm^2 ger instrumentet istället 5µm/år i korrosionshastighet.
- Kloridinducerad korrosion är ofta en lokal form av korrosion: Det kan rosta på små områden och olika delar/sidor på samma järn. Vid mätning ovanpå och från sidan på samma järn på en kantbalk så kan man få helt olika korrosionshastigheter men samma värden på halvcellpotentialen(korrosionspotentialen) och resistiviteten. Detta även fast man gjort allt rätt och fått resonabla kurvor. Om korrosionen pågått ett tag så leder det till spjälkningssprickor, beroende på var sprickan ligger så kan man avgöra var på järnet det rostar.
- Tätt klotter kan hindra strömmen och det går därmed inte att få en säker mätning.

- **Exempel på uträkning av polarisationsarean**
  - Förutsättningar
    En kantbalk med enkla järn i de fyra hörnen med diameter 16mm samt ett järn med diameter 10mm mitt på utsidan. Byglar av diameter 10mm på ett cc avstånd av 300mm. Avståndet mellan övre/undre järnet till mittenjärnet är 130mm.

    Grundformeln är:

    $$A = L_p*\pi*[n_L*D_L*(1+(\alpha b_S)/D_L) + n_T*D_T*((\beta L_S)/ d_T)]$$

där *A* = polarisationsarean i cm^2, *Lp* = 10.5cm är den specificerade polarisationslängden mellan räkneelektroderna I_{CE}, *n* är antalet sammanbundna järn, *D* är järnens diameter, *d* är avståndet mellan grannjärnen, b_s och L_s är bredden respektive längden av sensorn, *α* och *β* är koefficienter vars värden beror på antalet intilliggande järn (antal grannar), betongens resistivitet samt stålets ytfilm. Bokstäverna ”L” och ”T” står för longitud samt transversell riktning för järnen.

Där α och β är lika med 2 om järnet som mätning sker emot har två grannar av samma storlek(diameter a/diameter b=1).
I exemplet ovan finns vid mätning på det övre och undre järnet på kantbalkens sida endast en granne i form av mittenjärnet. α blir således 1(mittenjärnets diameter i cm) / 1,6 (järnen i ök samt uk’s diameter i cm) = 0,625.

Polarisationsarean blir således

$$10{,}5*\pi*[1*1{,}6*(1+(0{,}625*4)/13{,}0) + 1*1{,}0*((2*15)/ 30)] = 95{,}9 \text{ cm}^2$$

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