FIELD MEASUREMENTS AND EXPERIENCE OF CHLORIDE INDUCED CORROSION OF REINFORCEMENT IN SUBMERGED STRUCTURES

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ABSTRACT

A summary of measured chloride levels, concrete cover and observed corrosion of reinforcement in concrete structures submerged in sea water is presented. The relationships between these are discussed. The significance of construction details and practice, as well as quality of workmanship on the type and extent of damage is emphasised.

Key words: chloride content, corrosion, concrete cover, construction details

1. INTRODUCTION

In the summer 1992 some evidence of corrosion was observed in the inlet culverts of the cooling water channels to Barsebäck nuclear power plant reactor no 2 (B2). This initiated a major investigation of all accessible concrete surfaces of the cooling water systems to the two reactors B1 and B2 during the year 1993. The object of these investigations was to asses the condition of the structures, with less emphasis being placed on investigating the damage mechanisms. At the time of inspection the cooling water channels had been in service for approximately 20 years.

2. STRUCTURAL DESIGN OF THE COOLING SYSTEMS

There are two identical cooling water systems which feed water from Öresund to the condensors of reactors 1 and 2. The structures consist of filtration tanks, small inlet culverts, a large outlet culvert plus a number of pump chambers, distribution channels and auxiliary culverts.

The rate of flow is 23,3 m^3/s resulting in a flow velocity of approximately 2,6 m/s. The increase in water temperature from inlet to outlet is 10°C. The greater part of the concrete surfaces are permanently submerged. There is a free water surface and splash zone 2-3 m in height (depending on the sea water level at the time) in the tanks, pump chambers and distribution channels. The system is emptied at most every two years for routine inspections and maintenance.

The culverts are designed as statically indeterminate frames with the main loading from the overlying fill material. The roof-slabs are 500-600 mm thick in section and heavily reinforced. The culverts are also designed to withstand internal surging pressures.

All structures are of ordinary reinforced concrete. The specified concrete quality is K40, water impermeable concrete and with an air content of 4,5%. Fixed steel shutters have been used for the culverts, while most of the chambers have been cast with slip-form. The concrete surfaces are untreated with the exception of the filtration tanks, pump chambers and auxiliary inlet culvert which are coated with anti-fouling paint.

3. TESTING AND INSPECTION PROCEDURES

The inspections were of a general nature and included a large number of chloride measurements. The tests were made by ion selective electrode in accordance with the RCT method. Hence, the given results in this work are expressed as the total acid soluble chloride content as a percentage of concrete weight.

It was obvious that chloride levels around the main reinforcement were very high in places. Patterns of reinforcement corrosion were identified and this prompted a detailed structural analysis. The observed reinforcement corrosion was very local in nature, unlike that so often found in atmospherically exposed concrete. A project team was formed which included structural analysts and concrete specialists to re-evaluate the structures on the basis of observed corrosion damage. Cathodic protection was proposed to stem further corrosion and a passive system using magnesium anodes was installed in the summer of 1994. A survey was simultaneously made to quantify the percentage reduction in reinforcement in each part of each structure.

4. CHLORIDE LEVELS AND DAMAGE PATTERNS

Probably the most confounding aspect of the condition of the structures is the enormous variation in chloride levels within one and the same structure. In TABLE 1 calculated values of surface chloride content at different locations in the structures of the cooling water systems are given. Chloride levels around reinforcement may vary by as much as five-fold. The average concentrations around the main reinforcement in the roof slabs of the inlet culverts at 15-30 mm depth under the surface is 0,25%, but may be as much as 0.5%.

TABLE 1. Calculated chloride contents and diffusion coefficients. (Initial chloride content 0,005% of concrete weight).

Sample	**Structure**	**Chloride content on the surface, % of concrete weight**	**Diffusion coefficient, mm²/year**
B1-1	Inlet culv., wall	0,72	105,4
B1-2	Inlet culv., roof-slab	0,75	82,2
B1-3	Outlet culv., wall	0,14	103,8
B1-4	Outlet culv., wall	0,17	185,4
B1-5	Outlet culv., wall	0,09	201,8
B1-6	Outlet culv., roof-slab	0,68	218,7
B2-1	Aux. inlet culv., wall	0,22	68,1
B2-2	Aux. inlet culv., wall	0,17	45,1
B2-3	Aux. inlet culv., wall	0,15	221,7
B2-4	Pump-chamber, wall, splash zone		
B2-5	Pump-chamber, wall below water level	0.09	19,4
B2-6	Outlet culv., roof-slab	0,62	146,0

There are also recognizable trends of higher chloride levels in roof-slabs compared to walls. In TABLE 2 some selected chloride levels in the outlet culvert of Barsebäck 1 are shown.

TABLE 2. Chloride content, % of concrete weight. (30-45 mm under concrete surface). Outlet culvert, Barsebäck 1.

Structure	Point 1	Point 2	Point 3	Point 4
Roof-slab	0,16	0,33	0,26	0,15
Wall	0,19	0,11	0,14	0,08

In TABLE 3 the chloride levels in different sections of the outlet culvert to Barsebäck 2 are given. These measurements were made in order to locate areas of high corrosion risk, prior to exposing and inspecting the reinforcement. For comparision, the reinforcement on three 1,5m² areas was exposed using high pressure water-jetting. At position +93 m there was evidence of corrosion in the roof-slab in the form of brown rust spots on the concrete surface. Careful inspection of the exposed reinforcement showed an average total reduction in x-section of 15%, with as much as 30% on individual bars. Maximum corrosion (80%) had occcurred on a distribution bar with 25 mm cover.

TABLE 3. Chloride content, visible damage and reduction in reinforcement. Outlet culvert, Barsebäck 2.

Position	Chloride content 25-35 mm under surface, % of concrete weight	Concrete cover, mm Average (Min)	Visible damage on surface, Yes/No	Actual average reduction in reinforcement, %
-10 m, wall	0,11	22 (9)	Yes 1)	100
-10 m, roof	0,10	27 (25)	No	-
+6 m, wall	0,09	44 (43)	No	-
+6 m, roof*	0,07	28 (27)	Yes 2)	10
+25 m, wall	0,29	34 (31)	No	-
+25 m, roof	0,11	29 (28)	No	-
+44 m, wall	0,16	40 (39)	No	-
+44 m, roof*	0,07	46 (44)	Yes	0
+69 m, roof	0,26	36 (35)	-	-
+93 m, wall	0,19	40 (36)	No	-
+93 m, roof*	0,44	31 (30)	Yes 3)	15

*approximately 1,5 m² of reinforcement exposed by water-jetting
1) construction joints
2) rust on 1 of 8 bars
3) rust on 9 of 11 bars. Reduction due to corrosion on distribution bar 80%

Many of the structures are fitted with active cathodic protection in the form of magnetite anodes. These have served to protect the pumps, valves etc. They have been in position since the plants were first brought into service. The investigations show that the protecting current from the anodes has even spread to the reinforcement. As can be seen in TABLE 4 the average chloride levels in the cathodically protected submerged structures are significantly lower than the unprotected structures. The measured electro-chemical potential of the reinforcement of the structures was between -900 and -1000 mV (copper-sulphate-electrode).

TABLE 4. Average chloride content, concrete cover and observed corrosion in different structures.

Structure	Chloride content 15-30 mm under concrete surface, % of concrete weight	Chloride content 30-45 mm under concrete surface, % of concrete weight	Average concrete cover, mm	Min concrete cover, mm	Observed corrosion, Yes/No	Comments
Pump chambers[1], B1	0,04	0,03	34	20	No	Anti-fouling paint, Cathodic protection
Filtration tanks[2], B1	0,15	0,14	32	27	No	Anti-fouling paint
Inlet culverts B1	0,25	0,21	18	15	Yes	
Inlet culverts B2	0,24	0,17	33	15	Yes	

[1] 20 structures   [2] 6 structures

An estimation was made of reinforcement reductions due to corrosion by visual survey of concrete surfaces. The results from one of these surveys are given in TABLE 5, which describe the average estimated reduction in roof-slab reinforcement of the inlet culverts to Barsebäck 1. Four areas, approximately 1,5m² were water-jetted to expose reinforcement., and the degree of corrosion was measured, see TABLE 6. Generally the correlation between estimated and actual damage was good. An overestimation of ~10% was normal.

TABLE 5. Estimated reduction in inner surface reinforcement to the roof-slabs in four different inlet culverts of Barsebäck 1. Estimations based on frequency of rust spots on concrete surface.

Culvert No	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7
2	70	50	25	10	80	30	50
3	5	80	15	10	30	40	70
4	70	80	50	40	90	80	80
5	50	90	30	30	60	80	90

TABLE 6. Observed corrosion damage after water-jetting. Inlet culverts, Barsebäck 1.

Culvert No/ Position	Chloride content 20-25 mm under surface, % of concrete weight	Concrete cover, mm Average (Min)	Visible damage on surface, Yes/No	Estimated reduction in reinforcement, %	Actual reduction in reinforcement, % (inner surface)
2/21 m	0,5	21 (15)	Yes	80	60 (70)*
5/15 m	-	- (10)	Yes	80	80 (100)*
5/21 m	-	- (23)	Yes	80	70 (90)*
5/35 m	-	- (20)	Yes	90	60 (100)*

( )*Reduction in x-section. Individual bars.

5. COVER TO REINFORCEMENT

From the investigations it was seen that reinforcement corrosion did not occur if the cover is of good quality concrete, homogeneous and at least 40 mm, regardless of chloride content. Cover to reinforcement varies significantly as can be seen in TABLE 4. The average cover thicknesses on the undersides of roof-slabs in the inlet culverts to B1 and B2 is 18 mm and 33 mm respectively. The corresponding reduction in reinforcement due to corrosion is on average 70% and <5%. Typically, the cover in roof-slabs undersides is less than the average cover to walls, see TABLE 7. Cover on the upper sides of slabs is normally very good, i.e min. 50 mm.

TABLE 7. Average cover thicknesses in mm.

Structure	**Underside roof-slab**	**Wall**
Auxiliary inlet culvert, B1	25	33
Inlet culvert, B1	18	30
Outlet culvert, B2	33	36

Poor cover to reinforcement can usually be attributed to awkward geometries, small sections, miss-alignment of starter bars, congested reinforcement and sagging. Cover thicknesses of 10 mm are not unusual in the lower parts of walls, where vertical bars have been spliced on to starter bars from floor-slabs. A similar pattern may at times be seen along the upper parts of walls.

Reinforcement corrosion is common where cover thickness is less than ~20 mm, see Figure 2.

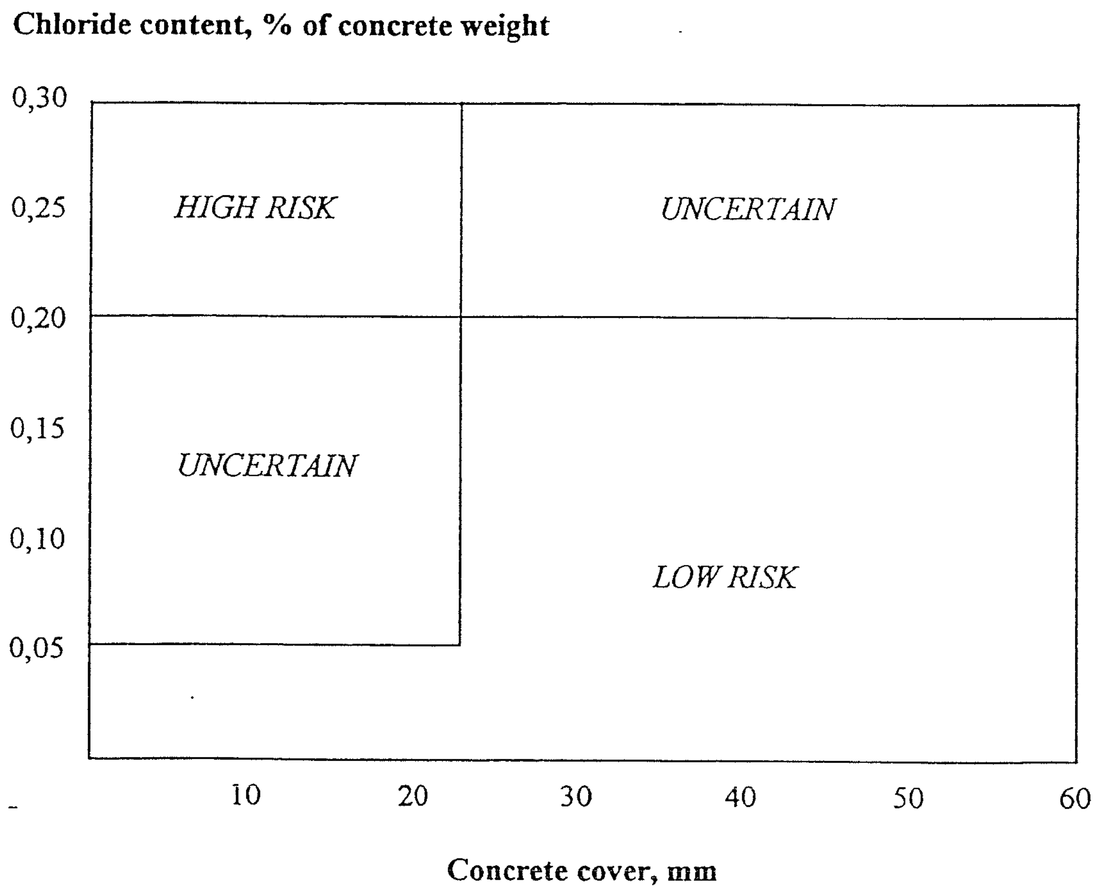

Figure 2. Estimation of corrosion risk in submerged structures based on measured chloride content and concrete cover.

6. DAMAGE TO REINFORCEMENT RELATED TO CONSTRUCTION DETAILS

6.1. Construction/casting joints

Floor-slabs and walls are cast as separate units. The construction joint between these being provided with a water bar to prevent seepage through this break in continuity. Vertical reinforcement through this joint prevents lifting due to internal water pressure, in particular those pressures caused by surging.

Construction joints are one of the most common areas of reinforcement corrosion in culverts. The main causes are poor compaction of concrete and entrapped air. The joint itself is a weak zone which may have further deteriorated due to shrinkage and leaching. The joint surfaces are often sandy, with much of the cement paste leached out. This combined with poor reinforcement cover at the joint, as described above, results in very localised corrosion to vertical bars, sometimes along sections of culvert up to 25 m in length.

The chloride profile through joints is often flat, with no measurable decrease in chloride content with depth from the surface. Bars are typically cut off by corrosion over a length of 25-50 mm coinciding with the joint, the remainder of the bar being quite unaffected.

A similar type of damage is found in casting joints in walls. There is evidence in the standby inlet culvert that the walls have been cast in stages, resulting in two or three horisontal joints with a depth of around 600 mm. Poor compaction in these joints results in localised corrosion to vertical bars as described above. This type of damage pattern is not found in the outlet culverts, presumably these having been cast to their full height in a continuous pour.

6.2. Concrete spacers

Concrete spacers are probably the single most common cause of serious damage to reinforcement in roof-slabs. They are used under distribution bars in the larger outlet culverts while in the inlet culverts they are placed at regular intervals of 1 m under the main reinforcement. They are small, precast blocks with a diameter of 50 mm and depth 30 mm, sometimes less. They consist of mortar only and are of a more porous nature than the surrounding concrete. Test made on spacers drilled from the roof-slab of the outlet culverts show that all of the surfaces are carbonated. This means that the supported bar is in contact locally with a carbonated surface and may therefore not benefit from the protective alkalinity of the concrete at this point.

The spacers cause local and very severe corrosion to reinforcement, while adjacent steel surfaces are unaffected. In some parts of the inlet culverts there is evidence of corrosion at each spacer, resulting in a reduction in reinforcement of 25%. The spacers are placed in lines along the slabs with the result that damage is concentrated to fixed points in the section, which is undesirable from a structural viewpoint.

6.3. Form-ties

Form-ties used in walls <u>may</u> be fixed to vertical bars causing local corrosion attack. The ties themselves tend to corrode leaving small and deep holes into the concrete allowing water and chloride ingress. It is however rare that form-ties are fixed to reinforcement and this is therefore not regarded as a serious problem in generally. They do cause rust spots on the concrete surfaces of walls, and care should be taken not to confuse these with evidence of relevant corrosion damage.

6.4. Joints between shutters

Joints between shutters allow separation of water and cement paste during casting leaving porous channels in the covering concrete. Although not a common cause of reinforcement corrosion, the problem does exist both in walls and roof-slabs.

A common feature of the mentioned above construction details is that they are not random but form lines along the culverts and thereby significant reinforcement reductions at sections. Random placing of concrete spacers would allow for distribution of stresses from one point to adjacent bars. This is usually not possible where corrosion follows paths created by detailing features.

7. OTHER FACTORS RELEVANT TO CORROSION RISK AND DAMAGE PATTERNS

7.1. Loading

The roof-slab of the standby inlet culvert to B1 is undamaged with the exception of a 15 m long section, where the reduction in reinforcement on the inner surface is 80%. This section lies directly under a water tank which causes extreme bending stresses in the roof-slab underside. The concrete surface is painted with a thick layer of anti-fouling paint which could conceal cracking in the concrete. No closer studies of the condition of the concrete have been made, but it seems probable that the corrosion damage is related to the extreme loading conditions.

7.2. Environment

There are two main categories of structure with respect to flow conditions. The large tanks and pump chambers contain water which is relatively still, particularily at the wall surfaces, while the culverts contain flowing water with varying degrees of turbulence.

It is interesting to note that no corrosion damage occurs anywhere in the submerged surfaces of tanks, despite the fact that construction methods are largely similar. The measured chloride levels are on average one half compared with the culverts, which may possibly be attributed to the anti-fouling paint.

There are indications of a higher frequency of corrosion damage in sections of culvert where water-flow is turbulent, e.g at the mouth of the inlet culverts and outlet culvert where water comes down from the condensor and collides with roof-beams placed across the culvert.

There exists a relationship between flow conditions and risk/rate of corrosion [1], and it may be explained in part by the fact that oxygen-transport to the concrete surface and ultimately to the reinforcement is helped by eddy-currents in turbulent zones.

In laminar flow conditions the transport of oxygen occurs by diffusion, the rate of diffusion increasing with flow-rate as the thickness of the laminar layer decreases. As shown in Figure 1, a transition from laminar to turbulent flow (at critical Reynolds number) is associated with a sharp increase in corrosion rate.

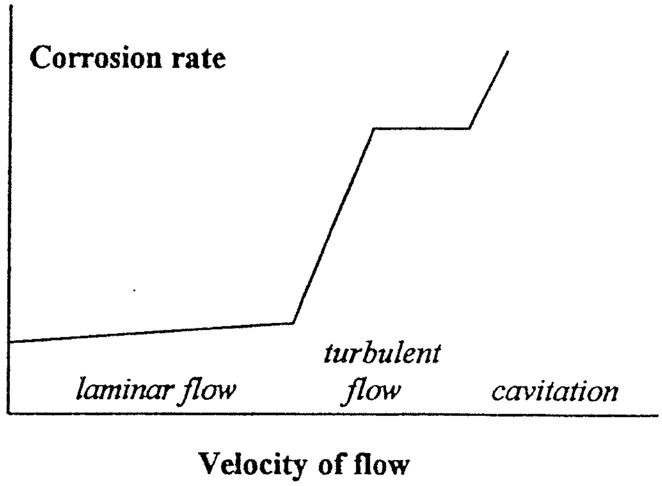

Figure 1. Corrosion rate versus velocity of flow [1].

It has been suggested that cathodically protected reinforcement will not affect concentrations of chlorides in surrounding concrete. As can be seen in TABLE 4 the measured chloride levels in structures (inadvertently) affected by existing cathodic protection are one quarter of those found in similar but unprotected structures. The measurements are consistent with each other and are based on surveys of more than 25 different structures.

7.3. Patterns of reinforcement corrosion - reinforcement spacing

In Figure 3 the distribution of corrosion damage along the main reinforcement of a section of outlet culvert roof-slab is shown. The main reinforcement on the slab underside is placed across the section at c/c-spacing 125 mm, with secondary reinforcement placed on top of these at 200 mm centres (typically). At the point shown the measured chloride levels are 0,45% of concrete weight and cover to main reinforcement is 30 mm. The corrosion damage is in the form of pitting, with reductions of as much as 30% on individual bars. The corrosion is spread up to about 300 mm along sections of the reinforcement and is confined to the surface nearest the exposed surface. The secondary bars are unaffected.

Damage patterns to main reinforcement in the inlet culvert are typically quite different. In the roof-slab, points of attack occur wherever concrete spacers are attached to the main reinforcement. Also a characteristic of the roof-slab reinforcement is severe point corrosion at the exact intersection between the main reinforcement and overlying secondary reinforcement. The degree of corrosion is 50-100% over lengths of approximately 50 mm. The adjacent steel surfaces are free from any indications of corrosion. Corrosion is confined to the main bars, with initiation on the surface nearest the exposed surface. The main bars are normally placed at 200 mm centres with overlying secondary reinforcement at 350-400 mm. The regularity of the points of attack is undesirable from a structural viewpoint.

Given that the conditions in the inlet and outlet culverts are very similar, it would appear that reinforcement spacing influences the nature of corrosion attack.

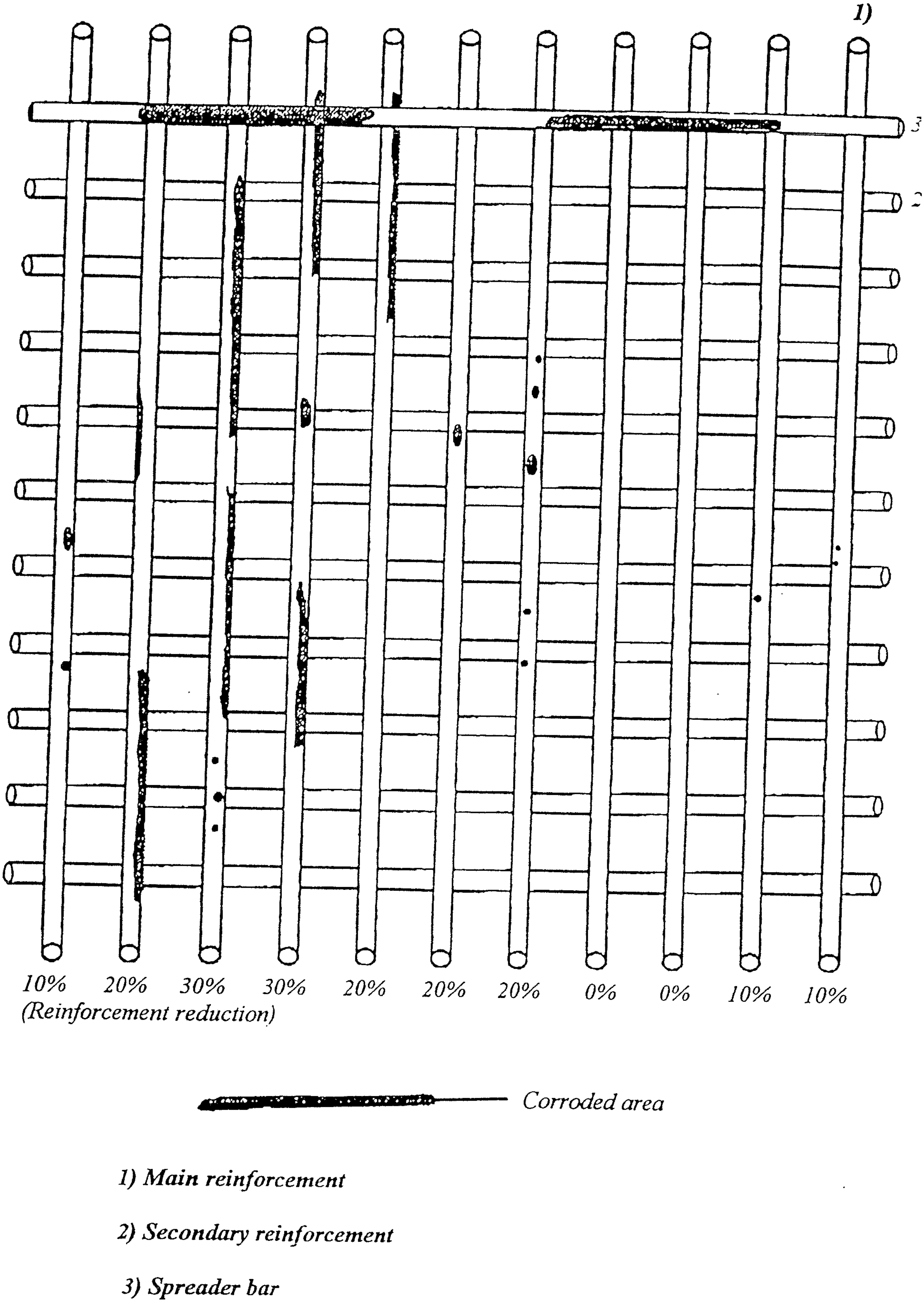

Figure 3. Corrosion to roof-slab reinforcement. Outlet culvert, Barsebäck 2. Position +93 m. Seen from below. From [2].

8. CONCLUDING REMARKS

The existence or non-existence of serious corrosion damage to reinforcement in submerged structures such as those described can be determined by visual inspection alone. The extent of corrosion can be measured quite accurately by the number of rust spots on the concrete surface and by relating these to the layout of the reinforcement. A 15% reduction in x-section caused by corrosion has been seen to be accompanied by cracking and deposits of corrosion products on the concrete surface.

Non-destructive testing techniques to determine corrosion at an early stage cannot be effectively used without first locating areas of high corrosion risk. Concrete sampling can be carried out quickly and accurately on site to locate such areas. Since the corrosion is very local then testing methods based on the Stern-Geary polarisation theory cannot be used.

In concrete structures built before 1980 the quality of workmanship varies to such an extent, that if conditions are such that there is a risk of reinforcement corrosion, there will be visible evidence in the form of isolated rust spots long before reductions in reinforcement become a serious problem from a structural viewpoint.

The observed patterns of corrosion indicate that initiation of corrosion is caused by variations in concrete environment around one and the same bar or between two bars in contact with each other. Typically corrosion occurs on bars which extend through cracks/construction joints or which are in contact with concrete spacers. A common form of corrosion occurs at the intersection of primary and secondary reinforcement, presumably a result of galvanic action between bars caused by the chloride concentration gradient from the concrete surface.

Corrosion under water is accompanied by cracking of the concrete cover. The cracks are very fine and do not cause spalling of the cover. Since no new points of corrosion initiation , i.e. points which are not accompanied by rust spots on the concrete surface, have been observed on the exposed bars , it seems that corrosion develops along the bar from the orginal point of attack. It is not uncommon for 80% of the bar section to be consumed at these points. This is quite different from the case of concrete exposed to air, as the original point of corrosion attack usually extend along the bar, accompanied by spalling of cover, long before reductions in bar section exceed 50%. It would seem therefore that in submerged structures the corrosion products do not hinder further attack at the initiating point.

Probably the most significant factor governing corrosion at an early stage is thickness of cover to reinforcement.

Cathodic protection to reinforcement will result in significantly lower chloride concentrations in the surrounding concrete.

There is evidence that the rate of corrosion is higher if water flow is turbulent. No corrosion has been obseved in structures containing relatively stagnant water.

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