Service Life Assessment of Harbor Structures

Case studies of chloride ingress into concrete structures and sheet piling corrosion rates

av

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Abstract

The two most used building materials in harbor structures are undoubtedly steel and concrete. These two materials are often combined in the structures of wharfs and quays where most steel sheet pile walls have cap beams of reinforced concrete. The degradation processes of these structures must be taken into account both when designing new structures and when inspecting existing harbor structures with the purpose of determining their remaining service life. Since the environmental loads on harbor structures differ substantially depending on their location, both globally and locally, the degradation processes also differ. Assessment of these types of structures must therefore combine general knowledge about degradation processes with knowledge about the local conditions.

This PhD-project has focused on degradation of steel and concrete structures in harbor environments. The purpose of the work has been to increase the understanding of the degradation processes in order to optimize the design of new structures in marine environment, and to make better predictions of the remaining service life for existing load carrying structures. The results presented in this thesis come from both laboratory studies and from field studies in three Swedish harbors together with a large inventory of earlier performed ultrasonic thickness measurements on sheet pile quays along the Swedish coast.

The results from the sampling of concrete specimens for determining the chloride ingress into concrete, is that core sampling and grinding gives less variations in chloride content using large core diameters compared to dry drilling and dust sampling with a small bore. If dust sampling is used in the field as the needed equipment is easy to handle, the dust sampling should be performed as mixed sampling from several bore holes in the same sampling area. From the results it is also clear that chloride contents should be expressed per mass of cement, not per mass of concrete.

Regarding to the corrosion rate of steel in a marine environment, the main factor of importance is the temperature. The results from field investigations and field exposures indicate that neither the salinity nor the pH-value of the water has any major influences on the corrosion rate, at least not in the short time perspective.

Key words
chloride ingress, sampling methods, corrosion rates, sheet piling, ultra-sonic measurements, service life, durability, quay structures, harbor structures

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Service Life Assessment of Harbor Structures

Case studies of chloride ingress into concrete structures and sheet piling corrosion rates

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Preface

This doctoral thesis has been written at the Division of Building Materials at the Faculty of Engineering at Lund University, Sweden. It consists of three papers published in scientific journals and three papers published in reviewed conference proceedings. The latter were presented at international conferences in Cape Town (South Africa), Quebec City (Canada) and Stockholm (Sweden).

The major part of the work presented in this thesis has been carried out at the Building Materials at Lund University. The research project has been financed by Skanska Sverige AB, The Development fund of the Swedish Building Industry (SBUF) and by the Road Bridge Tunnel Consortium, VBT, whom all are gratefully acknowledged for making this project possible.

The project started in March 2004 and the first milestone was my licentiate thesis with the title *Chloride profiling in marine concrete – Methods and tools for sampling*, presented in June 2007. The second part of the research project started in November 2010 and the result of this work is presented, together with the earlier research results, in this thesis completed in 2013.

Main supervisors have been Prof. Lars-Olof Nilsson (first part of project) and Prof. Lars Wadsö (second part of project), whom are gratefully acknowledged for all their support and supervision during the years.

I would like to thank all my colleagues at the Division of Building Materials for good working atmosphere. A special thanks goes to Jörgen Falk who has been my room-mate at Lund University for the last two years. Thank you Jörgen for interesting discussions and a good mood! Stefan Backe is gratefully acknowledged for all the help I have got when performing the field studies in the port of Trelleborg, in the port of Halmstad and in the port of Malmö. Thank you Bosse Johansson and Bengt Nilsson for help in the laboratory. The personnel in the three ports are acknowledged for letting us performing our investigations at site. Mr. Sverker Sjöberg at Skanska is acknowledged for helping me with estimations of the costs for repairing and building quay structures.

The personnel at MarCon Teknik AB is also acknowledged for helping me with providing data from their diving investigations and sheet pile measurements in harbors along the Swedish coast.

To my former manager at Skanska, Mr. Lennart Eriksson, I would like to say: thank you for all the interesting discussions about harbor structures during the years and thank you for leading me in to this field of construction.

Finally I would like to express my love to my wife and children, Charlotta, Ellinor and Erik, for their support over the years. I love you and I had not been able to finish this work without your support!

Ljunghusen November 2013

Contents

Abstract 1
Sammanfattning 5
The papers included 9
Introduction 11
Part I: Chloride profiling in marine concrete 21
- Background ... 21
- Previous research in investigating marine concrete ... 22
- Case studies on marine concrete structures ... 22
- Methodology for performing inspections ... 26
- Chloride in structures - large variations ... 29
- Measurements of chlorides in concrete - sampling techniques ... 32
- Case studies on marine concrete ... 32
  - Case study 1 - The port of Trelleborg (Paper I) ... 32
  - Case study 2 - The port of Malmö ... 37
  - Case studies on marine concrete – conclusions ... 42
- Chloride sampling methods ... 43
  - Dry drilling and core sampling (Paper II) ... 43
  - Simulated drilling using data from EPMA (Paper III) ... 46
  - Sampling methods – conclusions ... 50
- Sampling chlorides in marine concrete – conclusions ... 51

Part II: Corrosion of steel sheet piles in a marine environment 53
- Background ... 53
- Principles of design ... 57
- Measurement methods for determining remaining steel thickness ... 59
- Case studies on steel in marine environment ... 61
  - Case Study 3 - Inventory of ultra-sonic measurements (Paper IV) ... 61
  - Case Study 4 – Ultra-sonic measurements in a Swedish harbor (Paper V) ... 64
  - Case Study 5 – Field exposure of steel plates in a Swedish Harbor (Paper VI) ... 67
- Corrosion of steel in the marine environment – conclusions ... 70

Assessment of remaining service life based on regular investigations 71
Conclusions 77
Future research 79
References 81

Abstract

The two most used building materials in harbor structures are undoubtedly steel and concrete. These two materials are often combined in the structures of wharfs and quays where the steel sheet pile walls often have cap beams of reinforced concrete. The degradation processes of these structures must be taken into account both when designing new structures and when inspecting existing harbor structures with the purpose of determining their remaining service life. Since the environmental loads on these structures differ substantially depending on their location, both globally and locally, the degradation processes of the structures also differ. Assessment of these types of structures must therefore combine general knowledge about degradation processes with knowledge about the local conditions.

This PhD-project has focused on degradation of steel and concrete structures in harbor environments. The purpose of the work has been to increase the understanding of the degradation processes in order to optimize the design of new structures in marine environment, and to make better predictions of the remaining service life for existing load carrying structures.

The results presented in this thesis come from both laboratory studies and from field studies in three Swedish harbors together with a large inventory of earlier performed ultrasonic thickness measurements on sheet pile quays along the Swedish coast.

The degradation of concrete structures in the marine environment mainly consists of corrosion of the reinforcement due to chloride ingress. When the chlorides have passed through the concrete cover and reached the reinforcement, the passivating protection of the rebars is lost and the corrosion processes starts. When designing new concrete structures in marine environments, the only ways to increase the length of the expected service life of reinforced concrete structures are to either increase the thickness of the concrete cover and/or to use high quality concrete with a low water cement ratio that makes the concrete less permeable. Another way to secure non corroding rebars is, of course, to use rebars of stainless steel but this is expensive and is rarely used in ordinary construction works today.

Field studies in sampling concrete for chloride content analysis was performed in two harbors on the Swedish south coast. The sampling was done by dry drilling and dust sampling. In these studies the local climate, with a focus on the dominating wind direction, has also been studied. The results from the chloride analysis shows that if a surface on a concrete structure is exposed to open sea without any sheltering barriers in front of it, the chloride content tends to be much higher than in sheltered parts of the structure or in structures facing other directions. This is true irrespective of the dominating wind direction in the area.

Concrete slabs were exposed to saline water in laboratory. When the slabs had been exposed for about seven months, concrete sampling was performed with the purpose of testing different sampling methods. Both core drilling with a 100 mm core and dry drilling with different drill diameters was performed on the slabs. The cores were grinded and the dust from both grinding and dust sampling by dry drilling were analyzed with respect to chloride content. The results showed that dry drilling with small diameters collecting mixed samples from several nearby drill holes gave almost the same result as grinding the 100 mm core with respect to chloride content in percent by mass of CaO.

The chloride content in a sample from one of the exposed slabs was mapped with EPMA (Electron Probe Micro Analyzer) with the purpose of testing another sampling method. The result from the EPMA analysis was used to simulate drilling with different drill diameters and to compare these results with the results from the sampling made in the laboratory. The results from both dry drilling and the EPMA measurements showed that if the chloride content is presented as percent by mass of CaO instead of as percent by mass of concrete, the variations in chloride concrete were substantially decreased. Chloride data should therefore be presented per mass of CaO or per mass of cement.

The requested service life of steel structures in marine environments such as harbors is usually achieved either by over-dimensioning the steel thickness and assuming a certain even and constant corrosion rate in mm/year, or by applying a protective coating such as a paint on the structures to prevent corrosion. Car ramps and other steel structures that are not in direct contact with salt water are often coated with protective paint to prevent corrosion, while structures like sheet pile walls which are in direct contact with sea water most commonly are unprotected. A third way to protect wharfs from corrosion is to use cathodic protection with sacrificial anodes or by an impressed current cathodic protection system. Cathodic protection is common on ships and sheet pile walls.

A field study measuring the remaining steel thickness on existing quays was performed in the harbor of Halmstad on the Swedish west coast. An inventory of data from earlier measurements of steel thicknesses in harbors along the Swedish coast was also performed in this work. The purpose of these studies was to investigate whether the recommended design values on corrosion rates in the existing construction codes are accurate. In this study, corrosion rate design values from USA, Australia, Europe (Eurocode) and Sweden were compared with the results from measurements in Swedish harbors. The results from the corrosion rate measurements show that the measured corrosion rate is generally lower than the recommended Swedish design values, but in the same order as the recommended design values given in the European design code for sheet piles in marine environment.

With the purpose of investigating the corrosion loss on steel in a marine environment in a controlled way, steel plates were exposed to a marine environment for almost one year. The plates where mounted on ropes at different depths at three sites in the harbor of Halmstad. One of the exposure sites was located in the river of Nissan (fresh water) which has its outflow in the sea of Kattegatt. The two other sites were located inside the docks. The purpose of this study was also to determine if salinity affects the corrosion rate since the salinity in the fresh water river is generally lower than in the docks. The result from this study showed that salinity (and pH) did not influence the corrosion loss in the short time perspective (about 50 weeks). The corrosion losses on the exposed plates was almost three times as high as the measured corrosion losses on the existing sheet pile walls in the same harbor. This result suggests that the corrosion rate is non-linear in the short time perspective with the highest losses in the beginning of the exposure. This agrees with recent models of steel corrosion in marine environments. However, for harbor structures with 100 year service life, the thickness decrease can be modelled as being proportional to time.

The results from the present studies have implications both for the design of new harbor structures and for the assessment and maintenance of aged harbor structures. Increased knowledge of sampling procedures and improved degradation models make it possible to make more precise predictions of remaining service life for existing structures and will lead to more accurate design values for new steel and concrete structures in marine environments. Periodical inspections could be used for more accurate predictions of remaining service life of a given structure, for example using the method of Bayesian updating.

Sammanfattning

De två mest använda byggnadsmaterialen i hamnkonstruktioner är utan tvekan stål och betong. Dessa båda material kombineras ofta i konstruktioner, som t.ex. i kajer där spontväggarna, som är av stål, nästan alltid har en krönbalk av armerad betong. Nedbrytningsprocesser i denna typ av konstruktioner måste beaktas både när man designar nya kajer och vid inspektionen av befintliga sådana. I det första fallet för att uppnå önskad livslängd; i det andra fallet med syfte att bestämma återstående livslängd. Miljöbelastningen på denna typ av konstruktioner skiljer sig kraftigt mellan olika placeringar – både i globalt och lokalt perspektiv – vilket återspeglas i nedbrytningshastigheten, skadebilden mm.

Detta doktorandprojekt har fokuserat på nedbrytning av stål- och betongkonstruktioner i hamnmiljö. Syftet med arbetet har varit att öka förståelsen för nedbrytningsprocesserna i syfte att optimera utformningen av nya konstruktioner i marin miljö, samt att möjliggöra bättre prognoser av återstående livslängd för befintliga konstruktioner.

De resultat som presenteras i denna avhandling kommer både från laboratoriestudier och från fältstudier i tre svenska hamnar, samt från en omfattande inventering av tidigare utförda ultraljudsmätningar av återstående godstjocklek i spontkajer längs den svenska kusten.

Nedbrytningen av betongkonstruktioner i havsmiljö sker huvudsakligen genom kloridinitierad armeringskorrosion. När kloriderna har vandrat genom täckskiktet i betongen och nått armeringen, så bryts det passiviserande skyddet runt armeringsjärnen och korrosionsprocessen startar. Vid utformningen av nya betongkonstruktioner i marin miljö, är de enda sätten att öka den förväntade livslängden hos materialet att öka tjockleken på det täckande betongskiktet eller att använda betong med ett lågt vatten- cement-tal som gör betongen tätare.

Provtagning av betong för analys av kloridinnehåll har utförts i två hamnar längs den svenska sydkusten. Provtagningen utfördes genom uttagning av borrkax med hjälp av slagborrhammare på olika djup och i olika vädersträck i konstruktionerna. I dessa två fältstudier har även en analys av det lokala klimatet i hamnarna undersökts med fokus på den dominerande vindriktningen. Resultaten från kloridanalyserna visar att kloridhalterna i de betongytor som är exponerade mot öppet hav utan några skyddande barriärer framför, är mycket högre än i övriga mer eller mindre skyddade betongytor oavsett dominerande vindriktning i närområdet.

För att undersöka kloridinträngning och provtagningsmetoder i betong under kontrollerade former, så exponerades ett antal betongplattor i saltvatten i laboratorium. När plattorna hade legat nedsänkta i saltlösningen i ca sju månader togs de upp för provtagning och analys med avseende på kloridinnehåll. Provtagningarna genomfördes både genom kärnborrning med 100 mm kärna och genom uttag av borrkax med olika borrdiametrar på olika djup. Borrkärnorna skivades upp på olika nivåer och skivorna maldes ned för respektive nivå. Både materialet från kärnorna och borrkaxet från provtagningen med slagborr analyserades med avseende på kloridinnehåll. Resultaten av analyserna visade att blandprover från flera närliggande borrhål uttagna med liten borrdiameter (8 mm) gav nästan samma resultat med avseende på kloridhalt i mass-% av CaO-innehållet i betongen, som provtagning med 100 mm kärnor.

Kloridinnehållet i ett tvärsnitt av ett betongprov från en av de exponerade plattorna karterades med EPMA (Electron Probe Micro Analyzer). Resultaten från EPMA-analysen användes för att simulera de borrningar som utförts i laboratoriet med olika borrdiametrar inklusive kärnprovtagning. Kloridinnehållet studerades både som mass-% av betongvikt respektive som mass-% av cementvikt. Studien visar tydligt att variationerna i kloridinnehållet för en given betong minimeras om kloridinnehållet presenteras som klorid i förhållande till mass-% cement (eller i förhållande till mass-% kalciumoxid).

Önskad livslängd hos stålkonstruktioner i marin miljö, såsom spontkajer, uppnås vanligen genom överdimensionering av ståltjockleken (förutsatt en given korrosionshastighet mm/år) eller genom att skydda konstruktionen med katodiskt skydd. Katodiskt skydd kan utföras som både aktivt (pålagd ström) eller passivt (offeranoder). Övriga stålkonstruktioner i marin miljö som inte är i direktkontakt med saltvatten såsom bilramper, färjeklaffar mm skyddas oftast genom en korrosionsskyddande färg.

En fältstudie som omfattade mätning av återstående godstjocklek hos befintliga spontväggar har utförts i Halmstad hamn vid den svenska västkusten. I samband med denna fältstudie gjordes även en inventering av data från sponttjockleksmätningar längs den svenska kusten från Västervik i nordost till Falkenberg i nordväst. Syftet med studierna var att undersöka om de korrosionshastigheter som anges som dimensioneringsvärden i olika normer för design av stålkonstruktioner i marin miljö, kan anses vara i rätt storleksordning. Värden på dimensionerande korrosionshastigheter från USA, Australien, Europa (Eurocode) och Sverige jämfördes med de värden som uppmättes i fältstudien. Jämförelsen visar att den uppmätta korrosionshastigheten generellt är lägre än de svenska rekommenderade dimensioneringsvärdena, men i samma ordning som de i Eurocode angivna värdena på korrosionshastigheten.

I syfte att undersöka korrosionsförlusterna hos stål i marin miljö på ett kontrollerat sätt, så genomfördes en fältstudie i Halmstad hamn varvid stålplåtar exponerades på tre olika platser i hamnen. Stålplattorna monterades på linor på olika djup. En av försöksuppställningarna var belägen i ån Nissan (sötvatten), vars utlopp utgör en del av själva hamnen. Övriga två exponeringsplatser var belägna inne i själva hamnen och hamnbassängen. Syftet med denna studie var också att undersöka om salthalten i vattnet påverkar korrosionshastigheten hos stålet. Denna jämförelse skulle vara möjlig eftersom vattnet i Nissan har lägre salthalt än övriga hamnen. Resultaten från fältstudien visar emellertid att salthalt och pH inte påverkar korrosionshastigheten i ett kortare tidsperspektiv (50 veckor). Vidare visar denna studie att korrosionsförlusterna hos de exponerade plåtarna var nästan tre gånger så hög som de uppmätta korrosionsförlusterna hos de befintliga spontväggarna i samma hamn. Resultaten antyder alltså att korrosionshastigheten är icke-linjär med de högsta korrosionsförlusterna i början av exponeringen. Detta överensstämmer med de senaste modellerna för korrosion av stål i marin miljö. För hamnkonstruktioner med 100 års livslängd kan dock tjockleksminskningen modelleras som linjär och proportionell mot tiden.

Resultaten från ovan beskrivna fältstudier och inventeringar, påverkar både synsättet på utformningen av nya konstruktioner i marin miljö och bedömningen av underhållsbehovet av äldre befintliga konstruktioner. Ökad kunskap om provtagningsmetoder och förbättrade modeller för bedömning av nedbrytningsprocesser gör de möjligt att både optimera nya konstruktioner med avseende på materialåtgång för en given önskad livslängd, dels att göra mer exakta bedömningar över återstående livslängd hos befintliga konstruktioner i marin miljö. De resultat som har framkommit i detta arbete kan t ex användas i inspektionsprogram som bygger på Bayesiansk uppdatering med återkommande periodiska undersökningar, för att med större säkerhet kunna förutsäga befintliga konstruktioners återstående livslängd.

The papers included

Paper I

Initial Survey of Concrete Structures in Swedish Harbours – A Case Study in the Port of Trelleborg. H. Wall and L.-O. Nilsson, *Proceedings of the International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR) 2005, Cape Town, South Africa.*

Paper II

Chloride Profiling in Concrete Harbour Structures – A Study of Extensive Variations. H. Wall and L.-O. Nilsson, *Proceedings of the 2nd International Symposium on Advances in Concrete through Science and Engineering 2006, Quebec City, Canada.*

Paper III

A Study on Sampling Methods for Chloride Profiling – Simulations Using Data from EPMA. H.Wall and L.-O. Nilsson, *Materials and Structures (2008) 41:1275-1281.*

Paper IV

Sheet Pile Corrosion in Swedish Harbours – An inventory of Corrosion Surveys along the Swedish Coast. H. Wall and L. Wadsö, *Proceedings of Eurocorr 2011, Developing Solutions for the Global Challenge 2011, Stockholm, Sweden.*

Paper V

Corrosion rate measurements in Steel Sheet Pile Walls in a marine environment. H. Wall and L. Wadsö, *Marine Structures Vol. 33 (2013) 21-32.*

Paper VI

Corrosion of Mild Steel Plates on Various Depths in a Marine Harbor Environment H. Wall and L. Wadsö, *Submitted to Marine Structures*

The contribution of the authors to the papers included in this thesis was as follows:

Paper I HW did the archive study, the evaluation of meteorological data and wrote the major part of the paper. LON contributed with comments on the manuscript.

Paper II HW planned the study, did the experimental setup, the laboratory work, the evaluation of the measurements and wrote the major part of the paper. LON had the initial idea and contributed with comments on the evaluated data and on the manuscript. The paper, which is a part of the conference proceedings, was peer reviewed by the Rilem committee before being accepted and published in the proceedings.

Paper III HW did the evaluation of the data and wrote the major part of the paper. LON had the initial idea and contributed with comments on the evaluated data and on the manuscript.

Paper IV HW had the initial idea, did the collecting of measurement data, evaluated the data and wrote the major part of the paper. LW contributed with comments on the collected data and with comments on the manuscript.

Paper V HW had the initial idea, did the planning for the investigation, evaluated the results from the measurements and wrote the major part of the paper. LW contributed with the uncertainty calculations and wrote parts of the material. LW also contributed with comments on the evaluated data and the manuscript.

Paper VI HW had the idea, did the planning of the experimental setup, evaluated the data and wrote the major part of the paper. LW contributed with optimizing the experimental setup, with measurements in field and with comments on the manuscript.

Introduction

On 16 April 2013 the following article was published in The Daily Mail (UK); "*World's oldest port found in Egypt – complete with scrolls revealing everyday life for Ancient Egyptians*". The ancient port was found by archaeologists on the Red Sea coast and is believed to date back about 4.500 years. This finding shows, among others, that the shipping industry has a very long history and that the transport by sea has always been – and most probably also will be in the future – an important route for exchanging goods around the world.

There are about 5000 major artificial cargo and passenger ports in the world today. This includes inland harbors, ports along rivers, and sea ports. The largest harbor with respect to the total handled cargo volume is the port of Shanghai in China, with an annual tonnage of 736 million (2012) and a total quay length of 20 km. The largest port in Europe is the port of Rotterdam in the Netherlands that handles an annual cargo volume of 430 million tonnes (2010) and has a total quay length of 89 km. The construction cost for one meter of new standard sheet pile wall quay with a cap beam of reinforced concrete is about 150 000 SEK (corresponding to 23 000 USD, 15 000 GBP or 18 000 EUR; May 2013) including fenders and bollards and an excavation depth of 9 m. Considering these numbers, it would cost about 450 million USD to build all the quays in Shanghai and about 2020 million USD for the same effort in the port of Rotterdam. There is thus a substantial economic value in the world's harbors, and improving the knowledge about the deterioration processes and corrosion losses on these structures will improve the harbor owners' planning of building new structures or upgrading existing ones. Better models for predicting corrosion loss in the design phase together with improved methods for inspections of existing structures and prediction of their remaining service lives are the key elements for optimization of the structures with regard to both economy and technology.

The total length of the commercial quays in Sweden today is about 200 km and approximately 100 km of these quays are handled by the Swedish communities and technical services [1]. The number of commercial ports in Sweden is 52 (2013) and there are also 56 industrial harbors. The commercial harbors accounted for 80% of all the transported goods at sea in 2012 and the volume of the handled goods in the Swedish harbors is today four times higher than in the beginning of the 1980s.

In Sweden the dominating materials used in quay structures are steel and concrete; old quay structures were also built of timber and natural stone. The majority of the structures found in Sweden have reached an age that exceeds the original design life, which in theory means that the structures should be replaced by new ones. Despite this, the structures are in many places still working as they should but the information about for how long time they will last is rather limited. Therefore we need improved accurate and precise methods to perform inspections of these structures – ultrasonic measurements on steel sheet piles and chloride profiling in concrete structures are two examples of such methods – in order to determine their remaining service life and to be able to plan the maintenance efforts needed to keep them up to date. The results of more precise inspections is also a valuable tool when designing new steel and concrete structures in the marine environment.

This work concerns *methods and tools for determining the present state of steel and concrete structures in the marine environment*, and the aim has been to improve existing inspection and sampling methods within this area. It is well-known that the results from chloride sampling, which is the most important tool in determining the status of concrete in marine environments, show a large scatter. This is also true even if the sampling is performed within a very small area and in apparently homogeneous concrete without any visible defects or inhomogeneous climatic conditions. When it comes to ultrasonic measurements on steel sheet piles, the most common method to investigate sheet piling, there is also a scatter in the results. The ultrasonic probe is small compared to the structures and local pit corrosion could give very misleading results referring to the corrosion rate on the whole structure making the prediction of the remaining service life time incorrect. Repeated measurements are also usually not performed in the same positions, which can make comparisons difficult.

The most common deterioration mechanisms in concrete exposed to the marine environment are undoubtedly reinforcement corrosion caused by chloride ingress and frost damage. Figure 1 shows an example of a damaged concrete structure; possibly damaged by one or possibly both the mentioned mechanisms.

Figure 1
Damages on concrete piles on the underside of a concrete quay.

A literature search on deterioration of concrete in the marine environment shows that reinforcement corrosion is the main deterioration factor; something that is also stated by among others de Roij and Polder [2]. A lot of research has been done in the field of reinforcement corrosion. In reference [3] Tuutti presented a model for reinforcement corrosion in concrete. The model is built up in two stages, one initiation stage followed by a propagation stage, see Figure 2.

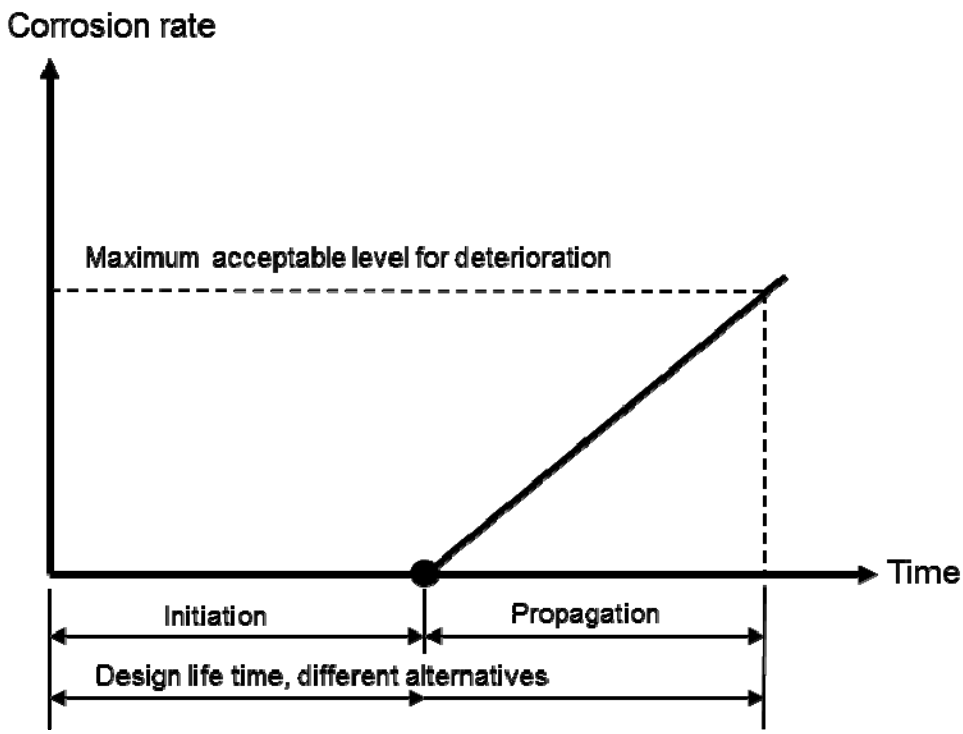

Figure 2
Initiation and propagation of reinforcement corrosion, after [4].

During the initiation stage carbon dioxide diffuses into the concrete and carbonates it and chlorides (if present) penetrate the cover. When the carbonation or the chlorides reaches the reinforcement steel, it is depassivated, ending the initiation stage. In the propagation stage the reinforcement corrosion is initiated and continues until an unacceptable damage level of the structure is reached. The corrosion rate in the propagation stage is dependent on the available amount of oxygen at the cathode and on the electrical resistance of the concrete.

During the initiation phase the performance of the structure is not considerably changed. In fact, the strength of the concrete itself can actually increase due to the continued hardening. At the end of the initiation phase and the start of the propagation phase, the cross section of the reinforcement bars starts to decrease and the developed corrosion products creates a pressure, which after a certain time can result in cracking and spalling of the concrete cover, Figure 3. Because of this, when the propagation stage is reached, the load-carrying capacity of the structure will decrease with time.

Figure 3
Corroded reinforcement bars with spalled concrete cover on a load carrying concrete beam in a quay deck.

In many cases, inspections of reinforced concrete structures are performed in an uncertain way, mainly as visual inspections. When performing visual inspections, traces of corroding reinforcement, cracks and damages on the concrete surfaces are detected. The problem is that when these signs are visible to the naked eye, it is often too late for rehabilitation measures as the reliability of the structure is already too low. The focus when performing inspections for preventive maintenance of reinforced concrete structures should instead be on concrete without visible signs of deterioration.

The degradation of carbon steel in marine structures such as in sheet pile walls, differ from the degradation process of reinforcement bars in concrete. Here the steel is directly exposed to the elements of nature, including sea water (Figure 4), and the corrosion process of the steel begins at the very moment when the steel is exposed to air or water. Figure 4 shows typical corrosion damages on a sheet pile wall in the water line and Figure 5 shows a sheet pile wall with a hole in the front flange under the water line that is only detected by diving inspections.

Figure 4
Typical corrosion pattern in the water line on a sheet pile wall. The backfill is visible through the holes in the piles.

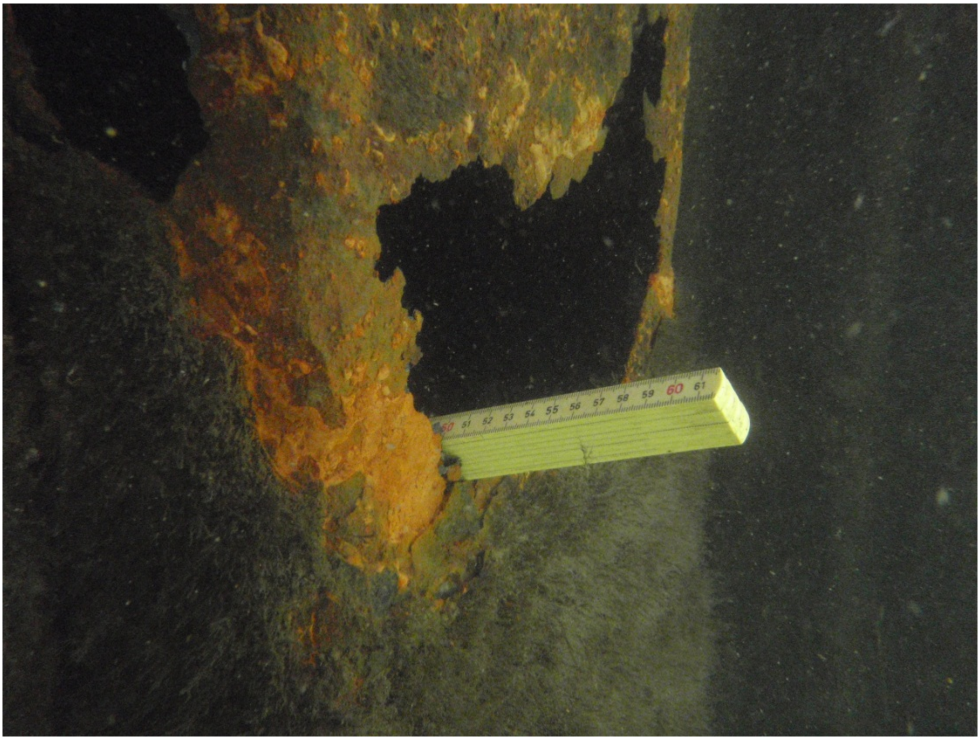

Figure 5
Corrosion damages on a sheet pile wall under the water line. The filling behind the wall has been washed away and the remaining service life of this wall should be considered as zero.

When designing new quay structures and when inspecting existing structures, the corrosion rate is in practice almost always taken to be constant and expressed in mm/year. This approximation is reasonable if seen over a rather long time and quay structures are often are designed for a service life time of 50 or even 100 years. However the initiating corrosion process is non-linear and can be divided in several stages according to Melchers [5], Figure 6. The corrosion is highest during the first two to three years, at least in the Nordic countries where the mean water temperature is about 10 °C, but when considering the mean corrosion over the service life time for e.g. a quay structure the corrosion rate can be considered to be constant, see also reference [6] and Figure 7.

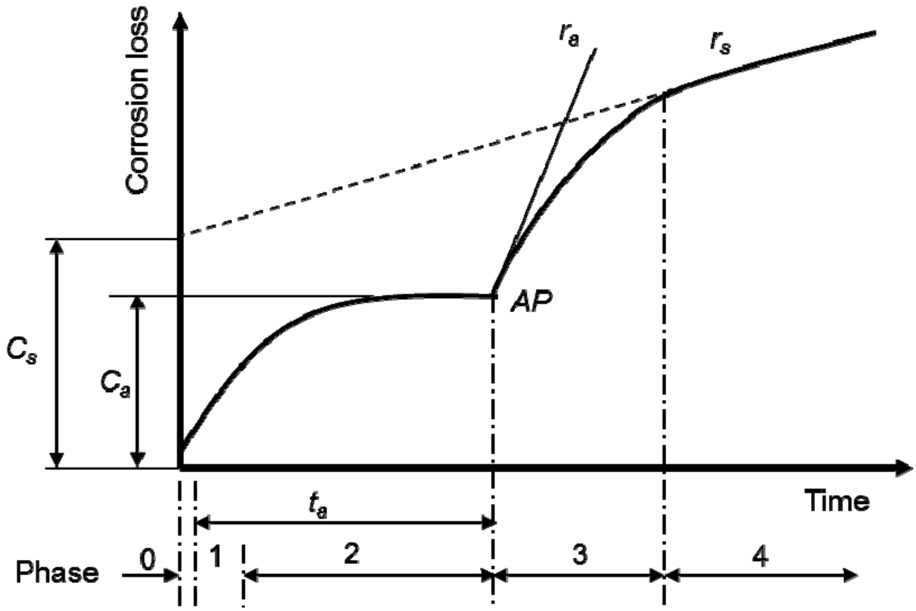

Figure 6
Corrosion loss-exposure model for immersion corrosion of steel in natural seawater, after Melchers [5]. The figure only shows the first years; after this the corrosion can be considered to proceed with a rate rs.

The different phases in Figure 6 are described – here in brief – in the word of Melchers [5] as:

Phase 0: "The steel surface is colonized by biofilms, bacteria and marine organisms and is subject to a complex mix of influences."

Phase 1: "Very soon, the rate of corrosion becomes controlled by the rate of arrival of oxygen at the corroding surface."

Phase 2: "With continued corrosion a build-up of corrosion products (rust) occurs on the corroding surface. This tends to limit the rate of oxygen diffusion."

Phase 3: "The increasing thickness of the rust layer reduces the capability for oxygen to reach the corroding surface, thereby allowing localized anaerobic conditions to develop at the corroding surface."

Phase 4: "A near steady-state situation develops eventually over the corroding surface. The rate of corrosion depends on the balance between the rate of supply of nutrients and the rate of loss of the rust layer through erosion and wear."

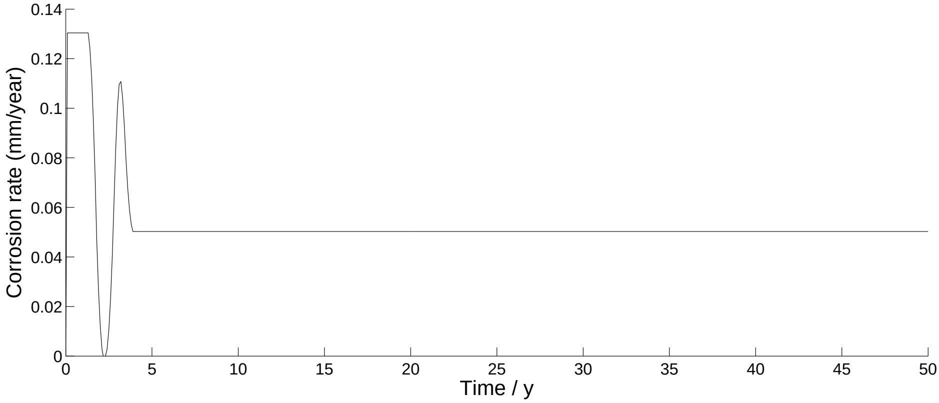

Figure 7
Corrosion rate in mm/year at a mean water temperature of 10°C according to the model in reference [5].

As seen from Figure 7, the corrosion rate at 10 °C expressed in mm/year is as much as 0.13 mm/year during the first years according to Melcher's model. However, after this period the corrosion rate becomes constant at a value between 0.05 and 0.055 mm/year.

Another important factor to consider – apart from that the corrosion process in a harbor environment is very complex – is that the corrosion on the front side of a sheet pile wall facing the open sea differs from the corrosion on the backside of the wall, which most often is back-filled with soil. This is usually not taken into account, neither when designing new structures, nor when inspecting existing ones.

Part I: Chloride profiling in marine concrete

Background

The end of the service life of important structures is often defined by end of the initiation phase, see Figure 2. When the initiation phase has reached its end, the remaining service life of the structure is zero. The methods for maintenance and upgrading the structures during the initiation phase are much less costly and much more reliable than if such efforts are done during the propagation phase. For this reason the determination of the state of the structure should be done during the initiation phase before any signs of corrosion or visible changes can be observed during a visual inspection. With respect to reinforcement corrosion, the purpose of the determination of the status of the structure is mainly to verify how far the ingress processes (carbonation and chloride ingress) have gone and how much of the initiation phase that remains to take place.

The determination of the present state of a given concrete structure can be divided into six steps:

1) Description/documentation of the influence of the surrounding climate on the structure
2) Documentation of the response from the structure by the surrounding climate
3) Determination of the properties of the materials in the structure
4) Analysis of changes to the structure from when it was built until the inspection is made
5) Prognosis on future changes without any maintenance actions
6) Prognosis on future changes with maintenance actions

The main part of the chloride ingress project concerned field studies in two harbors in southern Sweden and a study in the laboratory on concrete specimens submerged in a saline solution. The field work concentrated on concrete superstructures in and above the splash zone. The sampling in the field studies have been performed by dry drilling, and the sampling in the laboratory has consisted in both sampling by dry drilling and profile grinding of cores.

The concrete part of this research project was started by a state-of-the-art literature study on the subject *inspection of concrete in marine environment*. Simultaneously a study of wind and water data for southern Sweden was made with the purpose of detecting possible patterns between the environmental load and chloride ingress when performing the case study in the port of Trelleborg. The results from the literature and climate study are described in the following.

Previous research in investigating marine concrete

Most of the literature published within the area of marine concrete deals with the influence of the marine environment on concrete with different compositions. However, a few references include case studies and inspection methodology. These are summarized here, limited to literature that fits under the criteria *Inspection and determination of the state of concrete structures in marine environment*.

Over the years several more or less advanced calculation models for predicting chloride ingress into concrete have been presented and there is no lack of methods for predicting the future chloride ingress into concrete, see for example reference [7]. Most of these models use Fick's second law of diffusion. Input for these calculation models is among other things values on chloride content measured in existing concrete structures. The sampling methods used for collecting this data and the selection of sampling points are of importance for the result of the calculations.

Case studies on marine concrete structures

There are numerous studies on specimens exposed to the marine environment. Common for these studies is that most of them are on small specimens cast with different concrete mixes that are submerged in harbors in order to evaluate the influence of chloride exposure. The literature does not contain any significant number of case studies on real structures and the studies that are found are often quite general, missing detailed information on how the sampling was performed. Most results published on investigating concrete exposed to salt and saline solutions are from road bridges and tunnels. Unfortunately many results from investigations of marine concrete structures are unpublished because the investigations have been performed by private companies that are not willing to share their results with competitors.

Durability of reinforced concrete wharves in Norwegian harbours

Gjørv [8] performed an investigation of most of the existing Norwegian harbours with the purpose of determining the present state of the concrete structures in this kind of marine environment. In total 719 different concrete structures were investigated. A detailed inspection was performed on 170 of the structures.

The inspections showed that the most dominating deterioration mechanisms were reinforcement corrosion. The parts of the concrete structures that were situated above the highest high water level showed mainly signs of on-going reinforcement corrosion, while frost damages were observed as the dominating deterioration factor on the structures situated in the splash zone. Those parts of the structures that were constantly submerged were almost intact and no significant signs of deterioration could be observed with the naked eye at the time of inspection. It was also noted that the influence of the wind on the structures were of importance with respect to service life.

Durability of a 60-year-old reinforced concrete pier in Oslo harbour

During 1986 a 60 year old reinforced concrete pier in Oslo Harbour was demolished. Gjørv and Kashino [9] performed field studies at the time of the demolition with the purpose of investigating the state of the concrete structures. Visual inspections on site were performed together with sampling for laboratory analysis. About 25% of the reinforcing steel showed signs of on-going corrosion while the remaining 75% where found to be in excellent condition. The most extensive corrosion damages were found in the concrete slabs on the quay deck and on the supporting beams.

Durability of concrete structures along the North Sea coast of the Netherlands

Wiebenga [10] presented the results from investigations of 64 concrete structures of varying age along the North Sea coast of the Netherlands. Most of the investigated concrete structures contained blast furnace slag. The conclusions were:

1) The carbonation depth was small even in the oldest structures.
2) Reinforcement corrosion is mainly caused by chlorides.
3) Reinforcement corrosion was observed only in those structures that had been exposed for chlorides for a long time and had a thin concrete cover. No correlation between cement content and reinforcement corrosion was found.
4) The maximum depth of penetration of chlorides was a function of the exposure time and the porosity of the concrete.
5) The degree of weathering of the concrete surface did not correlate with its age or the cement content.

Sixty-year-old concrete in a marine environment

Ozaki and Sugata [11] presented the results from investigations of a 60 year old breakwater. The breakwater was built as an 11 m wide and 8 m high caisson made of reinforced concrete with a 1.7 m thick upper deck that also was made of reinforced concrete. At the side of the breakwater, on the bottom of the sea seabed protection blocks where situated to prevent erosion. The following parameters were measured:

- compressive strength of the concrete
- porosity of the concrete
- salt concentration
- carbonation depth
- corrosion level on the reinforcement

The results from the analyses showed that the compressive strength of the concrete has not decreased even after 60 years of exposure to sea water. The pore sizes were generally smaller than would be expected for ordinary concrete, but the total porosity was as expected. The carbonation depth was generally small except in the foot protection blocks that were made of lower concrete quality than the caisson. The salt content near the concrete surface was high, varying between 0.3 and 0.6 percent by mass of concrete. At a depth of 80 mm, the salt content was found to be constant at around 0.1 %. Tests showed that the corrosion of the rebars was minimal, despite the high salt content in the concrete.

Case studies of concrete deterioration in a marine environment in Portugal

Costa and Appelton [12] performed case studies on three different types of reinforced concrete structures, all of them located in marine environments in Portugal. The case studies focused on reinforcement corrosion, which was the most common deterioration mechanism. The investigation included three dry docks of 30 years of age, four 30 years old quays or wharfs, and one arch bridge 35 years old.

- **Dry docks** - At the time of the design of the docks, no service-life analysis was performed to control the expected service life of the structures. The poor concrete quality together with poor workmanship during the casting had resulted in an extremely fast deterioration of the reinforced concrete. The corrosion process started already 4 to 5 years after the docks were built. Macro-cell corrosion was detected on the dock walls that were exposed to direct sun-light. The two main factors that accelerated the corrosion process were high temperature and the good access of oxygen due to the drying concrete.
- **Quays** - No durability criterion was considered during the design of the quays. Two grades of degradation were observed along the wharves. The

upper parts of the wharves just above the splash zone showed large areas of spalling of the concrete cover caused by reinforcement corrosion, while the degradation within the splash zone seemed to be more moderate.

- **Bridge** - No larger maintenance efforts had been done on the bridge since it was built 35 years earlier. The damages that were detected on the bridge were primarily spalling of concrete cover on the deck beams over the arch. The authors believe that in this case the reason for the high degradation level is bad workmanship during casting. Poorly made construction joints were also a common observation on this structure. The investigation showed that the concrete cover was less than 20 mm along significant areas of the beams.

  The overall conclusion of this study was that the main reason for the extensive degradation of the investigated structures is chloride induced corrosion because of poor workmanship together with lack of knowledge of the deterioration mechanisms for the materials. This leads to insufficient planning and wrong estimation of environmental effects such as strong sun-light (high temperature) together with high access to oxygen, which accelerates the corrosion process.

Deterioration of concrete of coastal structures in Japan

About 30 structures made of reinforced concrete along the Japanese coast were inspected as described by Seki [13]. Typical structures investigated were sea walls and wharfs that had been exposed to marine environment for time periods between 15 and 40 years.

The field investigations were performed both by visual inspections of the concrete surfaces, and with non-destructive methods, such as the Schmidt hammer and the ultra-sonic method, as well as with core sampling. The cores were sampled from the upper part of the structures and were analysed in the laboratory in order to determine the density of the concrete, water absorption, depth of carbonation, salt content, compressive strength and the mix proportions of the concrete. The depth of carbonation was between 10 and 37 mm and no relationship between the age of the structures and the depth of carbonation was found.

The author concluded the following:

- Most deteriorated areas were located at the cold joints. No obvious relationship was found between the level of deterioration and age of the structures at the time for the investigations. This indicates that one of the most important factors when casting concrete in the marine environment is quality control.

- It is likely that the degree of deterioration is primarily a function of the water cement ratio, provided that the structures are built with good construction practices with quality control.

Torshamnen, oil pier, damaged concrete structures

The investigation of the oil pier in Torshamnen, Gothenburg, was performed as there were signs of deterioration of the concrete. The investigations mainly consisted of measurements of chloride ingress into the different parts of the pier [14]. The author performed service life predictions of the remaining service life of the pier based on the results from the chloride analyses. The predictions were performed both for the case when no maintenance procedures were used and for the repaired structures. The chloride profiles for the structure were determined by analyses of dust sampled from dry drilling and from core grinding of 100 mm cores. The variations in chloride content were extensive, especially in 10 sampling points on the upper quay deck. The 10 samples were collected along a line less than one meter on concrete that appeared too homogeneous from a visual inspection. About 25 mm below the concrete surface the chloride content varied between 0.4 and 1.9 percent by mass of cement without any obvious reason.

Methodology for performing inspections

Concrete in marine environment is exposed to an extreme climate. The structures in a harbour are exposed to chlorides and, in the cold parts of the world as for example in Canada, the Nordic countries and Russia, also to frost. This sets strong demands on both the concrete itself and on the workmanship when casting the structures. In order to be able to detect possible damages on these structures in time, it also sets demands on accurate inspection methods for determining the present state of a structure. The literature contains several papers on case studies and sampling on concrete at site, with the purpose of using the data from chloride profiling in service life predictions. However, often the sampling itself is not described in detail as the main interest is the results. The focus lies on the use of the chloride profiles and it seems that how the sampling is performed were not of interest. In the final report from the European project on rehabilitation of concrete structures REHABCON [15] an evaluation of alternative repair and upgrading options for concrete is presented together with a description of different sampling methods on concrete structures. However, the report contains no special recommendations for how to perform inspections on concrete structures exposed to the marine environment.

Nilsson et al. [16] described the different exposure zones in the marine environment. This report also discusses the influence of wind action on structures. The results from the Grimsøystraumen Bridge in Norway was used as the surface chloride content has been measured for the box girder of the bridge in several points. The influence of the dominant wind direction on the surface chloride content is discussed in one section of the report.

In the following text in this chapter, the papers and reports that best fit into the subject of *Inspection of marine concrete* are presented.

Determination of the present state of harbour structures owned by the Swedish Communities

The Association of Local Authorities in Sweden have made a survey with the purpose of making an inventory of quays and wharves in Sweden [1]. In the published compilation the most common quay and wharf types in Swedish harbours are presented with respect to age and structural design type. Detailed inspections have been performed on structures in five of the harbours with an investigation method that has been developed for the wharfs in Stockholm. The method for determining the present state of the investigated structure is divided into four steps:

1) **Zero inspection** - a general description of the inspected quay with data on the age of the structure and how it was designed. The Zero inspection also includes a visual inspection.

2) **Main inspection** - an inspection that is performed with the purpose of finding those types of damages on the quay structures that could affect the load bearing capacity of the structure within a 10 year period. In this step the quays are divided into groups called TK 0 to TK 3 depending on the state of the structure. TK 3 is the most serious state. Sampling from the concrete structures is performed with the purpose of determining the chloride content and the carbonation depth. The compressive strength of the concrete, its frost resistance and composition is analyzed in laboratory.

3) **General inspection** - preferably performed once a year in order to follow up and register the deterioration processes of a quay.

4) **Special inspection** - done of those parts of the structure that has been classified to one of the higher groups TK 2 and TK 3. This inspection is normally performed on selected parts only and does not necessarily include the whole quay.

Inspection, maintenance and repair of maritime structures exposed to damage and material degradation caused by a salt water environment

The scientific organization PIANC-AIPCN has through a working group, WG 17, written a State-Of-The-Art report over inspection, maintenance and repair of marine structures [17]. The report includes structures of timber, natural stone walls, concrete and steel. A description of common deterioration factors is given for each type of material and quay, followed by recommendations for inspection methods and for maintenance and repair. The report is summarised by giving references for inspection, maintenance and repair divided into material groups (steel, wood, concrete etc.).

Inspection of concrete offshore structures

An inspection program suitable for oil rigs built of reinforced concrete was created by Browne et al. [18]. The inspection program is divided into two parts:

1) Planning of frequent major general inspections.
2) Execution of an inspection by visual observations and testing of the concrete with non-destructive methods.

Due to the size of an oil rig platform, probabilistic methods are used to choose suitable so called "critical points" for spot tests. Using a probabilistic method it is possible to consider the uncertainties of the environmental loads on the structure like wind direction and the influence of the wave action. In its simplified form, the execution of the inspection is described in a table: "Standard of inspection adopted for different areas of inspection". The inspection is divided into three classes, where class 1 describes the most detailed inspection and class 3 is the most general of the inspections.

Diagnosis and repair of marine structures - towards a unified approach

In this article Browne et al. [19] discuss different approaches for determining the present state of a marine concrete structure. A financial approach is presented for determining the cost efficiency of possible actions to restore the structures. The testing methods are not presented in detail, but the authors recommend monitoring corrosion rate at site. The content in this article is quite general.

It is claimed that the low chloride content at the concrete surfaces found when doing analyses in field, is not due to washing out of chlorides or leaching. It is suggested that this phenomenon is due to carbonation at the surface. Concrete's capacity to bind chlorides is significantly reduced by carbonation. Carbonation therefore releases bound chlorides, allowing them to diffuse further into the cover zone.

Analysis of structural condition from durability results

In 1983 a conference on corrosion of reinforcement in concrete construction was held in London. In the conference proceedings [20] Browne et al. presented how to perform a survey of an existing concrete structure and how to evaluate the results and how to choose repair methods. The authors state that the existing methods for undertaking inspections of concrete structures are too limited, and often rely on visual inspections only. Furthermore the authors also commented that the used techniques of repair in many cases are ineffective.

In short, the survey presented in this paper can be divided into the following steps:

- *The Structure's History and Environment* in which the original design data for the structure together with general climate information for the area where the structure is located is collected.
- *The Field Specification* consists of a planning document describing the survey objectives, methods and scope.
- *The Global Survey* provides information for the whole structure and normally consists of a visual inspection and photographic survey together with the usage of non-destructive-test measurements.
- *The Detailed Survey* contains both non-destructive-testing and concrete sampling for analysis in laboratory. The sampling is usually performed as dry drilling collecting dust or core sampling with 100 mm cores.

Preliminary inspection of pier structures

Wesselink & Harley [21] presented a model for inspection of quays. The model has been developed at Exxon. The inspection consists of four parts:

1) General inspection
2) Detailed inspection
3) Damage analysis
4) Suggestions for repair actions

The paper focuses mainly on the general inspection. The authors present a table containing common construction parts in quays and piers together with descriptions of where the most common damages on the structures usually appears.

Chloride in structures - large variations

When performing sampling on concrete structures in marine environments, a frequent problem is the extensive variations in chloride content between different sampling points on the same structure. Figure 8 shows an example from an inspection of a quay deck in a harbour in western Sweden. The 10 sampling points are located on a line with a length of less than one meter. No obvious explanation to the differences in the analyzed chloride content was found at site. The concrete surface, from which the samples were taken, showed no signs of cracks or cavities that could explain this phenomenon.

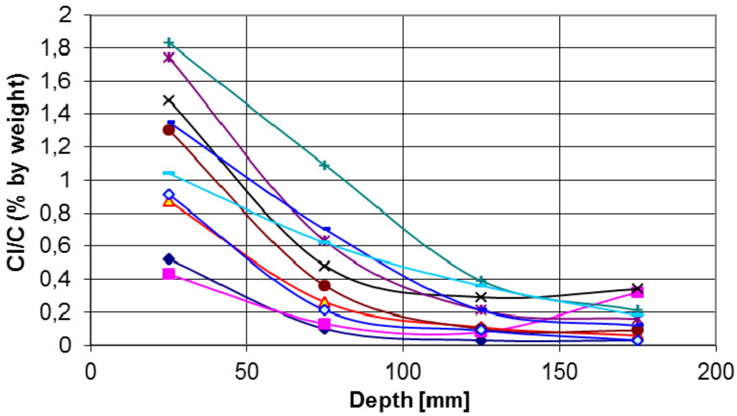

Figure 8
Example from chloride profiling, after [14].

In reference [16], which gives recommendations for sampling, it is stated that core grinding or grinding at site gives more accurate results than dust sampling by dry drilling. No other methods for decreasing the extensive variations seen in Figure 8 are given in the report, except to use dry drilling when the examined concrete contains aggregates with a size smaller than 16-20 mm, which in practice rules out this method for most concrete structures in the marine environment.

Variation of chloride profiles in homogeneous areas

A paper by Goltermann [22] presents the results from an investigation of variations in chloride content in apparently homogeneous concrete. Sampling for analyzing chloride content was performed on the bridge columns in a road bridge in Denmark. Both core sampling and dust sampling by dry drilling were performed. The diameter of the cores sampled varied between 75 and 100 mm and for the dust sampling a 20 mm drill was used. Close to every sampling point for core sampling, dust where sampled from three boreholes. The dust from every equal interval in the three holes was mixed and formed one sample. In the laboratory the chloride content, cement content and moisture content was determined. The sampling was performed in areas on the bridge columns that consisted of apparently homogeneous concrete. The cores and the dust were sampled in small areas in order to be able to compare the sampling methods.

The results from the laboratory analysis showed no correlation between the chloride content and the moisture content in the samples. A good correlation was however found between the moisture content and the cement content. The coefficient of variation of the measured chloride content in the dust samples was larger than for the collected cores. This was shown to be of minor importance when estimating the remaining service life of the structure. For this estimation a calculation model based on Fick's second law was used.

The paper finally concluded that when using dust from dry drilling with the purpose of determining the chloride content in the concrete, the number of drilling holes situated close to each other should be not less than 4 or 5 in order to get more accurate results compared to when mixing dust from only 3 holes.

Probabilistic Approach for Local Chloride Heterogeneity near Reinforcement

De Rooij and Polder performed sampling by core drilling in the eastern Scheldt storm surge barrier [2]. Sampling with a core diameter of 50 mm was performed on eighteen year old concrete. In total, six cores were collected about nine meters above mean sea level within an area less than 0.5 m^2. The chloride profiles from the analysis showed extensive variations down to about 35 mm beneath the concrete cover (Figure 9). No explanation for this behaviour was found other than the heterogeneity of the concrete at a micro structural level.

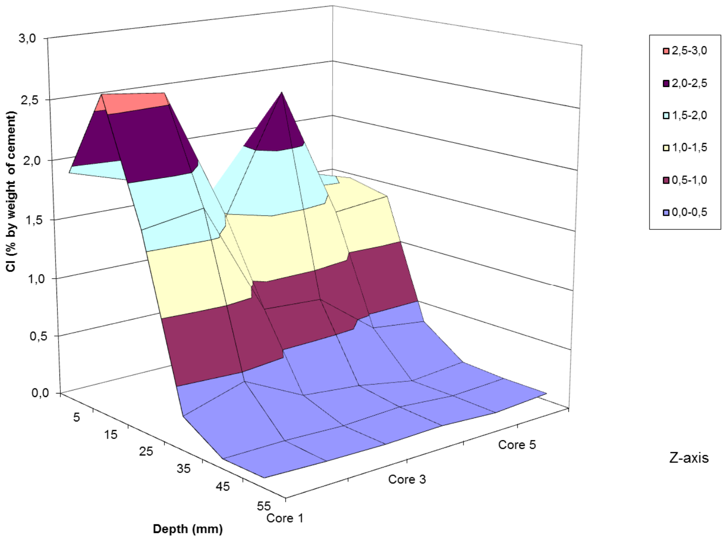

Figure 9
Chloride profiles along a 1.2 m long line which is indicated by the Z-axis, after [2].

Measurements of chlorides in concrete - sampling techniques

Very few references have been found to literature where chloride sampling methods have been evaluated.

Farstad et al. [23] performed a study of two different ways to perform sampling on concrete for chloride analysis. The methods used were core drilling by a 98 mm water cooled core sampler and dry drilling for sampling dust with a hand held drilling machine.

Concrete with known content of chloride was used in the tests. The chloride content in the analyzed concrete samples was 0.0%, 1.0% and 3.0% by weight of concrete respectively. In order to get a more accurate result from the dry drilling sampling, the dust was collected as mixed samples from five boreholes placed near each other representing one sample. The mean values from these five boreholes were used for comparison with the chloride profiles from grinding the collected cores nearby.

The analysis showed that the determined chloride content from the collected cores agrees with the known chloride content in the concrete. Even the correlation between the different cores is good. The measured chloride content in the dust samples gives a lower accuracy than the cores. It is concluded in the report that when sampling dust it is necessary to use a drill diameter that exceeds the maximum aggregate size in the concrete in order to get accurate chloride content results.

Other recommendations on how to collect samples of concrete for chloride analysis are given by RILEM Technical Committee, TC-178 in [24]. Also in this report, the recommendation is to refer the chloride content to the concrete mass.

Case studies on marine concrete

Case study 1 - The port of Trelleborg (Paper I)

In the late summer of 2005 an opportunity of executing a field case study on harbor concrete structures in the Port of Trelleborg, a harbour in southern Sweden, was given. Before the field work started, an archive study on drawings of the existing concrete structures was performed together with a study of climatic data for the region. About 30 years of data on wind speed and wind direction together with air and water temperature was analyzed in order to be able to see if these parameters had influenced the chloride ingress into the existing concrete super structures. The climatic data was collected by the Swedish Meteorological and Hydrological institute at the weather station in Falsterbo, about 20 kilometres west of the port of Trelleborg. The results from this study are presented in paper I.

The climatic study showed that the mean wind direction coincides with the opening of the port entrance, which could affect the structures that lies in this direction inside the docks. The study of the variations of the temperature, which was measured three times per day, also showed that there is little risk for frost in Trelleborg harbour in the winter.

The pier that was chosen for detailed inspection is a pile sheet wall with a head beam of reinforced concrete, see Figure 10. It was built around 1955, which means that it had reached its design service life at the time of inspection. No obvious signs of extreme deterioration were, however, found at the initial visual inspection. The pier, which is about 200 m long, is located in the circle in Figure 10. The top beam of the pier is made of reinforced concrete (Figure 11) and is exposed to the local climate in three directions, west, south and east.

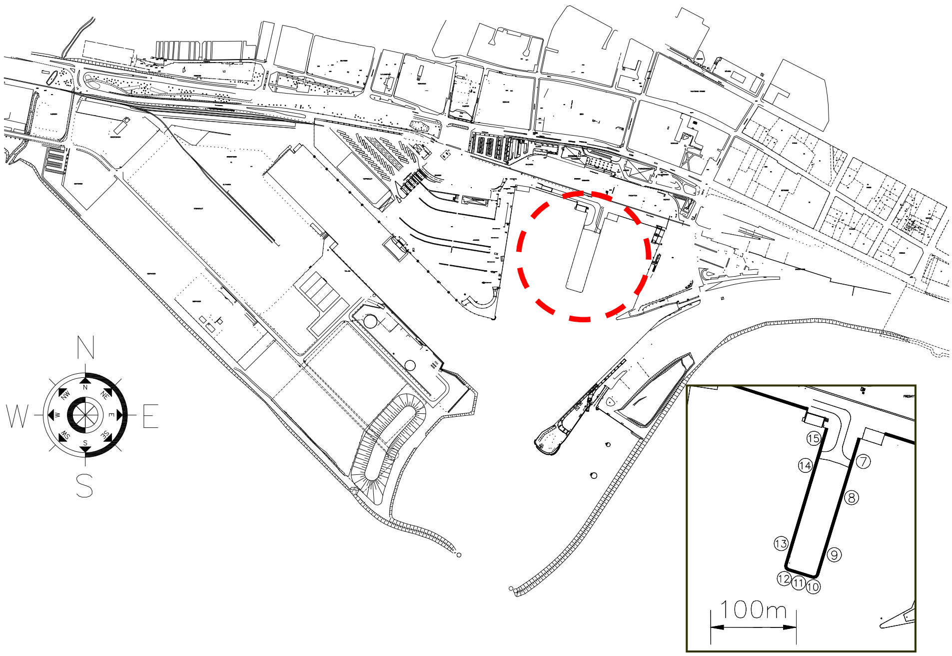

Figure 10
Plan over the Port of Trelleborg showing the inspected pier. The small figure on the right shows the location of the sampling points.

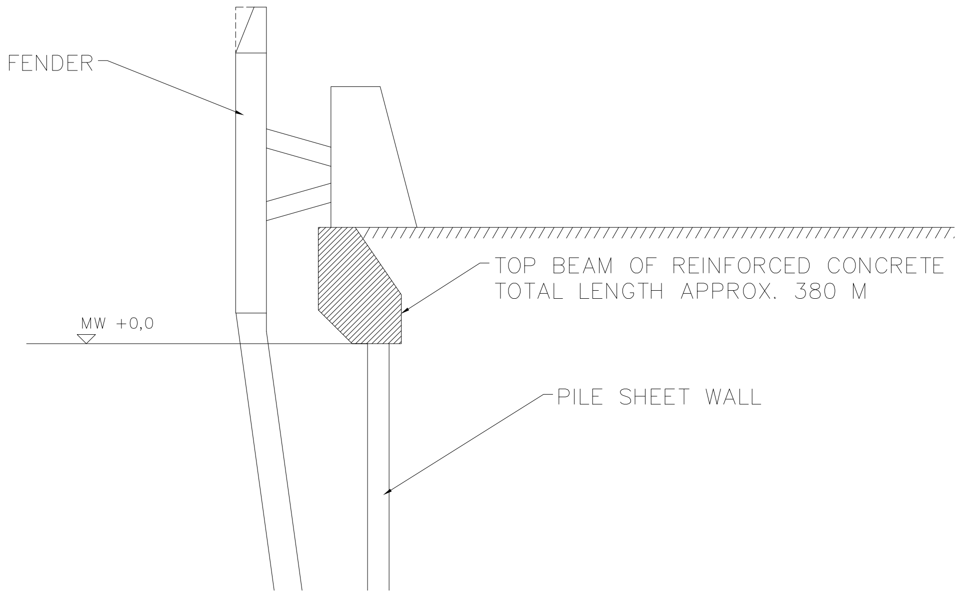

Figure 11
Section through the inspected top beam.

The detailed investigation of the head beam was performed by dry drilling and sampling dust along the head beam of the pier. The samples were all taken on the same level on the head beam of the quay about 1 m over mean sea level, and the diameter of the drill was 20 mm. Nine sampling holes were drilled on each side in groups of 3, that is 27 holes in total, down to a depth of 100 mm. The boreholes were placed in areas without cracks or other anomalies, and were organized in such a way that in every sampling point three holes were drilled in order to be able to see differences between the results when the dust had been analyzed. The distance between the boreholes in each sampling area, was less than 200 mm. The sampling depth interval was set to 10 mm between the depth of 0 and 40 mm and to 20 mm between 40 mm and 100 mm depth. Between every interval, the holes where cleaned with a small brush and by a hand held air blower.

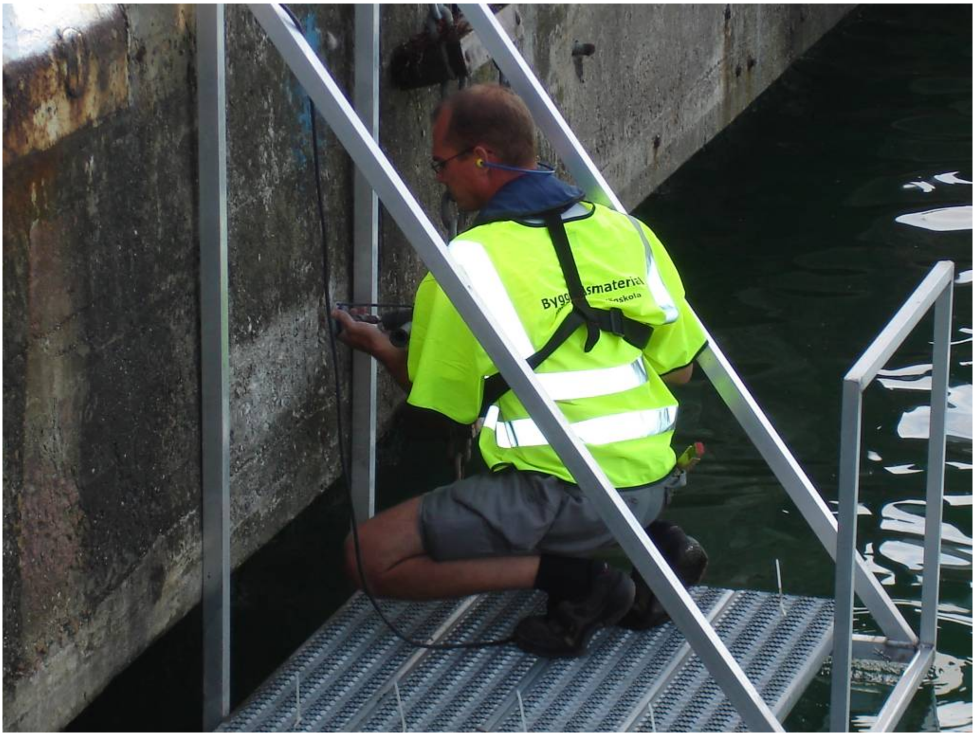

Figure 12
Dry drilling with a hand held drilling machine.

From the analysis of the collected dust it is seen that the end of the pier (south face)is the most exposed one with respect to chlorides. At 15 mm below the concrete surface the chloride content varied between 0.7 and 4.2 % by weight of cement. The chloride content in the east and west side of the head beam was about 0.5 % by weight of cement as an average value, see Figure 13.

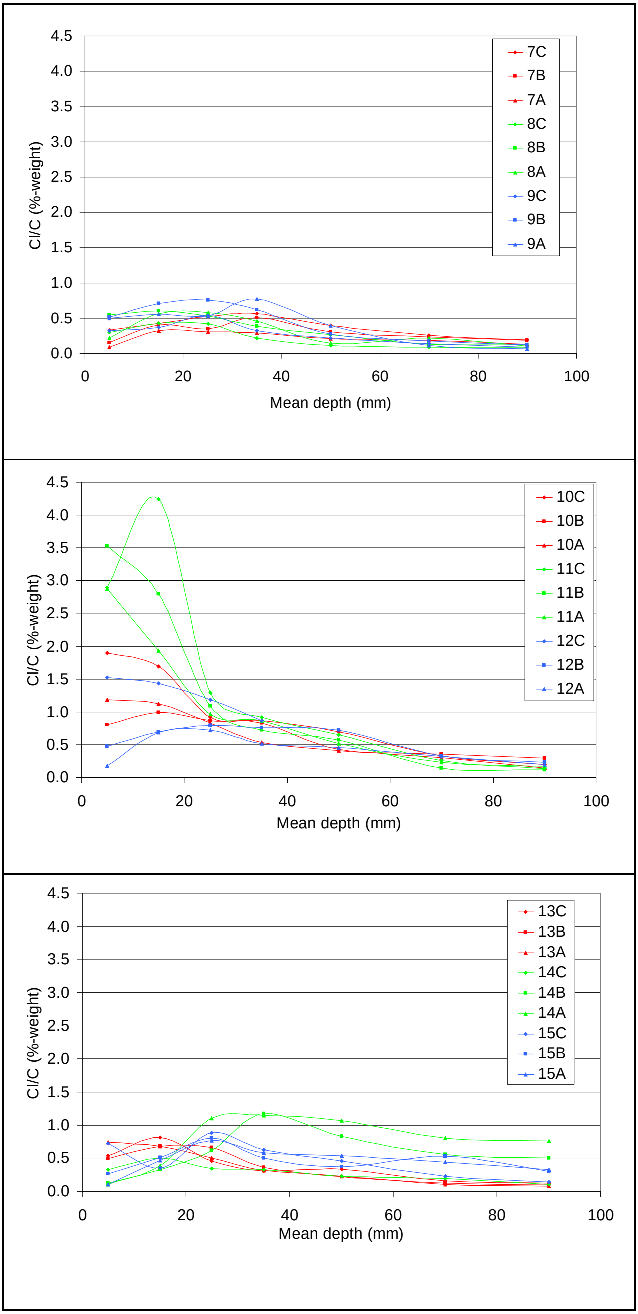

Figure 13
Chloride profiles from the east, south and the west side respectively

No obvious reason for the variations in the results in the samples collected from the south end of the pier was found. A possible explanation to the high chloride levels at the end of the pier is that it has been exposed to cyclic wetting and drying caused by the waves coming in from the Baltic Sea since the direction of the pier coincides with the main wind direction in the harbour. The east and west side of the pier are more sheltered from the wind and from the open sea and the moisture content in the concrete is probably more constant here. The highest surface chloride values in single sampling points were in those sampling points that were taken near the location of the bow thrusters of the vessels frequenting the harbour at the ferry berths as seen in Figure 14.

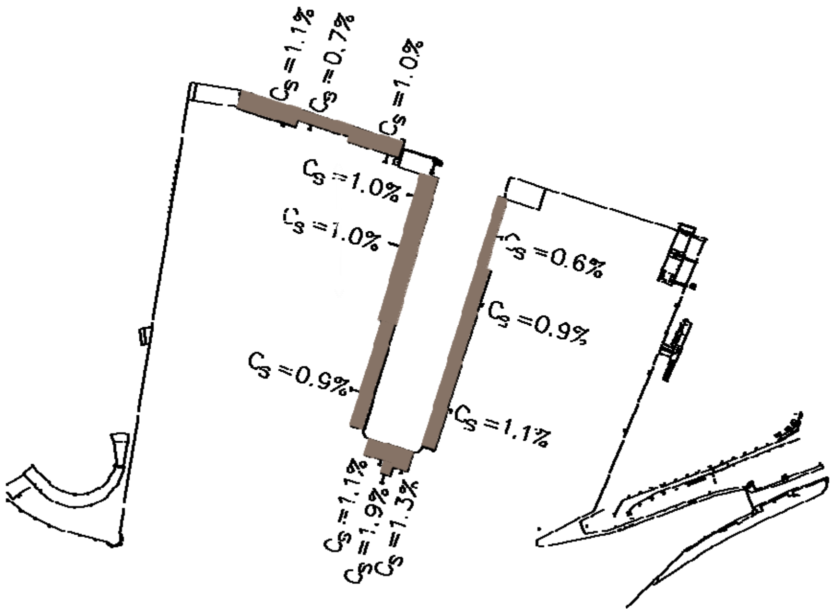

Figure 14
Surface chloride contents determined by curve fitting, around the pier and on the quay besides the pier.

Case study 2 - The port of Malmö

In the autumn of 2005 an inspection of an oil pier in the port of Malmö in southern Sweden was performed with the purpose of determining the remaining service life of the structure. The pier was built in the late fifties and the design life was reached at the time of inspection. The pier is exposed to the open sea from the north. Figure 15 shows a photo and a plan over the investigated pier.

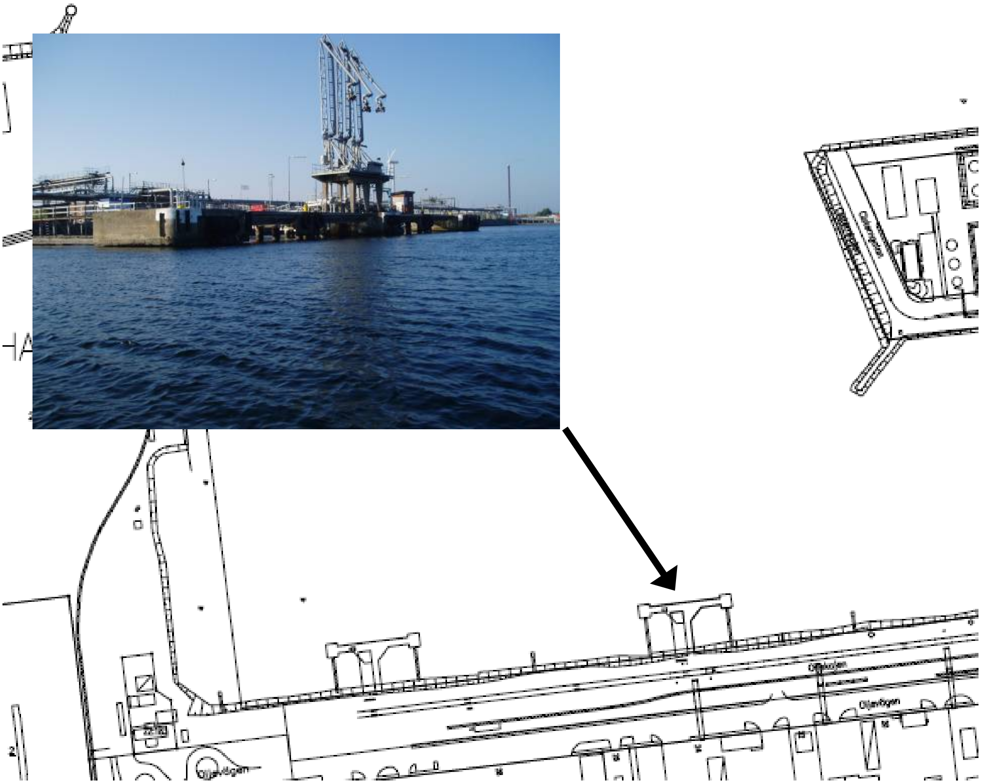

Figure 15
Pier 1004 in Malmö Oil Harbour, facing the open sea at north.

In total five sampling points on the structure were selected for dust sampling by dry drilling, see Figure 16. Sampling points 1 to 3 were located at the vertical surface of the west caisson about 2 m above mean sea level. Sampling point 4 was located on the west side on a column on top of the deck about 5 m above mean sea level and point 5 was located on the bottom side of the quay deck between the caissons, about 3 m above mean sea level.

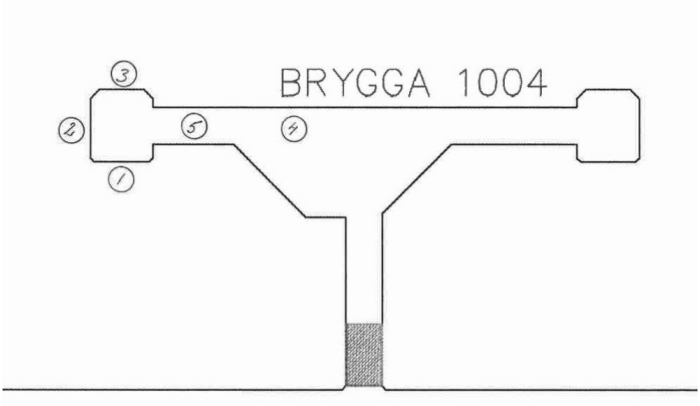

Figure 16
Schematic plan of the oil pier showing the location of the sampling points selected for inspection. Point 3 is facing the open sea from the north.

The dust sampling was performed with a hand held drilling machine, see Figure 17, with a 20 mm drill and the dust sampling interval was set to 20 mm with a maximum depth of 100 mm below the concrete surface. Between every interval, the holes where cleaned with a small brush and a hand held air blower. Three boreholes were drilled in every sampling point which means 15 boreholes in total. The distance between the boreholes in every sampling point was less than 200 mm, and the location was selected in homogeneous concrete without any signs of cracks or other visual damages.

Figure 17
The equipment used when sampling dust by dry drilling in the ports of Malmö and Trelleborg.

As seen from the graphs in Figure 18, the variations in chloride content between the different sampling holes in each sampling point is in most cases quite small. The variations in sampling points 2 and 4 are almost negligible compared to points 1, 3 and 5. The chloride content in point 1 is quite constant throughout the investigated depth. The points 2 - 5 show chloride profiles with very different chloride levels and penetration depths.

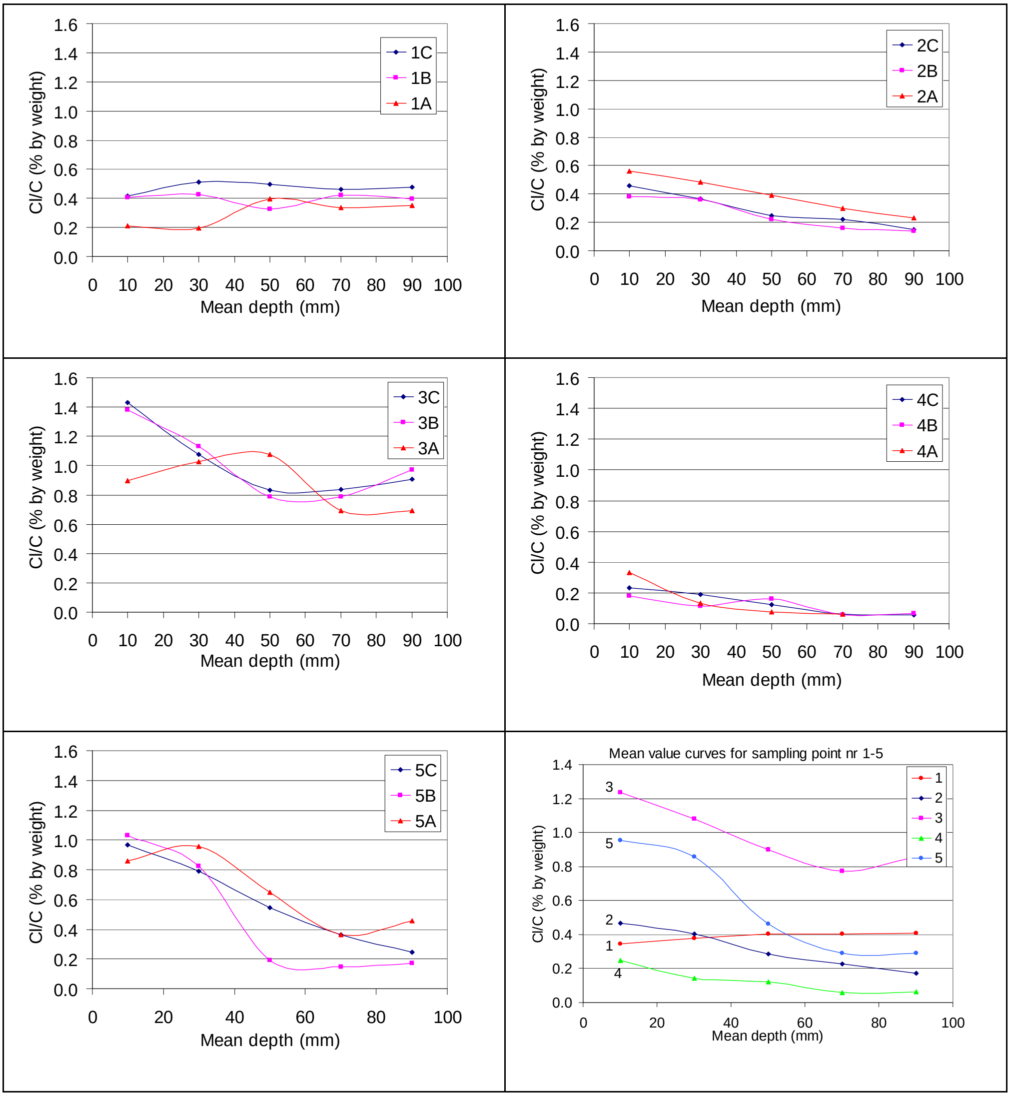

Figure 18
Chloride profiles for sampling points 1 to 5. The bottom right figure shows the mean values in chloride content for point 1 to 5. The y-labels Cl/C are the mass of total chloride per mass of cement.

As seen from Figure 18, the highest values of the chlorides in the concrete are in sampling points 3 and 5. The high chloride values in point 3 confirm the observations in the earlier case study in Trelleborg, that the exposure to open sea is the main factor to chloride ingress into marine concrete super-structures. The high values in point 5 on the underside of the quay deck are probably caused by splashing. This side of the structure is not exposed to cleaning by rainfall which also can explain the high chloride values at the surface. Looking at the results in points 1 and 2 it is seen that the chloride content in the concrete is quite low compared to point 3 and 5. The reason why the chloride content in point 1 is higher than in point 2 could be the lack of cleaning by rainfall, since this sampling point was located under a sheltering bridge connecting the pier with the shore. The chloride content in point 4 was extremely low with respect to the age of the structure. Since the location of the sampling point was located about 5 m above mean sea level, it is probably almost only airborne chlorides that have affected the column. This is also seen in Figure 19, which shows the values of the surface chloride content determined by curve fitting. It is obvious that the north surface facing the open sea has the highest surface chloride content followed by the underside of the quay deck.

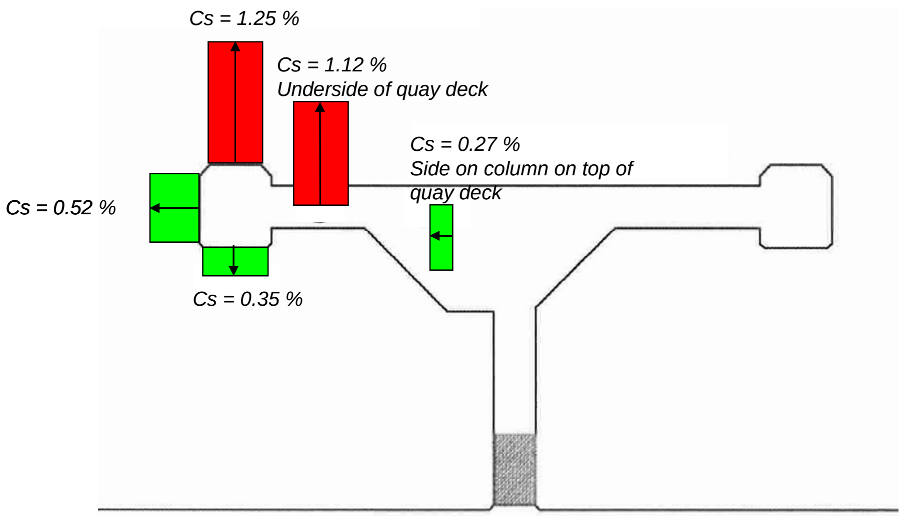

Figure 19
Surface chloride contents for the concrete in the investigated pier.(Percent chloride per mass cement)

Case studies on marine concrete – conclusions

The conclusions of the two case studies are that when inspecting a reinforced concrete structure exposed to the marine environment, surrounding factors that influence the structure should be taken into account. It is not enough to select for example the oldest structure in the port or harbor when performing an inspection, thinking that because of its age it has to be the most damaged one with respect to reinforcement corrosion. The present case studies have shown that the exposure of chlorides on the structures depends, not only on the dominating wind direction, but more on the exposure to the open sea.

In Trelleborg the dominating wind direction is from south to north. That coincides with the direction of the port entrance which can be one of the factors why the chloride content reached its highest level on the end of the inspected pier which direction is perpendicular to the wind direction in the harbour. The south end of the pier is exposed to wave actions from the open sea while the east and the west side of the pier coincide with the direction of the wave direction, and are therefore not that exposed.

In the case study in the port of Malmö, a structure facing the open sea at north was inspected. Since the distance between Malmö and Trelleborg is only about 30 km, it is reasonable to think that the dominating wind direction is the same in both cities. The highest chloride values in the inspected caisson in Malmö were on the north side of the caisson, while the lowest values on the same structure was found on its west and south side. A correlation between the exposure to the open sea at north and the chloride content is therefore probable.

The results from the dry drilling shows that the variations in chloride content between the different sampling holes in the sampling points decrease when presenting the chloride content in % by mass of cement instead of % by mass of sample. This was shown in both case studies. However, the sampling points on the end of the pier show extensive variations even though the chloride content is expressed as % by mass of cement without any clear reason.

Chloride sampling methods

Dry drilling and core sampling (Paper II)

With the purpose of trying to understand the reason for the extensive variations in chloride content in samples collected in field, a laboratory study was performed. The testing was performed on a concrete slab which had been submerged in a saline solution for about seven months and stored in a laboratory environment. The mix used for the concrete in the slab was composed so that it should be similar to the concrete compositions used in older harbour structures in Sweden.

The sampling of concrete specimens from the slab was performed both by core sampling and by dry drilling, sampling dust. In order to imitate sampling performed by industry, personnel from the Swedish Road Administration performed the dry drilling. To be able to investigate the influence of the drill diameter on the analyzed chloride content in the specimen, three different drill diameters was used, 8, 12 and 20 mm. The 100 mm cores were profile grinded. The dust sampling was performed in circles around the location of the sampled cores in order to be able to compare the results from both sampling methods, see Figure 20. Dust sampling was performed both when the slab was in a horizontal position and vertical standing up for the purpose of detecting the influence of sampling position on the achieved results. Theoretically the chloride profiles should be the same in all the samples.

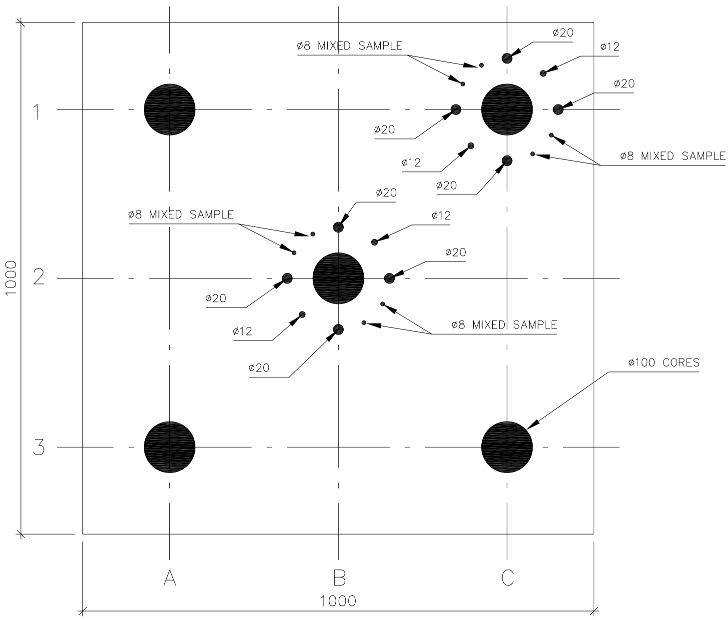

Figure 20
Sampling points for core sampling and dry drilling in laboratory.

The results from this investigation showed that coring is the best method for analyzing the chloride content in concrete, at least when such large core diameters as 100 mm are used. Coring gives much smaller variations in chloride content compared to dust sampling. The study also showed that when using small drill diameters, mixed samples should be used in order to minimize the variations in chloride content between different samples.

One observation from the dust sampling is that the mean value from the boreholes made with a 20 mm drill was higher than the mean value of the cores, see Figure 21. This could be the effect of a systematically depth error caused by wrong measurements when drilling in intervals, or even by poor cleaning of the borehole between the intervals resulting in transporting chlorides into the concrete giving a result on “the safe side”. No significant differences in the chloride content or cement content in the samples caused by sampling from a horizontal or a vertical surface respectively were found when performing the dust sampling.

As seen in Figure 21 the variations in chloride content are significant even when using as large drills as 20 mm when presenting the chloride content as % by mass of sample. The dashed line represents the mean value of the five cores analysed by profile grinding and is used as a reference curve.

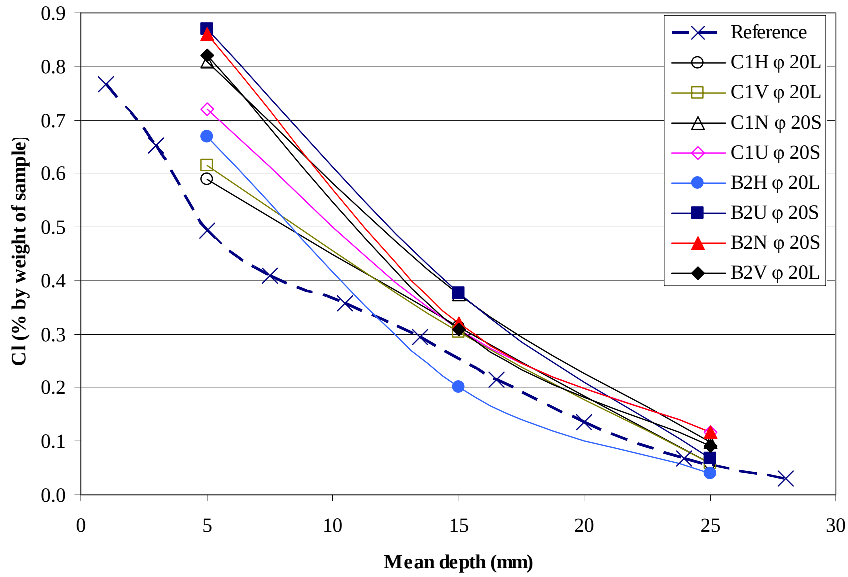

Figure 21
Results from dust sampling with 20 mm drill. Chloride presented as % by mass of sample. From paper II.

When sampling dust, the binder seems to become over-represented in the collected samples. This is seen in Figure 22 showing the binder content in the analysed samples. This could be due to lateral vibrations of the drill resulting in preferential loosening of the cement paste compared to the aggregates.

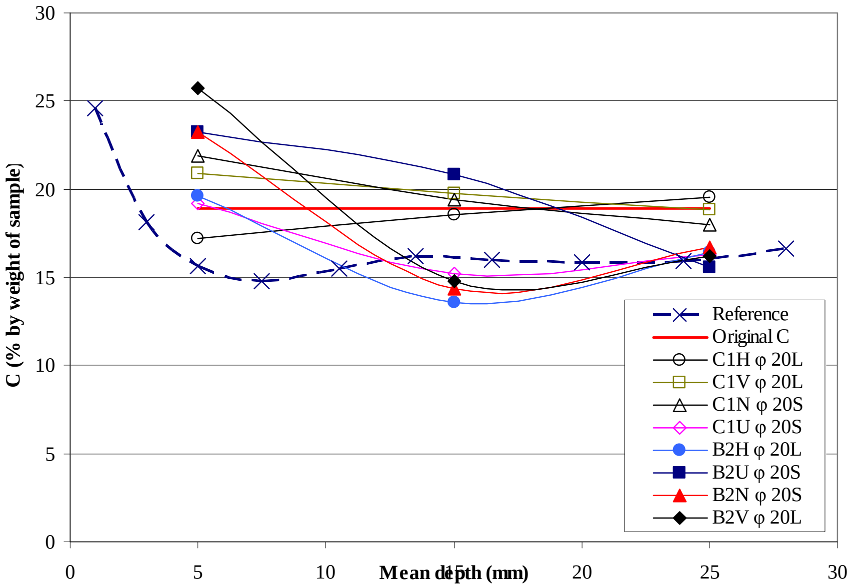

Figure 22
Cement content in samples collected with 20 mm drill. From paper II.

The fact that the binder is over-represented in the samples gives too high chloride values when analysing the dust, giving results on "the safe side". This also means that the sample is not representative for the concrete in the analysed structure.

The main conclusion of the study is that when analysing concrete in order to determine the chloride content, the calcium oxide should also be analysed at the same time. Presenting the chloride content as percent by mass of calcium oxide, or by mass of cement, gives much smaller variations between the different boreholes than when presenting the chloride content as percent by mass of sample. The complete results from this investigation are presented in paper II.

Simulated drilling using data from EPMA (Paper III)

A sample from the same slab as described in paper II was sent to a laboratory for EPMA analysis. The EPMA, or the Electron Probe Micro Analyser, uses a focused beam of high energy electrons to non-destructively ionize a solid specimen surface for inducing emission of X-rays characteristic for different elements. The typical size of a sample to be analysed by the EPMA is a slice with height×length×thickness = 50×75×10 mm^3. The analysis is two dimensional and the EPMA delivers values of the analysed element in pixels with the size of 0.1×0.1 mm^2, one value for every pixel on the sample. Five different elements could be analysed at the same time. The result from the EPMA is the concentration of the analysed element or elements as matrices with the dimension of 500 rows and 750 columns due to the size of the pixels. The elements analysed in this study were chloride, calcium, silica, potassium and sodium.

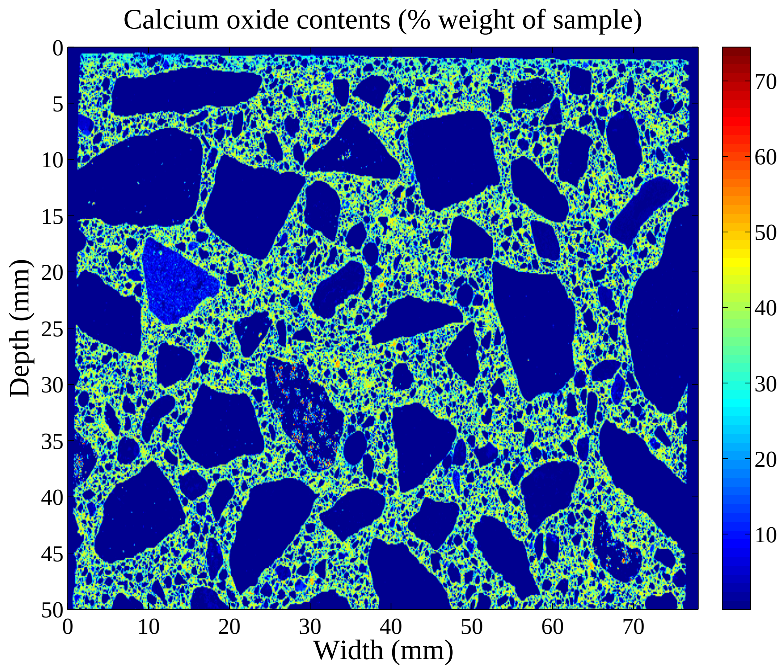

Figure 23
Calcium content in concrete specimen analysed with EPMA.

The results from the EPMA analysis have been used to simulate two dimensional drilling and dust sampling. In this study the "drill" is a strip in two dimensions, cf. Figure 24. To simulate different drill diameters, different strip widths have been used. To be able to compare the results from the dust sampling, the same strip widths have been chosen as the drill diameter in the laboratory test, namely 8, 12 and 20 mm.

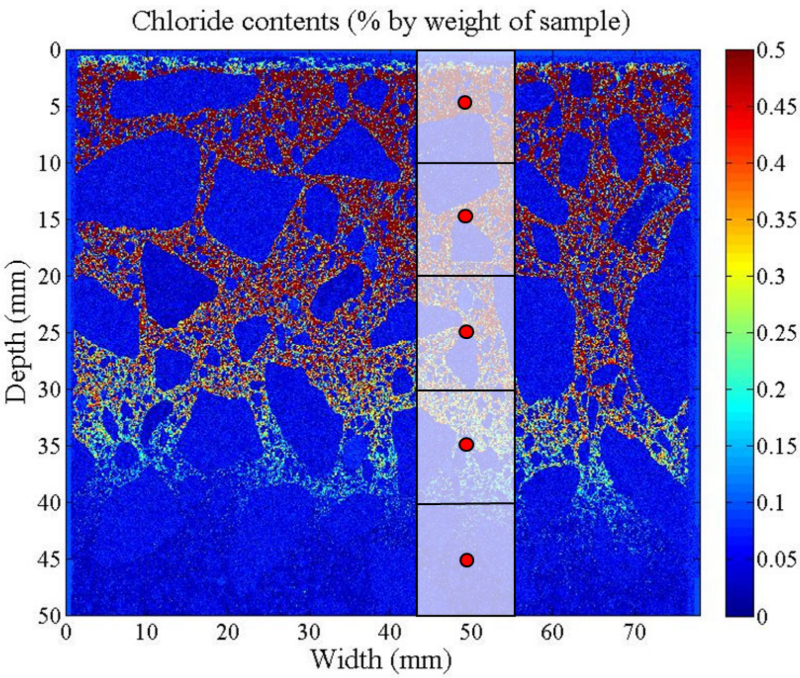

Figure 24
Chloride content in concrete specimen analysed with EPMA showing the simulated dry drilling intervals.

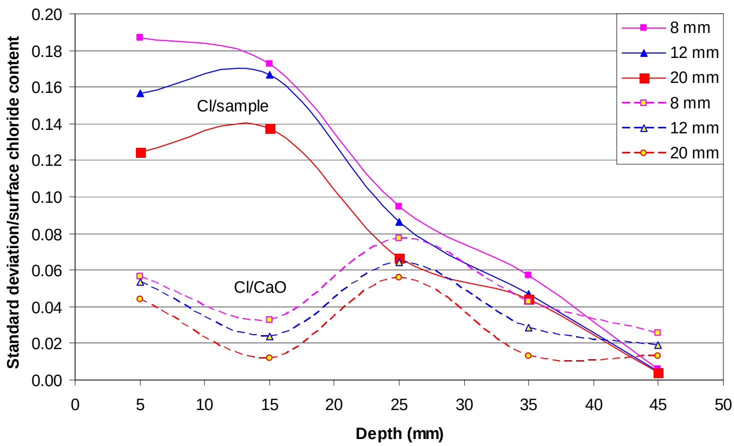

Figure 25
Standard deviation divided by surface chloride content: comparison between Cl/CaO and Cl/sample.

In Figure 25 the scatter in chloride content in the sampling results from the simulations are compared. The graph shows clearly that the variations in the estimated chloride content are very much higher when measuring the chloride content by mass of sample than when measuring by mass of binder.

Figures 26 and 27 show the chloride content in percent by mass of binder analysed by simulating data from EPMA and by dry drilling and core sampling in laboratory respectively. As seen from Figure 26 the chloride content in the simulated drillings is exactly the same as the chloride content in the simulated core. This is not the seen in Figure 27. It is rather obvious in these results that the binder content is over-represented in the samples collected by dry drilling and confirms the suspicion that the drill could loosen cement particles from the walls of the drill hole between the aggregates when drilling. This gives results that overestimate the chloride content in the analysed concrete, and which are not representative for the investigated structure.

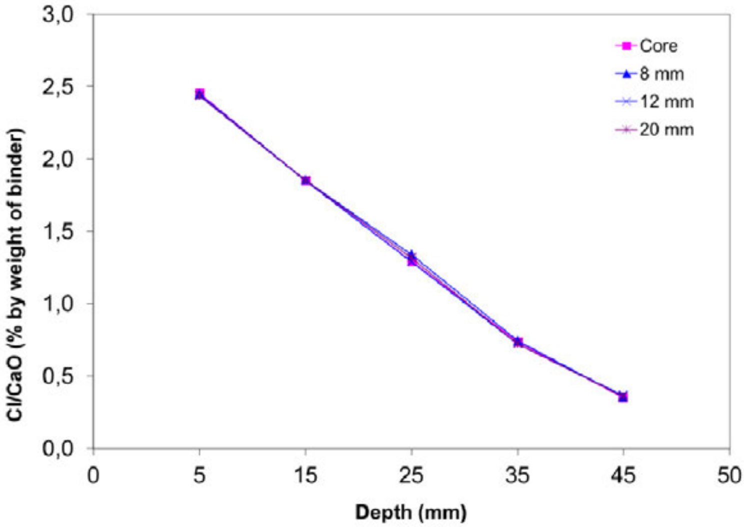

Figure 26
Chloride content in percent by mass of binder from simulations on data from EPMA.

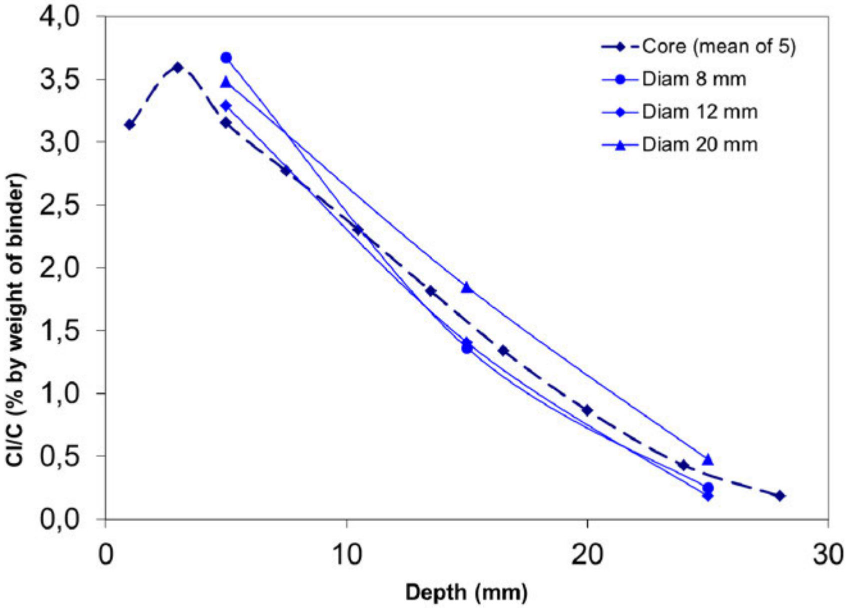

Figure 27
Chloride content in percent by mass of binder from dry drilling and core sampling in the laboratory.

The results from this study mostly confirm the results from the dry drilling tests. The variations in chloride content are significant when presenting the results as percent by mass of sample independent of strip width, but slightly smaller when using large widths. Presenting the chloride content as percent by mass of calcium oxide gives almost no variations at all in the simulations. An interesting observation is that the mean value for the chloride content in the whole sample coincides with the mean values from the simulation with the strips. This is of course what should be expected, but it also confirms the suspicions from the results from the dry drilling that the binder content is over-represented in the collected dust samples or that chloride is transported into the concrete when performing dry drilling, giving higher chloride values. The complete EPMA study is described in paper III.

Sampling methods – conclusions

The study showed clearly that the smallest variations between different samples where achieved by core sampling and profile grinding. The mean value curve from the core grinding has been used for comparison with the results from dust sampling. The dry drilling was performed both when the slab was in a horizontal direction and when it was in a vertical direction with the purpose of detecting if there was any difference on the results caused by the sampling position. No such differences could, however, be seen from the results of the analysed dust.

The dust samples show significant variations in chloride content even when as large drills as 20 mm are used. This is most obvious when presenting the chloride content as percent by mass of sample. If the chloride content is presented as percent by mass of cement or binder, the variations are decreased. In order to get enough dust for the analysis, mixed samples from two holes where used when the dry drilling with 8 mm drill was performed. When comparing the results from the 8 mm drill with the ones taken with the 12 mm drills, it is seen that the variations in the results from the 12 mm drill is larger. The conclusion of this is that mixed samples are to prefer and gives smaller variations, when using small drill diameters when dry drilling.

Another observation, especially in the results from dry drilling with 20 mm drill, is that the results are affected by a systematic error. The mean value of the dust sampling curves lies above the curve from core grinding, which means that either the measurement of depth interval is inaccurate or the chloride infected dust is transported into the borehole between the drill intervals giving higher chloride values than expected. Another possibility that gives the same results with too high values on the chloride content is that the binder is over-represented in the dust sample. If the drill finds its way besides or between the aggregates when dry drilling, the sample contains more binder than what is representative for the binder content in the investigated concrete structure, giving higher chloride values. This means that the results from dry drilling are not representative for the investigated structure. These errors are avoided when using data from EPMA. Simulating dry drilling using the data from the sample analysed with the EPMA, has shown almost the same results as when dry drilling in the field. It is clear that presenting the chloride as percent by mass of sample gives significant variations between the simulated boreholes, also when looking at the results from dry drilling.

Sampling chlorides in marine concrete – conclusions

Finding sampling methods for determining the chloride content in marine concrete structures that give small scatter in the results, is part of the solution to the problem of getting good input data for a service-life model for such structures. This study has taken one step further on how to decrease the extensive variations in chloride content when sampling on reinforced concrete exposed to marine environment.

It should be pointed out that when measuring the chloride content this should be expressed as percent by mass of cement or calcium oxide, giving much smaller scatter between different chloride profiles taken from the same structure compared to if the chloride content is presented as percent by mass of sample. This is particularly important when collecting dust by dry drilling, especially when using small drill diameters, since the influence of the aggregates on the achieved results seems to be the main reason to the extensive variations in chloride content.

The studies in this work have also shown that dry drilling gives too high chloride values, probably because of the over-representation of binder in the samples. This means that the sampling is not representative for the investigated concrete.

The case studies in this work also showed the importance of how to choose sampling points on an existing structure. If a surface on a concrete structure is exposed to open sea without any sheltering barriers in front, it seems that the chloride content on this side tends to be much higher than in the surfaces facing other sheltered directions on the same structure, irrespectively of the dominating wind direction. This should be considered when evaluating the results from an investigation of a structure. Even if one side of the structure shows values of chloride content exceeding the supposed threshold value for reinforcement corrosion, it does not mean that the remaining service-life is zero for the whole structure. In this case it could be enough to perform maintenance efforts only on the most deteriorated parts of the structure to a moderate cost compared to if the whole structure should be repaired.

Part II: Corrosion of steel sheet piles in a marine environment

Background

Corrosion of steel structures in the marine environment is a major problem. This is true for both ships and offshore steel structures as well as for land-based steel structures in contact with the sea, such as sheet pile structures and ferry ramps. As corrosion decreases the thickness of the steel structures, measures have to be taken to prevent the structures from malfunctioning during their intended service life. The two main methods for submerged structures such as sheet pile walls are oversizing and cathodic protection, while ships and shore steel structures are often coated with a protective layer of corrosion resistive paint [25]. However, irrespective of what method used, deterioration of this kind of structures is costly and difficult to predict both when designing new structures and when estimating the remaining service life time for existing structures.

The most common quay structure today is the steel sheet pile with a cap beam of reinforced concrete (the principles of design is described in reference [6] and below), Figure 28 which shows the building of a sheet pile quay during construction behind an older existing wall.

Figure 28
Sheet pile wall during construction. The cap beam of reinforced concrete is casted to a level about 1 meter below mean water level as corrosion protection for the steel. The old sheet pile wall is used as a protection from the open sea during the construction work.

In such harbor structures the steel and concrete work together as composite structures since the cap beam transfers the loads from the moored ships down to the sheet pile wall via bollards. Both the reinforced concrete and the sheet pile are exposed to deteriorating mechanisms: the reinforcement steel will start to corrode when chloride ions from the sea water have diffused through the concrete cover layer to the steel surface, and the sheet pile thickness is continuously reduced by corrosion. The deterioration of the reinforced concrete in harbor structures and methods for determining the chloride ingress into these have earlier been described by the author in [26, 27]. This paper describes a study of steel corrosion rate in sheet piles exposed to marine environment. Similar studies have been performed in other locations of the world. In 1997 [28] Alberts and Heeling presented results from German field measurements of sheet pile structures. The measurements where compared with laboratory test measurements and a statistical method for estimating the maximum value of corrosion was presented. The results from these measurements are partly implemented in the Eurocode for sheet piling [29]. Matsushima presents corrosion rates from measurements of average corrosion rates for steel in marine environment in different corrosion zones in [30] and the rates presented are in the same order as in the author's studies ([6] and [31]). In reference [32] Melcher and Jeffrey present results from exposure of steel in the marine tidal zone with a focus on Accelerated Low Water Corrosion (ALWC). Jeffrey and Melchers also present results from a field exposure of 1 m long vertical steel strips in Australian waters where the lowest immersed parts of the strips was 0.9 m below the water surface [33]. The authors concluded that the corrosion loss was much higher in the splash zone than in the at the water line and in the atmospheric zone. The corrosion in the immersion zone immediately below the waterline was also significant. In reference [34] results from the Swedish Corrosion Institute's deep sea station for long-time testing of steel are presented. The purpose of this study was to investigate pit corrosion on stainless steel alloys and carbon steel at different depths. The results from the study of carbon steel alloys, shows that the corrosion losses were relatively low (less than 80 μm/year) independent of immersion depth.

Although there are a large number of factors that influence steel corrosion in marine environments, in the most recent model [5] of such corrosion temperature is the main factor. According to Melchers [5], the annual mean temperature is in practice the only input needed when predicting corrosion rate as a function of time. One reason for this is that the oxygen concentration – which also is an important factor in corrosion – is a function of the temperature as most waters down to a few meters below the surface are saturated with oxygen. The effect of oxygen is thus included in the temperature. The effect on corrosion due to temperature is also discussed by Matsushima [30] who states that the corrosion rate approximately doubles for every 30 °C rise in temperature for a given oxygen concentration.

The highest corrosion losses often appears in the splash zone [6] and it is possible to prolong the service life of quays by upgrading the splash zone parts of old structures. The construction costs for casting a new cap beam on an existing sheet pile wall down to about one meter below mean water level to protect the steel from further corrosion and strengthening the structure are about one third of the construction costs for a completely new quay. Periodical inspections could thus prevent the necessity for replace the wharves instead of repairing them, with corresponding significant economic advantages.

A large share of the existing quay structures in use today are steel sheet pile constructions. Many of these quays have reached an age of 60-70 years and often suffer from severe corrosion, cf. figure 29. Due to the increasing volume of transported goods in the harbors, the loads on the quay decks also tend to increase and the actual loads on old quay decks sometimes exceed the design loads, which can lead to a collapse of these structures.

Figure 29
Sheet pile wall on the Swedish west coast suffering from severe corrosion.

With knowledge about the sheet pile dimensions and year of installation, it is possible to estimate the corrosion rate expressed in mm/year after measuring remaining thickness in the sheet piles. This information is valuable for the structural engineer who shall verify the bearing capacity of an existing sheet pile structure. This data is also valuable when designing new sheet pile structures, which, in Sweden, often have a prescribed design life time of 120 years. Having knowledge about the actual corrosion rate at a certain harbor site gives both economic and environmental gains when optimizing this kind of structures.

When investigating existing steel sheet structures, one usually measures the uniform corrosion rate over a certain area of the structure. This is, however, a simplification of the corrosion process on this kind of structures, since there is also often pit corrosion, which is concentrated to small areas. Pit corrosion can give very misleading results when measuring the steel thickness with ultrasonic gauges. The most severe corrosion in Swedish sheet pile structures normally appears in the splash zone where the steel can be entirely gone when almost no corrosion can be detected a couple of meters below mean water level. This complicates the estimation of the status of sheet pile structures.

Principles of design

When designing a new sheet pile quay there are several aspects to consider. The geotechnical conditions are for example important for the operation of the structure. Sometimes it is necessary to replace the natural soils behind the quay wall to better filling material. Other design criteria are the prescribed ground load on the quay deck behind the sheet pile and the prescribed service life of the quay.

A steel sheet pile structure can be designed in several ways. The most common quay structure in Sweden today is a back anchored steel sheet wall as shown in Figure 30. The wall is back anchored either in bedrock or in anchor plates behind the wall itself. The material used in the tie rods is steel and the anchor plates are usually precast concrete slabs or steel sheet piles.

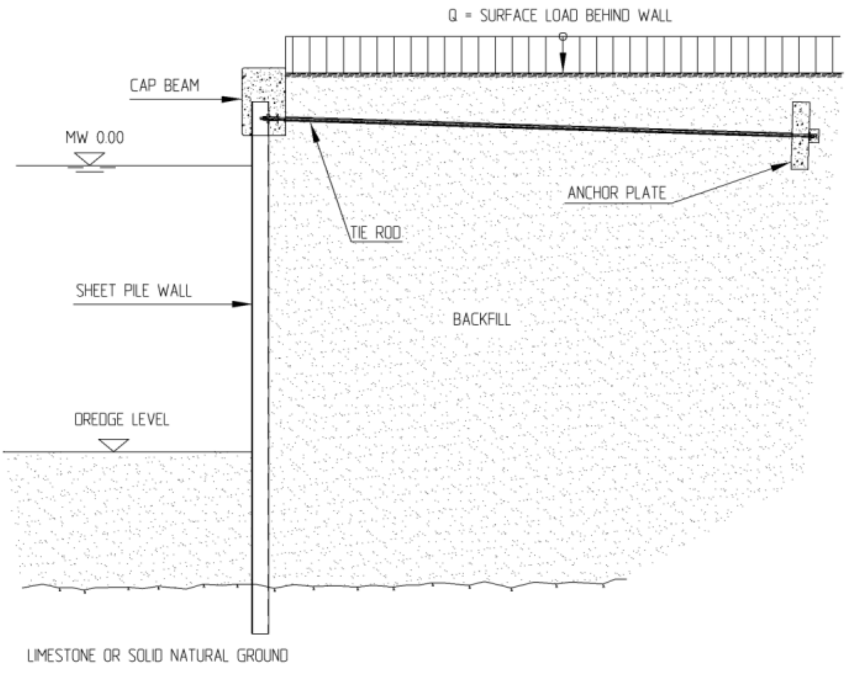

Figure 30
Standard back anchored steel sheet pile wall

The most commonly used pile sections in harbor constructions in Sweden are Z- and U-profiles (Figure 31). The sheet piles are delivered in steel grades with minimum yield strength between 240 and 460 MPa.

Figure 31
Z-profile and U-profile

The most sensitive section in a sheet pile wall is about one third of the excavation depth from the sea bottom where the highest bending moment occurs. The largest shear force is located at the level of the attachment of the rods (Figure 32). Because of this it is important to detect potential weaknesses in the flanges below the water surface *and* in the web at the location of the attachment of the tie rods. If the sheet pile wall supports the direct vertical load from for example a crane, the corrosion of the whole section is to be considered since this load case gives rise to additional compression tension over the whole sectional area.

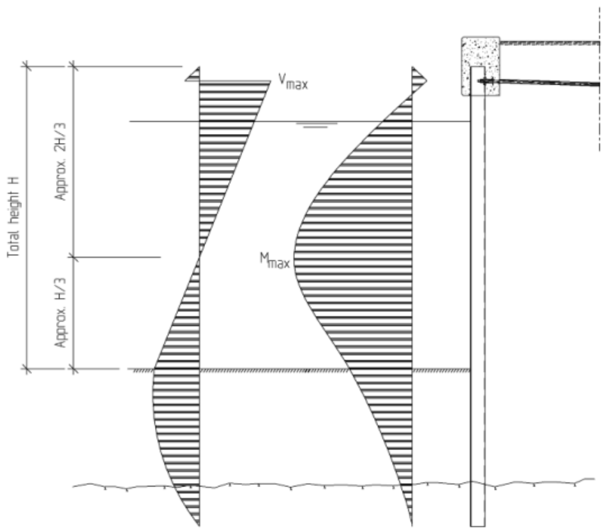

Figure 32
Principles for bending moment (M) and shear force (V) diagrams for a back anchored sheet pile wall

Measurement methods for determining remaining steel thickness

The most common method for determining the remaining thickness in steel sheet piles today is measurements with ultrasonic thickness gauges. This is a non-destructive method and there are a number of suppliers of such instruments on the market. Another method to determine the steel thickness is to cut out steel pieces from the quay wall and measure the thickness with a caliper. However, this destructive method demands expensive repairs after the sampling, and the uncertainty of the soundness of such repairs makes this an unusual method.

The measurements presented in this thesis have been performed with an ultrasonic thickness gauge (Cygnus Underwater, Cygnus Instruments Ltd., Dorchester, UK), Figure 33. The accuracy of the instrument is ±0.1 mm according to the manufacturer. The device uses a triple echo verification, which means that no thickness value is displayed unless the time for three consecutive bounces of the ultrasonic signal are equal.

Figure 33
Ultra-sonic probe by Cygnus Instruments Ltd., Dorchester, UK.

The ultrasonic gauge was tested in the laboratory under different conditions. The test was performed with the purpose of investigating the reliability of the measuring method. The following conditions were tested (Figure 34):

- Sheet pile with no filling
- Sheet pile with coarse filling behind (12-16 mm quartzite)
- Sheet pile with fine filling behind (0-8 mm natural sand)
- Sheet pile with coarse filling behind and water on both sides
- Sheet pile with fine filling behind and water on both sides

Figure 34
Arrangement for testing the ultrasonic gauge in the laboratory. Sheet pile with a fine backfill on the left and with a coarse backfill on the right.

The height of the tested sheet piles were approximately 1 m and the measurements were performed at three locations on both sets of sheet piles – on the outer web, on the flange and on the inner web. The profile tested was sheet pile AZ 18-10/10 with nominal web and flange thicknesses of 10 mm. The sheet piles were evenly corroded and had been used in a provisional retaining wall during a construction work. The remaining steel thickness was slightly less than 10 mm.

The vertical distance between the measurement points were 10 cm. Three values from each observation point where taken to test the precision of the measurements. In all, 90 measurements were performed in 30 points on each set of sheet pile. To test the accuracy of the instrument, measurements with a digital caliper was performed along the edges of the sheet piles along with ultrasonic measurements in the same measuring points. The difference between the results from the caliper and the ultrasonic gauge was in most cases not detectable (less than 0.01 mm). The standard deviation of the measurements in each point was between 0 mm and 0.08 mm. There were no significant deviations between the results depending on whether performing the measurements before the filling or after filling with gravel and/or water. The conclusion from this test is that the instruments shows accurate and precise values and that the method is reliable.

When using this instrument out in field measuring existing structures, the algae and corrosion products under the water line have to be removed from the surface to be measured. This is often done by hand with a scraper or with a flat-ended hammer. It is important that the instrument is held at a right angle to the steel surface.

Case studies on steel in marine environment

Case Study 3 - Inventory of ultra-sonic measurements (Paper IV)

With the purpose of investigating the steel corrosion rate along the eastern and western Swedish coast, an inventory of performed ultra-sonic measurements on existing sheet pile walls has been performed. The measurements presented in this chapter are from investigations performed by divers in Swedish harbors. The clients are either the port authorities themselves or consultants who are hired for the purpose of determining the status of a specific quay or structure. The data has been collected from steel sheet quays starting south of the city of Stockholm on the east coast down to the south coast of Sweden and up along the southern half of the east coast, see Figure 35. The age of the investigated wharfs varied between 17 and 51 years at the occasion of the measurements. The complete background and facts about the inventory and detailed results are presented in reference [31].

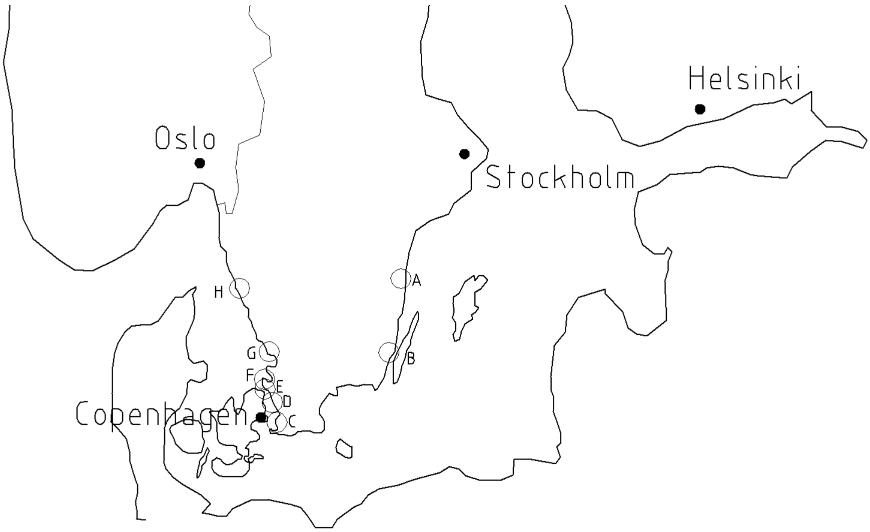

Figure 35
Location of the investigated harbors named A to H.

The reason for the selection of the harbors shown in Figure 35 is that the steel profile in the quays and the years of installation are known. Very often there is a lack of this information and the measurements of remaining goods thickness in the sheet piles could only be used as indicative values on what is left. Without knowledge about the age of the investigated sheet pile, no prognosis for remaining service life according to an estimated even corrosion rate can be done.

As expected, the highest corrosion loss appears in the mean water or splash zone. The salinity in the investigated harbors varies between approximately 0.65% to 2.5% with the lower values on the east and south coast and the higher on the west coast, Table 1.

Table 1
Measured corrosion rates along the Swedish coast. Quays with cathodic protection are marked “Anode”.

Location	Approx. salinity (%)	Corrosion rate at MWL (mm/year)	Corrosion rate at -3m (mm/year)
A	0.65	0.20-0.22	0.08-0.09
B	0.7	0.08-0.22	0.04-0.07
C	0.8	0.02-0.15	0.01-0.09
D	1.3	0.04-0.06 (Anode)	0.03-0.04 (Anode)
E	1.3	0.08-0.33 (Anode)	0.05-0.24 (Anode)
F	1.3	0.04-0.10	0.01-0.05
G	1.5	0.04-0.12	0.02-0.07
H	2.5	0.025-0.1 (Anode)	0.017-0.11 (Anode)

The results presented in Table 1 are mean values of the measured corrosion rates on each quay at the mean water level and at the depth of 3 m below mean water level respectively.

The salinity at the locations of the investigated sheet pile quays ranges from about 0.65% to approx. 2.5%. The results from the ultrasonic measurements do not show any correlation between salinity and corrosion rate.

Tests in the laboratory and field tests shows that small probes like the ultra-sonic probe used in the investigations, could give misleading thickness values of the steel due to pit corrosion. The studies in the laboratory also showed that there is a risk of getting wrong results if the ultrasonic gauge is held at an angle to the investigated surface.

Case Study 4 – Ultra-sonic measurements in a Swedish harbor (Paper V)

In late autumn 2011 steel sheet pile wharfs located in the port of Halmstad on the Swedish west coast were inspected by ultrasonic measurements. The investigations where performed by a Swedish diving company, Marcon Teknik AB, and the diving team consisted of three members.

Figure 36
Picture from the investigation during October and November 2011.

The age of the inspected sheet pile structures ranged from 36 to 51 years. The dimensions of the original sheet pile sections where known. One of the quay structures is located along a river. The salinity at all wharfs varied from low values at the surface to approx. 2% at the bottom (also in the river outflow).

The purpose of the investigation was to determine whether there is a difference in corrosion loss depending on the local climate in a specific harbor. Since the harbor of Halmstad is situated at the outflow of the river Nissan, it is reasonable to think that the fresh water influences the corrosion losses in the harbor. The purpose was also to determine whether the values on recommended corrosion rates used in European and international codes are of the same order as the measured corrosion losses or not. Design values on corrosion rates in USA, Australia, Sweden and Europe are presented in Figure 37.

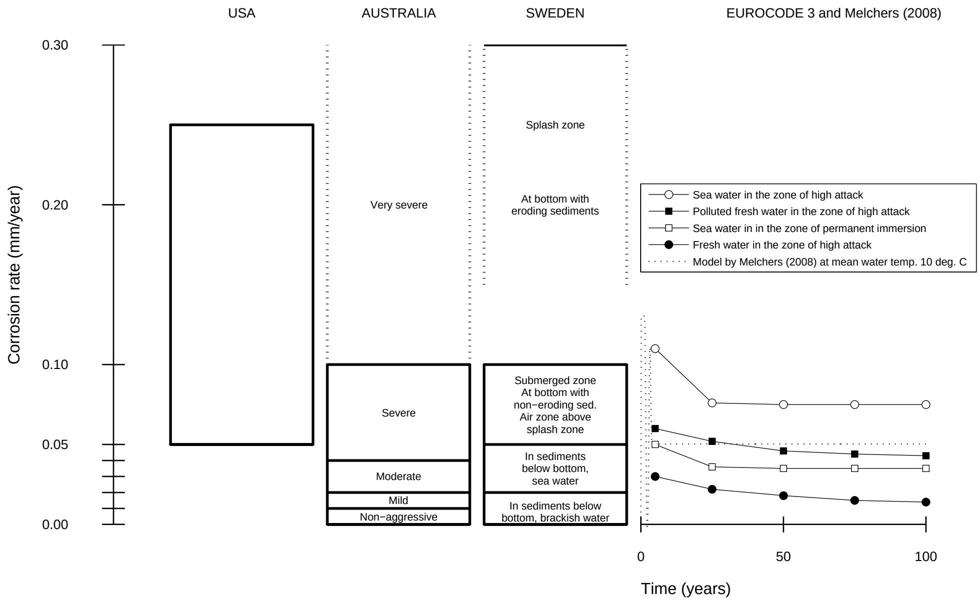

Figure 37
Recommended design corrosion rates for steel in marine environments in different parts of the world [5, 29, 35-37]

Three wharf structures with a total length of about 700 m were inspected, Figure 38. None of the inspected wharfs had or have had cathodic protection. The three inspected wharfs are here named A, B and C. Wharf A is located along the outflow of the river, while wharfs B and C are located in a basin east of the river with direct contact to the sea of Kattegat. Wharf B was built in three stages between 1960 and 1975.

The thickness measurements of the steel sheet pile structures were performed by divers. In total 15 sections were inspected, three along wharf A, nine along wharf B (three along each part of the wharf) and three along wharf C. Measurements on the sheet pile structures where performed at every even meter below the mean water surface down to the bottom. The depth along the inspected wharfs varied from approx. 9 m at wharf B and C down to approx. 6 m along wharf A. The inspection was performed during a three-day period in late autumn 2011. The visibility in the water was rather poor, sometimes less than one meter, due to turbidity caused by the ships operating in the harbor.

Parts of the sheet pile wall were cleaned by the diver before the measurements. Shells and algae were removed manually with a steel scraper. Three palm size areas (on the outer flange, on the web and on the inner flange) were cleaned every meter from the water surface down to the bottom.

With the purpose of testing the precision of the instrument used, three values in each palm sized area were measured in selected sections. These measurements showed very little scatter except in a few points that probably were influenced by pit corrosion.

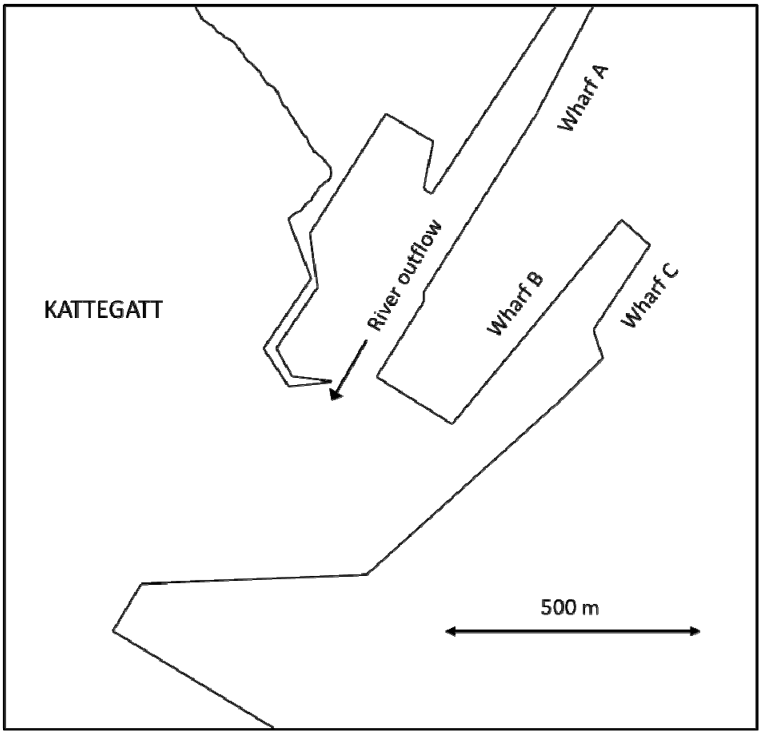

Figure 38
Location of the investigated wharfs A to C in the port of Halmstad.

The results of this investigation shows that the average measured corrosion rate is generally lower than the recommended values in the Swedish guidelines, but are similar to the values given in the Eurocode [29] and by Melchers [5].

With these rather low values of the average corrosion rate the tolerance of the initial steel thickness, usually ±6%, has a large influence on the determination of the remaining service life of a wharf. The tolerance on the steel thickness is never considered in the literature when discussing corrosion rates and service life of steel sheet pile structures. A simple model including the tolerances of the initial steel thickness shows that the age of the sheet piles should be almost 50 years before a good estimation of the corrosion rate can be made if the true original thickness is not known. The complete results from this investigation together with the model for how to treat tolerances of steel thickness are presented in paper V [6].

Case Study 5 – Field exposure of steel plates in a Swedish Harbor (Paper VI)

Mild steel plates have been exposed to the marine environment submerged at different depths for one year. The plates have been placed in three different locations in the port of Halmstad on the Swedish west coast. Once a month, the temperature, pH, dissolved oxygen content and salinity have been measured as a function of depth at different locations in the harbor. The purpose of this field exposure has been to study the corrosion of steel in a local climate with both salt water and brackish water. One of the exposure sites was in the river of Nissan (fresh water) and the two other exposure sites were located inside the harbor docks with contact to the open sea. The salinity in the open sea (Kattegatt) outside the harbor varies between approximately 2.0% and 3.0%.

In all, 25 steel plates with length×height×thickness = 150×150×5 mm^3, were mounted with a vertical distance of 1 m on polypropylene ropes fastened with high performance ties of weather and radiation resistant fluoropolymer (Figure 39). Before mounting, the plates where weighed in the laboratory.

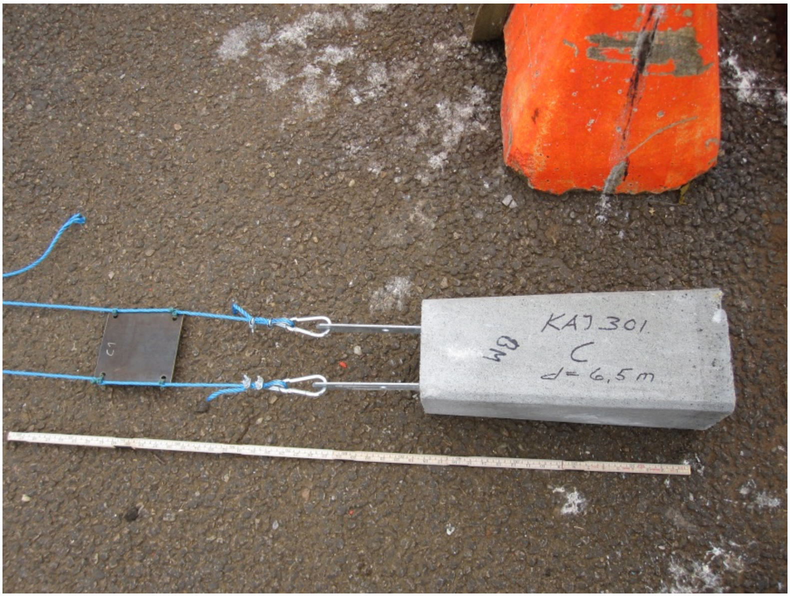

Figure 39
Steel plate mounted on nylon ropes with a concrete weight

Three sets of plates named A, B and C were exposed in the harbor of Halmstad. The exposure period was nearly one year (50 weeks) with start in the beginning of May 2012. Set A and B contained 8 steel plates each while set C contained 9 plates.

The location for the setups is shown in Figure 40 as circles. The depth on the exposure sites varied between approximately 7 and 8 meters. The lowest steel plate on each set is placed 1 meter above the sea bottom and each set of plates were weighed down by a concrete plinth to secure that the steel plates stayed on the intended levels during the whole exposure.

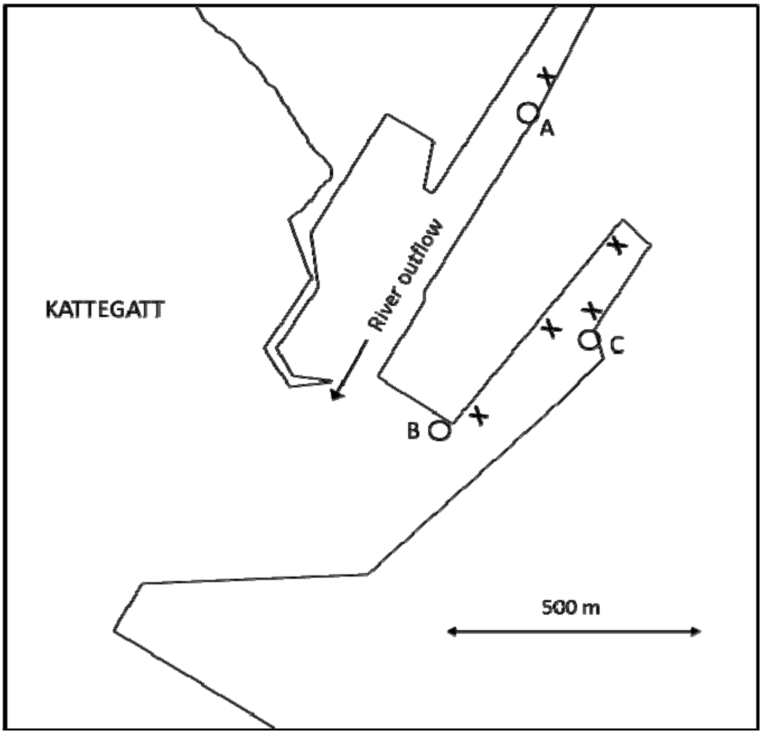

Figure 40
Location of the three experimental setups (O) and the water sampling sites (×) in the harbor of Halmstad.

The water sampling was performed once per month during the whole year of exposure at the sampling sites marked with an × in Figure 40 at the following levels: water surface, -1.0, .2.0, -3.0, -5.0, -7.0 and -9.0, were applicable.

After approximately 50 weeks of exposure the plates were taken up and transported to the laboratory. The algae and barnacles where gently scraped off with a soft plastic tool and the plates were cleaned with fresh water. After cleaning and drying, the plates where sent to a second laboratory for repeated pickling. During the pickling, the corrosion loss was registrated by weighing.

Figure 41
Steel plates before and after exposure.

Figure 42
Steel plate before and after cleaning.

The result from this study combined with the results from the measurements on existing sheet piles indicate that the corrosion loss is higher in the beginning of the exposure. The corrosion losses in this study over one year are almost three times higher than the corrosion losses evaluated from inspections of the 40-50 year old existing structures in the same harbor described in reference [6] and as the results presented in reference [31]. The salinity and pH does not seem to have any influence on the corrosion losses in a short-term perspective. The complete methods and results are described in reference [38]. All these conclusions agree with the recent model of steel corrosion in the marine environments by Melchers described in reference [5].

Corrosion of steel in the marine environment – conclusions

Corrosion of steel in marine environments is a complex mechanism to investigate and understand. The investigations of corroding steel in harbors presented in this thesis are mostly based on field studies and inventories of earlier performed thickness measurements in Swedish harbors. The aim of the field studies and inventories has been to increase the understanding of the corrosion problem on sheet pile structures in a practical way with data and observations from "the real life". The field studies on existing sheet pile structures and the exposure of steel plates has been performed in the port of Halmstad in which no cathodic protection is used. The detailed inspections, results and conclusions of this work are presented in papers V and VI. It is concluded that:

- The water stream from the propellers on the ships seems to erode the protective layers of the sheet pile walls, increasing the corrosion loss about 3 to 6 m below the mean water line at the most frequented wharfs.
- The recommended values on corrosion rates in the Swedish guidelines are higher than the corrosion rates measured in the field studies.
- The salinity and pH-value in the surrounding water does not seem to influence the corrosion losses in a short time perspective as one or a few years. This is also true for the measurements done on the existing sheet pile structures.
- The corrosion rate in a short time perspective, in this case about one year, is nearly three times as high as the corrosion rates measured on the existing sheet pile structures in the field study in Halmstad.
- The high uncertainty in the initial steel thickness could give misleading results for the remaining service life when not taken into account. A simple model, presented in paper V, shows that sheet piles should have reached an age of almost 50 years before a good estimation of the corrosion rate can be made if the uncertainty of the initial steel thickness is ±6%.
- Performing periodical inspections and using a statistical Bayesian update model for treating the data, more accurate predictions of the remaining service life of a given structure could be made.

Assessment of remaining service life based on regular investigations

The reason for performing these studies of deterioration processes in harbors, with a focus on methods for investigating steel and concrete structures, is that such methods are valuable when predicting the remaining service life of a harbor structure. Harbors are long-term investments, and for the owner of a harbor it is important to know the remaining service life of each part of the harbor, both to be able to plan for the repair or replacement of parts that do not fulfil the requirements, and to know the economic value of the harbor. Considering that the cost of building 1 m wharf is in the order of 150 000 SEK (18 000 EUR), the replacement of a 500 m wharf (like the one investigated in the Port of Trelleborg) costs 75 MSEK. If one has a good knowledge of the service lives of different parts of a harbor, one also has control of present and future costs of keeping the harbor in service.

The present study is about chloride ingress and sheet pile corrosion, two important degradation mechanisms in harbor structures. However, one cannot simply conclude that the service life time is reached only when the remaining steel thickness has decreased to a certain critical level or when the chlorides have reached the reinforcement. If the sheet piles are partly corroded through in the splash zone, this is not the same as that the remaining length of life is zero since the maximum bending moment occurs in the immersed zone at a height of about one third of the excavation depth above the sea bottom. The bending moment is in most case low in the splash zone for back anchored quay walls, but one must check the bearing capacity with focus on shear capacity in the remaining goods at the level of the tie rods, since the shear force maximum occurs in this point. The problem with corrosion holes in the splash zone is not generally a load bearing capacity problem. Here we have other problems to deal with, like loss of backfill from the quay area behind the sheet pile wall, causing settlements in the ground behind the wall.

The same arguments also yield for the reinforcement corrosion on quay structures caused by chlorides from sea water. A picture of the whole structure and its load bearing components has to be made in order to make an accurate statement on its remaining service life time and remaining bearing capacity at the time for inspection. As an example in some cases the cap beam on a sheet pile wall works only as corrosion protection for the steel in the wall without any structural bearing purpose. In this case reinforcement corrosion with loss of concrete cover and discolored concrete surfaces is only an aesthetical problem and not a structural bearing capacity problem.

Although the studies performed have shown that there are several complications that make both investigations and service life predictions difficult, we will here discuss a conceptual model for how service life questions of harbor structures can be handled. To do so, we simplify greatly by only looking at steel thickness reduction and chloride ingress in one part on a sheet pile structure. Note that this example illustrates the concept of updating service life predictions, but does not reflect the complexity of treating a whole harbor structure where a much larger number of factors have to be taken into account (see above).

Figure 43 shows diagrams of remaining steel thickness and chloride ingress. Both diagrams have the same components: the design values (thick lines), results from inspections (markers), and predicted development of the steel thickness and the chloride ingress. In this simplified example the service life comes to an end when the steel thickness reaches a minimum value t_0 or when the chlorides reach the steel reinforcements (rebars); both of which are designed for a service life of 100 years in the example. The two processes of interest here – sheet pile corrosion and chloride diffusion – have different kinetics. The sheet pile corrosion can for a harbor structure be taken to be proportional to time, while the ingress of chlorides follows a square root of time dependence.

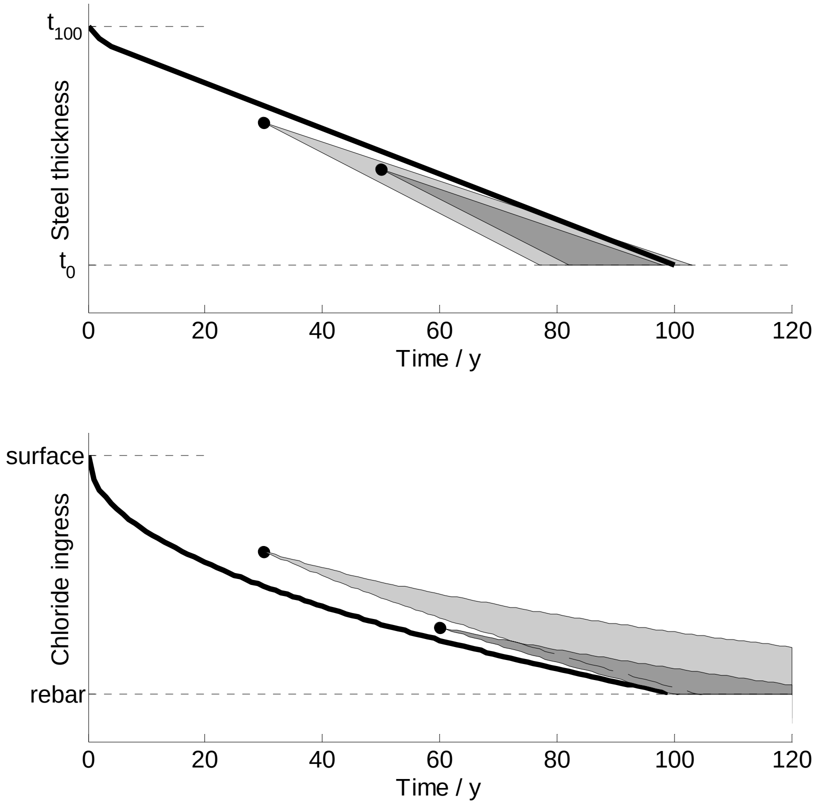

Figure 43
Example on how Bayesian updating can be used to predict remaining service life of a harbour structure. The thick lines are the design values, markers are results of inspections, and the filled areas represent prediction of remaining steel thickness and chloride ingress.

When a wharf structure is designed, this is done with the aim of reaching a required service life. In the example in Figure 43 the design service life is 100 years. This is done with the help of available codes, models, experiences and practices. For sheet pile corrosion, the Eurocode [29] could be used, or one can rely on a published non-codified model like the one of Melchers [5]. Additional input can come from previous experiences with steel piles in the harbour in question, or from national or local practices.

After a certain time – for example 25% of the design service life – a first investigation of the state of the structure is made. The results from this investigation can be used both to see whether the initial design was accurate or not, and to make a prediction of the remaining service life. In the example shown in Figure 43 measurements of steel thickness and chloride ingress after 25 years indicates that the design was non-conservative for the steel thickness (as the steel thickness has decreased more than expected), but conservative for the chloride ingress (that is slower than expected).

Let us look closer at the top diagram in Fig. 43 for sheet pile corrosion. Every determination of remaining steel thickness has an uncertainty and when we use the 25 year measurement to predict the remaining service life we end up with a rather large span of 52-78 years of remaining service life. This span (filled areas in Fig. 43) some from both the uncertainty in the results of the inspection and the uncertainty of the prediction model; note that to do this prediction we need to use a model of how the corrosion will progress. In the example in Figure 43 the corrosion rate (after the initial rapid corrosion) used when designing the structure was used to make the prediction of the future corrosion loss. When a second investigation is made, after 50 years in the example in Figure 43, the combined results from the first and the second investigations can be used to make an improved service life prediction, which is then based more on actual performance and not on the design values. This improves the predictions, both because we are closer in time to the end of the service life, and because we have more data on performance over time. In the example the remaining service life is predicted to be in the range 32-47 years, i.e., a smaller uncertainty range than after 25 years.

After having made several investigations at different times of the status of a structure, information on the result of the exposure to the local conditions can be incorporated into the predictions. For sheet pile corrosion, this can for example be the occurrence of passive currents from electrochemical potential differences between the steel and for example coal on the bottom of the harbor, or aggressive media in the back-filling.

The bottom diagram in Fig. 43 of chloride ingress here the second inspection is made at 60 years (ten years later than the steel thickness inspection) and the kinetics is different. However, the diagram has the same components as the top diagram.

The example given above is very simplified and there are a number of complications when doing the analysis on real complex structures:

- Each structure – like a sheet pile wall – has different parts that will deteriorate in different ways and by different processes. To make a sound judgment one needs to have an idea of what is most important. For example can the steel thickness one third of the excavation depth together with the integrity of the cap beam be the two most important factors for a sheet pile wall.
- Structures like wharfs not only degrade by deterministic and thus comparatively easily handled processes as chloride ingress and even steel corrosion, but also by processes that are more difficult to predict. For example can cap beams be damaged by ship collisions and steel often degrade by localized pit corrosion. Because of this one always has to do a reality check in parallel with making service life predictions with the more easily handled models.
- Each measurement is associated with an uncertainty. This has to be taken into account, possibly through the use of Bayesian updating, where different pieces of information, each with its own uncertainty, is combined to an overall conclusion with its associated uncertainty. For example should thorough (and more expensive) measurements of sheet thickness be associated with less uncertainty than a more superficial investigation. This is shown schematically in Fig. 43 as filled areas inside which the true value will be with a certain probability.

From the above it is clear that there is a value in regularly investigating the status of harbor structures. It is also clear that how investigations are made and which models used to interpret the results is important. This work has added to the body of knowledge concerning some of these factors.

Conclusions

Paper I

Deterioration of concrete structures in the marine environment is commonly due to corroding reinforcement caused by chloride ingress and frost. The chlorides could penetrate the concrete either by capillary suction or as airborne chlorides settling on the concrete surfaces and in a longer perspective penetrates the concrete reaching the reinforcement bars. Knowledge about the local climate such as dominating wind direction and wave actions is valuable when designing a sampling programme for a certain structure with the purpose of finding the most exposed parts of the structure. Choosing accurate sampling points for determining the chloride contents in the concrete gives more accurate and precise predictions of the remaining service life of the inspected structure.

Paper II

When performing dust samplings on existing concrete structures by dry drilling with the purpose of analysing the chloride content, the variations in the results often shows a wide scatter even though the sampling points are located in a small area. The results in chloride content are occasionally presented as % Cl by weight of concrete mass which also gives misleading values since the chlorides are bound to the cement paste and not to the aggregates. The results from the investigations presented in paper II shows clearly that core sampling and grinding gives the most reliable results regarding to chloride contents when presented in % by weight of cement contents. The study also shows that dry drilling with small drill diameters, here 8 mm, and mixed samples from several holes in a small area also gives acceptable results regarding to chloride content. Dry drilling with 20 mm drill diameter gives almost the same result as core drilling with 100 mm diameter.

Paper III

Using EPMA as a tool for analysing chloride content in a concrete specimen could be a very useful method if the costs of the analysis are reduced. The simulations of dry drilling and core sampling on the results from the EPMA analysis shows the same results as the results from the dry drilling and core sampling in the laboratory. It is also shown by this analyse method that if the chloride content is presented as % by weight of sample, the scatter in the results are not useful to use for life time predictions. Presenting the chloride content as % by weight of cement content gives a minimum of variations.

Paper IV

Data from performed ultrasonic measurement along the Swedish coast was collected and studied. Only data from sheet pile structures with known profiles where analysed. The salinity of the water in the investigated harbors varied between 0.65 % and approximately 2.5 %. No correlation between corrosion loss and salinity could be found from the results of the measurements.

Paper V

The remaining steel thickness in three existing sheet pile walls in the port of Halmstad was measured with an ultrasonic gauge. The age of the quays varied between 36 and 51 years at the occasion of the investigation. One of the investigated quays was situated in the outflow of a sweet water river. The measurements were performed on different depths from the mean water level down to the sea bottom. The aim of the investigation was to determine whether the recommended design values on corrosion losses in modern codes are reasonable or not. The results from the measurements shows that the corrosion losses are generally lower than the Swedish recommended design values but in the same order as in the Eurocode. Evaluating the remaining service life from corrosion loss measurements could give misleading results when not taken the tolerances of the initial steel thickness into account. A simple model with a tolerance of ± 6% shows that it takes almost 50 years before a good estimation of the corrosion rate can be made if the original goods thickness is not known.

Paper VI

With the purpose of studying the corrosion losses on steel in marine environment in the short time perspective, steel plates were exposed to marine environment at different depths in three locations in the harbor of Halmstad. The exposure lasted for almost one year and the corrosion losses of the plates were almost three times higher than the corrosion losses measured on the existing sheet piles wall in the same harbor. This indicates that the corrosion losses are highest in the beginning of the exposure of the steel. During the exposure pH, water temperature, dissolved oxygen content and water temperature was measured from the mean water level down to sea bottom once a month. No correlation between corrosion loss, salinity and pH could be detected in the short time perspective. The corrosion loss was highest at the mean water level and lowest between 1 and 2.5 m below the mean water level.

Future research

Chloride profiling in marine concrete

The next step in this research area should be to core sampling together with dry drilling on real marine concrete structures, with the purpose of improving the sampling methods and to study threshold values for chloride initiated corrosion at the same time. The studies in this work have shown that the exposure to open sea is of great importance regarding to environmental load on structures in marine environment. Consequently, the sampling should follow a detailed investigation of the climatic loads on the chosen marine structures.

Using sampling methods that decrease, or preferably eliminate, those extensive variations in chloride content which are often the fact when sampling on marine concrete, gives us a chance to get closer to the threshold value for reinforcement corrosion. The threshold value is dependent on several parameters, for example the moisture content in the concrete, the pH-value in the concrete close to the reinforcement and on the compaction of the concrete around the steel bars, just to mention a few, and it will be easier to find the dependency of these parameters if the variations in the analysed chloride content are small.

Corrosion of steel in the marine environment

In order to optimise new structures, both technically and economically, we need more accurate and precise design values on corrosion losses on steel in the marine environment than what is available today. Since the tolerances of the initial steel thickness in new sheet piles seems to be of large influence when interpreting the results from the ultrasonic measurements, the tolerances does also be taken into account when determining the remaining service life of the investigated structure. Therefore the initial steel thickness for each sheet pile should be measured and documented at the time of the installation. Since the length of each sheet pile is documented when installed the data on the steel thickness could be saved in the same data file.

For new sheet pile structures a detailed inspection programme containing periodical inspections should be established. The programme should contain data on the initial steel thickness for each numbered sheet pile. Certain inspection points for measuring the steel thickness should be chosen so that the periodical measurements are performed in the same points at every occasion. Using the data from the periodical inspections together with a statistical model containing Bayesian updating, more and more precise estimations of the remaining service life of the structure could be made. As a future research programme, a number of new sheet pile walls should be selected and investigated in a long time perspective. This is – of course – not possible in a PhD-project, but could be established as a long time research project at a university.

Steel coupons mounted at various depths in different harbors should be exposed for a longer time, say 5 to 10 years, to better understand the corrosion process in marine environment in the long time perspective. Several setups should be established at each location in order to be able to measure the corrosion losses annually. Each year one set of steel coupons is taken up at each location for analysis. The number of setups at each location should therefore be the same as the number of years the project is thought to proceed.

Another way of performing non-destructive repetitive measurements of the remaining steel thickness could be measurements by automatic or robotic by permanent corrosion sensors. Such sensors are not available at this time, but should be able to develop for practical use in field.

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