THE TREATMENT OF STEEL SHEET PILES WITH ANTI-CORROSIVE MEANS

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ABSTRACT

The problem of steel sheet pile corrosion is a very serious one. Research has revealed that the phenomenon of corrosion appears especially in the zone between the water mark and 1 - 1.2 m beneath the water level. Most often, this zone is constuctionally heavely applied - for non-anchored as well as for anchored sheet piles - so that the evolution of the corrosion in this zone is determining for the lifetime of the sheet piles and the construction above.
There are various existing procedures for the protection of the steel, such as application of coal tar coverings, addition of alloying elements to the steel, cathodic protection, overdesign by a surplus sheetthickness, all of them procedures which, however, do not offer an efficacious protection.
The protection method which offers a feasable solution and which is economically justified, is the one that consists of the application in situ of a protective coating.

INTRODUCTION

The use of steel sheet piles in waterworks for the construction of quaywalls, canal- and riverbank protection structures and similar, is a well known and widely used method.

The fact that the Belgian Government invested for years several billion Belgian franks in these structures makes it necessary that they last at least for the time period the were designed for and make the investment pay (1).
In practice most of these structures fail to meet the requirements, especially what stability is concerned, sometimes long before their expected lifetime. (2,3,4,5,6,7)
The main cause is undoubtedly corrosion, as might be seen from figure 1.

CORROSION DAMAGE

In 1987 CEBELCOR examined, in charge of General Coatings NV, an approximately 15 year old sheet pile section along the Ghent-Terneuzen Canal at Zelzate. (8)
This evaluation on the actual corrosion state of the sheet piles (see figure 2) shows three different corrosion patterns.

In the atmospheric zone corrosion is found in the form of rather thick non adherent black rust scales.
These rustscales are typical for corrosion found in very humidic conditions. The largest damage therefore is found in a zone approximately 20 cm above the water mark, better known as the splash zone.

1992, 10e Havencongres, Antw.

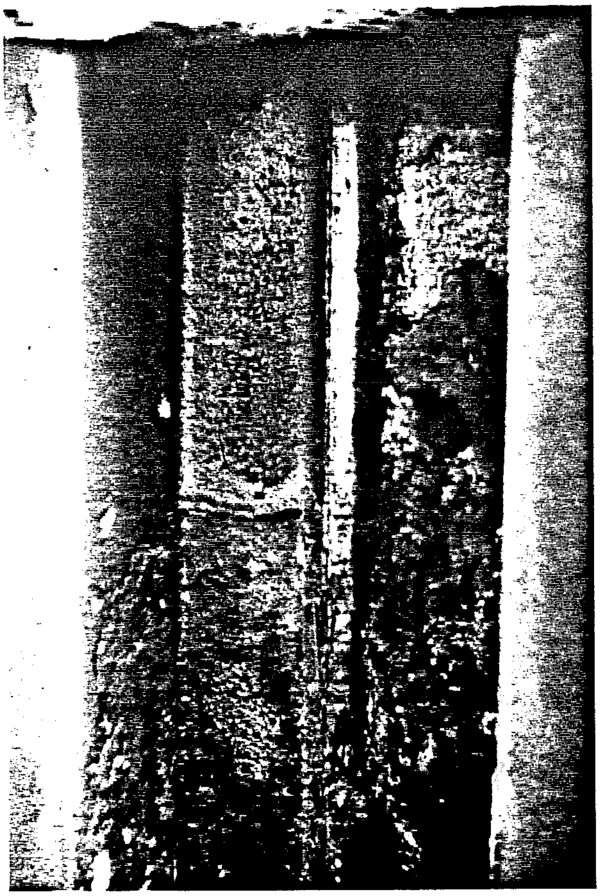

FIG. 1 : Corroded sheet piles at Zandvliet (Scheldt-Rhine Connection)

In the submerged zone from 0 - 0,8 m depth the sheet pile was found to be completely covered with a black film which itself was covered with a dark green biofilm. Under these deposits the metal was found to be active (grey metallic aspect).
The rust scales which came off the wall are quite larger than the one observed in the atmospheric and splash zone as shown in figure 3.

Once a huge rust scale of approximately 70 cm x 20 cm x 1 cm was found by General Coatings during work on another sheet pile section along the Ghent-Terneuzen Canal. A part of this rust scale is shown in figure 4.
Apart from rust scales several parts of the sheet pile wall showed a tubercular aspect. Closer examination reveals the presence of postules, as shown in figure 5, covered by a biological film.

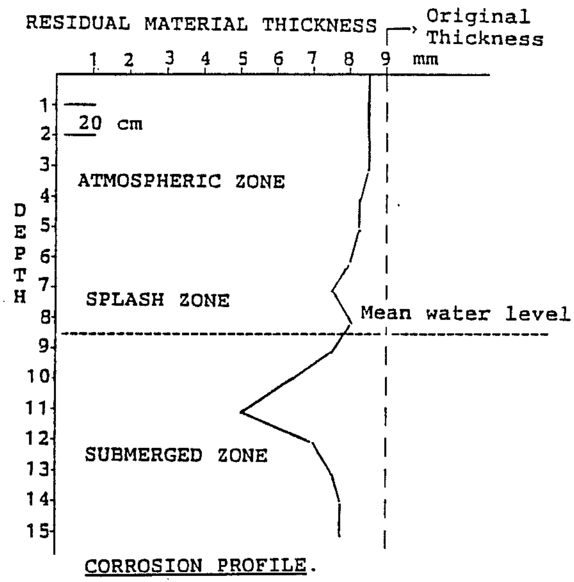

FIG. 2 : General view on the corroded sheet pile section.

FIG. 3 : Rustscales collected from the sheet pile wall.

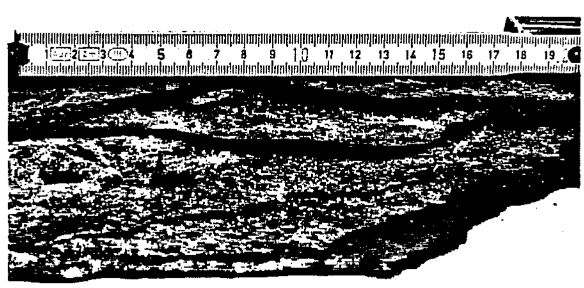

FIG. 4 : Part of a ± 70 x 20 x 1 cm rustscale. Notice the consecutive build up of non-adherent layers of corroded steel.

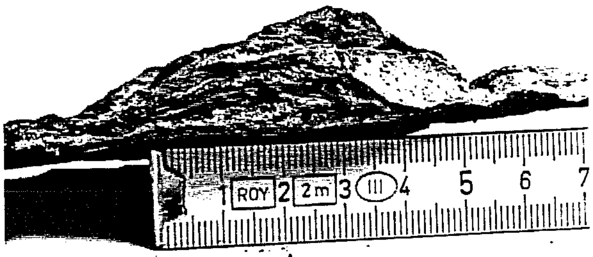

FIG. 5 : Example of a postule.

Sometimes these postules accumulate to large deposits (see figure 6), which leave after removing them from the sheet pile a deep heavily corroded steel surface.

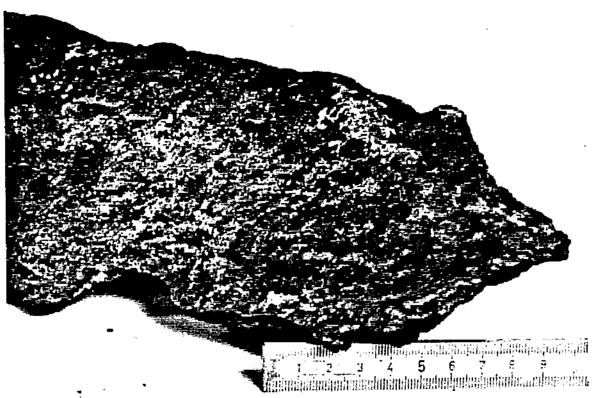

FIG. 6 : Accumulated postules.

This localised form of corrosion is the result of bacteriological corrosion as will be discussed separately below.
Qualitative chemical EDAX-analysis show the presence of iron, sulphur, phosphor and calcium.
The results of further chemical analysis on pH, chloride and sulphur content on the postule/metal and postule/canalwater interface are given in table 1.

In the submerged zone from 0,8 - 1,2 m the same black deposit and biofilm was found but the number of postules was largely reduced.

	INTERFACE SHEET PILE	INTERFACE CANAL
pH	5.5	6.7
Chloroides %	0.2	0.015
Sulfur %	0.46	0.14

TABLE 1 : Postule analysis at the metal/postule and postule/canalwater interface.

The corrosion was quite general and uniform.
The residual thickness of the sheet pile was measured on a clean metal surface after removing all corrosion products by sandblasting. Results are given in table 2.

	GENERAL CORROSION (average thickness in mm)	LOCALISED CORROSION (minimum thickness in mm)
Atmospheric zone		
> + 0.2 m	8.4	/
+0.2 - 0 m	7.4	7.0
Submerged zone		
0 - -0.8 m	7.8	2.1
-0.8 - -1.2 m	7.3	/

TABLE 2 : Residual thickness measurements in areas suffering from general and localised corrosion.

The corrosion rates calculated on this residual thickness measurements are given in table 3.

The severest corrosion attack occurs in the submerged zone. Figure 7 and 8 show the locations which are generally found to suffer from corrosion.

	Calculated general corrosion rate in µm/year (based on data from table 2).
Atmospheric zone	
> + 0.2 m	40
+0.2 - 0 m	110
Submerged zone	
0 - -0.8 m	80 (*)
-0.8 - -1.2 m	120
(*) Calculated rate for localised corrosion is > 450 µm/year	

TABLE 3 : Calculated corrosion rates based on table 2 - data.

Additonal proof for severe corrosion dammage in the submerged zone up to 1.2 m below the water mark was given by potential measurements with a Ag/AgCl-reference elektrode. The measurements were done by General Coatings research personel. The results are given in table 4.

Depth (m) vs the watermark	Potential (mV) vs Ag/AgCl-electrode
0	- 320
- 0.60	- 426
- 1.20	- 651
- 1.80	- 697
- 2.40	- 673
- 3.00	- 669

TABLE 4 : Potential measurments on a steel sheet pile at Zelzate along the Ghent-Terneuzen Canal.

Evaluation of these results were done according to the Bulletin CP 1023 of NACE (National Association of Corrosion Engineers - 1973). The evaluation criterion is given in table 5.

This evaluation was found to be completely in accordance with the results obtained by residual thickness measurements and visual inspection previously described.

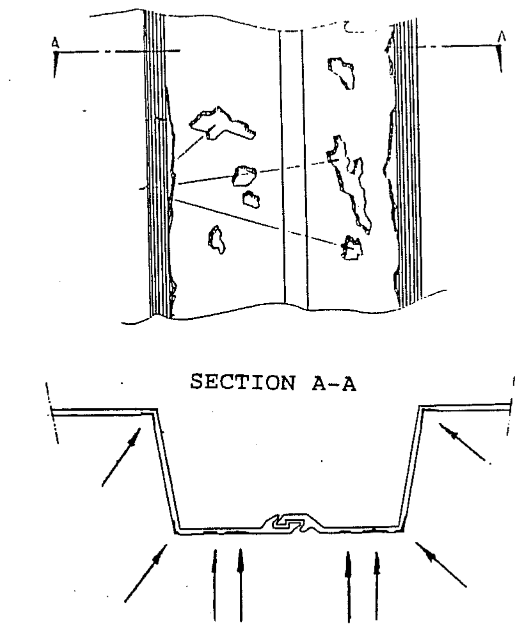

FIG. 7: Areas suffering from deep localised corrosion.

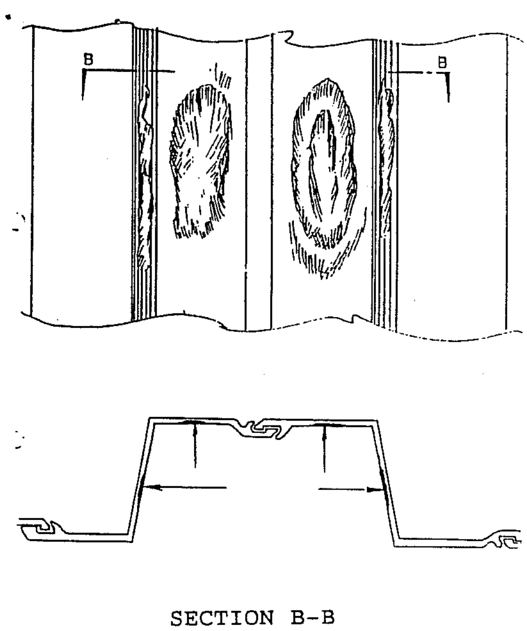

FIG. 8: Areas suffering from uniform general corrosion

Potential (mV) vs Ag/AgCl	Corrosion-state of the steel
- 450 to - 550	Concentrated
- 550 to - 650	General
- 650 to - 750	Little
- 750 to - 850	None
< - 850	Overprotected

TABLE 5 : Corrosion evaluation criterion for steel (NACE).

On sheet pile sections, other than the one examined, complete perforation of the sheet pile was found (see figure 9). In the worst case 16 perforations were found in a 4 m long section.

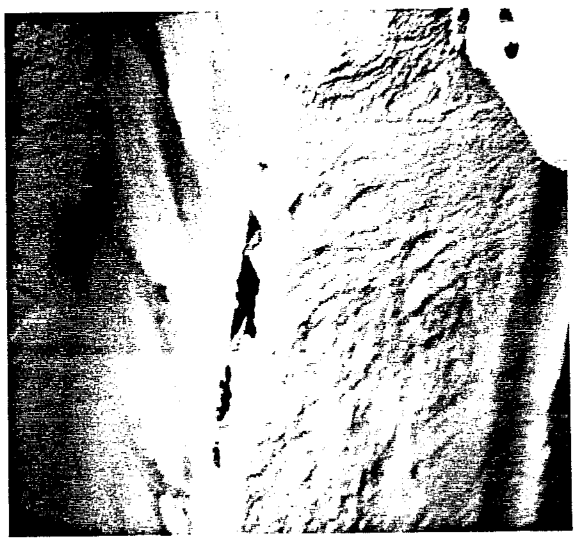

FIG. 9 : Perforated corner edge of the sheet pile.

The result of perforations is that water from the canal gets access behind the sheet pile - starting washing out the soil and finally leading to grade depressions. An example is given in figure 10.

This observed grade depression was at least 5 years old, meaning that the average corrosion rate leading to perforation can be estimated to be:

$$\frac{9 \text{ mm}}{(15 \text{ year} - 5 \text{ year})} = 0{,}9 \text{ mm/year}.$$

One can imagine that after perforation the neighbouring part of the sheet pile will also start to corrode from the rear side leading to an increased corrosion rate in that area.

FIG.10 : Depression of the side walk along the canal bank.

BACTERIOLOGICAL CORROSION

Most of the cases in which biological organisms are the sole cause, or an accelerating factor, corrosion involves localised forms of attack. A brief description will be given on this type of localised corrosion.(9)

Bacteriological corrosion does not only occur on metal surface but also in flaws of some coating systems. Bacteriological corrosion results in tuberculation, this is in the formation of postules on the attached surface. The process of tubercule formation is acting in conjunction with electrochemical corrosion and is a complex one.

A number of reactions that can take place are illustrated in figure 11.

The process starts with a deposit of slime-forming and iron-oxidizing bacteria at a point of low flow velocity. Deposition of these microbiological organisms occurs in the form of discrete colonies or at least spotty, rather than continuous films. A schematic representation of such a biofilm is given in figure 12.

The slimy biofilm isolates the metal underneath from oxygen creating a so-called oxygen concentration cell. This isolated metal starts to act as an anode promoting the dissolution of iron as Fe^{2+} under the deposit. As the Fe^{2+} ions move outward, they are oxydized to Fe^{3+}, this occurs electrochemically as they encounter

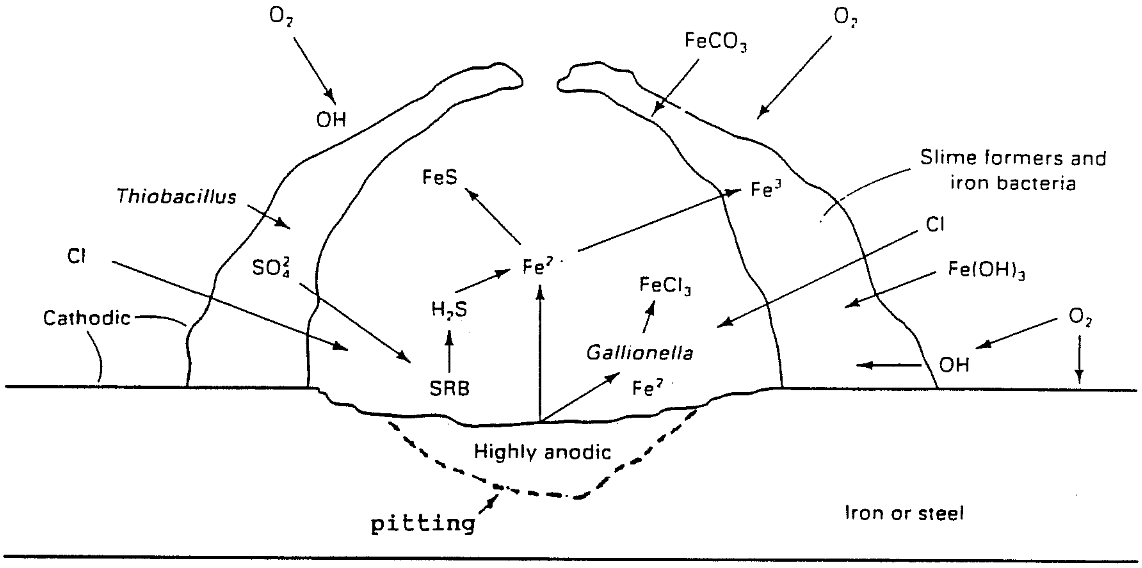

Fig. 11 : Schematic diagram of electrochemical and microbiological processes involved in tuberculation.

BULK WATER

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AEROBIC WATER PHASE

Growth of Sulfur-oxydizing bacteria

Sulfur-compounds -------------> SO_4^{2-}

BIOFILM - ANAEROBIC ZONE

Growth of iron-bacteria

Fe^{2+} ------------------------> Fe^{3+}

BIOFILM - ANAEROBIC ZONE

Growth of Sulfur-reducing bacteria

SO_4^{2-} ------------------------> S^{2-}

METAL

FIG. 12 : Schematic representation of the bacterial biofilm.

higher oxygen concentrations and/or by the action of iron bacteria. The resulting corrosion product $Fe(OH)_3$ mingles with the biodeposit to form the wall of the growing tubercule. The outside part of this wall becomes cathodic.
As the tubercule matures some of the biomass may start to decompose providing a source of sulfates for the sulfate-reducing bacteria (SRB) present in the interior anaerobic solution. If present, sulphur oxydizing bacteria may assist in the formation of sulfates as a nutrient for the SRB.
The SRB produce the acidic H_2S. This acidic environment promotes corrosion of the metal (production of FeS).
If a source of chlorides is present together with the iron-oxydizing bacteria Galionella a highly acidic ferric chloride ($FeCl_3$) solution may form inside the tubercule.
Production of FeS and eventually $FeCl_3$ will result in a higher sulphur and chloride concentration in the interior of the tubercule, which was also found in practice (see table 1).
As the individual tubercules grow on a surface they may eventually combine to form a mass leaving a severely pitted surface underneath.
Although the toxicity of cuprous ions is well known toward biological organisms, this does not mean that copper containing steels are immune to biological effects in corrosion [9]. It does mean however, that only those organisms having a high tolerance for copper are likely to have a substantial effect. The sulphur oxydizing bacteria Thiobacillus thio-oxidans for example can withstand copper concentrations as high as 2 %.
This means that corrosive action is possible on copper containing steel sheet pilings.

CORROSION PROTECTION METHODS USED ON STEEL SHEET PILES

Without going into detail on the differnt methods a summary will be given of possible corrosion protection methods together with their limitations.

PRELIMINARY COATING OF THE STEEL.

This is a frequently used method. The coatings used are bituminous products and coal tar epoxies.
Case studies and experience show that the bituminous products are only effective in the immersed zone. The poor UV-resistance of these coatings when exposed to the atmosphere leads to cracking. Volatilization of low molecular components of the coating results in shrinkage, later followed by cracking; a typical "aligator"-cracking pattern is observed. The metalsurface underneath is no longer shield off from corrosion (10).
Coal tar epoxies show a better performance compared to bituminous products but their brittleness might cause problems.
Another important disadvantage of preliminary coated sheet piles is that the transport and most of all the driving of the sheet piles itself cause a lot of unavoidable damage to the coating. The extra-work for this damage repair is very expensive and difficult to justify. ARBED, the manufacturer of the Belval-type sheet piles have stopped their preliminary coating activities.

ADDITION OF ALLOYING ELEMENTS TO THE STEEL.

Studies carried out on marine test sites showed that addition of alloying elements such as copper, nickel and chromium in higher concentrations provide enhanced corrosion resistance in the atmospheric zone (11,12).
The improved corrosion resistance of alloyed steel is attributed to the fact that these alloying elements promote formation of relatively insoluble corrosion products resulting in a highly adherent protective rust layer (13,14,15).
In the immersed zone no significant benificial effect is found at all (8,12).
When pitting corrosion is involved, one has found that the presence of chromium may result in a negative effect towards corrosion resistance.

From an economic viewpoint one has to take into account that the higher price for alloyed steel has to be paid for the entire length of the sheet pile.

CATHODIC PROTECTION.

Cathodic Protection (CP) is a well known method for corrosion protection of buried and immersed metal structures. In general CP is used in combination with organic coatings (bituminous or coal tar epoxy types), preventing corrosion at holidays in the protective coating (16).
For large structures such as steel sheet pilings CP is used with impressed-current systems rather than with sacrificial anodes since general investment costs are relatively lower (17).
On the other hand the impressed-current system requires more maintenance and the installation is more complex (17).
Compared to sacrificial-anode systems, where the voltage differences between anodes are limited to approximately 1V or even less, depending on the anode material, impressed-current systems can use larger voltage differences producing more efficient current distribution patterns along the protected cathode. A disadvantage however is that these larger voltage differences can lead to overprotection causing hydrogen embrittlement in high strength steels or debonding of the protective coating. Debonding occurs when moisture penetrates the coating and hydrogen is generated at the metal surface beneath the coating. The gas can accumulate until pressure causes blisters or cracks in the protective coating (17). Once thick coating damage occurs, the demands for protective current increase may exceed the capabilities of the system.
Studies have revealed that CP is only effective in the immersed zone.
The conclusion of a P.I.A.N.C.-report (18) dealing with this matter states : "*Cathodic protection is applied to protect the steel from the bottom in the mud to the mean tide level, and a coating is necessary to protect the very aggressive zone above the mean tide level. Cathodic protection is only partially effective in the tidal zone*".

OVERDESIGN OF THE SHEET PILE THICKNESS.

The supply of a surplus thickness to the steel does indeed result in an extension of the life span but can hardly be considered as a protective measure since it does not fundamentally alter the behaviour of the steel against corrosion.
Furthermore the approach is useless for existing steel sheet piling.
If considered for new sheet pile construction, it is not economically justified since the surplus thickness has to be paid for the entire length of the steel sheet.

THE HUMIDUR SYSTEM

The patented system developped by General Coatings consists of two major parts.

1. An installation providing a simple means for the dry-setting of the sheet pile wall.
2. A specially designed protective coating, easily applicable and allowing a fast displacement of the installing along the wall.

The installation called D.S.I. (Dry-Setting Installation) as shown in figure 13, is patented in most of the countries in the world.

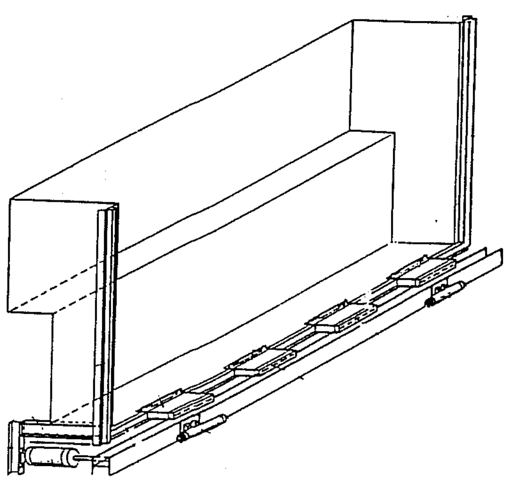

FIG. 13 : Schematic representation of the D.S.I.

This mechanical device allows to adjust itself automatically to the steel sheet wall rendering the wall dry after a few minutes.
The D.S.I. adapts itself to local differences of the sheet piles (such as the perpendicular position, centre, ...). Even in extreme situations watertightness is assured.
It is possible, depending on local access conditions, to use the D.S.I. from a pontoon or by means of a hydraulic crane.
The use of a pontoon is preferable since all auxiliary equipment can be centralised, increasing the mobility of the whole equipment.
Another great advantage of the D.S.I. is that it can be used in a very flexible way for local inspection of the sheet piles under the water mark in ideal conditions. At the same time it allows structural repair work if necessary. For example welding of metal strips on heavily corroded and perforated sheet piles.
The coating, named HUMIDUR, was specially designed for this kind of work.
The HUMIDUR-coating is an epoxy based two component system, solventfree, free of coaltar and unfit to crystallize.
A modifying constituent is incorporated into the binders, resulting in an excellent adhesion on metal surfaces.
For pigmentation, abrasion resistant extenders and colouring pigments are used.
The system is elastified by adding a high molecular plasticiser assuring sufficient flexibility.
The product mixture has waterrepelling properties, allowing hardening under water, even at low temperatures.
Beside the excellent anti-corrosion properties the HUMIDUR-coating has also an improved mechanical resistance together with an excellent chemical and solvent resistance.
The continuity of the coating is demonstrated by an electrical test showing that the breakdown voltage over a 440 micron film exceeds 25 kV.
The HUMIDUR-coating shows no cathodic disbonding when applied on cathodic protected steel (- 1000 mV with regard to Ag/AgCl) in seawater.
The HUMIDUR-coating results in excellent adhesion characteristics on dry blank blasted steel surfaces.
The build-in properties not only provide an excellent corrosion resistance but allow at the same time that the job can be done easily and fast.

A number of specific properties make that possible.

- The coating is solvent free and hardening is possible under water. This means that drying and hardening is a chemical process instead of a physical one. The major advantage is that directly after application of the coating and inspection of the coated surface the D.S.I. can be removed and brought to the next section.
- The coating can be airless sprayed in one layer of at least 400 microns thick.

Up till now approximately 50 000 m^2 of steel sheet piling have been treated with the HUMIDUR-system. Inspection and evaluation tests performed on 5 years old coated sheet piles show, in general, beside esthetic considerations that the coating is still in good shape and offers an adequate corrosion protection for the sheet piles.

APPLICATION.

The D.S.I. is placed in position in front of the sheet pile wall. The hydraulic clamping device keeps the D.S.I. in position. Evacuation of the water takes only a few minutes. The cleaning of the steel surface consists of

- removal of silt and biological deposits
- pneumatic removal of rust scales
- blasting up to Sa 2,5
- additional blasting until a complete dry surface is obtained
- structural repair if necessary. For example welding of metal strips on the metal surface in perforated or deeply corroded areas
- dedusting
- pretreatment of the joints with Humidur by brushing
- Airless spraying of the Humidur in a single layer of at least 400 microns thickness
- end control and inspection of the executed work
- filling up the D.S.I. with water by switching off pumps
- transfering the D.S.I. to the following section.

CONCLUSION

The HUMIDUR-system provides an excellent means for corrosion protection. This preservation technique offers the possibility for significant extension of the expected lifetime of the sheet piles.
The simplicity, effectiveness and the high yields obtained with this restauration technique makes it economically justified [1].
Although originally developped as a preservation technique higher yields with respect to investment cost can be achieved when preventively used on newly constructed sheet piles.

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