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Corrosion of vertical carbon steel at the ground water table region in soil – Laboratory investigation

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Abstract

The corrosion behaviour of carbon steel at the ground water table region in soil has been investigated in the laboratory. Carbon steel coupons were placed at five different depths in sand soil in a high plastic cylindrical container. Two such coupon sets were placed into each other. The five coupons in each set were coupled electrically to each other. By means of a communicating vessel the "groundwater table position" could be kept constant in the sand soil during the 6 week test. Further, long steel strips were placed vertically next to the steel coupons in the cylinder. The experimental set-up allowed a detailed study of the corrosion processes taking place on different parts of a vertical steel construction passing through the groundwater region, based on measurements of the corrosion potentials, the corrosion currents and the corrosion rates of the test specimens.

It was found, in summary, that the coupons below the groundwater table were more or less anodic and the coupons above the table more or less cathodic. The highest average penetration was found on coupons immediately below the water table. Also some shallow local corrosion attacks were found at this level. Immediately above the groundwater table the average corrosion was lower but the local attacks were deeper. The corrosion potentials and the direction and intensity of the measured corrosion currents support the findings.

Introduction and background

Carbon steel is frequently used in the ground as vertical load bearing construction members, e.g. as piles and sheet pilings beneath buildings and bridges and as ground anchors for the support wire of large power line towers and telecommunication towers. Most of these construction installations pass through the ground water table. During the years it has been discussed whether the steel section in the groundwater region could be exposed to enhanced and localised corrosion attacks. The background to this discussion is that the Swedish power companies have made observations of heavy localised corrosion attacks at some depth in the soil on ground anchors for power line towers. In some instances the corrosion has resulted in breaking of the solid steel anchor and a risk of the falling down of the tower with adjacent risk of electric power black-out in the society. See **figure 1**.

In Sweden a great number of field investigations have been carried out concerning corrosion and protection of vertical steel in soil. Investigated structures are steel piles and steel pilings, which most often are driven down in undisturbed soil, as well as power line tower foundations and ground anchors, which are buried in disturbed soil. Most of the investigations are described in a handbook, containing a compilation of knowledge concerning soil corrosion of vertical steel constructions published by the Royal Swedish Academy of Engineering Sciences (ref. 1). Others are described in single reports, e.g. (ref. 2,3,4). In the field investigations it has, however, not been possible to study the corrosion process in the groundwater region in detail.

Figure 1. Ground anchor for high voltage power line tower heavily corroded where it passes through the groundwater region.

Thus, a minor laboratory investigation was started at the Swedish Corrosion Institute (now the Swedish Corrosion and Metals Research Institute) with the objective to study the corrosion of carbon steel at the groundwater region as a first step in understanding the corrosion process at this special level in the soil. The investigation was financed by the Swedish Governmental Agency for Innovation Systems and the Swedish Corrosion Institute's member programme research found. The experimental work was carried out by Henrik Linder as an examination work at the Åsö Technical Senior High School, Stockholm.

Experimental

Experimental set-up

The intention of the experimental set up was to simulate the corrosion situation which is prevailing on a vertical steel construction which is passing through the groundwater region in the soil. One deviation from the field situation, however, is that the groundwater table was kept constant in the lab.vessels in the laboratory investigation, whilst the groundwater table in the field usually fluctuates due to seasonal variations and variations in rainfall.

A large and high plexiglass cylinder was filled with fine grained sand soil. Five small steel coupons were placed at different depths in the sand. Two such coupled coupon sets were placed parallel to each other. Thus, two vertical coupon test series were exposed in the cylinder. Further, three long steel strips were placed vertically in the sand next to the steel coupons. The total exposed area of each coupon was 26 cm^2. The exposure period was 6 weeks. See **figure 2**.

The five coupons in each set were coupled electrically to each other via a measurement socket. This allowed a temporary disconnection of each coupon from the others in order to measure the true “OFF- potential” of each coupon. The OFF-potential showed the potential of the coupon, which is influenced by the corrosion currents flowing to or from the other coupons in the cylinder. The OFF-potential is not influenced by the voltage drop (IR-drop) in the sand.

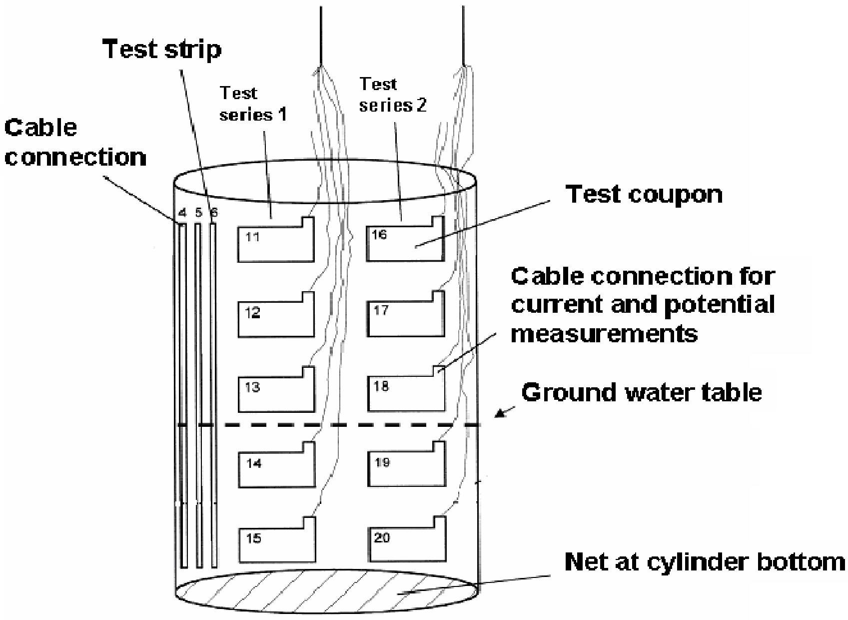

Figure 2. Experiment cylinder with test coupons and strips embedded at different levels in sand.

The bottom of the cylinder was covered by a net. The objective was to keep the sand in place in the cylinder. The cylinder was placed in an outer glass container containing water. By this a communicating vessel was obtained through the net at the bottom of the experiment cylinder. The water was Stockholm tap water with the addition of salt (NaCl) resulting in a chloride content of 130 mg Cl^-/liter. By filling the outer container with water to a certain level it was possible to obtain a “groundwater table” in the middle of the specimen cylinder, and to keep this level constant by keeping the water table constant in the outer container. See **figure 3**. The groundwater table was stabilised roughly between test level 3 and 4

The meaning of the coupons was to obtain a measure of the corrosion of different parts of a vertical steel structure which is passing through the groundwater table. The meaning of the steel strips was to obtain a picture of the corrosion appearance of a continuous structure passing through the groundwater region, and to compare this with the corrosion appearance of each single steel coupon.

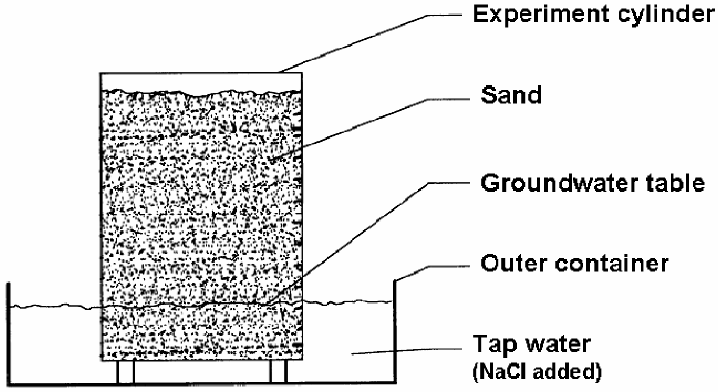

Figure 3. Experiment cylinder placed in an outer container, filled with water, for obtaining a communicating vessel.

Measurement of corrosion potentials and corrosion currents

During the exposure period the corrosion potential of each test specimen was measured at four occasions. The reference electrode used was a saturated calomel electrode (sat. SCE). The potential of the coupled coupons was measured immediately (approx. ½ sec) after a temporary disconnection of the actual coupon from the other four coupons in the test series. The corrosion current measurements were carried out with an ordinary multimeter instrument and by excluding the inner voltage drop in the instrument and thus the currents measured were true currents.

Water content of the sand soil

At the end of the exposure period a soil sample was taken from each of the five exposure levels in the cylinders and analysed with respect to water content.

Evaluation of corrosion

The process of cleaning the test specimens was repeated pickling in Clarkes solution. The corrosion was evaluated as “weight loss corrosion” and recalculated to average penetration, expressed as mm/year. Further, the depth of local corrosion attacks was measured in a microscope by using the “focusing method”, and recalculated as local corrosion rate expressed as mm/year.

Results

The water content of the sand at the five different test levels is shown in **table 1.**

Test level	Water content mass-% of wet soil	Degree of water saturation volume- %
1	0,05	0,2
2	1,5	6,4
3	5,9	26
4	18,6	96
5	19,0	98

Table 1. Water content of the sand soil at the five test levels.

Corrosion potentials and the direction of the corrosion currents measured at the end of the exposure period are shown in **figure 4**. The currents at each measurement occasion are shown in diagrams in **figure 5.** The corrosion rate of the coupons is shown in **figure 6**.

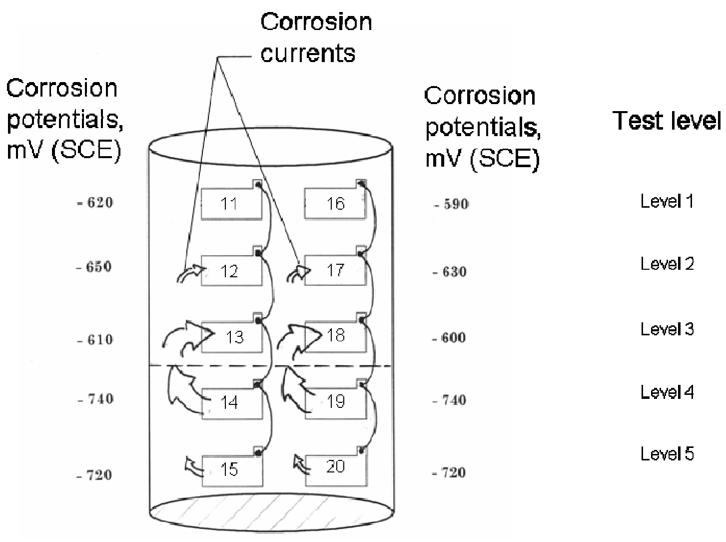

Figure 4. Corrosion potentials and direction of corrosion currents at the end of the exposure.

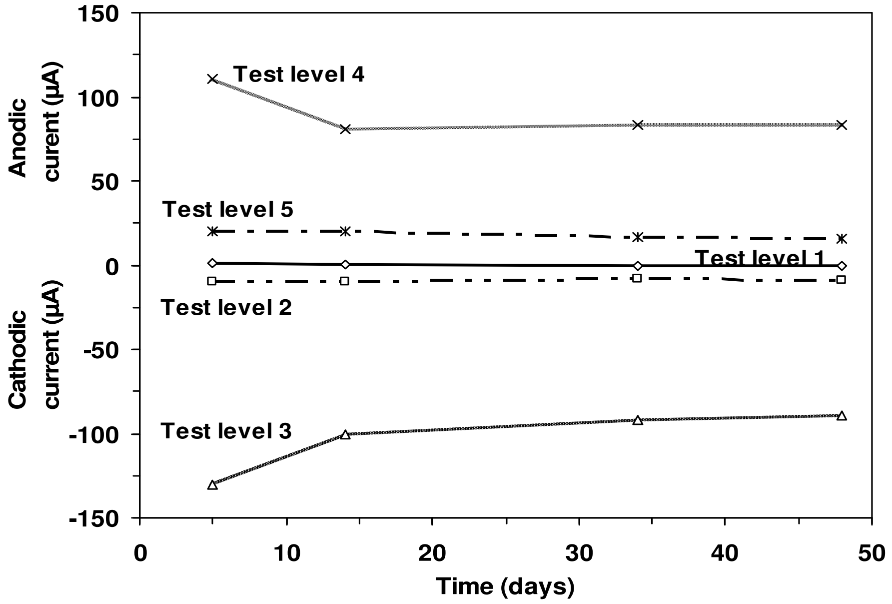

Figure 5. Corrosion currents measured at each measurement occasion in test series 1.

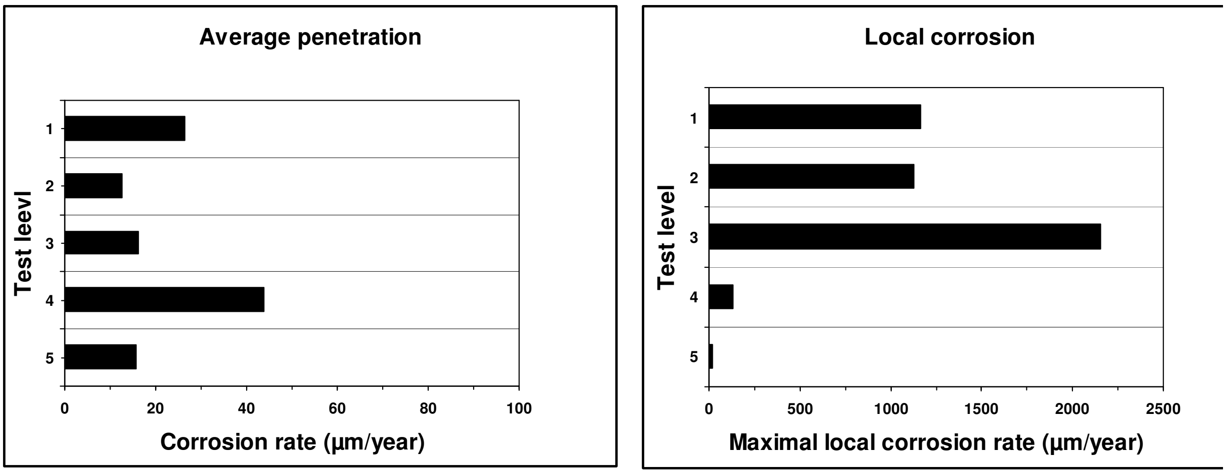

Figure 6. Corrosion rates of test coupons (mean value of coupons in test series 1 and 2).

The corrosion appearance of coupons and strips before cleaning from rust is shown in **figure 7**. Corrosion appearances of coupons after removal of rust are shown in **figure 8 – 10**.

Figure 7. Corrosion appearance of test specimens before removal of rust. Upper coupon from upper test level etc.

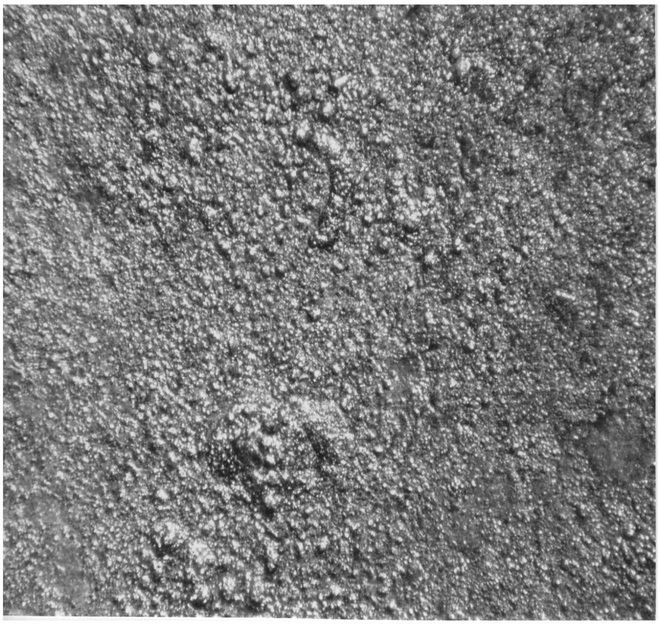

Figure 8. Appearance of corrosion on coupons from upper test level (level 1) after removal of rust. (x25)

Figure 9. Appearance of corrosion on coupons from test level 2 and 3 after removal of rust. (x25)

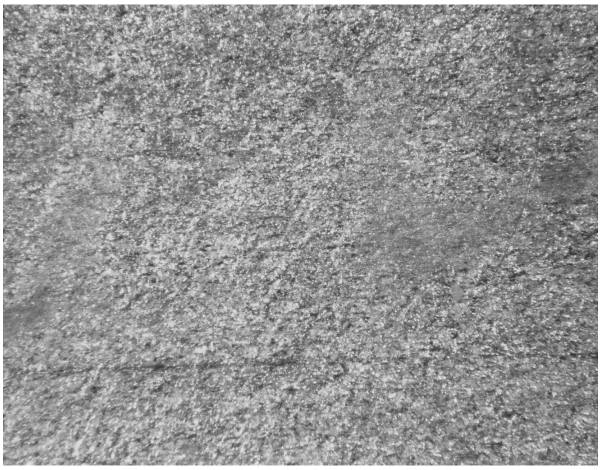

Figure 10. Appearance of corrosion on coupons from test level 4 and 5 after removal of rust. (x25)

Discussion

The groundwater level and oxygen diffusion
It can be seen in table 1 that the sand at the two lowest exposure levels (level 4 and 5) had a degree of water saturation near 100 %. Thus, the sand was saturated at these two levels. Above level 4 the sand is no longer water saturated. The water content becomes successively lower closer to the “ground surface”. Thus, it can be anticipated that the “groundwater table” has been situated somewhere between level 3 and 4.

Since the sand was saturated to different degrees at the exposure levels also the oxygen diffusion through the sand pores to the different coupons was different. The oxygen diffusion, and thereby also the cathodic corrosion reaction, is facilitated when the water content is low and the sand pores are more or less open. When the oxygen diffusion to the steel is facilitated the corrosion potential will shift towards more positive values. I figure 4 it can be seen that the true potential is more positive on coupons at higher exposure levels than on the lower levels. This is due to the difference in oxygen content (rate of oxygen diffusion) at the different levels. However, the dryer the soil is the higher is the specific electrical resistance (soil resistivity) of the soil. At high resistivity the corrosion current will be low. Thus, there is a balance between the degree of water saturation, oxygen diffusion and soil resistivity for obtaining optimal corrosion conditions.

The potential is also depending on whether the steel surface is exposed to a current flow to or from the surface. When positive current is leaving a steel (or any other metal) surface and flows into the surrounding soil or water the potential will shift towards more positive (anodic) values. The steel is polarised in the positive direction. When positive current is entering from the surrounding soil/water into a steel surface the potential will shift towards more negative (cathodic) values. The steel is polarised in the negative direction.

From the direction and the magnitude of the measured currents, shown in figure 5, it can be seen that coupons at the three highest levels were cathodes in relation to the coupons at the two lowest levels. Coupons at level 3 have received the highest current and coupons at level 4 have emitted the highest current. It seems that the coupons at level 3 have been strong cathodes against coupons at level 4. The water content at level 3 was approx. 6 %. Obviously this has been enough for a quite good electrical conductance in the sand between level 3 and 4 and also for facilitated oxygen diffusion to level 4. The fact that coupons, which have acted as cathodes, have “contributed” more to the corrosion on anodic coupons at level 4 than to anodic coupons at level 5 is probably because of shorter distance and lower soil resistance to level 4.

The current diagrams in figure 5 show the “co-operation” in current exchange between coupons at level 3 and 4. When the anodic current (current leaving) from coupons at level 4 has decreased during the exposure period, also the cathodic current (current entering) on coupons at level 3 have decreased.

From figure 6 it can be seen that the highest average penetration was found on coupons at level 4. This is in accordance with the measured corrosion currents. It was unexpected, however, to find the second highest average penetration on coupons at level 1. At this level the sand had the lowest water content and thus the sand was quite dry at this level. However, the oxygen diffusion rate was highest at this level, giving a good support for the cathodic corrosion reactions. The coupons at this level (level 1) were not influenced by current from other coupons, and thus the corrosion was of the type “self corrosion” at level 1.

The photos in figure 7 – 10 show that the most typical uniform corrosion attacks occurred in the fully water saturated sand (level 4 and 5). At level 2 and 3 local attacks were occurring, despite the cathodic protecting effect from the current flow from coupons at lower test levels. At the highest test level (lowest water content) the attack was of the uniform corrosion type, however some quite deep local attacks were also occurring at this level.

The soil environment, in which the corrosion was studied here, was static with no water fluctuations. Thus, the results show the corrosion situation only at a certain occasion. In the field, however, the groundwater fluctuates up and down due to seasonal variations. This means that the corrosion effect of the groundwater table will be more “distributed” over a vertical steel structure.

Conclusions

The main conclusions from the laboratory investigation are:

- In the groundwater region the corrosion of a vertical steel construction is different compared to the corrosion on the rest of the structure, due to the formation of differential aeration corrosion cells caused by differential oxygen diffusion to different parts of the steel structure in this region.
- The highest average penetration is taking place immediately below the groundwater table, where the soil is saturated with groundwater.
- Immediately above the groundwater table, but still in the groundwater region, the average penetration is smaller, but there are more and deeper local corrosion attacks appearing.
- On relatively dry and well aerated levels above the groundwater table, a comparatively high average penetration may appear together with quite deep local corrosion attacks.

References

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