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Comparison of soil properties measurements in pipeline corrosion estimation

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Soil corrosion is a hazardous electrochemical process that affects buried metals in contact with soil. Corrosion in soils resembles atmospheric corrosion with corrosion rates usually higher and depending on the soil type. There are numerous properties of soil and thus soils can be classified in many different ways. Soil resistivity is one of the main indicators of soil corrosivity and thus of the hazardous impact the soil has on metal materials in soil environment, although it is not the only parameter affecting the risk of corrosion damage.

In this work on site measurements and laboratory measurements of soil characteristics are performed and compared. On site measurements include measuring the redox potential and soil resistivity by Wenner 4-pin method, while the measurements in laboratory include measuring soil conductivity, as well as moisture content, pH, content of sulphates, chlorides and sulphides and polarization measurements, which give the most accurate results.

The measurements have shown that if the Wenner 4-pin method is performed in a convenient way the obtained results are not precise but can give an indicative picture of the corrosivity of the observed soil.

Keywords: Soil resistivity; Soil corrosivity; Wenner 4-pin method; Polarization method

1 Introduction

Many underground steel structures were designed to have a lifetime of about 30–50 years. Now, even in mildly corrosive environment, these ageing structures suffer threat of corrosion-induced failures that increase steadily each year. Since corrosion failure in underground structures can have severe consequences environmentally and economically large efforts are being made to develop advanced engineering practices of managing corrosion problems. [1,2] In parallel, an increasing body of scientific work in recent years is aimed at investigating corrosivity of soil environment. [3-13]

Soils come in many varieties and have many different properties that can be measured. Literature is replete with methods and systems that endeavor to predict metallic pipe corrosion from the properties of the soil surrounding the pipe. Soil properties that have been implicated include soil electrical resistivity, pH value, redox potential, and presence of sulfates in the soil solution, chloride concentration, moisture conditions, shrink/swell properties and others, thus they can be classified in different ways. [14-16]

Corrosion of carbon steel in soils is an electrochemical process, which can be affected by various environmental factors, including type of soil, soil composition, pH, moisture, salt concentration, oxygen content, temperature, microorganisms, etc. [15]

Soil resistivity is one of the key indicators of the corrosive classification assessment on metal materials in soil environment, [17-22] often because it is more practical to be measured than some other properties. Soil resistivity is by no means the only parameter affecting the risk of corrosion damage. A high soil resistivity alone will not guarantee absence of serious corrosion. Nevertheless, it has been used as a broad indicator of soil corrosivity. There are various methods applied for soil resistivity measurements. [5] The most often applied method for in situ measurements is the Wenner 4-pin method. The method has its advantages and drawbacks. Thus it is important to distinguish these characteristics to be able to provide the most precise

picture of the system. To gain a real picture of the corrosivity of soils other parameters are also needed.

In the present paper we investigate the correlation between on site local soil resistivity measurements by Wenner method and laboratory measurements of physico-chemical and electrochemical soil characteristics. We compared the results to the results obtained by polarization measurements. Polarization measurements give the most precise picture of the corrosivity of soil, but are more complicated to be performed and need special equipment and knowledge to interpret the results. Thus they are often not convenient to be performed. Field measurements were done at four geographically distant pipeline excavation sites with distinctively different soil types. The predictability value of soil resistivity measurements with respect to the observed general and/or localized corrosion forms is discussed.

2 Materials and Methods

On site of excavation soil resistivity was measured, as well as the redox potential at the depth of excavation. Samples of corrosion products and soil were taken from the sites and explored in laboratory.

2.1 On site measurements

2.1.1 Redox potential

The redox potential is calculated from the potential difference measured with a probe that contains an inert platinum electrode and reference electrode. [23] For the measurements in this work a Cu/CuSO₄ reference electrode was used.

2.1.2 Soil resistivity

On the excavation sites soil resistivity was measured using the Wenner 4-pin method. The method is described by various standards. [24-26] Four equidistant stainless steel pins are buried in the ground and spaced in a straight line. The spacing between the pins represents the

depth to which the resistivity is measured. By increasing pin spacing, the resistivity is measured to a greater depth (Figure 1). [22]

The soil resistivity obtained when measured from the surface of the ground over a pipeline, represents resistivity of the soil on the depth that is same as the distance between the pins:

$$\rho = 2\pi dR \quad (1)$$

where

$$R = \frac{\Delta\phi}{I} \quad (2)$$

ρ – soil resistivity (Ω cm), d – distance between electrodes (cm), R – average resistance (Ω), $\Delta\phi$ – gradient of the potential between the inner electrodes (P1 and P2), I – the total current between the outer electrodes (C1 and C2).

The Wenner method was used for measuring soil resistivity on the sites of four different locations of pipelines. A Metrel-Eurotest 61557 apparatus was used for the measurements.

2.2 Laboratory measurements of soil properties

Samples of soil were collected from all four locations and examined in laboratory by various methods. Moisture content was measured by weighing before and after drying the soil, [27] pH was measured directly using a pH meter in a mixture of soil and redistilled water in ratio 1:1. [1, 28] The content of sulphates was measured by turbidimetry, [29] chlorides by titrimetry [30] and sulfides with reagents. [31] The conductivity was measured using a MA 5962 conductance meter after big pieces of gravel were taken out. [1]

2.3 Polarization measurements

The corrosion rates were determined following ASTM standard by polarization measurements in narrow (± 10 mV) [1, 32] and wide (± 150 mV) [1] potential range. [32] A three electrode arrangement was used. Cu/CuSO₄ electrode was used as a reference electrode and a metal/metal-oxide electrode was used as a counter electrode. Although the potentials were measured with a Cu/CuSO₄ electrode they were recalculated towards a SHE electrode to

determine the corrosivity rating by comparing the results to the values in Table 1. The working electrode was made of API X52 5L steel in dimensions 15×20cm. All electrodes were dipped in soil samples taken from the different locations for 7 days prior to measurements. The steel plate was isolated on one side and the area dipped in soil was 185 cm². For the polarization measurements a PAR VMP2 potentiostat/galvanostat was used. Figure 2 presents the three-electrode system used for the polarization measurements.

3 Results and discussion

3.1 On site measurements

3.1.1 Redox potential measurements

The redox potential essentially is a measure of the degree of aeration in a soil. It depends on the dissolved oxygen content in the pore water and provides some information on the conditions under which sulfate-reducing bacteria could grow.

The oxygen concentration decreases with increasing depth of soil. In neutral or alkaline soils, the oxygen concentration has an important effect on corrosion rate due to its participation in the cathodic reaction. However, in the presence of certain microbes (such as sulfate reducing bacteria) corrosion rates can be very high, even under anaerobic conditions. Excavation can obviously increase the degree of aeration in soil, compared with the undisturbed state.

A high redox potential indicates a high oxygen level. Low redox values may provide an indication that conditions are conducive to anaerobic microbiological activity. Sampling of soil will obviously lead to oxygen exposure and to unstabling redox potentials. This is the reason why the redox potential has to be measured on all excavation sites immediately after excavation.

[33] In accordance with this the measurements were performed on all four sites immediately after excavation with minimal stirring of the soils. The use of redox potentials to predict soil corrosivity is presented in Table 1.

Table 2 presents the redox potentials measured on all four locations. When compared to the data in Table 1 it can be seen that all soils are generally aerated, with the ones on Locations 1 and 3 being strongly aerated. According to the redox potentials soils on all locations are generally low corrosive. They are “mildly corrosive” on Locations 2 and 4, and even “essentially noncorrosive” on Locations 1 and 3.

3.1.2 Soil resistivity measurements

In the water-saturated soil resistivity is a measure of the content of soluble salts able to form ions by dissolving in water, the volume fraction of pore space, and the mobility of the charge carrying ions. In general, corrosion rates are observed to increase with the conductivity of a soil, i.e. with increasing water content and the concentration of ionic species. [30, 31, 33] Sandy soils are high up on the resistivity scale, and therefore considered the least corrosive. Clay soils, especially those contaminated with saline water are on the opposite end of the spectrum. [34] The generally adopted corrosion severity ratings are shown in Table 3 [35].

Soil-resistivity was measured following the same procedure on all locations. It was measured using the Wenner 4-pin method on the excavation location of the pipeline in three positions presented in Figure 3 and the obtained results are presented in Table 4. The only difference was the distance between pins. The first type of measurement was performed on the site before excavation of the pipeline vertically above and close to the pipeline while the soil has not been touched yet (Figure 3-a). On this location four measurements were made with different distances between pins (Table 4.a). After excavation measurements were made horizontally in the excavation hole on different depths (Figure 3-b, results Table 4.b). In this position, the pins were always 1 m apart, but the measurements were made on different depths, 0.5, 1, 1.5 and 2 m from the ground level. The third type of measurements was made vertically beside the pipeline on the bottom of the excavation hole (Figure 3-c, results Table 4.c). In this position the

distance between pins was 1 m and no alterations were made because there was no space in the hole.

Table 4 presents the results of soil resistivity measurements on the four locations (L1-L4) by the Wenner 4-pin method and the corrosivity rating determined by comparing the results to Table 3.

The results from Location 1 show that the soil resistivity mildly decreases with depth from values 27 to 16 Ω m. The soil resistivity value measured from the surface for the depth of 2 m is 22 Ω m and the value measured horizontally in the excavation hole on 2 m of depth is 14 Ω m. When these two values are compared it can be seen that the value measured from the surface is higher. This is consistent with the fact that the resistance measured from the surface for each additional depth is the mean value of the resistance of the layers above this depth. Thus, the resistance of the soil measured from the surface of the soil on the depth of burial of the pipeline is the mean resistance of the soil from the surface to this depth.

In case of the soil on Location 2 soil resistivity increases with depth measurements from 407 to 1014 Ω m when measured from the surface. The values measured horizontally in the excavation hole, and vertically at the bottom of the excavation hole were again lower than those measured for the same depth from the surface.

The values of soil resistance measured on Location 3 from the surface also increase with depth measurements from 75 to 337 Ω m. The values measured vertically in the excavation hole at the depth of 1 m are 213 Ω m and are again somewhat higher than those measured for the same depth from the surface 175 Ω m. The last measurement, horizontally in the excavation hole next to the pipeline varies considerably and is larger than the other measured values at the same depth, 684 Ω m. This is probably due to the close proximity of the concrete base at this location, which affects the reading of the increased resistance.

At Location 4 the soil resistivity again decreases with depth and values measured in the excavation hole are somewhat lower than those measured from the surface.

Taking into account the resistance of the soil as the only parameter of corrosivity and if these values are compared with the values in Table 3 soils on Locations 2 and 3 are “essentially noncorrosive”, while on Location 1 the soil is “moderately corrosive” and on Location 4 it is “mildly corrosive”. When compared to the corrosivity rating according to the redox potential in Table 3 it can be seen that only the soils in locations 3 and 4 have the same corrosivity ratings.

3.2 Laboratory measurements of soil properties

Table 5 shows the results of the measurements performed on the samples of soil taken from excavation sites.

It can be seen that the pH value of all soils is neutral or near neutral. The soil on Locations 1, 2 and 3 is neutral, while on Location 4 it is slightly alkaline. [36] Soils usually have a pH range of 5-8. In this range, pH is generally not considered to be the dominant variable affecting corrosion rates. The pH level can affect the solubility of corrosion products and also the nature of microbiological activity. Obviously, more acidic soils represent a serious corrosion risk to common construction materials such as steel, cast iron and zinc coatings. Soil acidity is produced by mineral leaching, decomposition of acidic plants (for example coniferous tree needles), industrial wastes, acid rain and certain forms of micro-biological activity. Alkaline soils tend to have high sodium, potassium, magnesium and calcium contents. The latter two elements tend to form calcareous deposits on buried structures with protective properties against corrosion. With the soil from Location 4 being slightly alkaline, this could indicate that the soil from L4 is less corrosive.

Chloride ions are generally harmful, as they participate directly in anodic dissolution reactions of metals and their presence tends to decrease the soil resistivity. They may be found naturally in soils as a result of brackish groundwater and historical geological sea beds (some waters

encountered in drilling mine shafts have chloride ion levels comparable to sea water) or from external sources such as de-icing salts applied to roadways. The chloride ion concentration in the corrosive aqueous soil electrolyte will vary, as soil conditions alternate between wet and dry.

Compared to the corrosive effect of chloride ion levels, sulfates are generally considered to be more benign in their corrosive action towards metallic materials. However, concrete may be attacked as a result of high sulfate levels. The presence of sulfates does pose a major risk for metallic materials in the sense that sulfates can be converted to highly corrosive sulfides by anaerobic sulfate reducing bacteria.

Among the soil from the four locations both chloride and sulphate content is highest on Location 1 and it would be expected that also the corrosivity is highest on this site, especially since the moisture content is also relatively high. Location 3 has also relatively higher amounts of chlorides, but the moisture content is lowest in this case, so the corrosivity would be expected to still be low. All soils showed content of sulphates and chlorides, but the tests did not show any content of sulfides. This is most probably because the sulfides react very fast when exposed to air.

If resistance of soil can be approximated as the reciprocal value of conductivity in all four cases the values are similar if gravel is not present, although the measurements on the field presented in Table 4 showed different results on the different locations. Namely, when gravel is extracted from soil the resistance of soil is mainly determined by the diluted compounds, respectively the concentration of chlorides, sulphates and sulphides. If the conductivity results, i.e. rather the $1/\text{conductivity}$ results are compared to the data in Table 3, the soil on all four locations is “mildly corrosive”. The same results are obtained by both methods only on Location 4. At Locations 2 and 3 a significant proportion of gravel was present, so the resistance values of the soil after extraction of gravel were higher than those obtained on the site.

3.3 Polarization measurements

Polarization measurements give the best picture of the corrosivity of the soils because they are the only measurements that are influenced by all soil properties. This is the reason why we consider the conclusions made from the polarization measurements as the real picture of the corrosivity of soils and compare the other results to them.

The results of polarization in wide ($\pm 150\text{mV}$) and narrow ($\pm 10\text{mV}$) potential range are presented in Figure 4 a and b. It can be seen that the curve presenting polarization in soil at Location 3 (Figure 4a) is shifted towards significantly lower current densities, indicating that corrosion in such soil is slower compared to the soils from the other locations. From the slopes of the narrow potential range polarization curves (Figure 4b) it is obvious that the resistance towards corrosion is smallest at Location 4 (where the slope is smallest), while the resistance is greatest at Location 3 (where the slope is greatest).

Table 6 presents the corrosion parameters obtained from the polarization curves in Figure 4 according to the Tafel extrapolation [1] and linear polarization [1, 32] methods. Corrosion rates have been calculated from the corrosion current densities. [37]

The anodic and cathodic tafel slopes are greatest at Location 4 indicating the greatest metal dissolution. The polarization resistance, R_p , as well as the corrosion current density, j_{corr} , both confirm that the soil from Location 4 is most corrosive ($1051\text{ k}\Omega$ and $1.73\text{ }\mu\text{A cm}^{-2}$).

It can be seen from the corrosion rates calculated from the R_p data that the corrosion rate is smallest at Location 3, only $0.3\text{ }\mu\text{m yr}^{-1}$. Compared to the values at Location 4 where the corrosion rate is greatest, $97\text{ }\mu\text{m yr}^{-1}$, the rate is more than 300 times smaller. The rate at Location 4 is greater than on all the Locations, but compared to Locations 1 and 2 (40 and $21\text{ }\mu\text{m yr}^{-1}$) the difference is significantly smaller (2 and 4 times greater). If the polarization measurements are considered the most accurate then it can be concluded from the corrosion rates that soil from Location 4 is the most corrosive ($97\text{ }\mu\text{m yr}^{-1}$), while the soil from Location

3 is the least corrosive ($0.3 \mu\text{m yr}^{-1}$). If we compare these results to the Wener method's results in Table 4 measured vertically above the excavation hole with a distance between pins of only 1 m the results do not match. According to the obtained results soil from Location 4 has rather high resistivity, while the one from Location 3 has low resistivity. The picture is somewhat different if the resistivity is measured when pins are separated by 4 m. According to these results the soil from Location 4 has very low resistivity which matches the polarization results. The soil from Location 3 also showed greater resistivity compared to the measurements when pins were 1 m apart. It can be concluded that soil resistivity measurements are not precise but if they are measured the proper way they can give an insight on the corrosivity of the soil, but it needs to be carefully performed and it has to be considered that if large rocks or parts of concrete were present on the site the soil resistivity will be greater and thus the obtained picture will not be realistic.

Compared to the Wener method, the conductivity measurements are more difficult to be performed properly if there is significant proportion of gravel, as in the case of soil from Locations 2 and 3. If this gravel is excluded from the measurements the resistivity will be significantly lower, and thus the soil will seem more corrosive than it really is.

The pH values, redox potentials, moisture, chloride, sulphate and sulphides content alone cannot give an insight on the corrosivity of the soil unless the values are extreme.

4 Conclusions

The properties of soils from 4 different locations were measured both on site and in laboratory to determine what data is needed to be measured to determine the corrosivity of the soil since in real situations it is often not possible to measure all properties.

The results have shown that although the Wener 4-pin method for measuring on site soil resistivity gives only a superficial picture on the corrosivity of the soil, if it is performed in the right way it can give a good indication on the soil's resistivity.

All the other measured properties: pH values, redox potentials, moisture, chloride, sulphate and sulphides content alone cannot give an insight on the corrosivity of most soils.

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Figure 1. Wenner 4-pin method for soil resistivity measurements [22].

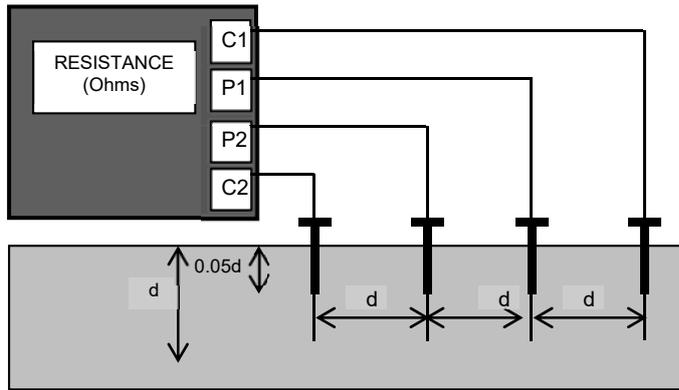


Figure 2. The system studied by polarization measurements.



Figure 3. Soil resistivity measured on-site by the Wenner 4-pin method.

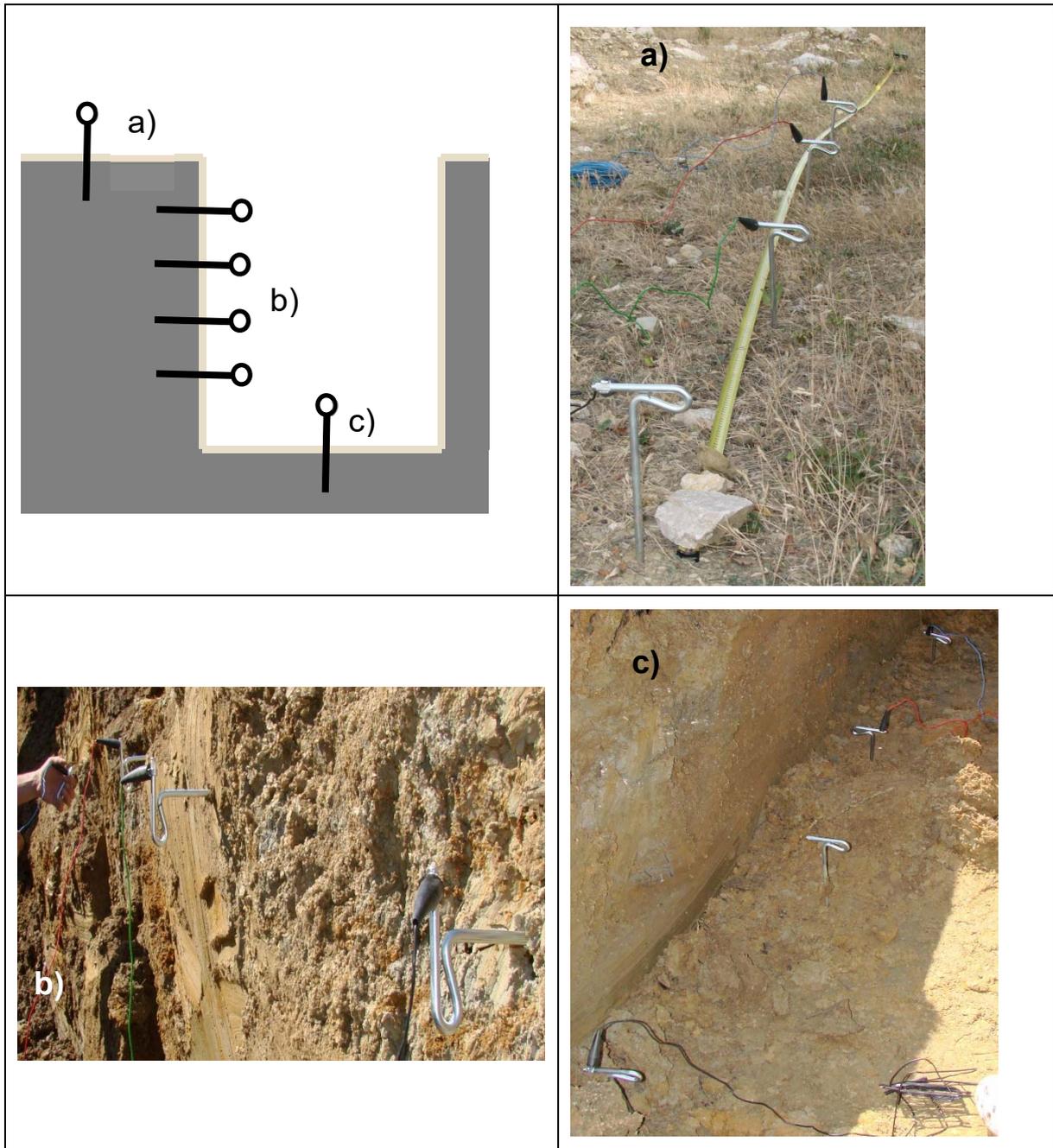


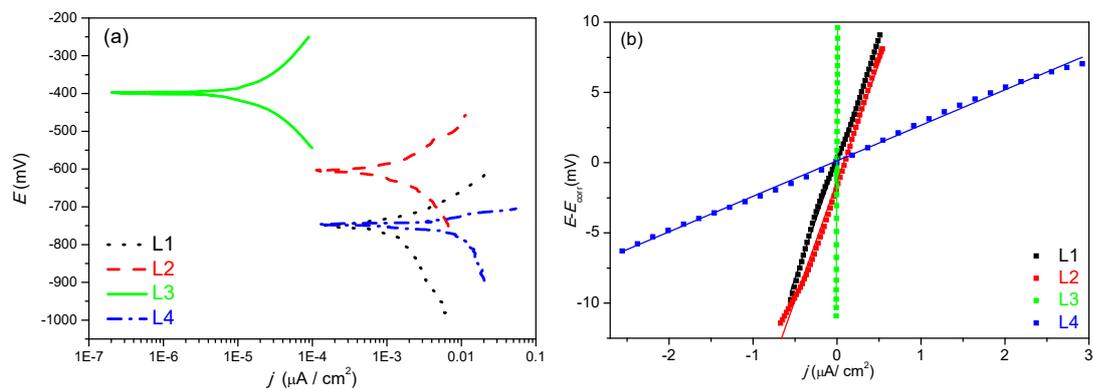
Figure 4. Polarization curves in: (a) wide and (b) narrow potential range.

Table 1. Soil redox potentials as an indicator for soil corrosivity [33].

Redox potential vs. SHE	Aeration	Corrosivity rating
Negative	Not aerated	Extremely corrosive
0-100 mV	None to weak	Corrosive
100-200 mV	Weakly aerated	Moderately corrosive
200-400 mV	Aerated	Mildly corrosive
Above 400 mV	Strongly aerated	Essentially noncorrosive

Table 2. Redox potentials measured on excavation locations.

		L1	L2	L3	L4
Redox potential	vs. Cu/CuSO ₄	+141	+32	+90	-99
[mV]	vs. SHE	+459	+350	+408	+219
Corrosivity rating		Essentially	Mildly	Essentially	Mildly
(according to Table 1)		noncorrosive	corrosive	noncorrosive	corrosive

Table 3. Corrosivity Ratings Based on Soil Resistivity [35].

Soil resistivity [Ω m]	Corrosivity rating
>100	Essentially noncorrosive
20-100	Mildly corrosive
10-20	Moderately corrosive
5-10	Corrosive
< 5	Extremely corrosive

Table 4. Soil resistivity measured by the Wenner 4-pin method and the corrosivity rating.

Distance between pins [m]	Soil resistivity [Ω m]			
	L 1	L 2	L 3	L 4
<i>a) Vertically above the excavation hole</i>				
1	27	407	75	295
2	22	674	170	177
3	18	804	237	52
4	16	1014	337	35
<i>b) Horizontally in the excavation hole</i>				
1	20 (-0.5m)	277 (-1m)	213 (-1m)	50 (-2m)
1	19 (-1m)	356 (-1.5m)		29 (-3m)
1	13 (-1.5m)	429 (-2m)		
1	14 (-2m)	794 (-2.5m)		
<i>c) Vertically beside the pipeline in the excavation hole</i>				
1	13	782	684	269
Corrosivity rating (according to Table 2)	Moderately corrosive	Essentially noncorrosive	Essentially noncorrosive	Mildly corrosive

Table 5. Laboratory results of the investigations on soils from the excavation sites

Location	L1	L2	L3	L4
Moisture content [%]	23.6	25.1	14.5	20.0
pH (1:1)	7.13	7.25	7.28	7.54
Conductivity (1:1) [S cm ⁻¹]	4.72·10 ⁻⁴	3.88·10 ⁻⁴	4.43·10 ⁻⁴	3.77·10 ⁻⁴
1/Conductivity (1:1) [Ω m]	21.2	25.8	22.5	26.5
Sulphates [ppm]	25	10	5	17
Chlorides [ppm]	23	6	11	9
Sulfides [ppm]	-	-	-	-

Table 6. Corrosion parameters obtained from the polarization curves.

Location	L1	L2	L3	L4
Anodic tafel slope, b_a [mV dec ⁻¹]	209	126	155	55
Cathodic tafel slope, b_c [mV dec ⁻¹]	-372	-154	-159	-377
Stern Geary coefficient, B [mV]	58.2	30.1	34.1	20.9
Corrosion potential, E_{corr} vs. Cu/CuSO ₄ [mV]	-749	-603	-396	-745
Polarization resistance, R_p [k Ω]	17.0	16.9	1051.0	2.5
Corrosion current density, j_{corr} [$\mu\text{A cm}^{-2}$]	1.33	1.13	0.01	1.73
Corrosion rate, CR – from R_p [$\mu\text{m yr}^{-1}$]	39.7	20.6	0.3	97.0

Graphical Abstract

Different soil properties were measured on soils from 4 different locations to determine which properties can give an insight on the corrosivity of a soil and to see if it is possible to determine by measurements on site the degree of soil's corrosivity. The results have shown that if the on site Wener 4-pin method is used in the proper way it is possible to get a picture of the corrosivity of a soil, although the results are not precise.

