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The effect of piling on the preservation of cultural layers

Physical-chemical assessment in a soil profile adjacent to a pile

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Summary:

Piling as a foundation technique on cultural layers has the advantage that the amount of excavated material is reduced. On the other hand, piling can have an adverse impact on the preservation of cultural layers in the ground due to physical deterioration and by enhancing biological degradation. The study presented in this report aimed at assessing the effect of piling and associated construction techniques on the environmental conditions in cultural layers that control biological degradation. Physical and chemical investigations in two excavated soil profiles near Hotel Klubben in Tønsberg were performed where piling was used as a foundation technique, and where drillings had earlier indicated a reduced organic content and worse state of preservation of the deposits close to the pile. Environmental conditions were assessed conducting field and laboratory measurements of basic physical and chemical parameters, as well as measurements of redox sensitive parameters. The results of the measurements revealed high oxygen concentrations near the foundation wall of the building where the cultural layers had been exchanged by porous fill masses. While areas that were not affected by oxygen intrusion had iron and sulphate reducing conditions that represent good preservation conditions in cultural layers, redox conditions near the building were aerobic and nitrate-reducing. These conditions enhance degradation of cultural layers.

Oxygen intrusion into the ground is most likely facilitated by coarse material that was refilled next to the building when a girder was built under the foundation walls of the building. This coarse material enables diffusion of air into cultural layers as well as percolation of oxygen rich rain water into the ground . A possible adverse effect of the pile on environmental conditions is totally overshadowed by the effect of the girder and refilling material and could not be detected. It was not possible to investigate the conditions closer than approximately 50 cm from the pile. Nor was it possible to investigate the conditions deeper than 2.2 m beneath the soil surface, and thus this report cannot conclude anything about the conditions and possible impacts outside the investigated area.

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1. Content

2. Abstract

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Oxygen intrusion into the ground is most likely facilitated by coarse material that was refilled next to the building when a girder was built under the foundation walls of the building. This coarse material enables diffusion of air into cultural layers as well as percolation of oxygen rich rain water into the ground . A possible adverse effect of the pile on environmental conditions is totally overshadowed by the effect of the girder and refilling material and could not be detected. It was not possible to investigate the conditions closer than approximately 50 cm from the pile. Nor was it possible to investigate the conditions deeper than 2.2 m beneath the soil surface, and thus this report cannot conclude anything about the conditions and possible impacts outside the investigated area.

3. Introduction

Piling is a preferred foundation technique when constructing modern buildings on weak ground. As piles reduce the amount of material excavated from sites, they thus reduce the impact of modern building activities in the cultural heritage resource. The potential footprint of this technique on the archaeology is often considerably less than strip or pad foundations. However, the use of piling techniques in cultural deposits is controversial because piling might have adverse effects on the preservation of cultural heritage in the ground. Piling in cultural deposits may cause physical damage to artefacts and structures when piles are driven into cultural deposits or increase degradation of organic material in cultural layers due to facilitated transport of oxygen into the layers along the pile. A brief discussion of the possible adverse effects of piling on cultural layers is included in Matthiesen (2006).

The possible conflict between modern urban development in medieval cities and preservation of cultural heritage makes it necessary to identify the actual impact of a foundation technique on the preservation conditions of cultural heritage. Therefore, Riksantikvaren has initiated investigations at Bryggen i Bergen, Tønsberg, Copenhagen and Lund to study if piling adversely affects the preservation conditions at cultural heritage sites. For these investigations Auger drilling at different distances from the pile were performed and soil samples of the different soil layers analysed with different physical-chemical and archaeological methods. The only location where the results of the archaeological and physical-chemical analysis indicated significantly poorer preservation conditions due to piling was at the Hotel "Klubben" in Nedre Langgate 49, Tønsberg.

This location was further investigated by excavating a soil profile near the pile in order to verify the findings of the previous study.

The objective of the present study was to reveal the effect of piling and associated construction techniques on the environmental conditions in cultural deposits next to the pile. Furthermore, the present study intended to quantify the area around the pile where the environmental conditions are affected by the construction works in the ground. The physical damage caused by the foundation techniques was not investigated.

3.1 Assessment of the environmental conditions in the unsaturated soil layers

Assessment of the environmental conditions in cultural layers is based on field investigations and laboratory measurements. If reliable analytical methods are available, measurements should preferably be performed in field because they are conducted at the prevalent environmental conditions. When performing analyses in the laboratory, the environmental conditions of a sample should be altered as little as possible during sampling, storage and analysis.

When choosing physical-chemical parameters for the assessment of the environmental conditions in cultural layers, it is important to understand the processes and conditions in soil that affect the preservation conditions in cultural layers.
A good preservation state is characterized by stable physical-chemical conditions where microbiological and chemical activity is low. Stable physical-chemical conditions are often associated with low hydraulic gradients or concentration gradients. This results in retarded degradation of cultural layers. Degradation of organic material and corrosion of metal surfaces are oxidation processes that are accompanied by the reduction of other compounds (e.g. oxygen). Microorganisms gain energy from such processes and use that energy to build biomass. Most energy is gained when oxygen is available for the oxidation of organic material. Somewhat less energy is gained if nitrate is used for the oxidation of organic material and even less if three valent iron (Fe III), four valent manganese (Mn VI), sulphate or oxidized organic material is used (fig. 1). In nature we can observe that aerobic conditions (in presence of oxygen) turn to nitrate reducing conditions when all oxygen is spent. These are followed by

manganese-, iron- and sulphate reducing and methanogenic condtions.

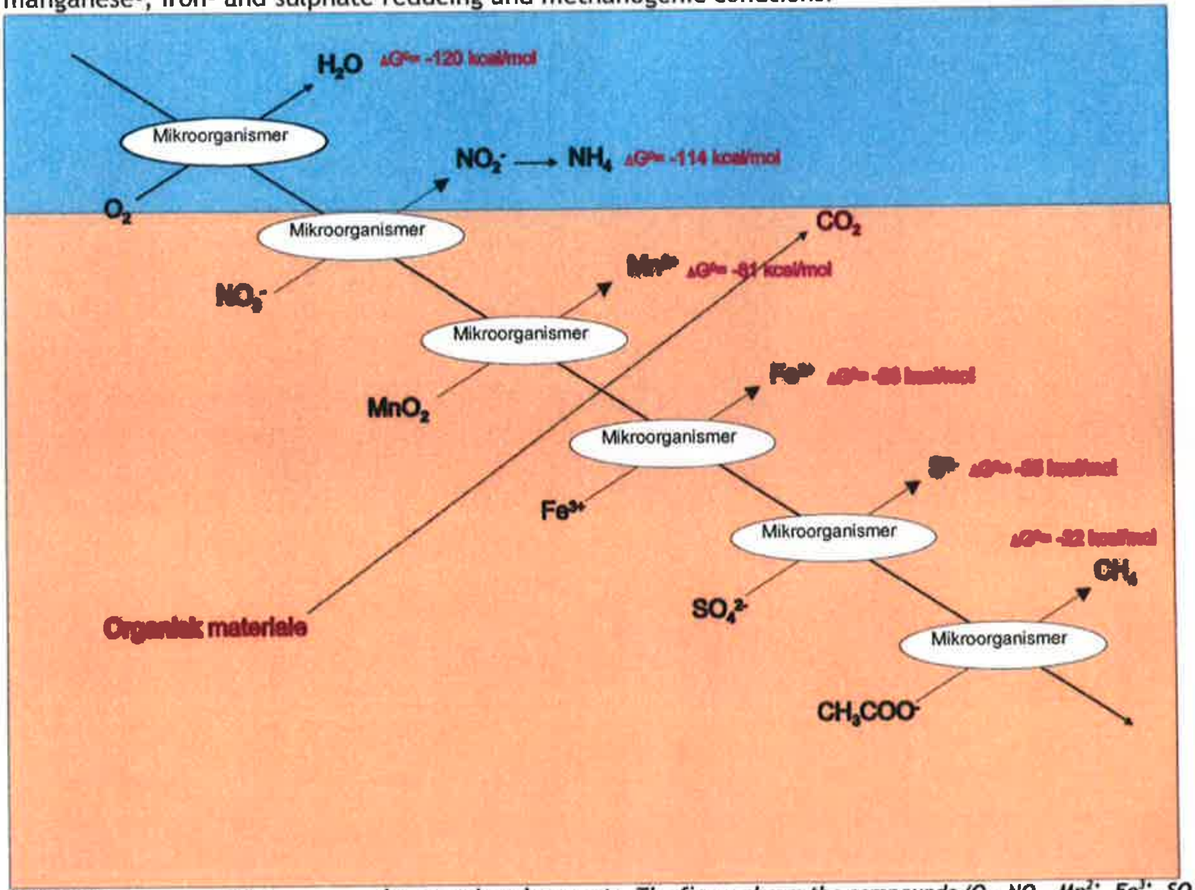

Figure 1: Important redox processes in natural environments. The figure shows the compounds (O_2, NO_3, Mn^{2+}, Fe^{3+}, SO_4^{2-}, CH_3COO^-) used by microorganisms to oxidise organic material. If a compounds is not present or used up, microorganisms use the one placed under.

Degradation of cultural layers occur fastest at aerobic conditions in the presence of oxygen, followed by nitrate-, manganese-, iron- and sulphate reducing and methanogenic conditions. Good preservation conditions are generally characterised by sulphate-reducing and methanogenic redox conditions, bad preservation conditions by aerobic and nitrate-reducing conditions.
Redox conditions in soil are assessed by measuring the concentration of redox sensitive parameters in soil and/or groundwater. Redox sensitive parameters are
oxygen
ammonium and nitrate as the reduced and oxidized nitrogen species,
two and four valent manganese, as well as two and three valent iron as the predominant reduced and oxidized metal species,
sulfide and sulphate as the reduced and oxidized sulphur species
methane

For instance, high oxygen concentrations in soil indicate aerobic conditions and high degradation rates for organic material in cultural layers. At these conditions nitrogen occur as nitrate, iron as three valent iron oxides and only low concentrations of sulfide are detected. If the environmental conditions are iron reducing, oxygen and nitrate are already used up and nitrogen occur as ammonium. Elevated concentrations of reduced two valent iron (Fe II) can be measured but only low concentrations of sulfide.

Other factors influencing on the preservation state of cultural layers are water content in soil and the permeability of soil for water and air. The permeability determines infiltration of oxygen rich water and diffusion of oxygen in the soil.
pH and concentration of soluble salts affect corrosion of metal surfaces, for instance, low pH and saline conditions accelerate corrosion of metals and weathering of bones and biotic artefacts.

4. Description of the field site and methods

The characterisation of the environmental conditions was performed at an excavated soil profile near a pile at Hotel "Klubben" in Tolbodgaten, Tønsberg (Norway) (see fig. 2).

Figure 2: Field location at Hotel "Klubben" in Tønsberg

The pile was installed in 1991, and consisted of a steel tube of ?? cm in diameter that was filled with concrete and a steel rod. The pile was placed about 50 cm inside the outer wall of the building and was not dissected because of structural concerns. A girder of concrete was placed at a depth of 1.6 m below surface along the wall. The trench that was excavated when the girder was installed, was refilled with coarse gravel and stones. The cultural layers start at 110 cm below surface and continue below the excavated pit.
The soil profile was excavated on May, the 29th 2007 up to a depth of 2.2 m below surface. Field work was conducted on the two following days. During and before field work air temperature was about 15° C and it rained about 20 mm between 29.-31.5.2007. Samples were predominantly taken from the north-eastern profile and most of the field measurements were carried out at that profile. Because of many stones in the coarse filling material near the surface measurements were not performed in these layers. Only few measurements were conducted in the western profile under the girder that extended 160 cm below surface.
Electric conductivity, pH, water content and oxygen were measured in field at different depths in the profiles and at different distances from the pile.
Soil samples were taken at various distances from the pile and at different depths using a hand auger with a cylinder diameter of 2,5 cm. The auger was horizontally driven into the profile and samples were taken from 20-50 cm in the soil. Soil samples were immediately packed in 500 ml zipper bags that were packed in additional zipper bags containing a sachet of Anaerocult A (VWR international). This ensures that the physical-chemical properties of the samples do not change significantly. Soil samples were stored at 4° C and opened in a nitrogen atmosphere in a glove box to keep anaerobic samples free of oxygen. All extractions of redox sensitive parameters were conducted in a nitrogen atmosphere. Soil samples were analysed for nitrate (NO_3^-), ammonium (NH_4^+), reduced (Fe^{2+}) and oxidized iron

(Fe^{3+}), sulphate (SO_4^{2-}), (acid volatile) sulphide (S^{2-}), pH, electric conductivity, redox potential, water content and loss on ignition.
Additionally, two timbers that were located 178-188 cm (log 1) and 188-193cm (log 2) below surface parallel to the north-eastern profile were examined with respect to wood density and strength. Wood strength was manually measured as penetration depth of a screw driver (4.5 mm in diameter) in the timber.

Figure 3: Field work at the excavated north eastern profile. On the left the girder is shown. The tubes that reach over the pit are electric power cables.

Figure 4: Installation of the oxygen sensor in the profile.

5. Results

The measured values of the field and laboratory analyses are presented in fig. 6 - 15. Some of the parameters like water content and pH were measured both in field and laboratory, but at different sampling points in the profile. Although different measurement methods were used in field and in laboratory, the measurements at adjacent sampling points are comparable and results of these parameters (pH, water content) therefore presented together. Electrical conductivity was also measured both in field and in laboratory. The field measurements were not reliable because of problems with temperature compensation. Data on electrical conductivity are therefore only presented for laboratory measurements. The figures show the measurement data at the single sampling or measurement point in red font. The grid based contour map shows the distribution of a parameter over the whole profile and is generated by geostatistical gridding using the software Surfer 6.0 (Golden Software). The contour grids reflect trends that are suggested in the data and interpolated data might deviate from real conditions.

5.1 Measurements in the north eastern profile

A picture of the soil profile with the main soil layers is shown in fig. 5.

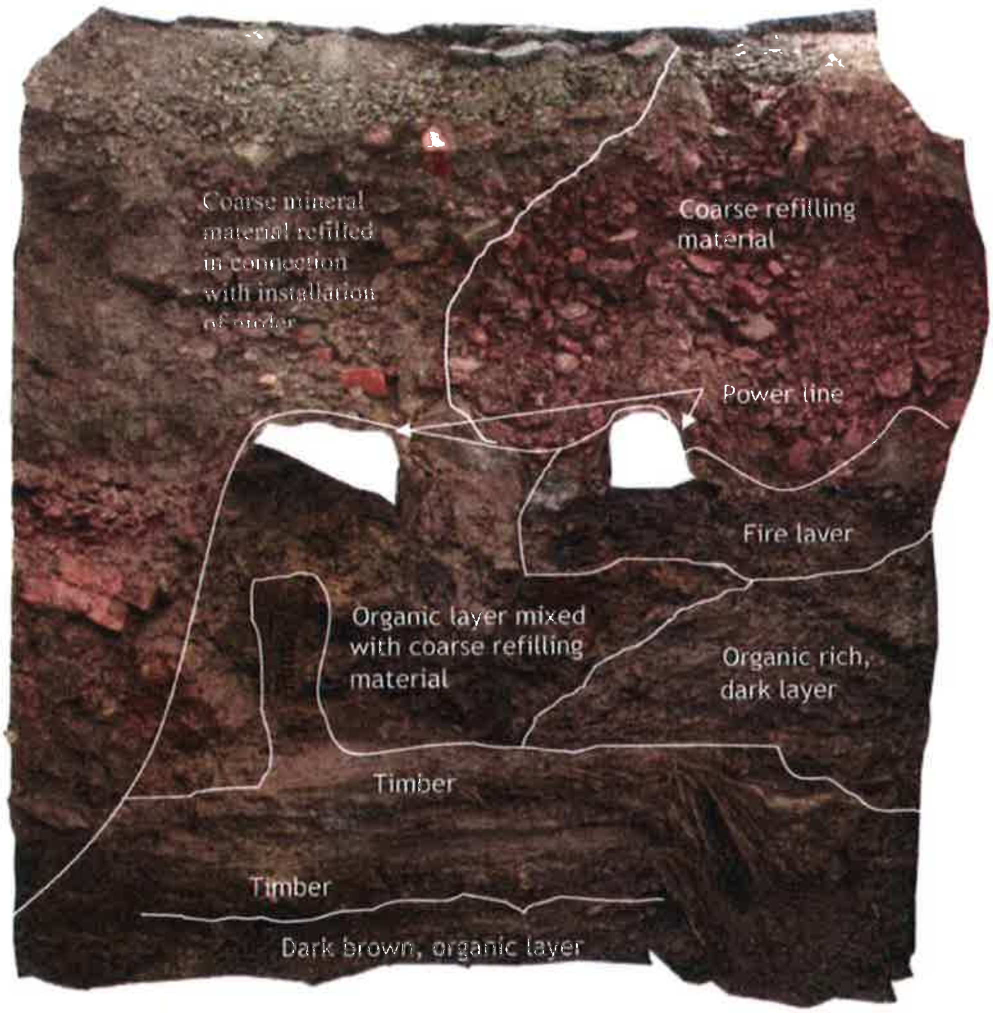

Figure 5: North eastern soil profile with soil layers

5.1.1 Oxygen

Oxygen concentrations in the soil profile varied between 0 and 104% oxygen saturation in the profile (fig. 6). Highest saturation was measured near the girder in a depth of 130 cm below surface where soil consisted of coarse gravel and bricks. With increasing depth and distance from the girder oxygen concentrations gradually declined. At depths below 180 cm oxygen concentrations dropped to 0% over the whole profile except for one measuring point where 2.2% oxygen saturation was measured. At a distance of 200 cm from the girder low oxygen concentrations were measured at soil depths of 100 cm below surface.
The soil porosity was measured in the same 13 areas as the oxygen, showing porosities between 32 and 86% (Appendix 1). The air filled porosity varied between 15 and 0% (by volume), with the highest air contents in the upper soil strata and in two wood logs.

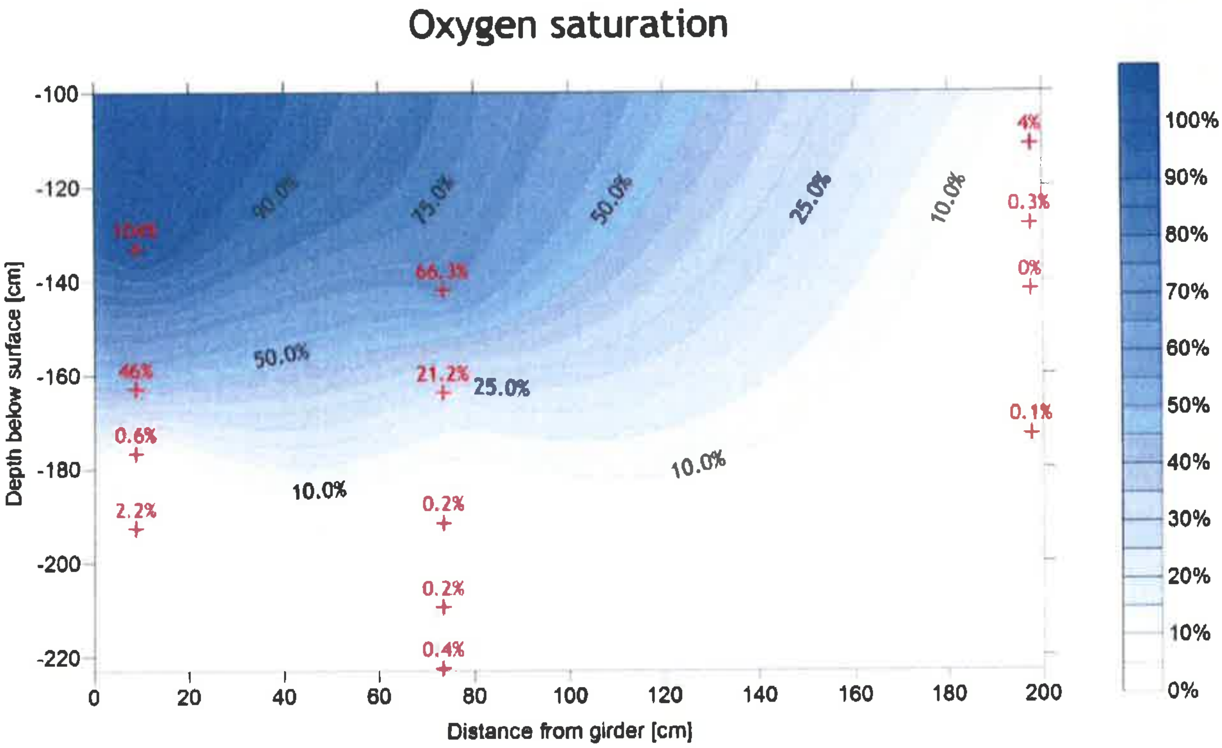

Figure 6: Oxygen saturation in the north-eastern profile

5.1.2 Water content

The volumetric water content in the soil profile was relatively high and varied between 15.3 and 85% (fig. 7). Highest water content was measured in a decayed timber at a depth of 160 and 180 cm and in the organic layer below 210 cm. The lowest water content was measured near girder in the coarse refilling masses at a depth of 160 cm. There was a gradient of the water content from the refilling masses along the girder to the cultural layers that are rich in organic material.

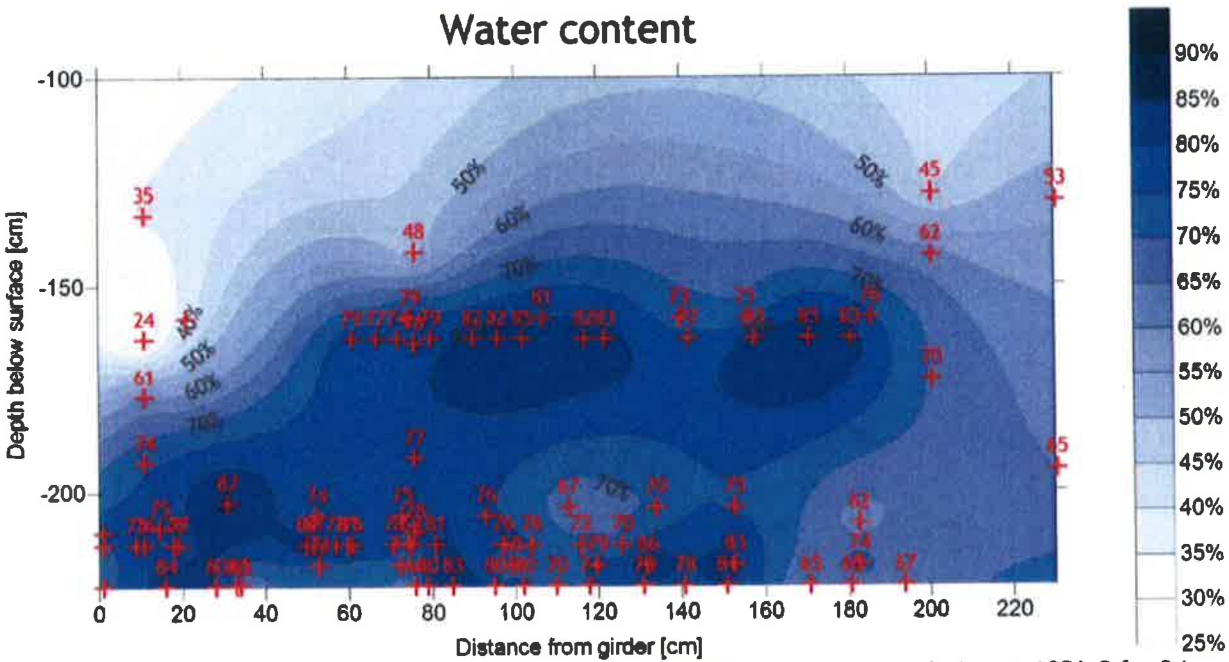

Figure 7: Volumetric water content in soil measured with TDR-sensors and by drying at 105° C for 24 hours

5.1.3 Organic material (loss on ignition)

Loss on ignition is the part of a sample that is lost after heating at 560° C for more than 6 hours and represents the portion of organic material in a sample (fig. 8). The organic content in soil varied between 3 to 94%. The lowest organic content was measured in the coarse refilling material near the girder and above the cultural layers near the surface. Highest organic contant was measured at a depth of 190 to 225 cm where timbers and organic deposits were located. In the cultural layers below 180 cm the organic contant varied between 24 and 95%. A gradient with increasing organic material was found with increasing distance from the girder (and refilling material) at 160 cm depth.

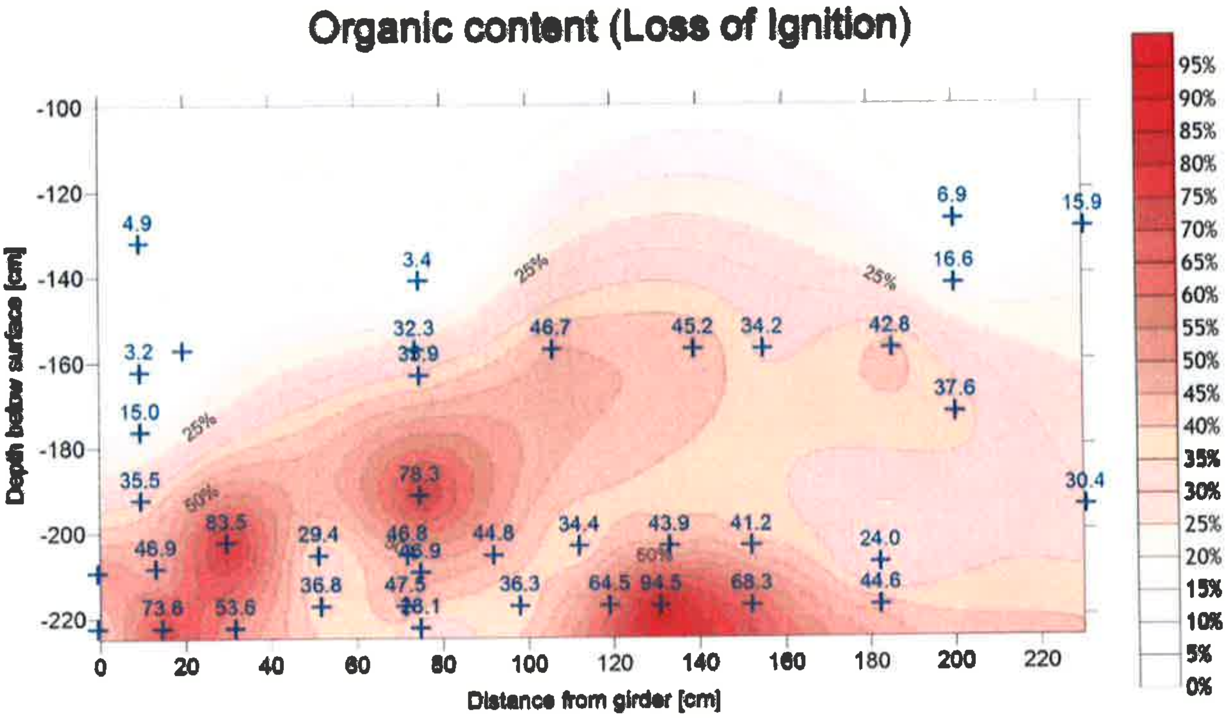

Figure 8: Organic content (loss on ignition) in the soil of the north eastern profile

5.1.4 Electrical conductivity

Electrical conductivity varied between 100 and 550 µS/cm. Lowest conductivity was measured in the areas with highest oxygen saturation, i.e. the area with coarse refilling material along the girder. Relatively low conductivity was also measured at higher depth near the girder. With increasing distance from the pile/girder the conductivity gradually increased, most distinctly in major depth.

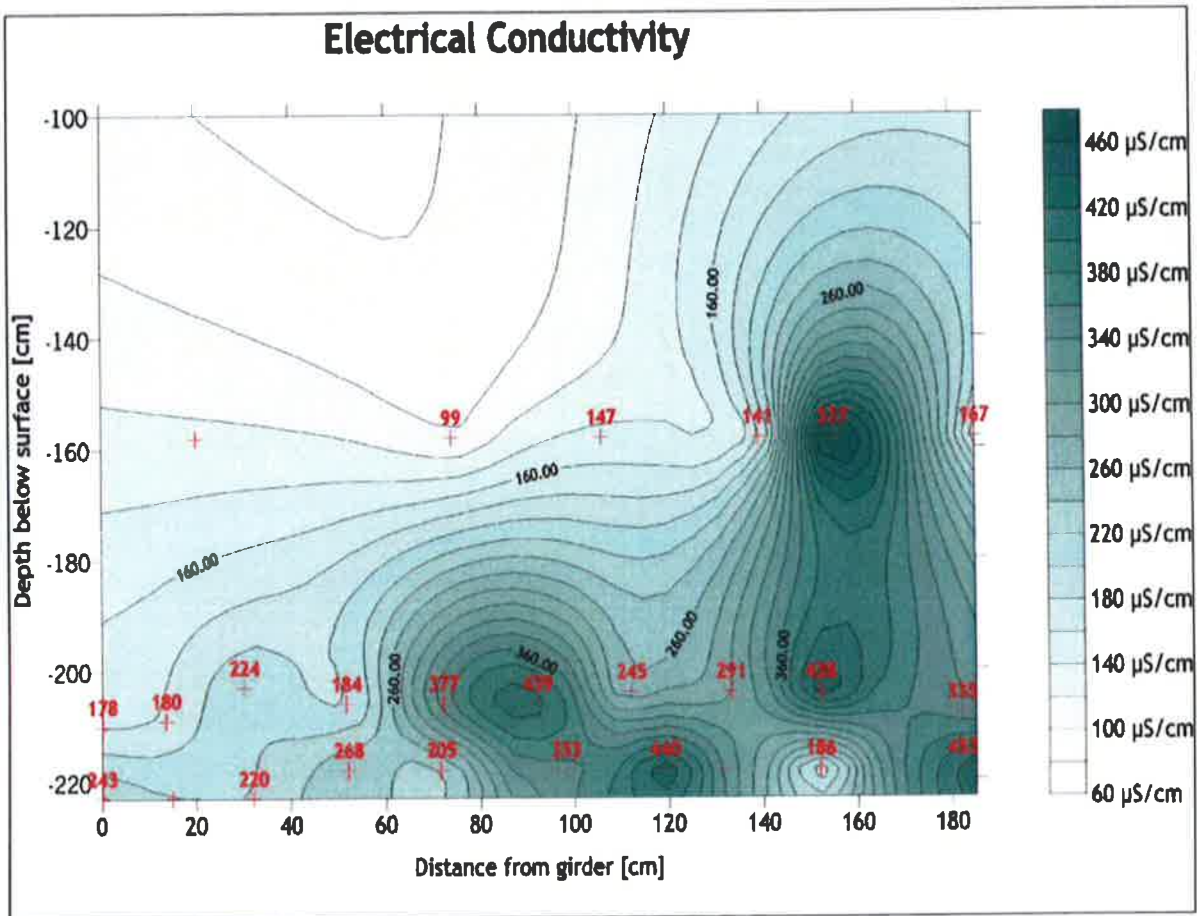

Figure 9: Electrical conductivity in the soil of the north eastern profile

5.1.5 pH-value

pH-value varied only slightly in soil between pH6.0 and pH6.8. Lowest pH-values were measured near the girder and in the areas with higher oxygen saturation. At major depth below 200 cm and at great distance from the girder the pH-value was higher with values between pH 6.4 and 6.8.

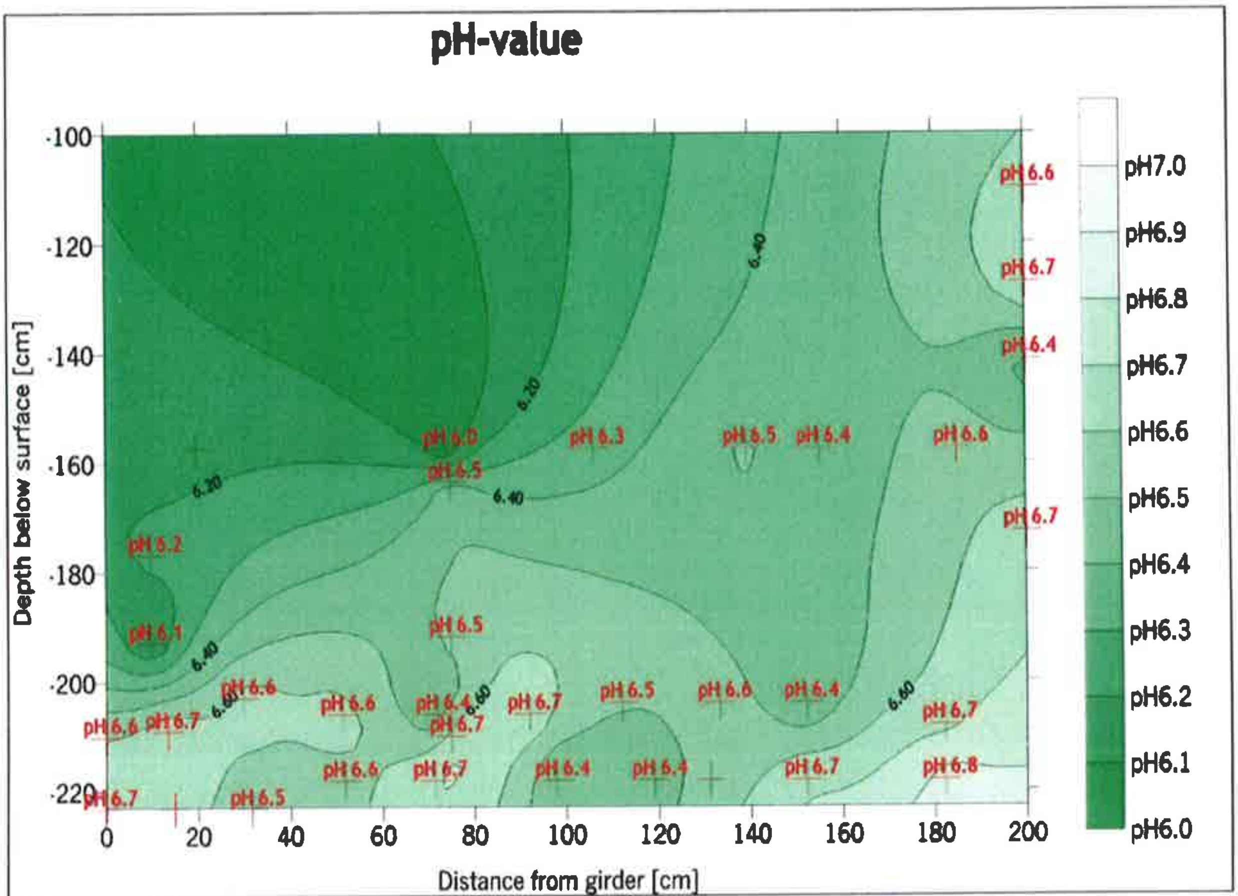

Figure 10: pH-value in the soil of the north eastern profile

5.1.6 Redox potential

The redox potential in the north eastern profile varies only slightly between 23 and 65 mV (fig. 11). The highest redox potential was measured in the sampling point where the highest oxygen concentration was measured, i.e. in the area near the girder with coarse refilling material. Lowest values (<30 mV) were measured in major depth of the profile and at a distance of 100 - 140 cm from the girder. At a greater distance from the girder redox potential increases again.

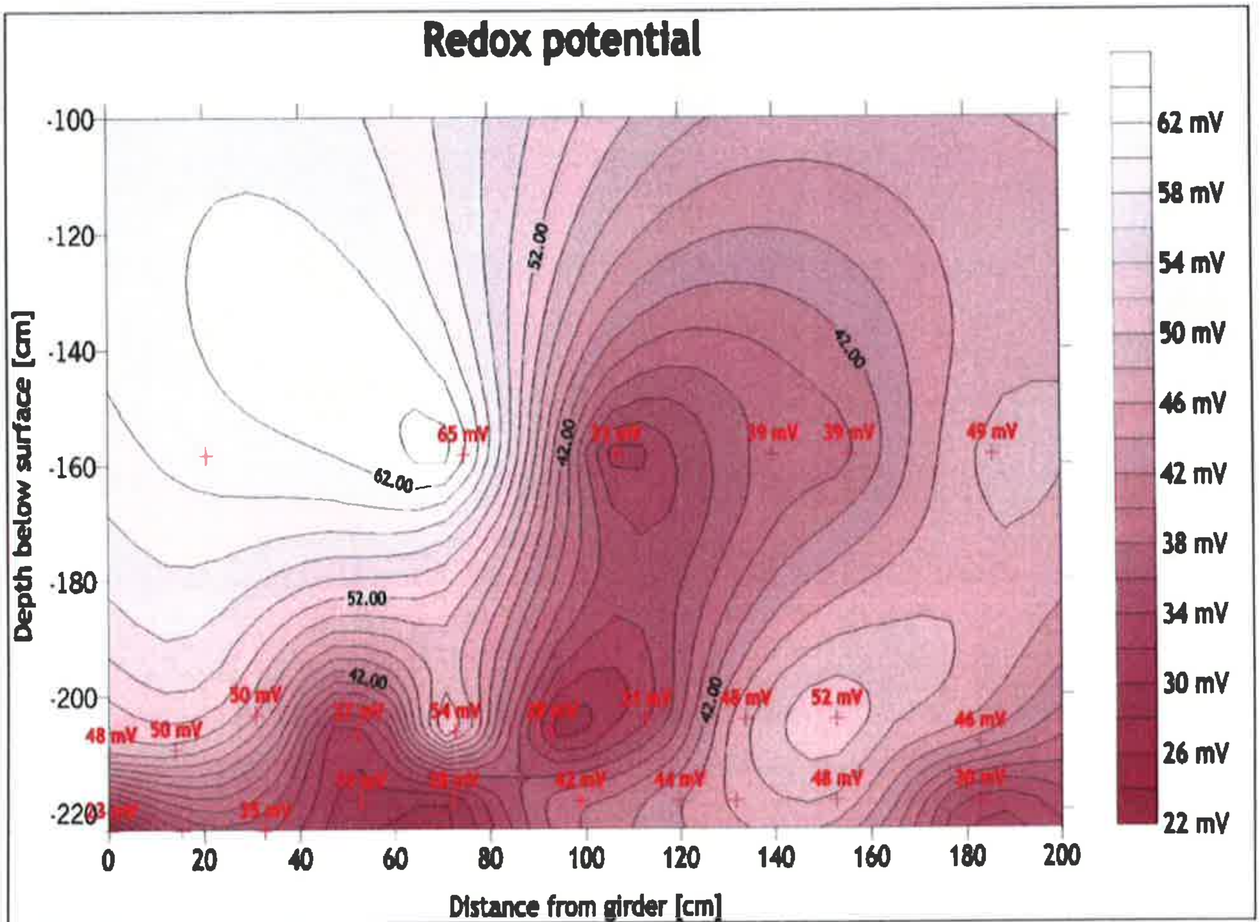

Figure 11: Redox potential (standard electrode potential) in the north eastern soil profile

5.1.7 Reduced and oxidized nitrogen species

Ammonium represents the major reduced species of nitrogen in natural environments, while nitrate is the oxidized species. The ratio of molar concentrations of reduced and oxidized species can be used to assess the redox conditions in natural environments and addresses the predominant redox processes at a certain sampling point. A ratio of 1 indicates that concentrations of reduced and oxidized species are equal.

Nitrate concentrations in the soil profile are very low while ammonium concentration varied between 12 and 388 mg/kg dw. In all sampling points the ammonium concentration was considerably higher than the nitrate concentration. The concentration of the reduced ammonium from 11 to almost 400 mg/kg. What is more, there is a trend that the ammonium concentration gradually increased with increasing distance from the girder.

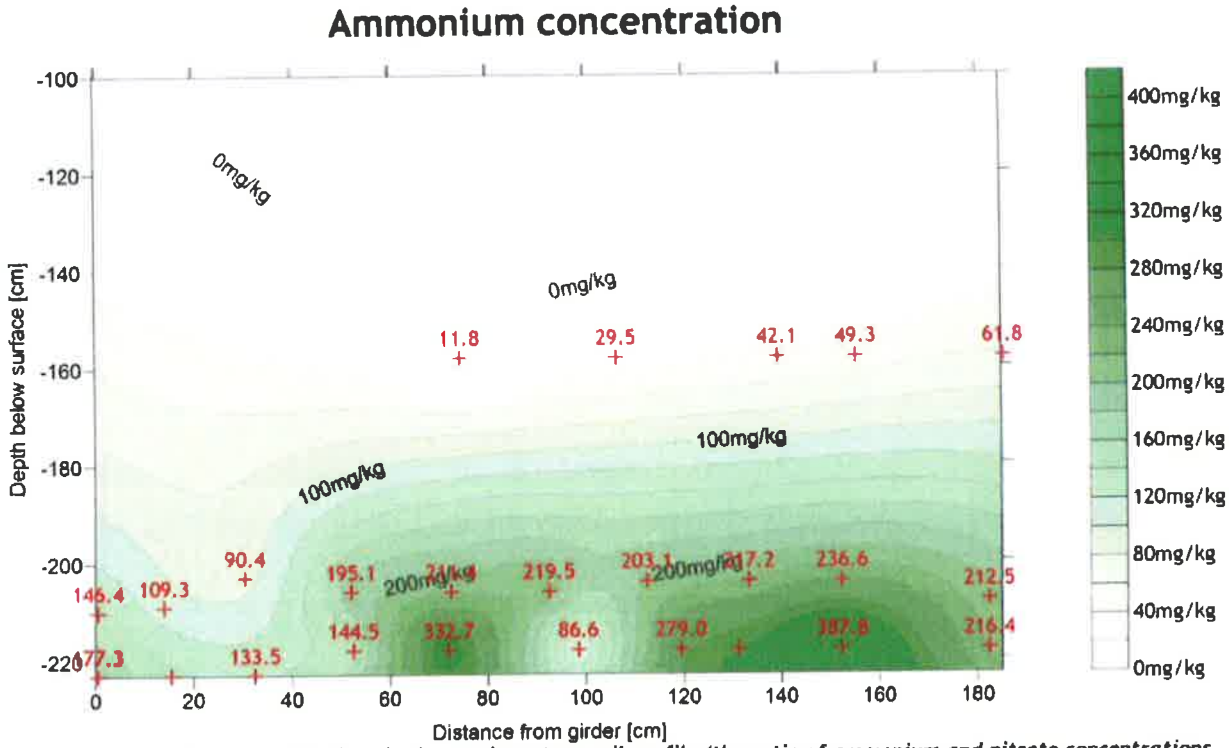

Figure 12: Ammonium concentrations in the north eastern soil profile (the ratio of ammonium and nitrate concentrations could not be shown because nitrate concentration in several sampling points were below detection limit).

5.1.8 Reduced and oxidized iron species

The ratio of molar concentrations of reduced and oxidized iron, namely two (Fe(II)) and three valent iron (Fe(III)) increased with increasing depth below surface and increasing distance from the girder/pile. The distribution of reduced and oxidized iron in the soil profile is similar to the distribution of oxygen. In areas with high oxygen saturation iron predominantly exists as oxidized iron (Fe III), whereas in areas with oxygen saturation near zero, iron exists for more than 90% as reduced iron (Fe II). This is the case for soil layers below 180 cm depth or with a minimum distance of 100 cm from the girder.
Compared to the distribution of reduced and oxidized nitrogen species, the reduced iron species exceeded oxidized species first at major depth and greater distance from the girder than reduced nitrogen species.

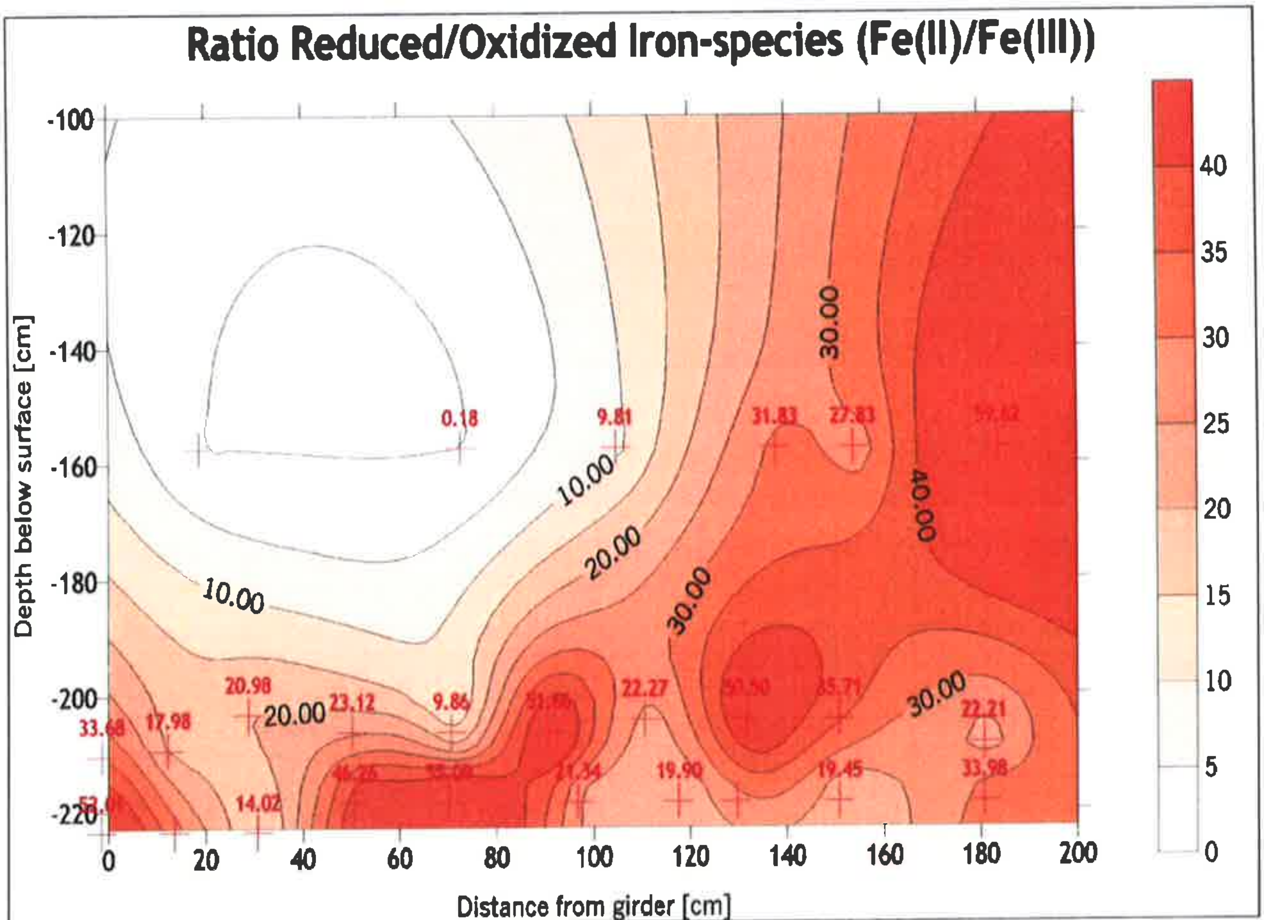

Figure 13: Ratio of reduced and oxidized iron species in the north eastern soil profile

5.1.9 Reduced and oxidized sulphur species

The ratio of reduced sulfide and oxidized sulphate in the soil profile was generally lower than that of the other redox pairs (ammonium/nitrate, Fe(II)/Fe(III)). Except of one value the ratio did not exceed 15 illustrating that there are considerable amounts of sulphate in the soil ranging from 6 to 250 mg/kg. Sulfide was also detected in all samples and varied between 60 and 270 mg/kg.
The ratio of reduced and oxidized sulphur species followed the same pattern as that of the other redox pairs with lowest values near the girder and close to the surface and high values at major depth and a distance of 120 cm from the girder.

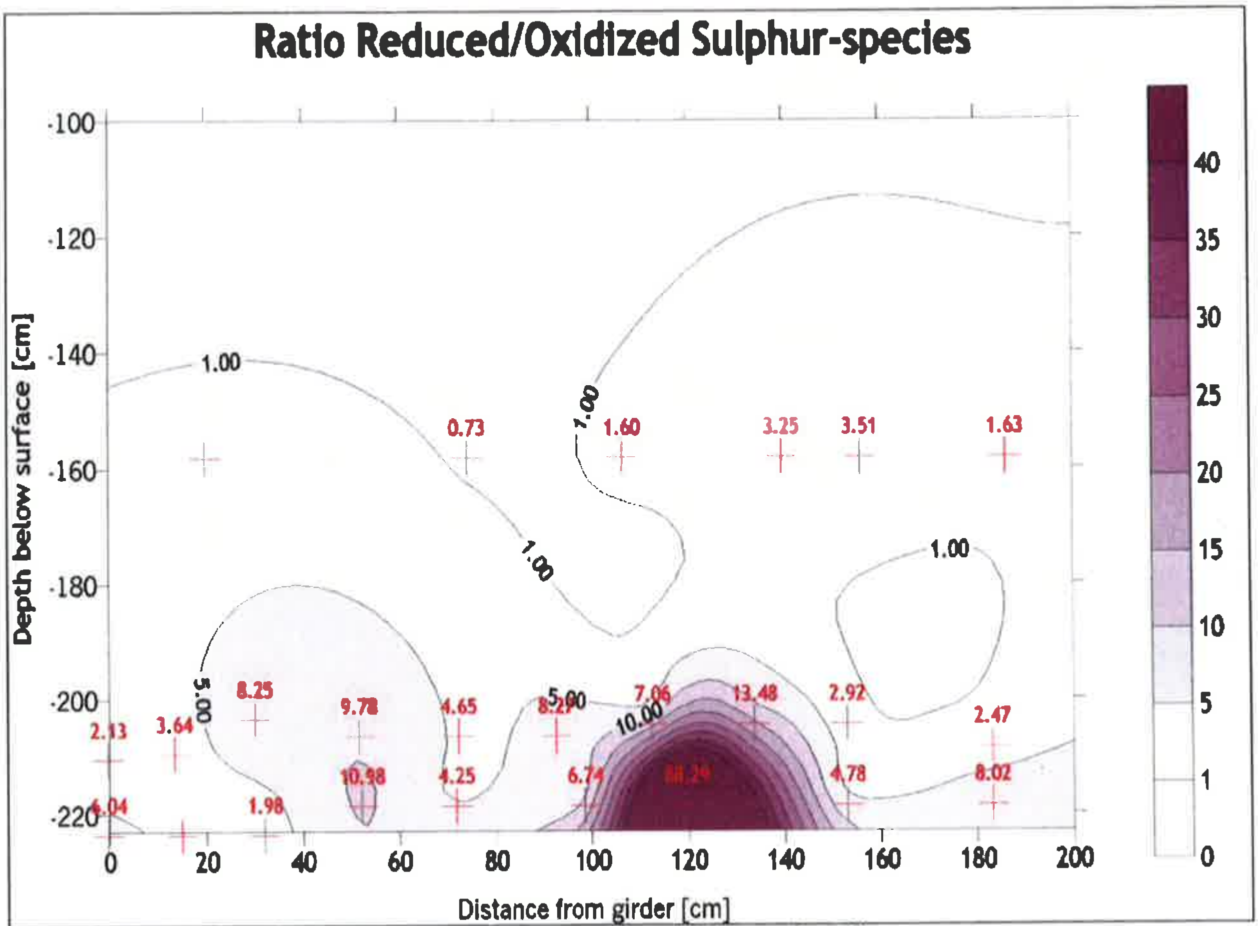

Figure 14: Ratio of sulfide and sulphate concentrations in the north eastern soil profile.

5.2 Assessment of the state of preservation of 2 horizontal logs

Two horizontal logs were encountered at 178-188 cm (log 1) and 188-193 cm (log 2) beneath the ground surface (figure 15). They were lying perpendicular to the girder, which made it possible to study if there was a gradient in their state of preservation with increasing distance to the girder and foundation pile.

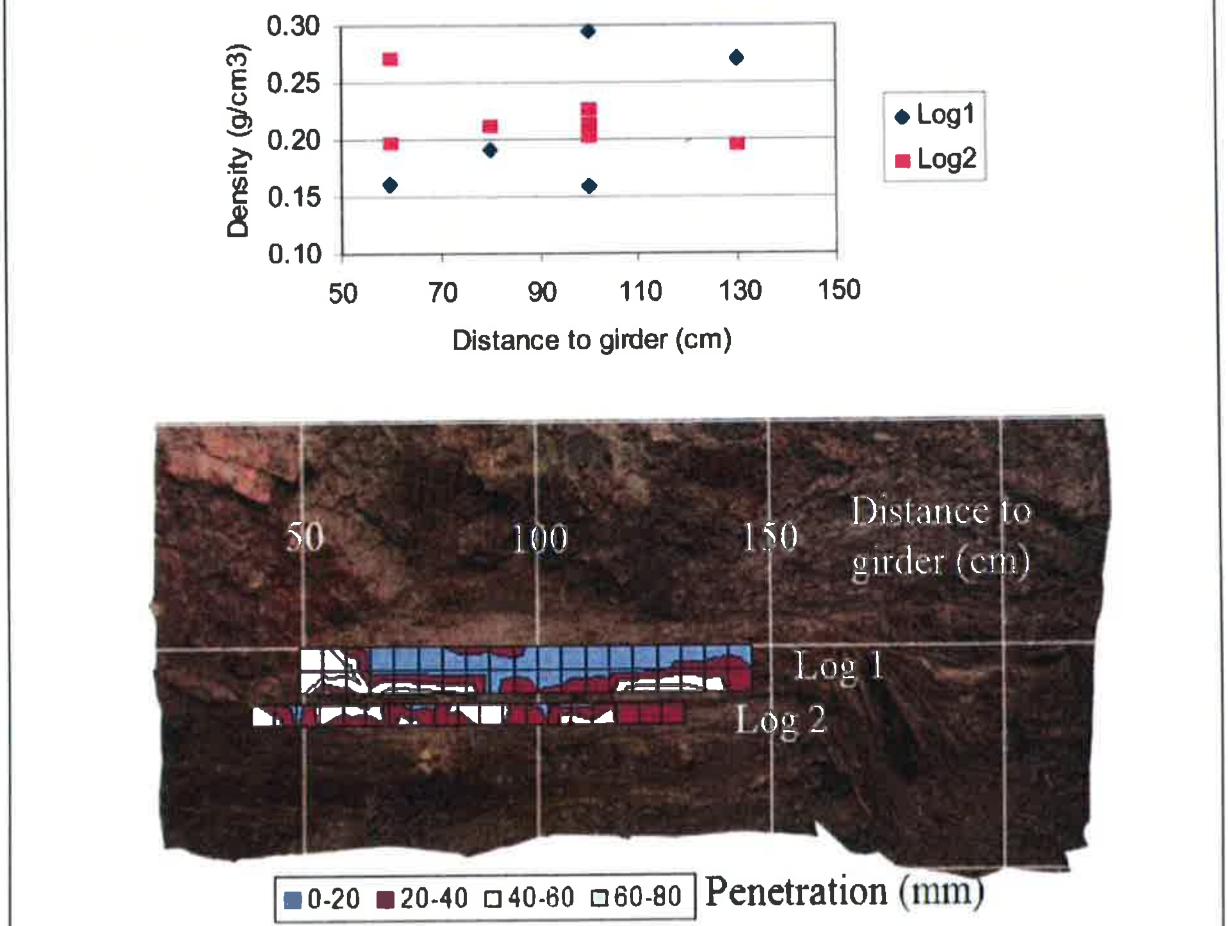

Figure 15: Density and penetration strength of two logs. The density was measured in the laboratory on subsamples from the logs, while the penetration strength was measured in situ as the depth of penetration of a 4.5 mm thick screwdriver pressed firmly into the wood.

12 samples were taken for measuring the density of the wood logs (figure 15 upper), giving results between 0.16 and 0.29 g/cm^3. These densities all indicate quite deteriorated wood (for comparison fresh pine tree has a density of 0.35-0.50 g/cm^3) and there is no clear density gradient from the girder and outwards. The penetration strength was measured in triplicate for each 5 cm, and indicated soft and decayed wood. There is a slight tendency that log 1 is more decayed in left hand side near the girder (penetration > 60mm) but this is not necessarily due to the girder or foundation pile: It is the left hand end of the log and fungal decay often takes place from the ends. The right hand end of log 1 was destroyed by the caterpillar and couldn't be used as a reference.

5.3 Measurements in the western soil profile

From the western profile only a few field and laboratory measurements of the soil samples were conducted. The results from the laboratory are shown in table 1. The water content in all samples of this profile was somewhat lower than in the north eastern profile but fairly constant in all three sampling points. For comparison the field measurements showed volumetric water vontents of 74-79% vol, with no clear gradient. The organic matter content varied between 20 and 47% but no gradient could be observed. The ratios of nitrogen, iron and sulphur species decreased with increasing distance from the pile.

Table 1: Measurements in the western profile

Depth below surface [cm]	Distance from pile [cm]	Water content	Loss on ignition	pH	Conductivity [µScm -1]	Redox potential [mV]	Ratio NH4+/NO3-	Ratio Fe II/Fe III	Ratio SO4/S2-
140	**50**	**62.13 %**	**31.30 %**	**6.38**	**212.5**	**42**	**32**	**255**	**1.5**
140	**60**	**66.22 %**	**46.90 %**	**6.47**	**177.3**	**33**	**30**	**73**	**1.5**
140	**90**	**60.71 %**	**20.60 %**				**2.3**	**0.20**	**0.9**

6. Discussion

6.1 Assessment of the environmental conditions in the soil profile

6.1.1 Characterisation of the redox conditions in the north eastern profile

The redox conditions in the profile are characterized using the ratio of the redox couples of nitrogen, iron and sulphur, as well as the oxygen concentration in the profile according to the principle described in chapter 3.1. Because the figure uses contour grids that are estimated by geostatistical gridding (see chapter 5) the boundaries of the different redox zones are not distinct as presented and real conditions might deviate somewhat. The zones indicate what kind of redox processes predominantly take place in the different parts of the profile based on geochemical characterisation.

The investigation shows that oxygen reaches the modern fill near the building and spreads from there into the cultural deposits. The high oxygen concentrations are accompanied by relatively low concentrations of ammonium and high concentrations of oxidized iron and sulphate. This indicates that the conditions in the area near the building down to a depth of 170 cm and a distance of 110 cm from the girder are aerobic (fig. 16). The low ratio of reduced to oxidized nitrogen species, as well as iron and sulphur species indicates that oxygen is present in this area over longer time periods.

Outside the aerobic zone redox conditions rapidly change with increasing depth and distance from nitrate reducing to iron reducing conditions (fig. 16). The iron reducing zone begins approximately at 190 cm depth and at a distance of 110 cm from the girder. The iron reducing zone is characterised by elevated concentrations of reduced two valent iron (Fe II). If oxygen occasionally reaches this zone e.g. with percolating water, it is instantly spent for the oxidation of Fe II to Fe III and probably not for the oxidation of organic material. According to Christensen et al. (2000) oxidation of Fe II proceeds very rapidly because this reaction does not involve complex changes in the molecular configuration while oxidation of organic material has to be mediated by microorganisms and proceed much more slowly. The sulphate reducing zone that is characterised by elevated concentrations of sulfide and the typical smell of addle eggs, is found at a depth below 200 cm.

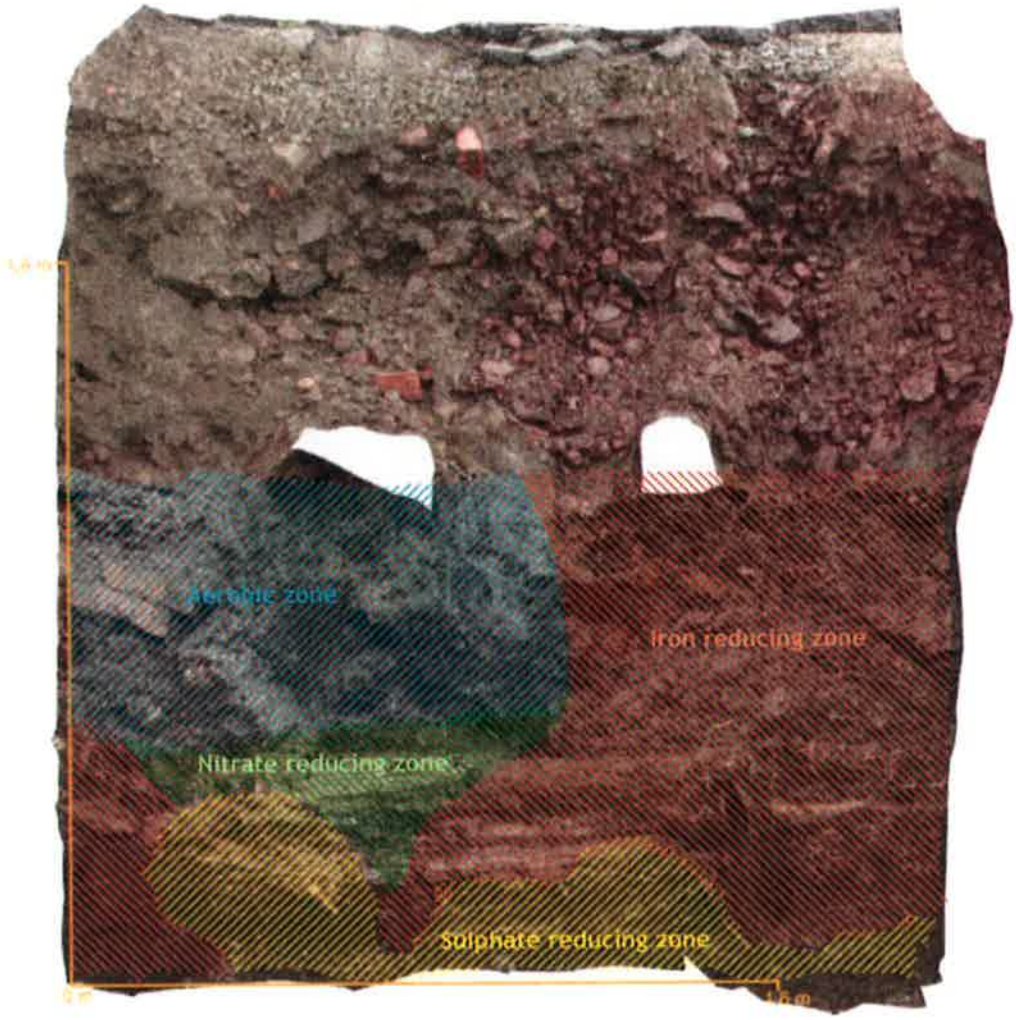

Figure 16: Redox zones in the north eastern profile

The slightly lower pH in the aerobic zone implies that organic material is biologically degraded and organic acids produced. However, this effect is not significant. The low electrical conductivity near the building indicates a higher permeability of the soil in this area. The overall low conductivity makes the influence of marine conditions unlikely in the profile. Concentrations of soluble salts that are measured as electrical conductivity in soil, are often higher in impermeable layers because salts are not washed out by percolating water. Lower salt concentrations and thereby also lower electrical conductivity indicate therefore higher permeability of the soil near the girder. Conductivity data indicate a higher permeability in soil down to depth of 180 cm and a distance of 140 cm from the girder.

The pH in the anaerobic zone (nitrate-, iron- and sulphate reducing zone) is slightly higher than in the aerobic zone and indicate lower degradation of organic material in that zone. Percolation of water seems to be hampered as indicated by higher electrical conductivity.

The redox potential reflects the redox conditions only partly. The distribution of high and low redox potentials approximate the redox conditions in the soil profile, however, the range between 23 and 65 mV is rather small and indicates aerobic and nitrate reducing conditions (Chapelle et al. 1996; Bjerg et al. 1995). Christensen et al. (2000) concludes that redox potential is not a suitable parameter for the characterisation of the dominant redox processes and at best should be used qualitatively. The impracticality is explained by the fact that the redox potential reacts very sensitively only on the concentration of reduced and oxidated iron compounds but not on other redox couples.

The water content in the profile is fairly high, which is not surprising given the high preciptition before and during field work. The high water content indicates that the majority of pores in soil are filled with water - samples from soil sample rings show air filled porosities of up to 10-15 % vol in the upper soil layers and in the wood logs, and down to a few % in the deeper, organic layers (appendix 2). The excavated soil profile is in the unsaturated zone above the groundwater level, however, it is not known how far the investigated profile is from the average groundwater level. It is difficult to assess the variation of the water content in periods with less precipitation. Nevertheless, if the water content in soil stays at a high level , oxygen diffusion in soil is impeded because water filled pores reduce oxygen diffusion considerably in soil.

The organic content in the soil varied greatly and reflects the location of the cultural layers at a depth of 150 cm and below. The increasing organic contant with increasing distance from the girder might reflect degradation of organic material in the aerobic area near the girder and near the surface but is at lower depth also due to replacement of organic rich material by coarse refilling material. In the cultural layers the organic contant varies considerably and is reflects the heterogenity of soil constituents in the cultural layers.

The preservation conditions for the cultural layers are considered to be bad in the aerobic and nitrate reducing zone because degradation rates for organic material are expected to be rather high and deterioration of the cultural layers accelerated. Good preservation of the cultural layers are expected in the iron and sulphate reducing zone. Degradation rates of organic material are usually lower in this zone at moderate sulphate concentrations and oxygen that reaches these zone is likely used for the oxidation of reduced iron (Fe II) instead of organic matter.

6.2 Redox conditions in the western profiles

The concentration ratios of the redox couples in the western profile indicate that redox conditions become more oxidized with increasing distance from the pile. In the sampling point 50 and 60 cm from the pile redox conditions are iron reducing with high concentrations of reduced iron (Fe II), in the sampling point 90 cm from the pile they are nitrate reducing with high concentrations of ammonium and oxidized iron (Fe III).

6.3 What causes oxygen intrusion into the cultural layers?

Oxygen intrusion into the cultural layers can be caused by the presence of several construction elements in the ground. The pile that is located 50 cm inside the foundation wall of the building can cause preferential flow of oxygen rich rainwater along the walls of the pile and enable diffusion of oxygen into deeper soil layers. On the other hand, the girder and the coarse refilling material used along the girder might facilitate oxygen transport into the cultural layers. Oxygen can easily diffuse along the girder downwards into the soil or through the large pores of the coarse refilling masses. Additionally, rain water rich in oxygen can easily infiltrate through the coarse material or along the girder.

If the pile is responsible for oxygen intrusion, the redox conditions should be oxidative at the pile and become more reductive with increasing distance from the pile. This is true for the north eastern profile with aerobic redox conditions nearest the pile. However, for the western profile this is not the case: here the redox conditions are more reductive near the pile and become more oxidatative with increasing distance from the pile. Another explanation for the aerobic conditions and more oxidative conditions in the north eastern profile is the adverse effect of the girder and the coarse refilling material. Its location and the size of the aerobic zone makes it likely that oxygen has been transported from the surface through the coarse material along the girder and has spread in the cultural layers. This has resulted in more oxidative conditions near the girder at a depth where the girder shields a possible effect from the pile. It is therefore unlikely that the aerobic conditions in the north eastern soil profile are caused by the pile.

7. Conclusion

Conductivity measurements in the soil profile revealed highly permeable layers along the girder where coarse material was refilled after foundation works. Field measurements and laboratory analyses indicate aerobic conditions in this material and it seems that this coarse material facilitates the transport of oxygen from the surface into deeper layers down to approximately 170 cm. Oxygen spreads into the cultural layers, which results in nitrate or iron reducing redox conditions instead of sulphate reducing conditions. The influence of oxygen intrusion on redox conditions can be detected down to a depth of about two meters and a distance of 1.2 m from the girder. In that zone the environmental conditions might accelerate degradation of cultural layers.

The location and size of the aerobic zone indicates that oxygen intrusion into cultural layers is facilitated by the coarse refilling material along the girder. The adverse effect of the coarse refilling material totally overshadows a possible adverse effect of the pile. If piling facilitates oxygen intrusion in cultural layers, this effect is either much smaller than the effect of the girder and refilling material or its range is less than 0.5 m (the distance of the pile to the first measuring point).

The investigations that were especially performed in the north eastern soil profile show that the characterisation of the redox conditions by measurement of the redox sensitive parameters (oxygen, nitrate, ammonium, oxidised and reduced iron, sulphate and sulfide) is a suitable approach to assess the preservation conditions in cultural layers. The organic content in the profile varies considerably but nicely reflects the location of the cultural deposits. Lower organic contents near the girder and near the surface indicate degradation of organic deposits due to elevated oxygen concentrations but also partly reflect the replacement of organic rich cultural deposits by mineralic refilling material. The water content in the profile is rather high in the cultural layers but considerably lower near the girder and in the gravel material. It can be concluded that in the organic rich layers pores are predominantly filled with water.

8. References

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9. Appendix

Nr	Material
1	Results of the field measurements
2	Results of the laboratory measurements

Appendix 1: Field measurements

Water content		
Depth below surface [cm]	Distance from girder [cm]	Water content [% Vol]
North eastern profile		
-63	150	74.3
-71	150	75.4
-81	150	77.3
-112	150	83.7
-119	150	78.4
-123	150	75.6
-133	150	78.0
-133	150	78.0
-143	150	80.6
-159	150	76.4
-166	150	75.9
-178	150	71.5
-188	150	70.4
-63	150	75.4
-73	150	75.5
-80	150	77.6
-114	150	81.0
-122	150	81.4
-137	150	67.5
-123	100	79.0
-129	100	77.3
-134	100	74.3
-142	100	78.5
-152	100	81.9
-158	100	82.4
-164	100	84.8
-179	100	82.2
-184	100	83.1
-204	100	76.8
-220	100	82.9
-233	100	84.7
-243	100	83.3
-90	160	80.4
-96	160	64.6
-141	160	80.4
-147	160	83.2
-157	160	80.4
-172	160	70.2
-164	160	79.9
-180	160	74.1
-193	160	77.5
-203	160	78
-213	160	80.6
-233	160	65.1
-243	160	64.7
-256	160	66.7
North western profile		
-175	15	77.3
-175	32	74.4
-175	59	78.9
-175	63	79.1

Oxygen, pH-value						
10	133	2	27.03	18000	104	
10	163	1	35.9	23000	46	
10	177	2	50.1	39000	0.6	6.22
10	193	1	56.7	40000	2.2	6.1
75	142	1	32.4	22000	66.3	
75	164	2	45.28	43000	21.2	6.46
75	192	3	58.66	31900	0.2	6.52
75	210	3	58.66	25100	0.2	6.7
75	223	3	58.64	17100	0.4	6.75
200	111	3	55.45	6700	4.0	6.63
200	128	3	58.51	20200	0.3	6.69
200	143	2	58.89	60200	0.0	6.36
200	173	1	58.66	33400	0.1	6.65

Appendix 2: Results of the laboratory measurements

Sample no.	Depth below surface [cm]	Distance from girder [cm]	Water content [%]	Loss of ignition [%]	pH	Conductivity [µS/cm]	Redox potential [mV]	Nitrate conc. [mg/kg dw]	Ammonium conc. [mg/kg dw]	Reduced iron conc. (Fe II) [mg/kg dw]	Oxidized iron conc. (Fe III) [mg/kg dw]	Sulphate conc. [mg/kg dw]	Sulfide conc. [mg/kg dw]
1	147	0	68.7	55.9	6.60	178	48	<3.0	146	135	4.0	249	177
2	146	14	65.6	46.9	6.68	180	50	<2.4	109	156	8.7	140	170
3	140	30	80.5	83.5	6.64	224	50	<4.4	90.4	145	6.9	53.6	147
4	143	52	64.1	29.4	6.64	184	27	<2.6	195	152	6.6	36.4	119
5	143	72	64.8	46.8	6.36	377	54	<2.6	218	169	17.1	103	155
6	143	92	65.8	44.8	6.69	439	28	<2.4	219	182	3.5	96.9	267
7	141	112	55.7	34.4	6.51	245	31	<2.1	203	133	6.0	48.8	115
8	141	133	59.7	43.9	6.55	291	48	<2.3	252	178	3.5	31.3	121
9	141	152	64.8	41.2	6.40	438	52	<2.6	237	178	5.0	115	112
10	145	182	50.5	24.0	6.67	335	46	<1.9	247	182	8.2	96.2	68.1
11	155	182	64.3	44.6	6.84	453	30	<2.6	281	242	7.1	42.2	86.8
12	155	152	74.7	68.3	6.69	186	48	<3.4	388	184	9.5	32.3	51.4
13	155	131	78.7	94.5									
14	155	119	69.6	64.5	6.45	440	44	<3.1	279	160	8.0	5.8	171
15	155	98	57.0	36.3	6.38	353	42	<1.7	86.6	115	5.4	33.2	74.6
16	155	72	64.1	47.5	6.71	205	28	<2.7	333	240	4.4	36.2	51.3
17	155	52	61.9	36.8	6.57	268	29	<2.4	193	149	3.2	39.7	109
18	160	32	71.3	53.6	6.49	220	35	<3.3	133	108	7.7	104	68.7
19	160	15	76.4	73.6									
20	160	0	62.1	43.0	6.70	243	23	<2.5	177	243	4.7	76.4	154
21	95	185	66.7	42.8	6.56	167	49	<2.9	61.8	377	6.3	111	60.1
22	95	155	60.8	34.2	6.43	537	39	<2.4	49.3	21	0.8	92.4	108
23	95	139	63.0	45.2	6.51	141	39	<2.5	42.1	229	7.2	90.2	97.8
24	95	106	72.7	46.7	6.35	147	31	<3.5	29.5	546	55.7	223	119
25	95	74	70.5	32.3	6.02	99	65	<4.5	11.8	170	944.9	247	60.4

Volumetric distribution of the soil constituents determined in the soil profile

Sample	*Depth below surface*	*Distance from girder*	*Mineral material*	*Water*	*Organic material*	*Air*
10-70	133	10	52 %	35 %	3 %	9 %
10-100	163	10	65 %	24 %	3 %	8 %
10-114	177	10	35 %	61 %	7 %	-4 %
10-130	193	10	14 %	74 %	11 %	1 %
75-79	142	75	40 %	48 %	2 %	9 %
75-101	164	75	10 %	78 %	8 %	4 %
75-129	192	75	4 %	77 %	11 %	9 %
75-147	210	75	10 %	78 %	11 %	1 %
75-160	223	75	16 %	66 %	9 %	9 %
200-48	112	200	4 %	73 %	13 %	10 %
200-65	128	200	36 %	45 %	4 %	15 %
200-80	143	200	26 %	62 %	8 %	4 %
200-110	173	200	11 %	70 %	10 %	9 %