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level at the rear of
Nordre Bredsgården,
Bryggen in Bergen.
Results from MB21 and
testpit from 2006.

Henning Matthiesen

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Title:

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Summary:

The present report focuses on environmental monitoring in the unsaturated zone above the groundwater level in urban deposits. Results are presented from field measurements in a testpit at the northern end of Bugården at Bryggen, where the groundwater level has been lowered to 3 m below the ground surface, and where there is substantial settling ongoing at a rate of 6-8 mm/year. Results from laboratory analysis of soil samples from the testpit and from a coring (MB21) nearby are also presented. Finally initial results from monitoring equipment permanently installed in the soil are presented.

The results show that during the excavation in September 2006, there was almost full oxygen saturation in the upper 1 m of the soil profile. Below this depth a dense and wet layer of finely grained lime was found, which effectively reduced the downward flux of oxygen. Beneath the lime layer (at 1½ m below the soil surface) there was almost no oxygen left, even if the soil was not waterlogged. Conductivity measurements indicated relatively stagnant conditions and a modest water exchange through the lime, which was also confirmed by logging of the water content. An estimate is given of the oxygen flux down to and through the lime layer. This indicates that most decomposition takes place in the uppermost soil strata and that a finely grained layer can have a positive effect on the preservation conditions underneath. It is emphasized that the lime layer is a local phenomenon and not representative for all of Bryggen.

Valuable experience has been gained concerning monitoring in the unsaturated zone. It is recommended to continue and improve logging of oxygen and water content in order to get a better understanding of the oxygen dynamics in the unsaturated zone, and especially in order to find out how much water is necessary to reduce the decomposition rate to an acceptable level at the site.

Signatures



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Introduction

Measurements of the buildings and ground surface at Bryggen have shown that the buildings of the Bredsgården and Bugården tenement are settling at a considerable rate -- up to 8 mm/year (Jensen, 2004). Settling can be caused by several factors, but most evidence points towards decomposition of the organic cultural layers caused by drainage from the nearby hotel site.

Work has been carried out from 2002 to 2006 to document and systematise information about the state of preservation of the cultural layers below Bredsgården and Bugården, and especially to evaluate if there is an ongoing deterioration of the layers. Results from two testpits in the (former) eavesdrop area between the Bredsgården and Bugården tenements are presented in Matthiesen (2004b). In September 2006 a third testpit was made at the northern end of Bugården (Figure 1) in order to investigate the preservation conditions and the state of preservation of the deposits, and to install monitoring equipment in the unsaturated zone above the groundwater level. Dipwells MB7 and 8 are situated a few metres west of the testpit, and a new dipwell (MB21) was installed ca. one metre east of the pit.

This report describes the results from field-work carried out during the excavation and from the analysis of soil samples from the testpit and coring. The first results from the monitoring equipment are presented as well.

Other reports from this project include an archaeological description of the excavation and coring (Dunlop, 2007), presentation of the settling data (Jensen, 2004), and presentation of the groundwater situation (de Beer et al, 2007). Some results from the testpit have already been presented in Matthiesen et al (2007) but are included in this report as well. The project has been funded by Riksantikvaren in Norway.

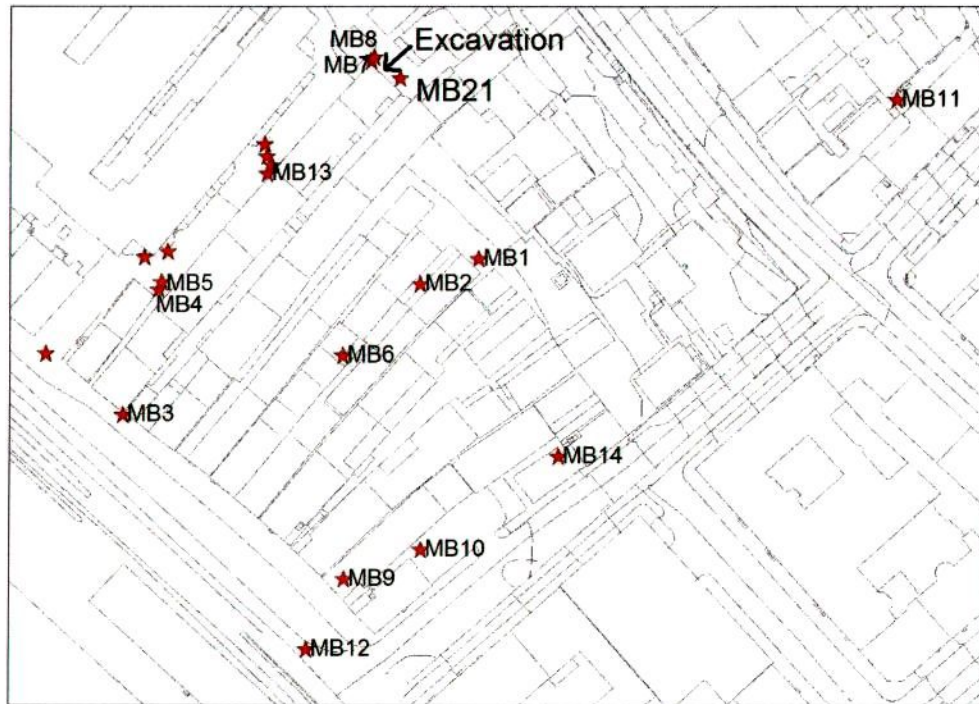


Figure 1: Map of Bryggen, showing the excavation site and dipwell MB21 at the northern end of Bryggen, along with other dipwells and drillings. The quay front is at the lower left corner of the map.

Technical background

The connection between decomposition of organic matter in the soil and settling of the soil surface is described in Matthiesen (2004b), where a preliminary model for estimating the settling potential of a given soil (described in Appendix 1) is also presented. The rate of decomposition of organic matter is, amongst others, determined by the reactivity of the organic material, water content, nature of microorganisms in the soil, temperature, and the supply of oxidants (Clymo, 1983). The latter is described in Figure 2:

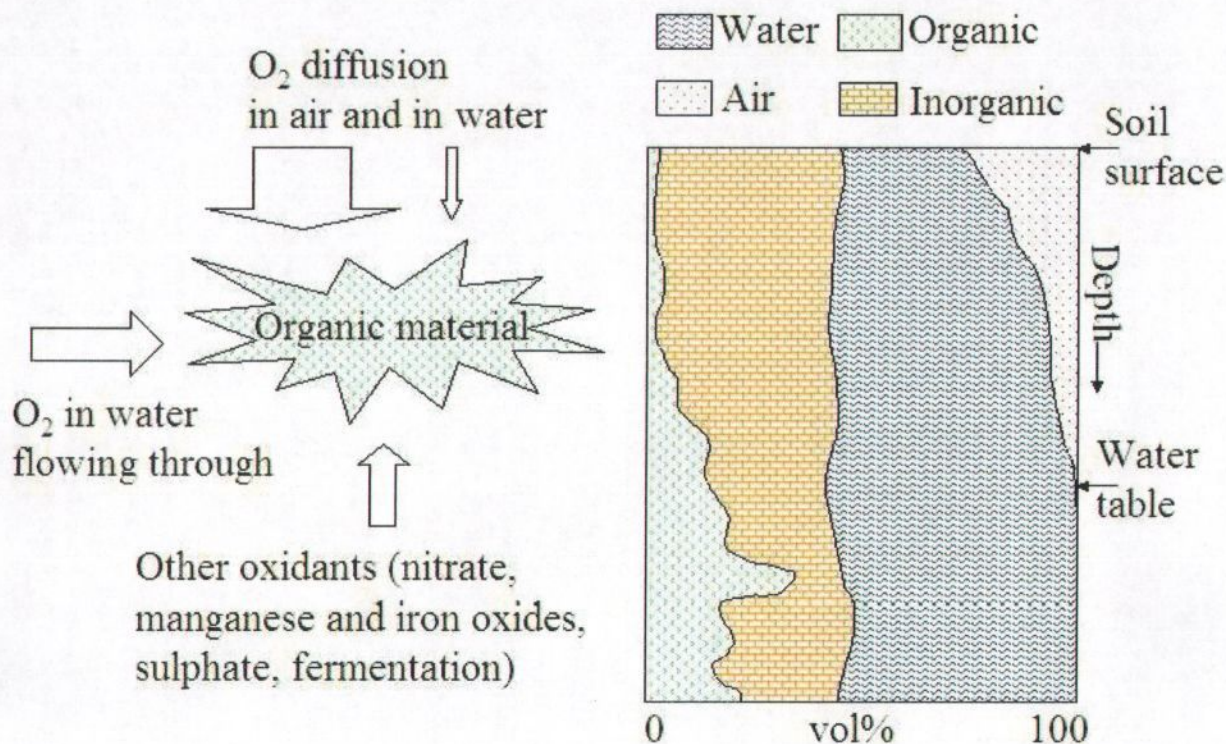


Figure 2: Transport pathways for different oxidants towards an organic soil particle (left). Oxygen may be transported in both air and water, nitrate and sulphate are only transported in water, manganese and iron oxides are solid particles that normally are not transported, and fermentation is a process where the organic material is decomposed without the use of external oxidants. The relative importance of the different transport pathways and oxidants will change down through a given soil profile (right). Oxygen is dominant in the upper soil, where there is a continuous supply from the atmosphere. Normally all oxygen is gone just a few cm below the water table under stagnant conditions. The other oxidants are used up one after the other with increasing depth, according to the energy output from the oxidation (Christensen et al, 2000; Froelich et al, 1979). Fermentation gives the smallest energy output and will in theory first take place when other oxidants are exhausted.

Oxygen is the most reactive and powerful oxidant and some of the deterioration processes (for instance fungal attack) will only take place if oxygen is available. In unsaturated soil it may be supplied through the air filled pores by diffusion, advection or pressure gradients. However, oxygen is also soluble in water and may be supplied by water flowing through the soil, or by diffusion through still water. These supply channels are less effective as the oxygen content in water is low (at 7°C – the average temperature in Bergen - 12 mg oxygen may be dissolved in 1 L of water, compared to 292 mg in 1 L of air at 1 atm), and as the diffusion of oxygen through water is very slow (the diffusion constant in water is $2.2 \cdot 10^{-9} \text{ m}^2/\text{s}$ compared to $1.8 \cdot 10^{-5} \text{ m}^2/\text{s}$ in air at 0°C – Elberling 2005).

The oxygen supply is greatly enhanced when the soil is drained, leading to air-filled pore space in the soil above the lowered water-table (Figure 2, right). The total pore space (i.e. the sum of the water and the air filled pores) is called the porosity of the soil, which may vary from approx 30%

vol for a well-packed sand to >0.95 % vol for undisturbed peat. Several models exist that try to estimate the oxygen supply from the oxygen concentration gradient, the soil porosity and the air and water content of the soil (for instance Jin & Juri, 1996). The models have mainly been developed for agricultural and environmental use and have not earlier been used for urban archaeological deposits.

Even in waterlogged soils some oxygen may be transported through the water, which may cause an undesirable deterioration of components in the soil, for instance archaeological remains. The same applies to the supply of other oxidants such as nitrate, iron and manganese oxides, and sulphate. Fermentation, where microorganisms are decomposing the organic material into (amongst others) methane, hydrogen and carbon dioxide, is in theory especially problematic as the process is independent of the supply of external oxidants. However, little is known about the activity and reaction rate in cultural layers hundreds of years old.

Methodology

Excavation:

Field measurements took place between the 12th and 15th of September 2006 focussing on the north-east profile of the testpit. *In situ* measurements of pH (ISFET solid state pH electrode from IQ instruments), as well as water content and pore water conductivity (WET sensor from DeltaT Instruments) were made. Oxygen concentration was measured in the soil by pressing optical oxygen sensors (from PreSens) approximately 30 cm into the soil profile. Ten soil samples were taken from the different soil strata and sent to an external laboratory (Eurofins in Denmark) for analysis of pH, water content, organic content and water soluble chloride, and 4 of these samples were also analysed for the content of nitrogen, phosphorus, sulphur and water soluble sulphate. Further samples were taken for determining the soil porosity and settling potential (at the National Museum), using soil sample rings of 100 cm³ volume. The porosity is calculated from the water content and loss on ignition as the total volume (100 cm³) minus the volume of inorganic material (estimated density 2.65 g/cm³) and the volume of organic material (estimated density 1.5 g/cm³). The settling potential is measured by drying and burning the sample (at 450°C), and measuring its volume in the soil sampling ring after applying a pressure of approx 0.5 kg pr cm². Alternatively, the settling potential can be estimated according to Appendix 1.

At the end of the fieldwork, three optical oxygen sensors (from PreSens) and three temperature sensors (thermocouples) were left in different soil strata in the north-east profile to allow future measurement of the oxygen concentration. The testpit remained open for a short period for archaeological description and installation of further monitoring equipment. Four soil moisture

sensors (SM200 from Delta-T Instruments) were installed and connected to a datalogger (DL6 from Delta-T), measuring the moisture content in the soil every 3 hours.

The soil strata in the test pit were described by archaeologist Rory Dunlop from the Norwegian Institute for Cultural Heritage Research (Dunlop, 2007). The testpit was primarily documented using close-range photogrammetry carried out by Marcin Gladki, making a 3-D model of the pit.

Coring

The installation of dipwell MB21 was carried out by Multiconsult avd. NOTEBY. The dipwell was installed by rotary drilling approximately 1 m east from the testpit. Soil sequences from the drilling were described by Dunlop (2007). Five soil samples from the drilling were sent to an external laboratory (Eurofins in Denmark) for analysis of pH, water content, loss-on-ignition and water soluble chloride, and four of the samples were analysed for the content of nitrogen, phosphorus, sulphur and water soluble sulphate as well. Soil samples from the same strata were also analysed for water content and loss-on-ignition by NOTEBY.

Results

The north-east profile of the testpit is shown in Figure 3. The narrow profile beneath 2.4 m asl is a small extension down to 1.8 m asl dug by hand during the field measurements.

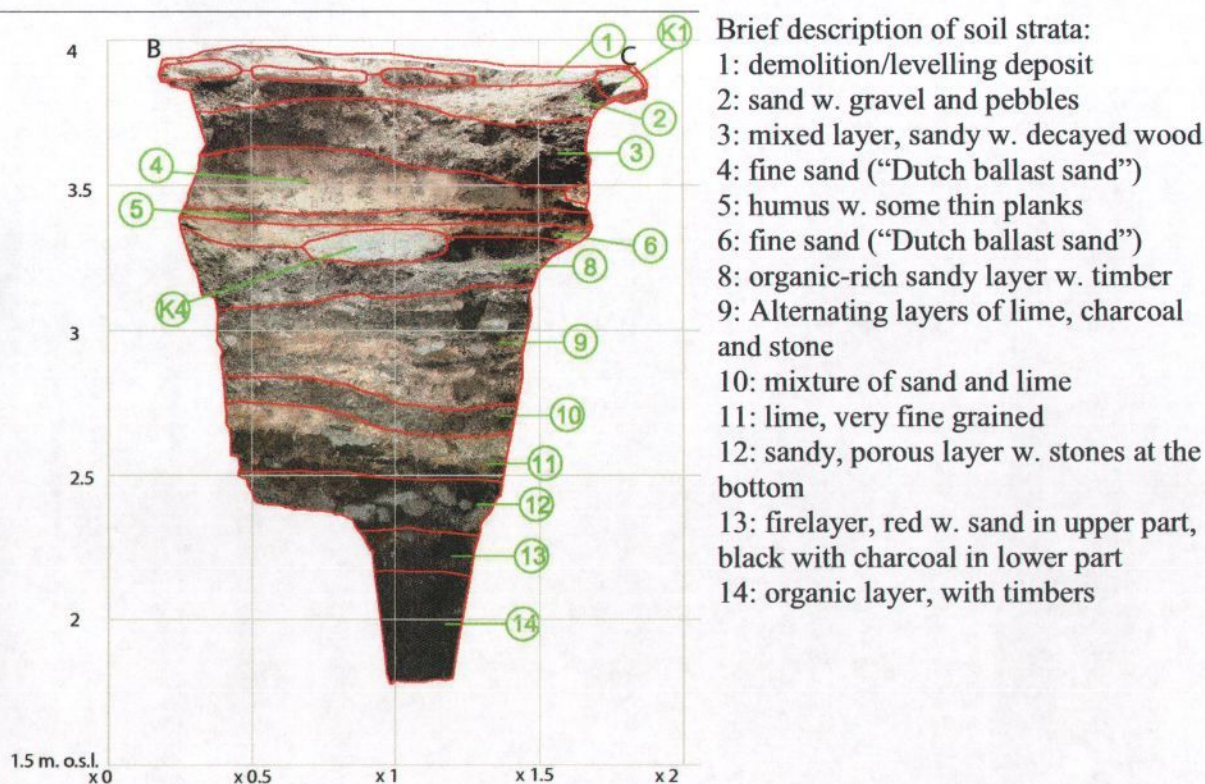


Figure 3: North-east profile of testpit. Each individual soil layer has been thoroughly described by archaeologist Rory Dunlop (2007) using the Bergen layer recording system. An ultra-short description of the layers is given to the right.

Field measurements

Results from the field measurements between the 12th and 15th of September are given in Figure 4. During the excavation the groundwater level in the dipwells close to the test pit was 1.07 m asl in MB21, 1.11 m asl in MB8 and 0.71 m asl in dipwell MB7. The precipitation in the last 2 weeks before the field measurements had been normal for Bryggen (76 mm from the 1st to the 12th of September, or 6.3 mm pr day on average).

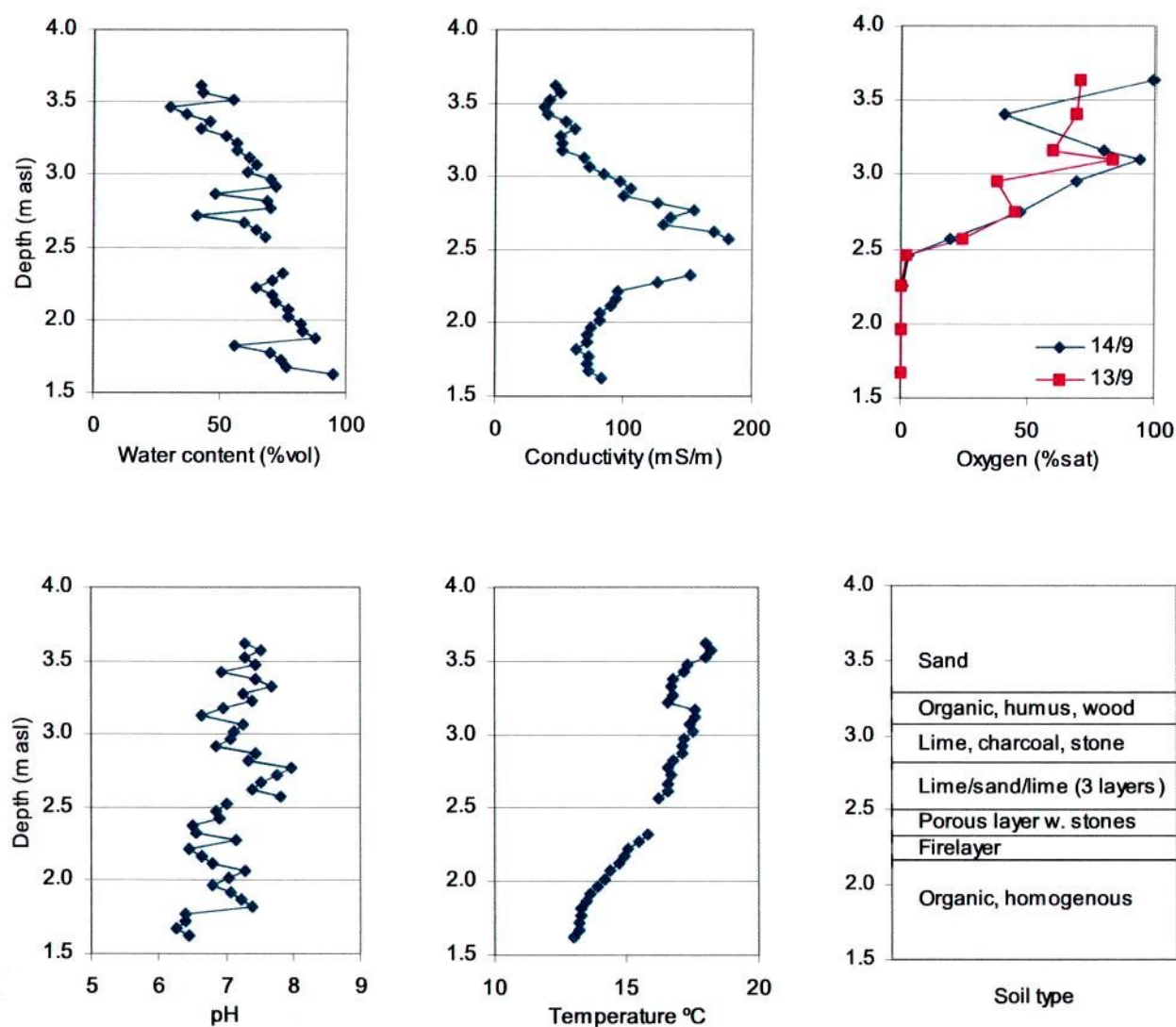


Figure 4: Results from field measurements. Water content is measured with the WET-probe, using the calibration “organic/sand” throughout. Conductivity is measured with the WET probe that automatically compensates for variations in water content (meaning that the conductivity given here is for the soil pore water, rather than the bulk conductivity). The testpit had been lying open for about seven days before the measurements took place, and it cannot be excluded that some of the parameters have changed compared to the in situ conditions before the pit was opened.

Laboratory analysis

Results from laboratory analysis of samples from the testpit, as well as MB21, are presented in Figure 5.

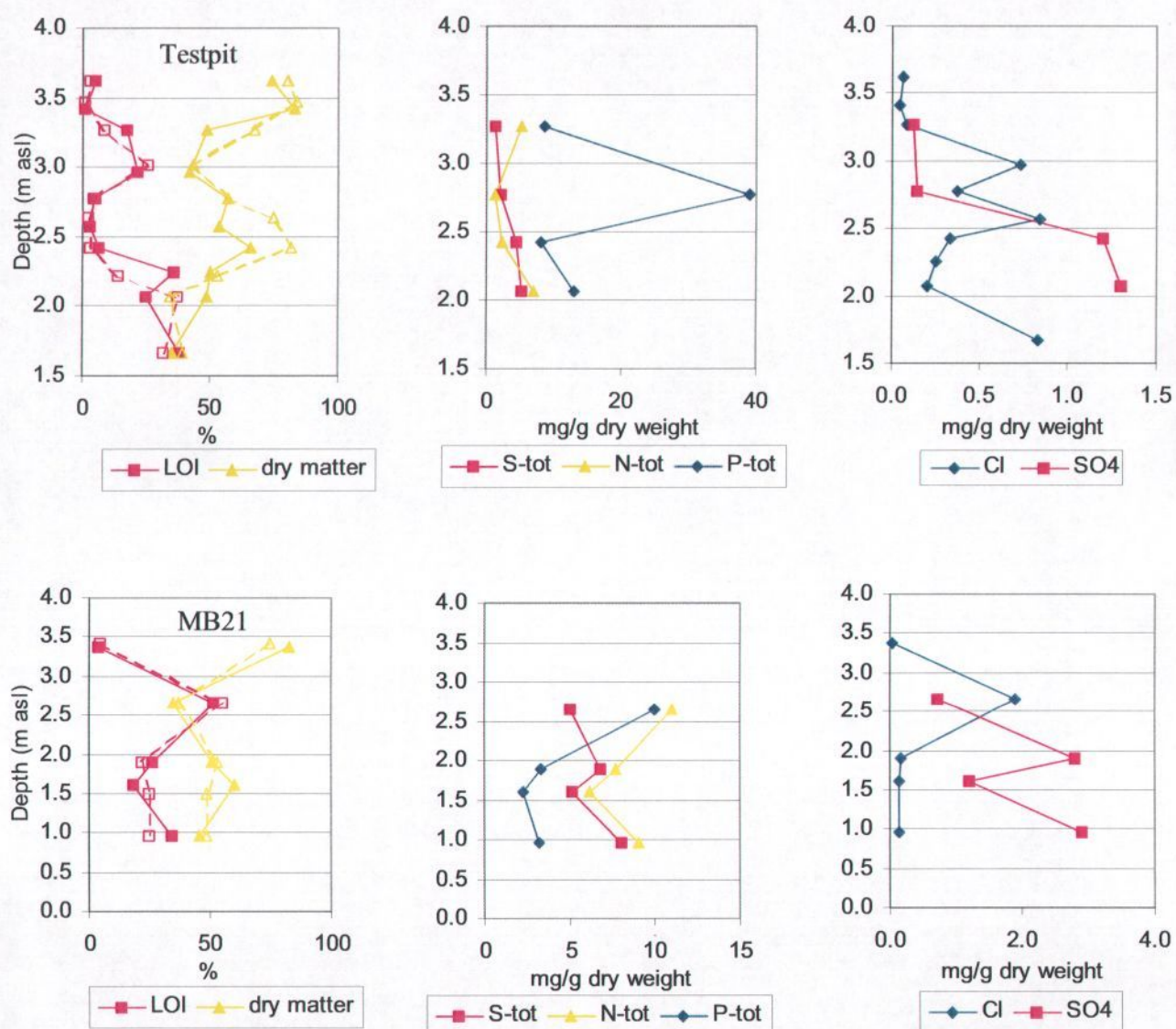


Figure 5: Results from laboratory analysis of loss on ignition, dry matter content, total content of S, N and P, and content of water soluble chloride and sulphate. Upper row shows results for soil samples from the excavation, and the lower row shows results from MB21. Loss on ignition and dry matter content was measured both at Eurofins (filled symbols) and at the National Museum/NOTEBY (open symbols)

Logging

Automated logging of the water content at four different depths in the soil profile has taken place after the excavation was finished and the testpit backfilled. Figure 6 shows the raw data from three SM200 sensors (the fourth was over range), along with the precipitation as measured at station "Florida" in Bergen.

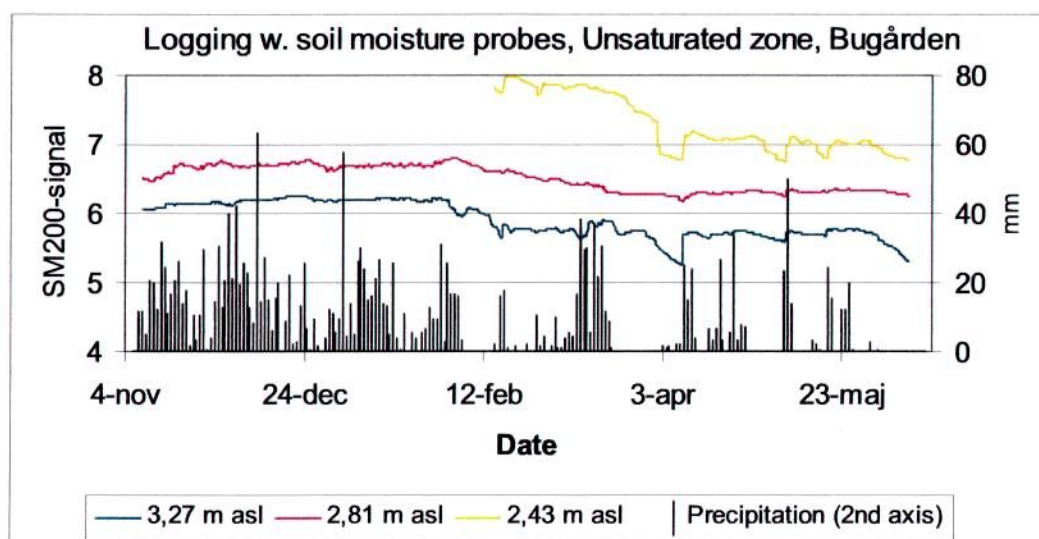


Figure 6: Results from three SM200 water content probes that were installed in the soil profile (a fourth probe at 1.98 m asl has given the signal “over range” throughout the monitoring period. The precipitation is taken from www.met.no, the Florida weather station in Bergen.

Three oxygen sensors, along with three thermocouples, were also left in the soil profile. These are not connected to a datalogger, but measurements are taken during field visits at Bryggen.

			01-03-2007			10-06-2007		
Oxygen sensor	Soil moisture probe	Height m asl	Temp (°C)	Oxygen (%sat)	Water (%vol)	Temp (°C)	Oxygen (%sat)	Water (%vol)
	1	3.27			52			46
6	2	2.81	4.2	0.2	68	10.1	0.1	65
5	3	2.43	5.4	3-7*	60	8.7	5*	49
4	4	1.98	6.0	0	too moist	8.2	0	too moist

Table 1: Measurements of oxygen and temperature at two visits to Bergen, using sensors left *in situ* in the soil profile.

The approximate water content given by the SM200 sensors is shown for comparison (their calibration is discussed beneath). *Oxygen sensor no 5 only gives a weak signal which increases the uncertainty of the measurement; possibly the sensor has been damaged when the testpit was backfilled.

Discussion

Oxygen supply

Water content and loss-on-ignition values measured in the samples taken with soil sampling rings are shown in Figure 7.

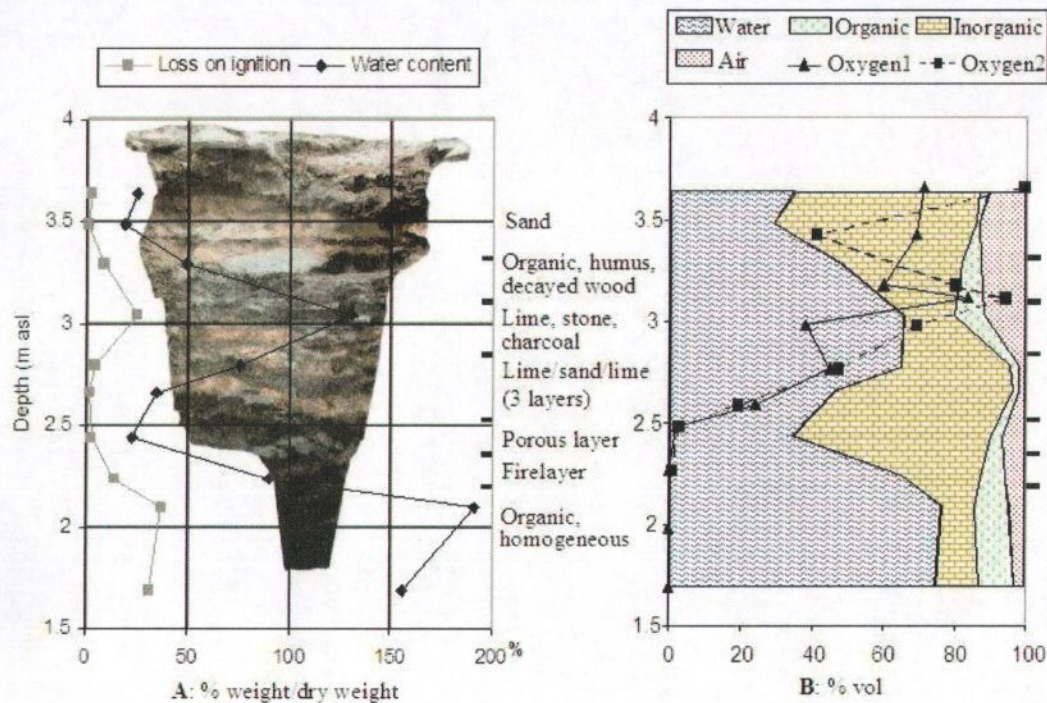


Figure 7: Water content and loss on ignition measured in 10 samples of 100 cm³ volume from different soil strata in the testpit. A) shows results as weight% relative to dry weight. B) shows the same data as the volumetric composition (%vol of water, inorganic, organic and air), where a density of 1 for water, 1.5 for organic material, and 2.65 for inorganic material has been used for the recalculation. B) also shows the oxygen concentrations (in % saturation) measured directly in the soil layers (2 series).

In Figure 7a the results are shown as weight percentage relative to the dry weight. The loss on ignition is normally interpreted as the content of organic matter in the soil, even if there are a few inorganic materials that may also contribute to the weight loss, such as for instance charcoal. In Figure 7b the weights have been recalculated to the volumetric composition. The volumetric content of air has been calculated by difference, which is only possible for samples where the total volume is known (in this case undisturbed samples of 100 cm³ volume). The volumetric soil water content was measured for each 5 cm in the field by a WET probe, and the results are in good correspondence with the soil sample data (see Figure 11). Figure 7b also shows the results from oxygen measurements in the soil, in % saturation.

Figure 7b shows, that the soil is unsaturated, and that the air content varies between 2% and 13% (vol), with an almost systematic decline with depth. The exception is the lime layer at 2.6–2.8 m asl that is nearly water saturated.

Looking at the oxygen concentration in the soil it is variable but high (70% saturation on average) down to 3.1 m asl, then it drops almost linearly, and at 2.4 m asl there is no oxygen left. This

indicates that a substantial oxidation of organic material can take place in the soil layers above 3.1 m asl: the oxygen concentration is high and can be supplied from the atmosphere through the unsaturated soil, and there is still up to 5-8 %vol (or 8-25% by weight) organic matter in the soil for future decay. Based on the soil porosity, air filled percentage, and oxygen concentration profile different models can be used to estimate the actual oxygen flux down into the deposits and thereby the decay rate for the cultural layers (Elberling, 2005). The effective diffusion constant in the upper soil layers may be estimated to $4 \cdot 10^{-7} \text{ m}^2/\text{s}$ and the order of magnitude of the oxygen supply through diffusion is $800 \text{ g/m}^2/\text{year}$ (all calculations and presumptions are given in Appendix 1). The estimate of the flux is very uncertain at this stage and the high concentration of oxygen in the upper soil layers indicates, that the decay of the organic material isn't necessarily limited by the oxygen supply.

Beneath 3.1 m asl the oxygen reaches an almost waterlogged lime layer, where the effective diffusion constant drops by a factor 50 to approximately $8 \cdot 10^{-9} \text{ m}^2/\text{s}$, and the downward flux of oxygen is estimated to $90 \text{ g/m}^2/\text{year}$ (Appendix 1). This is considerably less than in the uppermost soil, and the flux-estimate is less uncertain as there is a clear concentration gradient down through the lime. If the lime layer at some point becomes completely waterlogged the effective diffusion constant will decrease even further to approximately $1 \cdot 10^{-9} \text{ m}^2/\text{s}$ and at an unchanged concentration gradient the oxygen flux would be as low as $1 \text{ g/m}^2/\text{year}$ (Appendix 1).

Beneath 2.4 m asl there is no oxygen left, even though the soil layers are not completely waterlogged. It thus seems that the fastest decay will take place in the upper soil layers, and in the soil profile investigated it is mainly in the soil layers above 3.1 m asl. It also seems that the fine layer of lime forms an efficient barrier, protecting the lower lying soil strata in this profile (actually the mining industry sometimes cover mine waste with finely grained wet material in order to reduce oxidation of the waste - Elberling et al, 2003). More field data are needed to verify these results other places on Bryggen and to validate the oxygen transport models for urban deposits.

The above measurements during the excavation only give a snapshot of the conditions in the soil profile. The oxygen concentration has been measured on two further occasions in March and June 2007 (Table 1). On both these occasions the oxygen sensors at 1.98 and 2.43 m asl verified the picture from Figure 7 showing no or only little oxygen. The sensor at 2.81 m asl within the lime layer showed anoxic conditions on the two occasions, compared to 50% saturation during the excavation. Continuous logging of the oxygen concentration and with several sensors in each soil layer would be useful for studying the variation and showing how representative these first results are.

Water content

Figure 6 shows the raw data from 3 SM200 soil moisture sensors left in the soil profile. The fourth sensor (at 1.98 m asl) was “over range” for the whole monitoring period, which was also the case for the sensor at 2.43 m asl until the 15th of February. Looking first at the changes over time there is a good correlation between the output from the sensors and the precipitation: the signal decreases during dry periods and increases abruptly when it rains. It is remarkable that the fluctuations for the sensor at 2.81 m asl (in the lime layer) are much smaller than the fluctuations for the sensors at 3.27 and 2.43 m asl. This is probably due to the fine pores of the lime layer, giving a high capillary action and high flow resistance, which slow down and minimises the variations. The porous layer at 2.43 m asl has a much more abrupt reaction on the precipitation.

As for the absolute values, the calibration of the SM200 sensors is dependent on soil type, i.e. a given signal from the sensors corresponds to different water contents in different soil types. This means that ideally the sensors should be calibrated on site or in the laboratory using a soil sample (at least 1 L) from each different layer. In this study the monitoring equipment for logging soil moisture wasn't available when the excavation took place, and there were no extra sensors available for making the calibration in the laboratory afterwards. We are thus restricted to use standard calibration curves for different “standard soils” as shown in Figure 8. This means that the moisture contents shown in Figure 8 are uncertain and should not be over interpreted.

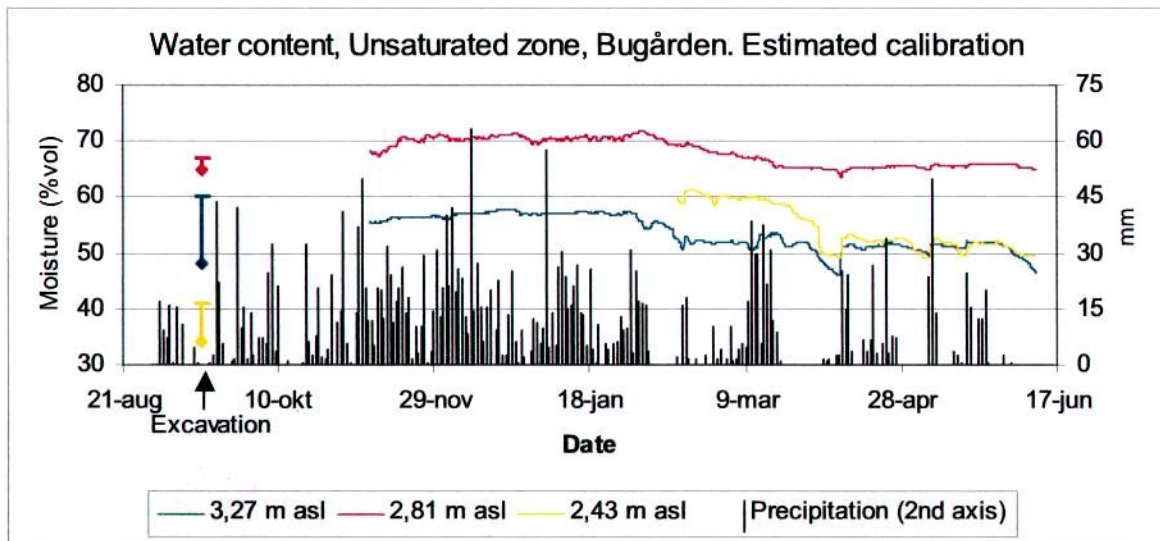


Figure 8: Results from SM200 sensors shown as approximate water content. A standard calibration for “Organic soil / sand” ($\text{moisture} = (\text{signal} - 1.4) / 8.4$) is used for the 3.27 m asl layer, a calibration for “water” ($\text{moisture} = (\text{signal} - 1.2) / 7.8$) is used for the 2.81 m asl lime layer, and a calibration for “mineral soil” ($\text{moisture} = (\text{signal} - 1.8) / 10.1$) is used for the 2.43 m asl layer. The results from the soil samples taken during the excavation in September are shown as well (water content shown as diamonds, porosity shown as horizontal line)

The moisture content is actually less interesting than the content of air in the soil, as the latter controls the oxygen supply. In principle the air content is readily calculated as the difference between soil porosity and water content. The porosity of the different soil layers was estimated from the water content and loss on ignition measured in soil samples of known volume (Figure 7), and is shown as short horizontal lines in Figure 8. For the layer at 3.27 m asl there is a good correspondence between the measurements during excavation and the water content estimated from the SM200 sensor, indicating an almost water saturated soil during the wet winter and an air content of 10% vol or more during spring/early summer. For the soil layer at 2.81 m asl there is a slight discrepancy between the two sets of data, as the water content estimated from the SM200 is slightly higher than the porosity – here a soil specific calibration of the SM200 sensor in the lime layer may help, along with more measurements of the porosity. Still, the layer seems to be water saturated during winter, and with a low air content (5% vol or less) during spring/early summer. As for the soil layer at 2.43 m asl there is a large discrepancy between the measurements as the logger indicates a water content 10-20 % higher than the estimated soil porosity. This may be due to the layer being very inhomogeneous and filled with large stones, making it difficult to measure the true soil porosity.

The logger data presented here doesn't show the full potential of the method, as the monitoring equipment wasn't available when the testpit was made, making the calibration questionable. Still, the data show that the approach is fruitful and under better conditions it should be possible to use the setup to model the water and oxygen dynamics in the unsaturated zone. For future studies it is recommended to use Theta-probes or even WET sensors, rather than the SM200 used in this study. The SM200 sensors were chosen because they were more readily available and less expensive. However, they can only measure water contents up to approx 60% by volume, which is a severe restriction. Theta-probes give a higher precision and can measure water contents up to 100%. The WET sensors also measure the temperature and conductivity of the soil pore water, which may reveal flushing of rainwater through the deposits and give further insight into soil processes in the dry periods. They are, however, not optimised for datalogging from the manufacturer and it will require some work to validate the results from permanently installed WET sensors.

Conductivity and chloride

The conductivity and chloride data corroborate the picture of relatively stagnant conditions in the lime layer. Figure 9a shows that the conductivity varies between 40-180 mS/m with a close correspondence to the soil type. Maximum values of > 150 mS/m were found in two thin lime layers at 2.71-2.82 and 2.50-2.62 m asl.

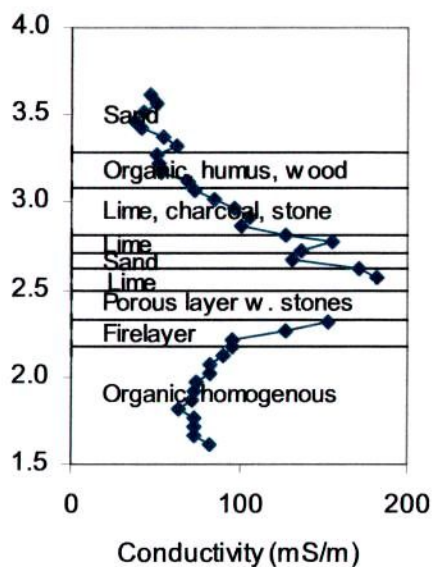


Figure 9a: Correspondence between soil type and conductivity of the pore water, as measured by the WET sensor. The sensor automatically compensates for differences in water content. It was not possible to use the sensor in the layer with stones at 2.5 m asl.

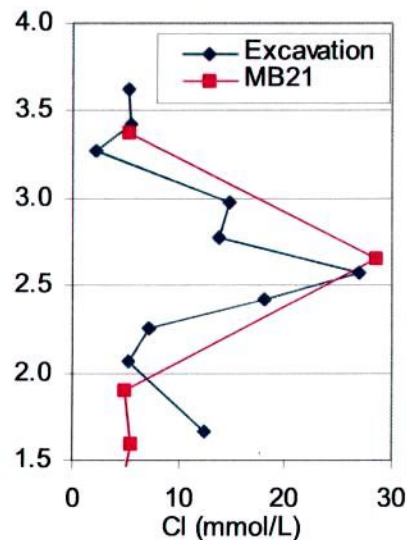


Figure 9b: Chloride content of the soil recalculated as mmol/L in the soil pore water, using the water content of the samples.

As for the absolute levels, conductivity measurements with the WET sensor have been made in a number of other excavations at urban sites: On Bryggen near the sheet pile in Bredsgaarden conductivities of 35-60 mS/m were found at 0.0 m asl (Matthiesen, 2005b), in an excavation at “Tusindårstorget” in Stavanger levels of 50-400 mS/m were found (Ringsted & Matthiesen, 2006), at an excavation in Næstved in Denmark 100-225 mS/m was measured (unpublished results), and at Marmorkirken in Copenhagen in Denmark the levels were 75-250 mS/m (unpublished results). In all cases the highest conductivities were found in dense layers such as clay, silt, or here lime, whereas low conductivities were found in the more sandy layers. This is interpreted as a result of a low water exchange in these dense soil layers, allowing higher concentrations of dissolved ions to build up.

The chloride data shows a similar picture, with high concentrations in the lime layer both in the excavation and in MB21. As for the absolute levels, most soil samples from drillings at the back of Bryggen (MB7, 13 and 14) have contained less than 10 mmol/L (Matthiesen, 2005a), so the 15-30 mmol/L found in the lime layers here are unusually high. This emphasises that the stratigraphy found in MB21 and the excavation is not necessarily representative for all of Bryggen.

Settling potential

Apart from the oxygen supply and variations in water content it is also necessary to address the settling potential of the soil. Is the soil already so mineralised that the settling will stop by itself, or must something be done to stop it? In principle this can be measured in the laboratory by taking an undisturbed soil column, and make an accelerated decay while keeping a realistic load on the soil (Simpson et al, 1997). In reality such a set-up is difficult to make, and it is especially difficult to sample an undisturbed column in heterogeneous cultural layers. It is, however, possible to make a simple model to illustrate the worst case scenario based on the assumptions: that all the organic material disappears over time (or at least does not contribute to the soil volume); that water is only found in the soil pores and doesn't cause any swelling; and that the inorganic components can pack to a porosity of for instance 0.4 (corresponding to unpacked sandy sediment). As an example this scenario would give a potential settling of 43% for the soil layer at 3.3 m asl in Figure 3b where there is 5% (vol) organic and 34% inorganic material today (Appendix 1). The deeper lying layers with only 10% inorganic material may settle as much as 83% according to this model. Admittedly the model is very crude, but it shows that some of the layers still have a potential for settling. In terms of oxygen consumption it may further be estimated that if the settling of 6 mm/year measured in this area was solely due to oxidation of organic matter (for instance in the soil layer at 3.3 m asl) it would require an oxygen consumption of approximately 1100 g/m²/year (Appendix 1). An oxygen supply of this order of magnitude is only realistic in the upper soil layers, and it is estimated that the oxygen flux of 90 g/m²/year down through the lime layer beneath 3 m asl is not sufficient to cause the observed settling.

Other analyses of soil chemistry

The pH measured in situ is shown in Figure 3. The soil pH varies between 6.2 and 8.0 with a clear maximum in the lime layers. Overall, there is a tendency for falling pH with depth, from approx 7.5 in the top layers to 6.5 in the deeper, more water filled layers. A pH around 6.5 is common for waterlogged, reduced deposits (Kirk, 2004; Matthiesen et al, 2004). There is a good correspondence between the in situ measurements and pH measurements made in the laboratory (Figure 11). The exception is the deepest soil sample, where the in situ measurement is almost 1 pH unit lower than the laboratory measurement; this may be due to the escape of carbon dioxide from the wet soil sample during the sample preparation in the laboratory (Matthiesen, 2004a).

As for the nutrient content (N and P) presented in Figure 5, the levels are comparable to what has earlier been found on Bryggen. The soil data from all corings on Bryggen will be compared in a forthcoming paper, but at this stage the nutrient contents do not indicate any systematic difference between samples from above and beneath the groundwater level. There is a single sample from 2.77

m asl in the testpit with an unusually high phosphorus content (39 mg P per g) which is the highest value measured at Bryggen until now. TOC has not been measured in the samples from the testpit or MB21, so it is not possible to calculate the exact C/N or C/P ratios (as has been done for samples from other corings).

As for the sulphur content in the soil samples, again the levels are comparable to what has been found earlier (see for instance Matthiesen, 2006). The exact nature of the sulphur is unknown, but a relatively high percentage is present as water soluble sulphate (Figure 10) whereas the sulphide content is very low (Appendix 2). It is assumed that the rest is present as organic bound sulphur or as pyrite. The origin of the water soluble sulphate is not known at this stage, but the relatively high content of sulphate compared to chloride (Figure 5) indicates that it is probably not from seawater (where the chloride content is 7 times higher than the sulphate content).

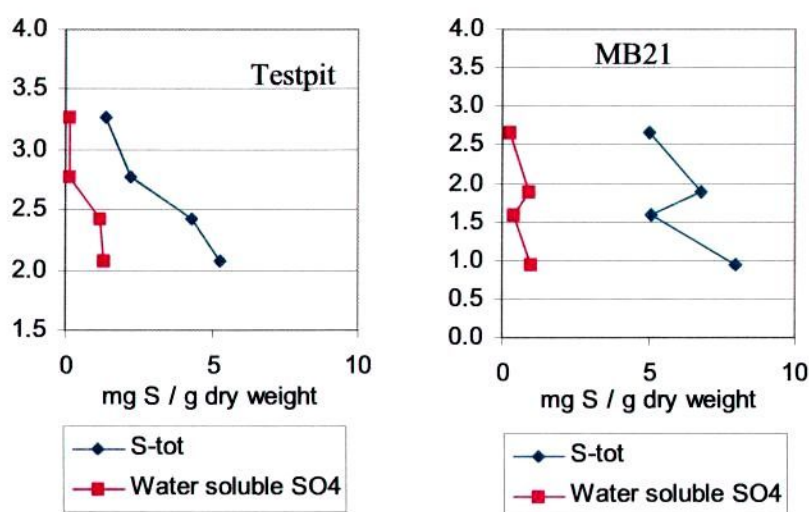


Figure 10: Comparison between total S and the amount present as water soluble sulphate.

Field measurements versus laboratory analysis

Figure 11 compiles some of the parameters that have been measured both in situ during the excavation and afterwards in the laboratory. Generally, there is a good correspondence:

The pH data have already been commented on (above).

The volumetric water content as measured with the WET sensor (at a fixed calibration: organic soil/sand) and using soil sampling rings shows an excellent correlation. The soil sample at 2.42 m asl stands out with a surprisingly low water content, but unfortunately it was not possible to make in situ measurements to validate it. It cannot be excluded that some water was lost during sampling of

the porous material from this layer, and that the true water content (and possibly also the porosity) should be higher.

There seems also to be a fair correlation between the conductivity measured in situ, and the concentrations of water soluble chloride. The chloride concentration from Figure 9b has been recalculated to a “theoretical” conductivity using a single ion conductivity of $76 \text{ S}\cdot\text{cm}^2/\text{mol}$ for chloride. We wouldn’t expect a 1:1 correspondence as there are other ions in the pore water that contribute to the conductivity and as the recalculation made here is greatly simplified, but still it shows that the chloride contributes significantly to the conductivity measured in the soil at Bryggen. The main advantage of the in situ measurements is their high spatial resolution and the availability of the results in the field, making it easier to decide where to take samples for further analysis in the laboratory.

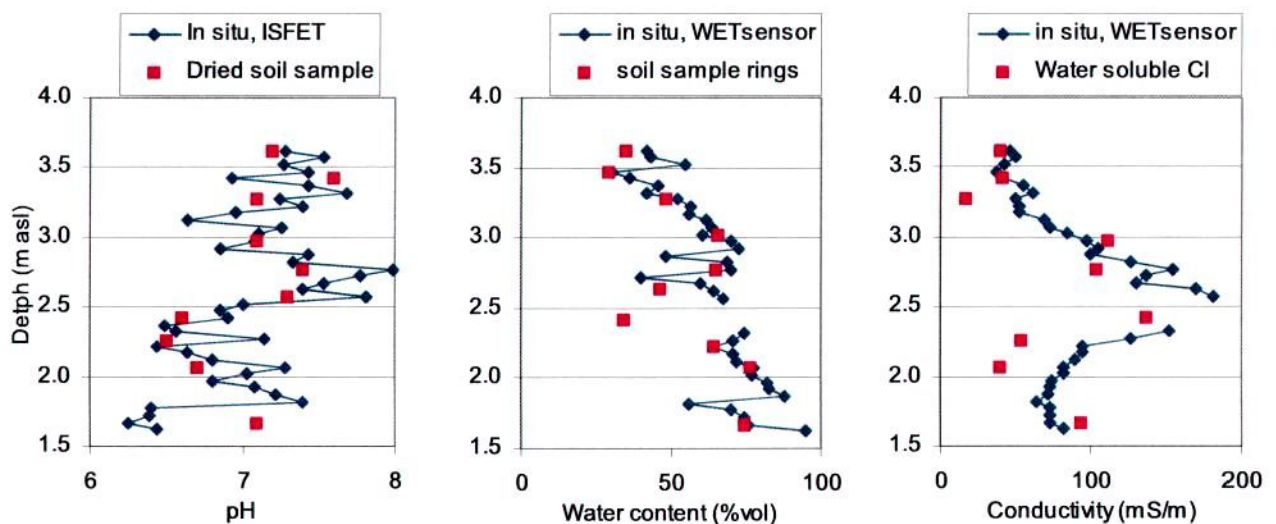


Figure 11: Comparison between in situ measurements, and results from analysis of soil samples. The concentration of water soluble chloride has been recalculated to a theoretical contribution to the conductivity.

Conclusions and future work

This work has provided a better understanding of the conditions in the unsaturated zone above the groundwater level along with some practical experiences with the monitoring equipment. The study has focused on a single soil profile, but still some general conclusions may be drawn:

- It has been demonstrated that the oxygen doesn’t necessarily penetrate all the way down to the groundwater level
- Models from agricultural and environmental science have been used to make rough estimates of the oxygen flux
- A layer of fine grained material (in this case lime) may form an efficient oxygen barrier

- There is a good correlation between the precipitation and the soil moisture as measured by SM200 probes
- It is an advantage to make a soil specific calibration of the soil moisture probes on site or in the laboratory, using soil samples from the excavation
- There is a good correlation between in situ measurements and laboratory analysis of soil samples and the two approaches supplement each other well

Specific for the testpit at Bugården

- The downwards flux of oxygen is estimated high enough to cause the settling observed
- The oxygen supply is highest in the uppermost 1 m, so this is where most decay of organic material probably takes place
- There is still sufficient organic material in the uppermost soil to cause a substantial future settling
- The sensors left in the soil will allow a fast documentation of the results from any attempt to raise the ground water level

Future work should include

- Continued logging of the soil moisture content using the existing SM200 probes
- Model the correlation between soil moisture in the unsaturated zone, groundwater level, and precipitation
- Continuous logging of the oxygen concentration with the existing probes for a period of time (will require that an oxygen logger becomes available)
- Validation of the results in other excavations (on Bryggen or at other sites with unsaturated cultural layers), using better soil moisture probes and more oxygen sensors
- Validation of the models used for estimating oxygen flux, settling potential and porosity

Some of this work could be done as a research project based on the experiences gained here (for instance using better soil moisture probes, making soil specific calibration of each probe, using more oxygen sensors, using continuous logging of the oxygen concentration, and combining with measurements of carbon dioxide production and closed chamber measurements of total fluxes). Such a project has already been initiated at a Danish wetland site (Maglemøsen), and as for urban sites it could be done in the testpit from this study (if it is ever reopened) or at any site with unsaturated organic deposits.

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Appendix 1 - preliminary models for estimating settling and supply of oxidants.

All these estimates build on a range of assumptions that need to be discussed and verified.

Settling due to oxidation of organic material

Consider a block of soil consisting of organic material, inorganic material, water and air.

$$V_{\text{tot}} = V_{\text{org}} + V_{\text{inorg}} + V_{\text{water}} + V_{\text{air}}$$

If the organic material is oxidised it will often also cause a loss of water, as organic material normally binds some water. For a worst case scenario we assume that all the organic material is mineralised, and that the soil volume only depends on the amount of inorganic material in the soil and its ability to pack (described by the soil porosity). If we set a theoretical porosity for the mineralised soil of 0.4, 60% of the soil volume is occupied by the inorganic material and 40% by pores and the total volume of the soil after mineralization will be

$$V_{\text{tot}} = V_{\text{inorg}} / 0.6, \text{ giving a potential settling of } 1 - V_{\text{inorg}} / 0.6.$$

If we look for instance at the layer at 3.3 m asl in Figure 7b it consists of 48% (vol) water, 5% organic, 34% inorganic, and 13% air. If this layer is mineralised each cm will shrink to $0.34 / 0.6 = 0.57$ cm, or a settling of 0.43 cm. This means that the settling of 6 mm/year observed in this area could be due to the oxidation of all the organic material in a 1.4 cm thick layer, containing $1.4 \text{ cm} \cdot 0.05 \cdot 1.5 \text{ g/cm}^3 = 0.10 \text{ g organic material/cm}^2$ (using a density of 1.5 g/cm^3 for organic material). In terms of oxygen consumption, if we assume the organic material has the brutto formula CH_2O and is oxidized by oxygen all the way to CO_2 and H_2O , it takes 32 g of oxygen to oxidize 30 g of organic material. Thus the settling of 6 mm/year is equivalent to an oxygen consumption of $0.11 \text{ g O}_2/\text{cm}^2/\text{year}$ or $1100 \text{ g/m}^2/\text{year}$.

Supply of oxygen through the unsaturated soil

Transport by diffusion is normally described by Ficks first law:

$$F = -D \cdot dC/dx$$

where F (flux) is the rate of oxygen transport per unit area of a section, D is the effective diffusion constant in the media, and dC/dx is the concentration gradient of oxygen. The diffusion constant in air (D_a) is $1.8 \cdot 10^{-5} \text{ m}^2/\text{s}$ at 0°C so in principle it is easy to calculate the oxygen flux from a concentration gradient. However, in soil there is only a limited pore space, and some of this space is filled with water where the diffusion is much slower ($D_w = 2.2 \cdot 10^{-9} \text{ m}^2/\text{s}$). Several models have been made to describe the transport of oxygen through unsaturated soil (see for instance Elberling, 2005), including the Millington-Quirk model for gas diffusion which can be used for a range of soil types (Jin & Juri, 1996):

$D_{e,a} = D_a \cdot \epsilon_g^2 / \epsilon^{0.67}$ where $D_{e,a}$ is the effective gas diffusion constant, ϵ is the total porosity, and ϵ_g is the gas-filled porosity.

For instance the almost saturated lime layer at 2.6–2.8 m asl in Figure 7 has a total porosity of 0.57 and a gas filled porosity of 0.017, which gives an effective gas diffusion constant of $8 \cdot 10^{-9} \text{ m}^2/\text{s}$.

There is a linear concentration gradient (dC/dx) of 67% pr half meter, which gives a calculated oxygen flux of $90 \text{ g/m}^2/\text{year}$ (using the oxygen content in air of 292 mg/L as 100% value).

For comparison the soil layers at 3.5–3.7 m asl in Figure 7 have a total porosity of 0.44 and a gas filled porosity of 0.12, which gives an effective diffusion constant of $4 \cdot 10^{-7} \text{ m}^2/\text{s}$, i.e. 50 times as high. Here there is no linear concentration gradient, but if it – for example – is set to 20% decrease per m it would give an oxygen diffusion of $800 \text{ g/m}^2/\text{year}$. Apart from diffusion oxygen may also be transported in the unsaturated zone by advection or pressure gradients, but these are more difficult to model (Elberling, 2005).

If the ground water table is raised and the layers become waterlogged, it will have a significant effect on the oxygen supply. The oxygen diffusion in water is very slow, with a diffusion constant (D_w) of $2.2 \cdot 10^{-9} \text{ m}^2/\text{s}$. In waterlogged soil the effective diffusion constant ($D_{e,w}$) is even lower, as the diffusion can only take place in the pores and the oxygen has to circumnavigate the sediment grains. The effective diffusion constant may be calculated as $D_{e,w} = D_w \cdot \epsilon_w$ where ϵ_w is the water filled porosity (Appelo & Postma 2005), even if there also exist other models.

For instance if the lime layers at 2.6–2.8 m asl in Figure 7 became completely saturated (i.e. all the soil pores were filled with water) the porosity of 0.57 would give an effective diffusion constant of $1 \cdot 10^{-9} \text{ m}^2/\text{s}$. At the current concentration gradient (dC/dx) of 67% per half meter, the corresponding oxygen flux would be as low as $1 \text{ g/m}^2/\text{year}$ (using the oxygen content in water of 12 mg/L as 100% value). Fluxes of this small magnitude means, that the oxygen will never reach deeper lying deposits through diffusion before it is used up.

Appendix 2

Analysis of samples from testpit (results from Eurofins in Denmark)

Number	477321											
Received	9-11-2006											
Report	23-11-2006											
		Number	1	2	3	4	5	6	7	8	9	10
		Depth (m asl)	2.07	2.42	2.77	3.27	1.67	2.25	2.57	2.97	3.42	3.62
		Eurofins no	47732101477321024773210347732104477321054773210647732107477321084773210947732110									
Parameter	Method											
pH	DS287, mod.	pH	6.7	6.6	7.4	7.1	7.1	6.5	7.3	7.1	7.6	7.2
Dry content	DS 204 mod.	%	48.3	65.9	56.7	48.3	34.6	50.1	53.2	41.6	83.2	74.3
Water content			107.0	51.7	76.4	107.0	189.0	99.6	88.0	140.4	20.2	34.6
Loss on ignition, total	DS204	%	11.8	4.06	2.52	8.4	12.9	17.8	1.62	8.77	0.38	3.56
Loss on ignition, of dry content	DS 204	% i ts.	24.6	6.16	4.44	17.4	37.4	35.6	3.05	21.1	0.455	4.79
Nitrogen, total	NF75:6/59/VKI	mg/kg	3400	1600	670	2500						
Phosphorus, total	DS259/SM3120ICP	mg/kg ts.	13000	8000	39000	8500						
Chloride, water soluble	DS/EN10304	mg/kg ts.	200	330	370	82						
Sulphate, water soluble	DS/EN10304	mg/kg ts.	1300	1200	140	120						
Sulphur, total	DS259/SM3120ICP	mg/kg ts.	5300	4300	2200	1400						
Sulphide-S	DS280M	mg/kg ts.										
Chloride, water soluble	DS239mod	mg/kg ts.					830	250	840	730	39	64

Analysis of samples of 100 cm³ volume from testpit (results from National Museum)

Depth (m asl)		1.67	2.07	2.22	2.42	2.64	2.77	3.02	3.27	3.47	3.62
Measured:											
Dry content	% of wet weight	39.1%	34.4%	52.7%	81.7%	74.5%	56.7%	43.3%	67.0%	83.7%	80.2%
Water content	% of dry weight	155.5%	191.0%	89.7%	22.4%	34.2%	76.5%	131.1%	49.2%	19.4%	24.7%
Loss on ignition	% of dry weight	31.3%	37.0%	13.5%	2.8%	2.1%	4.6%	25.1%	8.3%	0.5%	2.8%
Calculated:											
Water content	% of volume	74.5%	76.4%	64.5%	34.3%	46.4%	65.0%	65.7%	48.2%	29.4%	34.9%
Inorganic	% of volume	12.4%	9.5%	23.5%	56.2%	50.1%	30.6%	14.2%	33.9%	56.8%	51.8%
Organic	% of volume	10.0%	9.9%	6.5%	2.9%	1.9%	2.6%	8.4%	5.4%	0.5%	2.7%
Air	% of volume	3.1%	4.2%	5.6%	6.6%	1.6%	1.8%	11.7%	12.5%	13.3%	10.6%

Analysis of samples from MB21 (C-series analysed at Eurofins, A-series analysed at Multiconsult avd. NOTEBY)

		Number	C 1	C 2	C 3	C 4	C 5	A1	A2	A3	A4	A5
		Depth (m asl)	3.38	2.65	1.90	1.60	0.95	3.43	2.65	1.90	1.50	0.95
		Eurofins no	4773211147732112477321134773211447732115									
Parameter	Method											
pH	DS287, mod.	pH	7.2	7.2	6.4	6.5	6.8					
Dry content	DS 204 mod.	%	82.5	34.6	50.7	59.9	45.5	74.9	36.6	52.7	48.2	48.4
Water content			21.2	189.0	97.2	66.9	119.8	33.5	172.9	89.7	107.4	106.6
Loss on ignition, total	DS204	%	3.23	18	13.3	10.8	15.4					
Loss on ignition, of dry content	DS 204	% i ts.	3.92	51.8	26.2	18	33.8	4.5	55.1	21.8	24.6	24.6
Nitrogen, total	NF75:6/59/VKI	mg/kg		3800	3900	3700	4100					
Phosphorus, total	DS259/SM3120ICP	mg/kg ts.		10000	3300	2300	3200					
Chloride, water soluble	DS/EN10304	mg/kg ts.		1900	170	130	140					
Sulphate, water soluble	DS/EN10304	mg/kg ts.		730	2800	1200	2900					
Sulphur, total	DS259/SM3120ICP	mg/kg ts.		5000	6800	5100	8000					
Sulphide-S	DS280M	mg/kg ts.			<0.2	0.21						
Chloride, water soluble	DS239mod	mg/kg ts.	39									