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Preservation conditions in unsaturated urban deposits:

Reopening of testpit from 2006 and installation of monitoring equipment at the rear of Nordre Bredsgården, Bryggen in Bergen.

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Title:
Preservation conditions in unsaturated urban deposits: Reopening of testpit from 2006 and installation of monitoring equipment at the rear of Nordre Bredsgården, Bryggen in Bergen.

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Summary:
The present report focuses on environmental monitoring in unsaturated urban deposits. The study takes place at the rear of Nordre Bredsgården, Bryggen, where the groundwater level is low and the upper 3 m of the deposits are unsaturated. The soil surface settles by 6-8 mm/year in this area, which has been explained by degradation of organic material in the soil. Results from laboratory analyses and field measurements in a re-opened testpit are presented, and compared to measurements from 2006 when the testpit was first excavated. The installation of new monitoring equipment for measuring water, oxygen and temperature in the soil is documented.
Results from the 2006 and 2010 excavations show high oxygen concentrations in the upper 1 m of the soil profile. Below this depth a dense layer of finely grained lime is found. Logging of water content in the lime layer in the period 2006-2010 shows a high and stable water content, which may reduce the downward flux of oxygen locally. Beneath the lime layer is found a porous stone layer with fluctuating water content, and beneath that a thick, highly organic layer. Oxygen measurements during the excavations showed relatively low oxygen concentrations beneath the lime layer (at 1½ m below the soil surface) but this needs to be verified by the automatic monitoring equipment installed.
The high settling rate measured in the area has been explained by decay of organic matter in the soil, which implies that the organic content (and thus the loss-on-ignition) of the soil should decrease over time. Comparison of soil samples from 2006 and 2010 indicates such a decrease in one of the upper soil layers, but due to the heterogeneity of the soil it is difficult to give an exact rate of decay. The decay has been further evaluated by analysing modern wood samples that were placed in the soil in 2006 and retrieved in 2010. The samples showed attack by fungi and a lowered wood density in the upper soil layers, and also in the porous stone layer beneath the lime, indicating that oxygen is present at least occasionally.
The monitoring equipment installed will give a better understanding of the water and oxygen dynamics in the unsaturated zone and help evaluating how much water is necessary to reduce the decay rate to an acceptable level at the site. Furthermore, it will give insight into the thermal properties of cultural deposits.

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Introduction

Measurements at Bryggen have shown that the buildings and soil surface at the Bredsgården and Bugården tenement are settling at a considerable rate – up to 6-8 mm/year (Jensen, 2007). This settling is most likely a consequence of a lowered groundwater table in the area, giving an increased oxygen access and increased decomposition of organic material in the soil.

In September 2006 a 2½-metre deep testpit was opened at the northern end of Bredsgården (Figure 1) in order to assess the state of preservation of the deposits (Dunlop, 2008). Field measurements were made in order to investigate the preservation conditions, and modern wood samples and water content sensors were installed in the unsaturated zone above the groundwater level (Matthiesen, 2007). The report from 2007 contains a discussion on oxygen dynamics and how measurements of oxygen, porosity and water content in the soil may be used to estimate oxygen fluxes and decay rates. Some of the results have been published in Matthiesen et al (2008), and results from monitoring of water content were described in Matthiesen (2010). The testpit was re-opened in October 2010 in order to install supplementary monitoring equipment, to retrieve the wood samples for analysis, and to evaluate any changes in the state of preservation of the cultural layers. The opportunity was taken also to investigate the thermal properties of cultural deposits.

This report describes the results from field and laboratory measurements carried out and documents the monitoring equipment installed. The theoretical background is described in Matthiesen (2007) and is not repeated here. The project has been funded by Riksantikvaren (the Norwegian Directorate for Cultural Heritage).

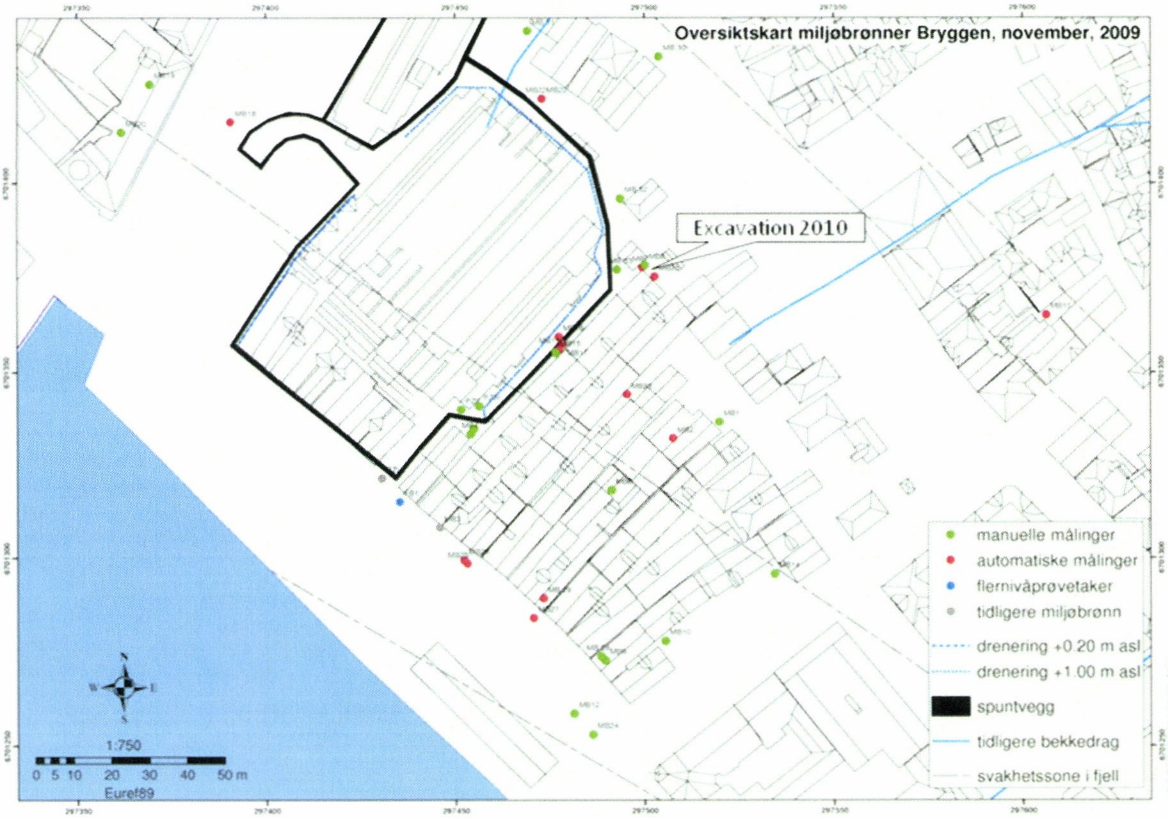


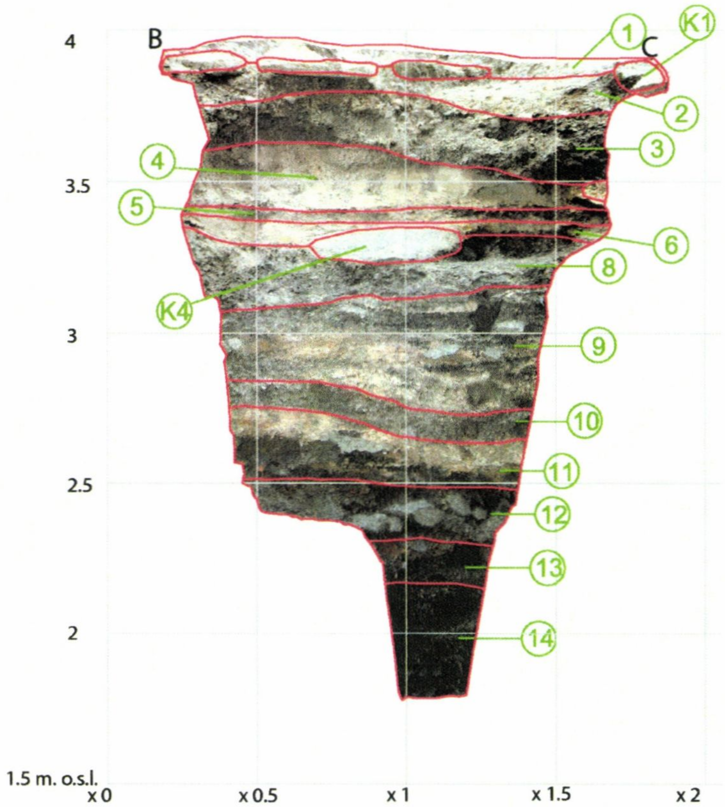
Figure 1: Map of Bryggen, showing the excavation site at the northern end of Bredsgården, along with dipwells and drillings. Dotted blue line shows a drain pipe, which lowers the groundwater level locally.

Methodology

Excavation:

The testpit from 2006 was reopened the 19th of October 2010. Field measurements and installation of monitoring equipment took place between the 26th and 29th of October.

The north-east profile of the testpit was documented in 2006 and a rectified photo is shown in Figure 2. The work in 2010 focused on the south-east profile of the testpit, which was better suited for the installation of sensors due to its proximity to the logger box on the building nearby. The same soil strata could be identified on both profiles although small differences in thickness and height above sea level were observed. The uppermost strata (layer 1-6) in the south-east profile were partly covered by backfill from 2006.



Brief description of soil strata:
1: demolition/levelling deposit
2: sand w. gravel and pebbles
3: mixed layer, sandy w. decayed wood
4: fine sand ("Dutch ballast sand")
5: humus w. some thin planks
6: fine sand ("Dutch ballast sand")
8: organic-rich sandy layer w. timber
9: Alternating layers of lime, charcoal and stone
10: mixture of sand and lime
11: lime, very fine grained
12: sandy, porous layer w. stones at the bottom
13: firelayer, red w. sand in upper part, black with charcoal in lower part
14: organic layer, with timbers

Figure 2: North-east profile of testpit. Each individual soil layer has been thoroughly described by archaeologist Rory Dunlop (2008) using a standardized layer recording system. An ultra-short description of the layers is given to the right.

Measurements & sampling

In situ measurements of water content and pore water conductivity (WET sensor from DeltaT Instruments) as well as heat conductivity and heat capacity (KD2 Pro from Decagon Devices) were made. Oxygen concentrations were measured using optical oxygen sensors (from PreSens) that were pressed approximately 10 cm into the soil profile.

Soil samples were taken in 100 cm^3 rings and used to determine the water content, loss on ignition, and soil porosity in the laboratory. Other ring samples were used to measure soil thermal properties as a function of soil water content, for a future modelling of the soil temperature variations.

Samples of modern pine wood were placed in the testpit by Ove Steinestø from Multiconsult during backfilling in 2006. These samples were retrieved in October 2010 by archaeologist Rory Dunlop when the testpit was re-opened. The wood samples were kept at 5° C until analysis at the National Museum by conservator Jan Bruun Jensen. The density of the samples as well as decay by bacteria and fungi was evaluated as described in Gregory & Matthiesen (2006).

Installation of monitoring equipment

Ten optical oxygen sensors (from PreSens), ten soil temperature sensors (107 from Campbell Scientific), and seven water content sensors (three SM200, and four Theta probes from Delta-T) were installed in different soil strata in the south-east profile. The water content and temperature sensors were connected directly to a datalogger (CR1000 from Campbell Scientific) whereas four oxygen sensors were connected via a four-channel oxygen meter (Oxy-4 Mini from PreSens). The datalogger was programmed to log the conditions in the soil every half hour. The full logger program is given in Appendix 1 and a wiring diagram is found in Appendix 2. The previous datalogger at the site (DL6 from Delta-T, installed in 2006) was dismantled. One of the water content probes from 2006 was damaged during reopening of the testpit, and had to be discarded (SM200-1). The other three SM200 probes from 2006 were moved to other soil strata and transferred to the CR1000 datalogger. In January 2011 (after 2 months of logging) another of the SM200 probes (SM200-2) short circuited, which made the logger system close down – this probe was disconnected in March 2011 and the system restarted.

The depth and soil type for the different sensors can be seen in Table 1 and photos of the south-east profile after installation of the sensors are seen in Figure 3. Only 4 oxygen sensors can be connected to the datalogger at a time and for the first monitoring period Oxy 5, 6, 7 and 8 have been selected:

m asl	Water content	Oxygen	Temperature	Soil layer
4.14				Soil surface
4.12			Temp 1	Cobblestone
3.92	SM200-4	Oxy 2	Temp 2	Sand
3.68		Oxy 3	Temp 3	Backfill
3.60	SM200-3			Backfill
3.46		Oxy 4	Temp 4	Backfill
3.31	SM200-2*	Oxy 1		Dutch sand (#6)
3.21		Oxy 5	Temp 5	Backfill
3.09	Theta 1			Organic (#8)
3.06		Oxy 6	Temp 6	Organic (#8)
2.77	Theta 2	Oxy 7	Temp 7	Lime/sand (#9/10)
2.50		Oxy 8	Temp 8	Lime (#11)
2.37	Theta 3			Gravel (#12)
2.31		Oxy 9	Temp 9	Gravel (#12)
2.00	Theta 4	Oxy 10		Organic (#14)

Table 1: Position of monitoring equipment. The heights above sea level (m asl) have been measured with a theodolite using the lid to dipwell MB21 as reference level (4.155 m asl). Numbers in the column "soil layer" refer to the layer numbers in Figure 2. *: this probe was disconnected in March 2011.

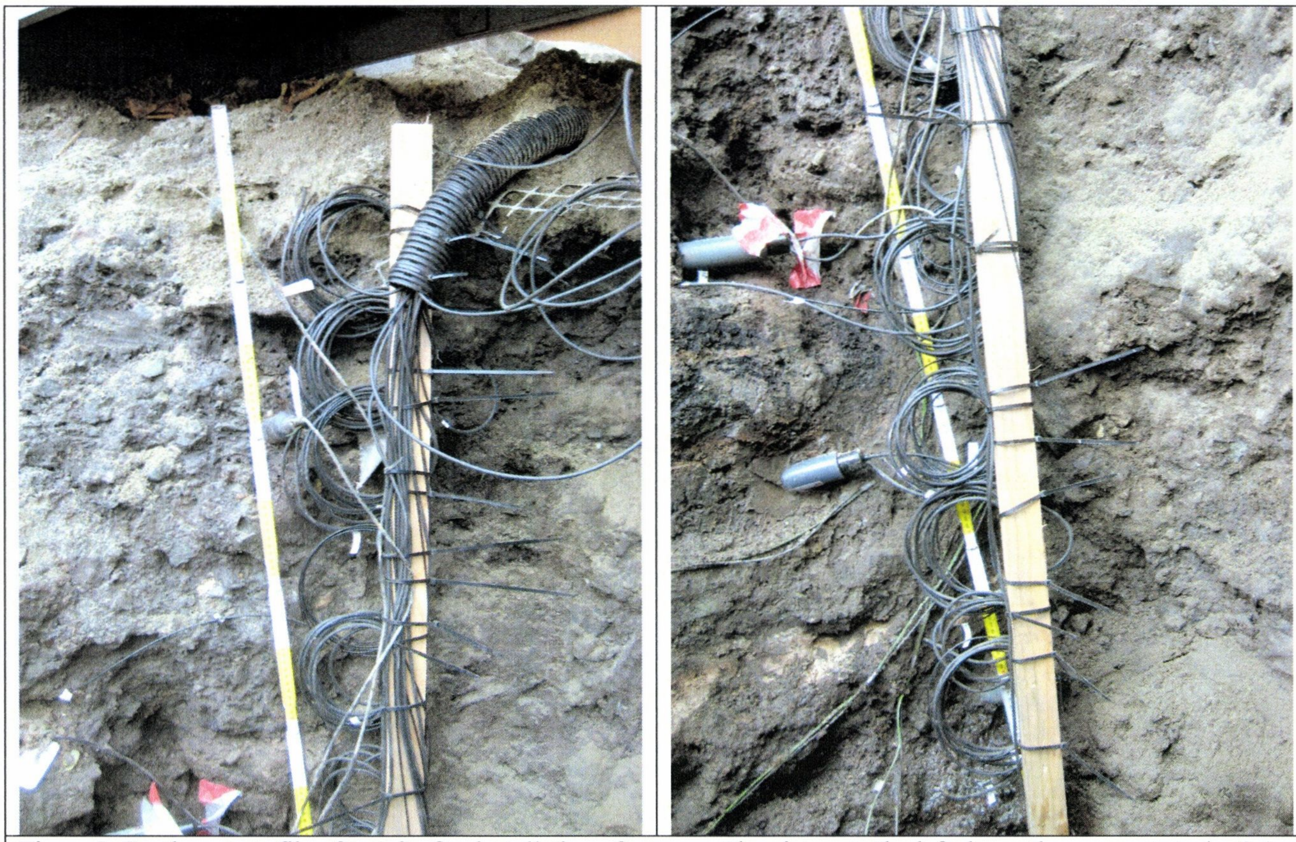


Figure 3: South-east profile of testpit after installation of sensors. The picture to the left shows the upper strata (ca 3.1-4.1 m asl), whereas the picture to the right shows the lower strata (ca 2.25-3.3 m asl) – the deepest lying sensors at 2 m asl are not visible.

Results

Field measurements

Figure 4 shows results from field measurements from 26^{th} to 29^{th} of October 2010, along with results from 2006. The testpit had been opened for approximately 1 week when the measurements were made, which may influence the results for most parameters to some extent: The water content may change because of drainage or air drying of the open profile; the conductivity may change if the soil profile is flushed by rainwater; the oxygen concentrations may change because there is an increased oxygen access through the open profile; and the soil temperature may change because of cooling or heating from the air. Thus the results from the excavation need to be compared to the logger results measured after the testpit was backfilled. Furthermore, the water contents (upper left in Figure 4) need to be validated in the laboratory, as the calibration of the equipment depends on soil type.

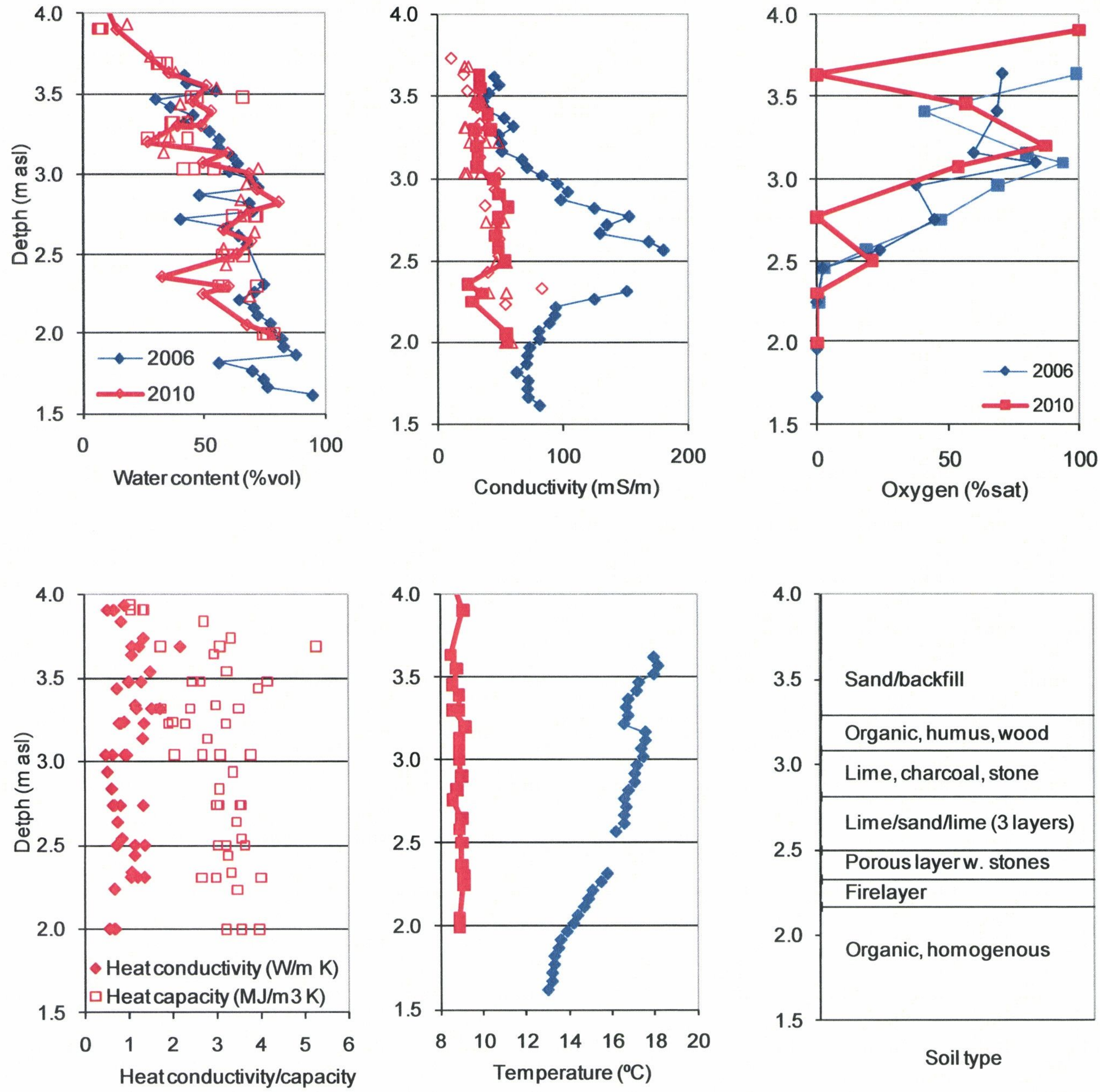


Figure 4: Results from field measurements. Results from 2006 are shown with blue, whereas results from 2010 are shown with red.

Laboratory analysis

Figure 5 shows the results from dry content and loss on ignition analyses made on soil samples from the testpit from both 2006 and 2010. For some of the soil strata samples were taken in duplicate in order to evaluate the heterogeneity of the soil.

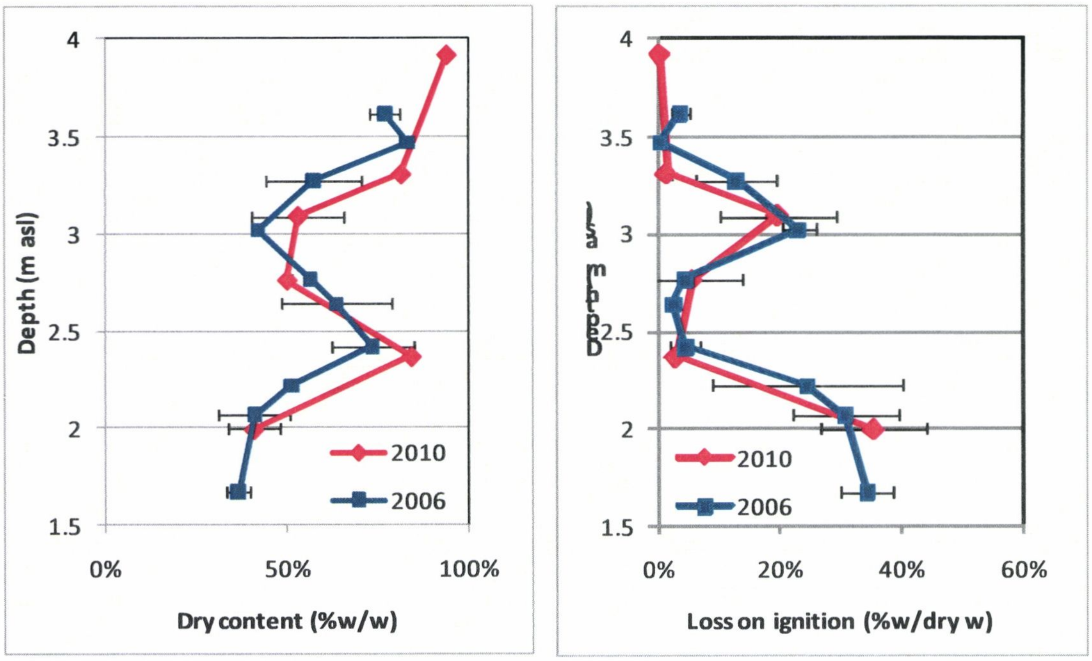


Figure 5: Results from laboratory analyses of loss on ignition, and dry matter content. Blue lines are results from 2006 and red lines are results from 2010. Error bars (horizontal black lines) show the standard deviation between two soil samples from the same soil layer.

The laboratory measurements are used to check the calibration of the water content probes: For each probe a soil sample of 100 cm^3 volume was taken, in order to compare the initial measurements of the probes with the water content measured in the laboratory. Table 2 shows this comparison. The water content probes gives the results in %vol (Table 2, right), whereas laboratory measurements of dry content and loss on ignition are normally given as weight% (Table 2, left). For a sample with known volume it is possible to recalculate the dry content to the volumetric water content, using a density of 1 g/cm^3 for water (Table 2, middle).

In Table 2 (middle) are also given estimates of the volumetric content of organic and inorganic material in the soil – the organic content has been calculated from the loss on ignition divided by the density of organic matter (estimated to 1.5 g/cm^3), and the inorganic content has been calculated from the weight after ignition divided by the density of inorganic matter (estimated to 2.65 g/cm^3). Finally the water, organic and inorganic content has been subtracted from the total volume of 100 cm^3 in order to estimate the volume of air in the soil. The sum of the air and water content of the soil is called the soil porosity, which is the theoretical maximum water content of the soil.

Height	Dry content	Loss on ignition	Water	Inorganic	Organic	Air	Porosity	Probe	Standard calibration	Initial result
(m asl)	(%w/w)	(%w/dry w)	(%vol)	(%vol)	(%vol)	(%vol)	(%vol)			(%vol)
2.00	36%	41%	71%	9%	11%	9%	80%	Theta 4	Organic	69%
2.37	84%	3%	28%	54%	3%	15%	43%	Theta 3	Inorganic	44%
2.77	51%	12%	68%	24%	5%	3%	71%	Theta 2	Organic	69%
3.09	62%	13%	56%	30%	**8%**	6%	62%	Theta 1	Organic	49%
3.31	82%	2%	32%	54%	2%	13%	45%	SM200-2	Inorganic	46%
3.60	-	-	-	-	-	-	-	SM200-3	Inorganic	29%
3.92	94%	0%	10%	60%	0%	29%	39%	SM200-4	Inorganic	15%

Table 2: Water content and loss on ignition of soil from ring samples. Section 1 shows data relative to weight, in section 2 the data have been recalculated to % volume, and in section 3 results from the water content probes are shown for comparison, where standard calibration for the different soil types have been used.

Results from the analysis of modern pine samples are summarised in Table 3. The depth of the samples was not measured during installation or retrieval. However, Ove Steinestø from Multiconsult, who installed the samples, describes that they were placed at the same depth as the water content sensors in 2006, with an extra wood sample between the two uppermost sensors. Furthermore, Rory Dunlop from NIKU, who retrieved the samples, describes their order of appearance from the top during the retrieval, with some uncertainty on the two deepest samples. This makes it possible to estimate the depths of the different samples.

Estimated height (m asl)	Soil layer	Sample id (Dunlop)	Density (g/cm^3)	White rot	Soft rot	Erosion bacteria	Other comments
3.27	Mixed	"1. fra topp"	0,40/0,39	-	X	**X**	Light coloured
3.04	Organic	" 2. fra topp"	0,41/0,41	-	**X**	X	Slightly darkened
2,81	Lime	"3. fra topp"	0,48/0,43	-	-	X	Light coloured
2,43	Stone	"1.55 m fra topp"	0,41/0,40	??	X	X	Darkened
1,98	Organic	"4?? fra topp"	0,45/0,46	-	-	X	Light coloured

Table 3: Analysis of modern pine samples after 4 years in the ground. **X:** massive attack ; X: identified; ?: possibly identified; -: not found.

Eight samples of archaeological wood from the testpit in Bugården have been sampled (in 2006 and 2010) and analysed. Seven of these had densities of 0.14-0.22 g/cm^3 and a single sample had a density of 0.43 g/cm^3.

Logging

Results from the previous datalogger (DL6) were downloaded (Figure 6). The logging stopped on the 19th of October 2010 when the testpit was reopened, as one of the sensors was damaged and short circuited the logger. Precipitation data has been found at www.met.no (Bergen, Florida station) giving daily values. In all diagrams the precipitation is shown at 12 o'clock (midday), as the exact timing of the rainfall is not known.

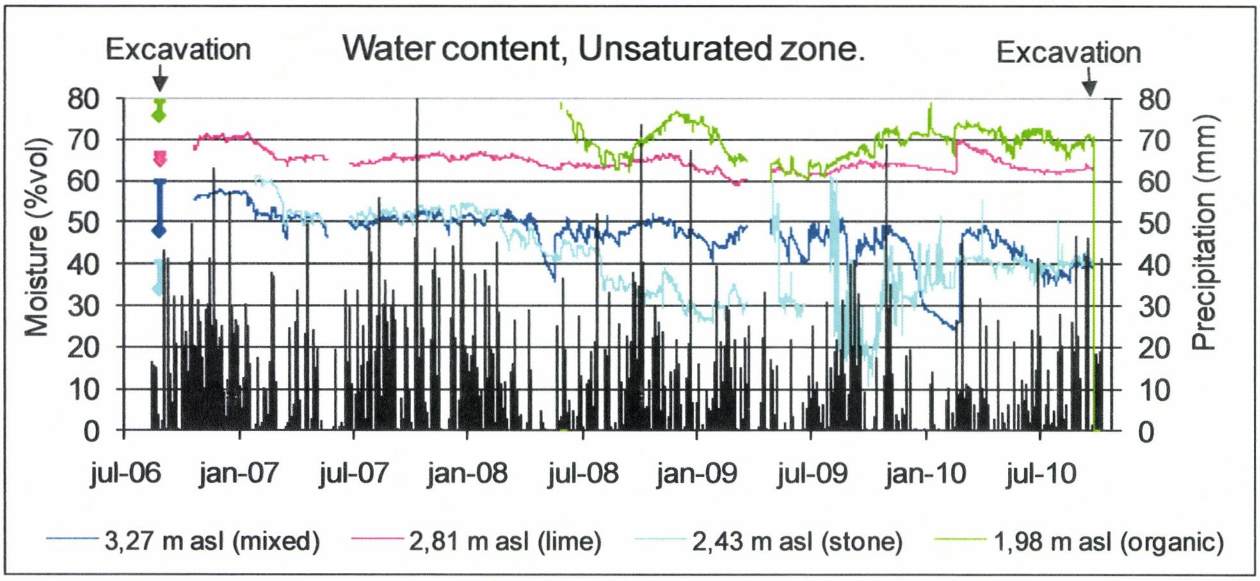


Figure 6: Water content measured at 4 depths with SM200 probes in the period 2006-2010, along with precipitation data. Standard calibration has been used for the probes. Laboratory results from the excavation in 2006 are shown (left side) for comparison, where diamonds show the volumetric water content, and horizontal lines show the porosity, as measured in ring samples.

The first data from the new data logger (CR1000) are presented in Figure 7-9. The data were downloaded in March 2011. A short circuit of the system gave erroneous results for the water content sensors and temperature sensors from the 1st of January, and the logger automatically turned off on the 23rd of January.

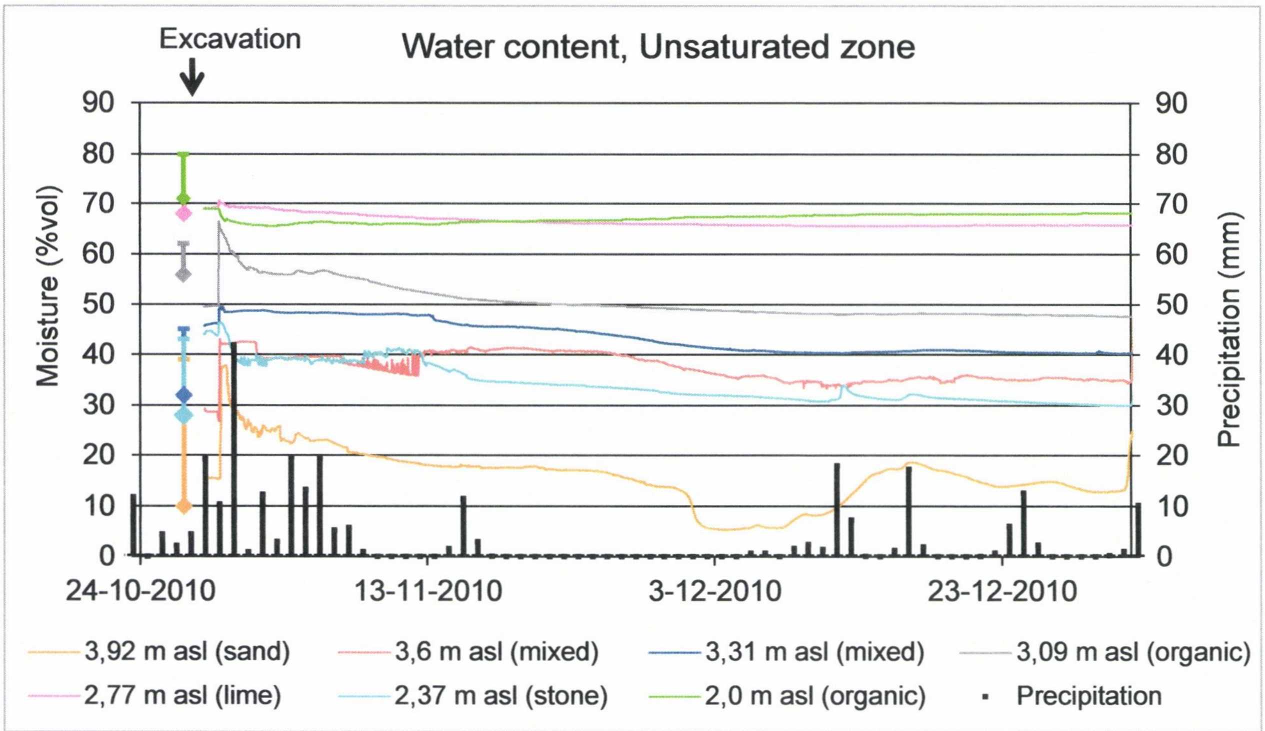


Figure 7: Initial results from water content probes. Laboratory results are shown (left side) for comparison, where diamonds show the volumetric water content, and horizontal lines show the porosity, as measured in ring samples. No ring sample could be taken from the soil layer at 3.6 m asl.

Figure 7 shows abrupt increases in the water content for most sensors on the 29th of October, which is due to the backfilling of the excavation pit: the excavated soil was used as backfill, but it had become very muddy due to rain. It probably takes a few weeks before the soil is settled. The uppermost sensor at 3.92 m asl shows a sudden decrease in water content on the 2nd December, which is probably due to freezing of the soil pore water (see temperature graph in Figure 9).

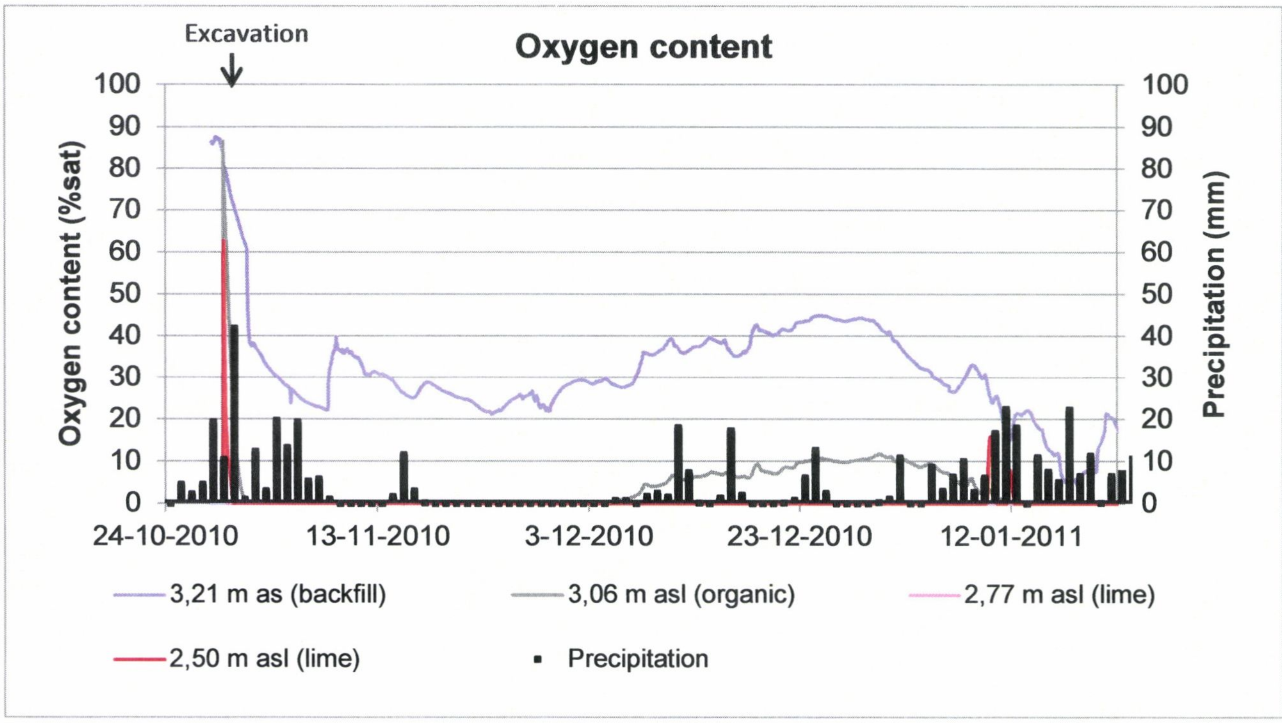


Figure 8: Initial results from oxygen probes. Four probes in and above the lime layer are connected to the datalogger in the first measuring period.

Figure 8 shows some abrupt changes in the oxygen content on the 29th October, which are also due to backfilling of the excavation pit – the sudden increase in oxygen indicates that air or oxygen rich water are pressed into the soil layers around the sensors during the backfilling, and this oxygen is consumed within one or a few days.

Only four oxygen sensors are monitored continuously: The uppermost at 3.21 m asl shows oxygen concentrations between 20 and 45 % saturation during the monitoring period, with a drop down to 5 % saturation during a very wet period around the 17th of January. The next sensor at 3.06 m asl shows anoxic conditions most of the monitoring period, but some oxygen (up to 10% saturation) appears in the period 6th of December to 11th of January. This is probably due to drying out of the soil, giving increased oxygen diffusion: There is a long period without precipitation from the 17th November to the 7th December, and the water content sensor at 3.09 m asl shows a low water content of only 40% vol from the 6th of December until it stops working on the 1st of January

(Figure 7). The two lowest sensors at 2.77 m asl and 2.50 m asl in the lime layer show no oxygen during the monitoring period, except for a brief occurrence at 2.50 m asl on the 9th and 11th of January – these peaks could be due to oxygen rich rainwater flushing through the soil during heavy rainfall, but we have no water content data from the soil to confirm or refute this.

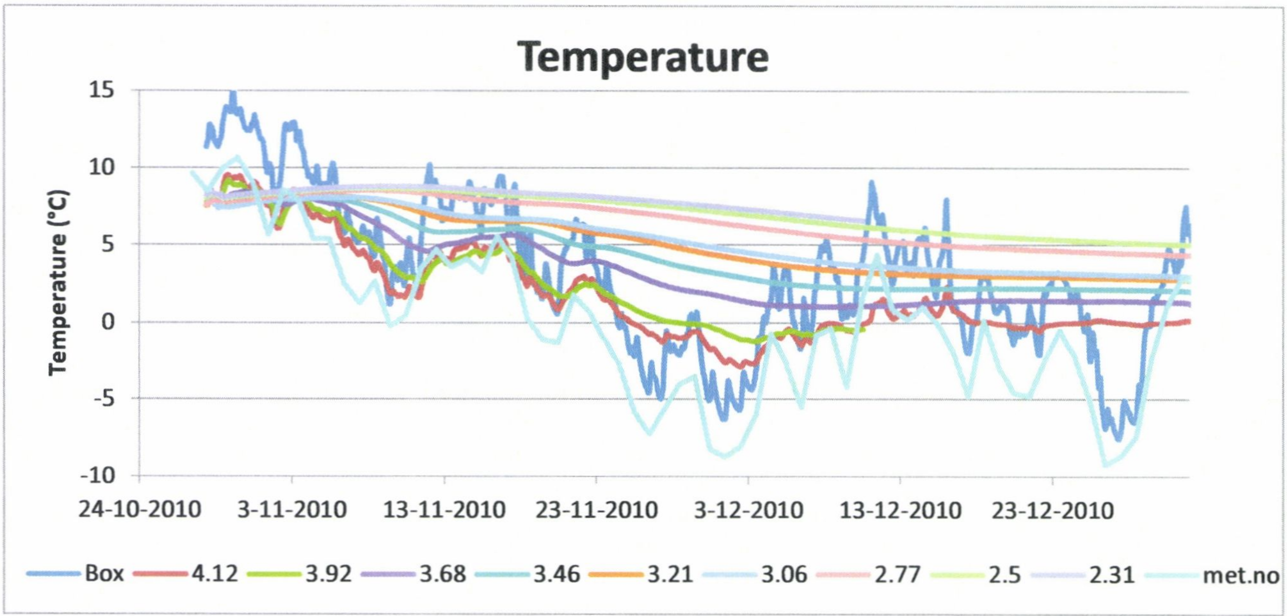


Figure 9: Initial results from temperature probes. Numbers show the height above sea level. "Box" refers to a reference temperature inside the logger box. "met.no" is the air temperature (daily average) from the Norwegian meteorological survey, station Florida in Bergen.

Figure 9 shows that all temperature sensors in the soil give equal results (around 8° C) at the beginning of the data series, but it only takes a few days after the backfilling before some variation is observed. The temperature inside the logger box is slightly higher than values given for the Florida weather station. This could be due to heat produced by the monitoring equipment inside the logger box.

Discussion

The purpose of re-opening the testpit from 2006 was two-fold: first of all to install monitoring equipment and secondly to investigate if the state of preservation of the cultural layers has changed between 2006 and 2010.

Changes since 2006?

Measurements show that the ground surface and buildings settle at 6-8 mm/year in this part of Bryggen (Jensen 2007), which corresponds to approximately 2-3 cm since 2006. The settling has been explained by decay of organic material in the ground, caused by a low groundwater level, which increases the oxygen availability. Based on the oxygen measurements in 2006 it was hypothesized, that the decay mainly takes place in the upper 1 m of the soil in the area of the testpit (Matthiesen 2007) as a layer of lime from 2.5-3.1 m asl may locally function as an oxygen barrier. The measurements during the fieldwork in 2010 again indicate that oxygen is mainly found in the upper 1 m of the soil, albeit with some oxygen at 2.5 m asl (Figure 4).

Over time the decay of organic material can give a decrease in the organic content and the loss of ignition (LOI) of the soil. Soil samples have been analysed in 2006 and 2010 and the results are compared in Figure 5. The Figure seems to indicate that there has been a decrease in the LOI in the soil layers around 3.3 m asl. However, the soil is very heterogeneous and it is difficult to achieve firm statistical evidence for the decrease within only 4 years.

Archaeologist Rory Dunlop has described the state of preservation of the different soil strata in 2006 and in 2010, but didn't observe any obvious decay in the state of preservation during this (rather short) period (Dunlop, personal comment).

Figure 4 shows that there has been a change in the conductivity of the soil: A high conductivity was found in the lime layer in 2006, which was suggested to be caused by slow water transport through the fine-grained lime. In 2010 the conductivity had decreased significantly in the lime layer, which could indicate an increased water transport through the layer; one explanation could be that the digging of the testpit may have disturbed the normal soil sequence, causing an increased leaching in the exposed soil profile.

In 2006 modern wood samples were installed at different depths in the testpit, and these were retrieved in 2010. Analysis of the samples shows that the density of the samples at 3.27, 3.04 and 2.43 m asl is 0.39-0.41 g/cm^3, whereas it is slightly higher (0.43-0.48 g/cm^3) at 2.81 and 1.98 m asl (Table 3). For comparison fresh pine has a density of 0.35-0.5 g/cm^3 and the archaeological wood samples from the testpit had a density around 0.2 g/cm^3. The microscopy analyses show that degradation by erosion bacteria has taken place in all samples, whereas degradation by fungi (soft rot and possibly white rot) has only taken place in the samples from 3.27, 3.04 and 2.43 m asl (Table 3). Decay by fungi only takes place when oxygen is present and it is significantly faster and more severe than decay by bacteria. Thus both the density measurements and the microscopy analyses indicate that the preservation conditions are not very good in these soil layers, which corresponds well with the environmental monitoring showing dynamic conditions at 3.27 and 2.43 m asl (Figure 6, water content). The wood samples from 2.81 m asl (lime layer) and 1.98 m asl (organic layer) are less degraded: for the lime layer it is probably due to the stagnant conditions in this fine grained layer (Figure 6) and for the organic layer at the bottom of the testpit it may indicate that no oxygen reaches this deep layer – however, this needs to be verified by the future oxygen measurements.

Installation of monitoring equipment

The monitoring equipment was successfully installed, all the sensors were working, and Figure 7-9 shows results from the first 2 months. A damaged sensor caused a short circuit and an automatic turn-off of the data logger in January 2011, but this was fixed 17th of March 2011 and the system was restarted. It is too early to discuss the results in any detail in terms of preservation conditions in the ground - a longer monitoring period is necessary to evaluate if the data are representative or if they are still influenced by the disturbance caused by digging the testpit. A detailed discussion of monitoring results is therefore postponed to a later report. However, a few comments concerning the installation and data quality may be given:

As for the water content probes (Figure 7) their response depends on the type of soil. Standard calibration curves have been made by the manufacturer (Delta-T) for different soil types such as for instance "organic", "inorganic", "sand" and "clay", and the results in Figure 7 are from such standard calibration curves. Ideally, individual calibration curves should be made for each soil strata to obtain the most accurate results, but this requires that large, undisturbed soil samples are taken from each soil layer, which is very difficult in these heterogeneous deposits. Instead standard calibration curves are used, and it is checked that the results are similar to laboratory measurements: the initial results from the logger should be similar to the water content measured in the laboratory, and furthermore the water content measured by the logger should at no point exceed the total porosity measured for the soil sample.

In Table 2 the initial results from the sensors are compared to the water content measured in the laboratory, and the same data are presented in Figure 10.

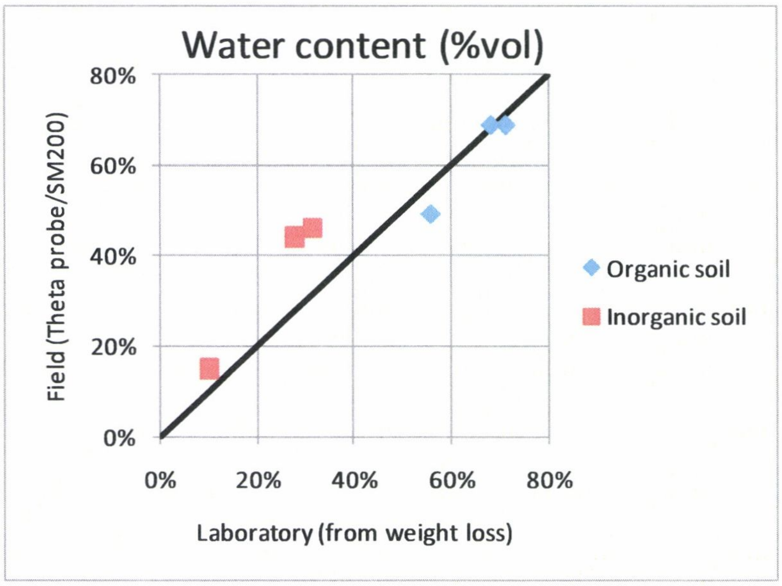


Figure 10: Comparison between water content measured in the laboratory on soil samples, and initial field results measured by the permanently installed water content probes using standard calibrations.

For the organic soil types the initial results from the sensors are in a good correspondence to the laboratory measurements, whereas for the inorganic soil types the sensor results are systematically higher than the laboratory results. This could indicate that a modified calibration should be used, but the laboratory results may also be too low as water might be lost during sampling (this is especially a problem for inorganic soils as for instance sand, where water drains freely). As for comparison to the soil porosity, Figure 7 shows that the water content measured by the sensors increases abruptly when the testpit was backfilled, but the soil porosity is only exceeded by a few per cent for the sensors at 3.09, 3.31 and 2.37 m asl. For the first results we will thus continue using the calibrations given by the manufacturer. The logger program (in Appendix 1) uses a calibration for "organic soil" for all sensors, but the results are recalculated for the inorganic soil strata after downloading the data.
Water content has been measured since 2006, using 4 SM200 probes at different depths (Figure 6). It was necessary to move these probes and also to change the datalogger, but still there seems to be a good continuity in the datasets: Just before the excavation the water content at 1.98, 2.43, 2.81 and 3.27 m asl was 70, 40, 63 and 40%, respectively, whereas at the end of the excavation the new datalogger gave 69, 44, 69 and 46% at (or near) these depths.

As for the oxygen probes the four sensors connected to the datalogger give good signals, showing that they were not damaged by backfilling the testpit (Figure 8). The calibration curves for the oxygen sensors are strongly dependent on temperature, so results from the temperature probes are used in calculating the oxygen concentrations. The four sensors chosen for logging in the first monitoring period are placed between 3.21 and 2.50 m asl, i.e. within and just above the lime layer, where we expect a concentration gradient from the field measurements (in Figure 4). After a few days with very high oxygen concentrations, the four sensors gave results between 0 and 45% oxygen saturation for the rest of the monitoring period. These values are lower than or equal to the values measured when the testpit was still open (0 to 90% oxygen saturation - Figure 4). This difference could be due to bias of the measurements in the open testpit (caused by the exposure to atmospheric air), but it is also possible that the system hasn't come in a steady state yet after backfilling the testpit. The same four sensors will be logged for the next few months.

The temperature probes (Figure 9) show soil temperatures between -2 and +10 degrees. Daily fluctuations are only seen for the uppermost sensors (at 4.12 and 3.92 m asl) whereas the deeper lying sensors are more stable. As expected the lowest temperatures are found at the soil surface during winter (shown in Figure 11 using 3 random days as an example). Work is ongoing to study the influence from temperature on the decay of organic material (Hollesen & Matthiesen, forthcoming).

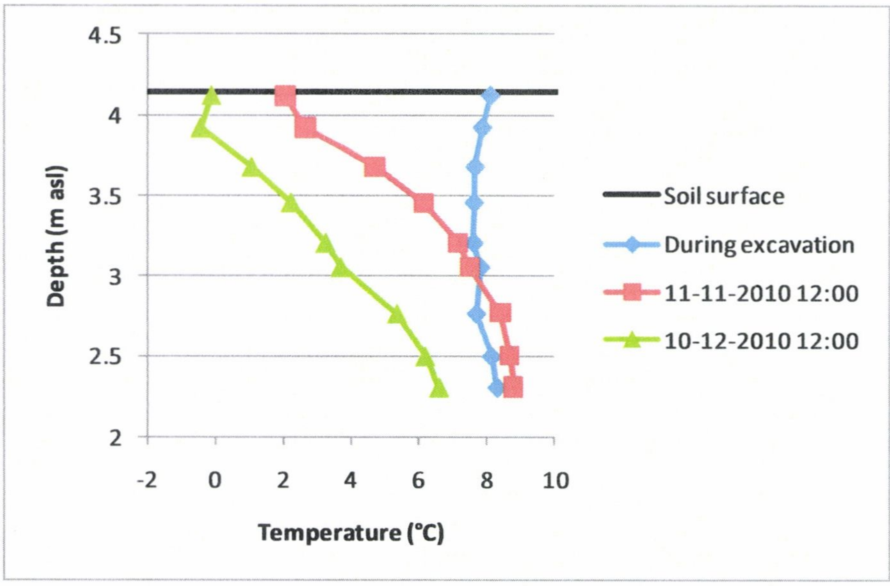


Figure 11: Example of temperature profiles in the soil

Conclusions and future work

In order to sum up:

- The installation of new monitoring equipment has been succesful: all probes are working, the calibration of the water content sensors is reasonable, and there is a good continuity to data from 2006-2010
- It is too early to draw conclusions about preservation conditions from the short series of monitoring data, especially as it takes some time after backfilling the testpit before the conditions are stable.
- The field measurements in 2010 gave results similar to what was found in 2006 and doesn't change the conclusions listed in Matthiesen (2007) significantly. The main exception is that a lower conductivity is measured in the lime-layer in 2010, which could be due to the testpit itself, causing a disturbance of the soil sequence and an increased vertical water flow.
- Measurement of the loss on ignition of soil samples from 2006 and 2010 indicate that there has been a small decrease in the organic content in one of the upper soil layers in this period, but due to the heterogeneity of the soil it is difficult to draw firm conclusions.
- Analysis of modern wood samples that were placed in the soil in 2006 and retrieved in 2010 show that the density is lower and there is more fungal decay in wood samples that were placed in porous layers compared to the more compact (lime and organic) layers. This confirms expectations from environmental analyses that indicate dynamic conditions in the porous layers.

- Fungal decay in a wood sample beneath the lime layer (at 2.43 m asl) indicates that there is occasionally oxygen present at this depth, and that the lime layer is not 100% effective as an oxygen barrier; this needs to be verified by logging of the oxygen concentration at the deepest sensors.

The future work includes:

- Download and interpretation of data from the new logger
- Modelling of the water and oxygen dynamics in the soil
- Evaluation of the effect of different mitigation actions, such as raising the drainage level at the hotel site, re-infiltration, and/or sealing the sheet piling
- Installation of a GSM module on the logger for remote data transfer

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Appendix 1:

'CR1000 Series Datalogger

'Program for Bryggen Bergen, October 2010

'Program author: Jørgen Hollesen

'Declare Public Variables---

'Temperature Sensors

```
Dim LCount_10
Public Batt_volt
Public RefTemp
Public T107_C_1(10)
```

'Oxygen sensors (Oxy 4)

```
Public ioxy As Long
Public SSOXY As String * 256
Public RROXY As String * 128
Public oxy(4) As String *256
Public OXYEr As Long
Public OXYstr(7) As String *16
Public OXYAmp(4)
Public OXYPha(4)
Public OXY_ATM_1
Public OXY_ATM_2
Public OXY_ATM_3
Public OXY_ATM_4
```

'Soil Water Sensors (SM200 and Theta Probe ML2x)

```
Public Sm200_2
Public Sm200_3
Public Sm200_4
Public SmVol_2
Public SmVol_3
Public SmVol_4
Public Theta_1
Public Theta_2
Public Theta_3
Public Theta_4
Public ThetaVol_1
Public ThetaVol_2
Public ThetaVol_3
Public ThetaVol_4
```

'Unit for each parameter is defined--

```
Units Batt_volt=Volts
Units RefTemp=Deg C
Units T107_C_1=Deg C


Units OXY_ATM_1=%
Units OXY_ATM_2=%
Units OXY_ATM_3=%
Units OXY_ATM_4=%


Units SM200_2=mV
Units SM200_3=mV
Units SM200_4=mV
Units SmVol_2=%
Units SmVol_3=%
Units SmVol_4=%


Units Theta_1=mV
Units Theta_2=mV
Units Theta_3=mV
Units Theta_4=mV
Units ThetaVol_1=%
Units ThetaVol_2=%
Units ThetaVol_3=%
Units ThetaVol_4=%

' Constants for calculating Oxygen Content------------------------------------------------------------------------------------------
Const Pi=3.14159265
Const Alpha=0.11
Const Alpha_1=0.89

'Channel 1
Const a_1_anoxy=-0.0048
Const b_1_anoxy=1.85485
Const a_1_oxy=-0.0042
Const b_1_oxy=0.6051

'Channel 2
Const a_2_anoxy=-0.0048
Const b_2_anoxy=1.85485
Const a_2_oxy=-0.0042
Const b_2_oxy=0.6051

'Channel 3
Const a_3_anoxy=-0.0048
```

```
Const b_3_anoxy=1.85485
Const a_3_oxy=-0.0042
Const b_3_oxy=0.6051

'Channel 4
Const a_4_anoxy=-0.0048
Const b_4_anoxy=1.85485
Const a_4_oxy=-0.0042
Const b_4_oxy=0.6051

'Data tables are declared-----------------------------------------------------------------------------------------------------------------------

'Data Table for Soil Temperature and Oxygen
DataTable(TempOxy,1,-1)'(DataO2_Temp,1,-1)
CardOut (1,-1)
DataInterval (0,30,Min,10)
Average (1,Batt_volt,IEEE4, False)
EndTable

'Data Table for Soil water content
DataTable (Water,True, -1)
'Data are stored each hours
DataInterval (1,30,min,10)
'Card is set to Fill and Stop and can have 365*24=8760 records a year
CardOut (0,-1) 'output to flashcard
Average (1,SM200_2,FP2,False)
Average (1,SM200_3,FP2,False)
Average (1,SM200_4,FP2,False)
Average (1,SmVol_2,FP2,False)
Average (1,SmVol_3,FP2,False)
Average (1,SmVol_4,FP2,False)

Average (1,Theta_1,IEEE4,False)
Average (1,Theta_2,IEEE4,False)
Average (1,Theta_3,IEEE4,False)
Average (1,Theta_4,IEEE4,False)
Average (1,ThetaVol_1,IEEE4,False)
Average (1,ThetaVol_2,IEEE4,False)
Average (1,ThetaVol_3,IEEE4,False)
Average (1,ThetaVol_4,IEEE4,False)



EndTable

'Subroutines for the program are declared ------------------------------------------------------------------------------------------------
```

```
Sub OpenSerial

SerialOpen (COMRS232,38400,0,20,1000)
EndSub


' The OXY 4 is activated by the CR1000------------------------------------------------------------------------

Sub OXYSend

OXYEr=SerialOut (ComRS232,SSoxy,RRoxy,1,10)
' SSoxy=SS$ RRoxy=Wait$ Tries=1 TimeOut=1sec (200)
EndSub

' Data from the OXY4 is recieved by the datalogger-------------------------------------------------------------
Sub OXYRecive

SerialIn (RRoxy,ComRS232,200,13,256)
' RR=Recive$ TimeOut=1.8sec(100) TermChar=CR LengtOfData=256
EndSub

' The atmopheric Oxygen content is calculated-----------------------------------------------------------------
Sub Oxy_Atm
OXY_ATM_1=((Alpha_1/((TAN((OXYPha(1)/100)*(Pi/180))/((a_1_anoxy*T107_C_1(5))+b_1_anoxy))-Alpha))-
1)*(1/(((Alpha_1/((((a_1_oxy*T107_C_1(5))+b_1_oxy)/((a_1_anoxy*T107_C_1(5))+b_1_anoxy))-Alpha))-1)*(1/100)))

OXY_ATM_2=((Alpha_1/((TAN((OXYPha(2)/100)*(Pi/180))/((a_2_anoxy*T107_C_1(6))+b_2_anoxy))-Alpha))-
1)*(1/(((Alpha_1/((((a_2_oxy*T107_C_1(6))+b_2_oxy)/((a_2_anoxy*T107_C_1(6))+b_2_anoxy))-Alpha))-1)*(1/100)))

OXY_ATM_3=((Alpha_1/((TAN((OXYPha(3)/100)*(Pi/180))/((a_3_anoxy*T107_C_1(7))+b_3_anoxy))-Alpha))-
1)*(1/(((Alpha_1/((((a_3_oxy*T107_C_1(7))+b_3_oxy)/((a_3_anoxy*T107_C_1(7))+b_3_anoxy))-Alpha))-1)*(1/100)))
OXY_ATM_4=((Alpha_1/((TAN((OXYPha(4)/100)*(Pi/180))/((a_4_anoxy*T107_C_1(8))+b_4_anoxy))-Alpha))-
1)*(1/(((Alpha_1/((((a_4_oxy*T107_C_1(8))+b_3_oxy)/((a_4_anoxy*T107_C_1(8))+b_4_anoxy))-Alpha))-1)*(1/100)))
EndSub

'The water content is calculated for the SW200 sensors
Sub Sm200Vol
SmVol_2=(-0.071+1.917*(Sm200_2/1000)-4.61*(Sm200_2/1000)^2+7.248*(Sm200_2/1000)^3-
5.48*(Sm200_2/1000)^4+1.611*(Sm200_2/1000)^5)*100
SmVol_3=(-0.071+1.917*(Sm200_3/1000)-4.61*(Sm200_3/1000)^2+7.248*(Sm200_3/1000)^3-
5.48*(Sm200_3/1000)^4+1.611*(Sm200_3/1000)^5)*100
SmVol_4=(-0.071+1.917*(Sm200_4/1000)-4.61*(Sm200_4/1000)^2+7.248*(Sm200_4/1000)^3-
5.48*(Sm200_4/1000)^4+1.611*(Sm200_4/1000)^5)*100
EndSub


'Main Program------------------------------------------------------------------------------------------------------------------
```

```
'The water content is calculated for the Thetaprobes
Sub ThetaVol
ThetaVol_1=(((1.07+6.4*(Theta_1/1000)-6.4*(Theta_1/1000)^2+4.7*(Theta_1/1000)^3)-1.6)/8.4)*100
ThetaVol_2=(((1.07+6.4*(Theta_2/1000)-6.4*(Theta_2/1000)^2+4.7*(Theta_2/1000)^3)-1.6)/8.4)*100
ThetaVol_3=(((1.07+6.4*(Theta_3/1000)-6.4*(Theta_3/1000)^2+4.7*(Theta_3/1000)^3)-1.6)/8.4)*100
ThetaVol_4=(((1.07+6.4*(Theta_4/1000)-6.4*(Theta_4/1000)^2+4.7*(Theta_4/1000)^3)-1.6)/8.4)*100
EndSub

BeginProg
Call OpenSerial
Scan (1,Min,0,0)
Battery(Batt_volt)
PanelTemp (RefTemp,250)

'The multiplexer is activated and the temperature sensors are connected
PortSet(2,1)
Delay(0,150,mSec)
LCount_10=1
SubScan(0,uSec,3)
'Switch to next AM16/32 Multiplexer channel
PulsePort(1,10000)
'107 Temperature Probe (4-wire) (CSL) measurements T107_C_7() on the AM16/32 Multiplexer:
Therm107(T107_C_1(LCount_10),3,13,2,0,_60Hz,1,0)
LCount_10=LCount_10+3
NextSubScan
'Switch to next AM16/32 Multiplexer channel
PulsePort(1,10000)
'107 Temperature Probe (4-wire) (CSL) measurements T107_C_7() on the AM16/32 Multiplexer
Therm107(T107_C_1(10),1,7,2,0,_60Hz,1,0)
'Turn AM16/32 Multiplexer Off
PortSet(2,0)
Delay(0,150,mSec)

'The Oxygen content is measured
' Set OXY- in mode3
SSoxy="mode0003"+CHR(13)
RRoxy=""
Call OXYSend
' Get Data from OXY-4
SSoxy="data"+CHR(13)
 RROXY=""
Call OXYSend
' Read 4 Data blocks from OXY-4
 For ioxy=1 To 4
Call OXYRecive
oxy(ioxy)=RRoxy
```

```
Next ioxy
' Extract data from 4 blocks
For ioxy=1 To 4

SplitStr(OXYstr(),oxy(ioxy),CHR(59),6,0)'incomig string split at ";"
OXYAmp(ioxy) = Mid(OXYstr(2),1,7)
OXYPha(ioxy) = Mid(OXYstr(3),1,7)

Next ioxy
Call Oxy_Atm
CallTable (TempOxy)

'The soil water content is measured

SW12 (1) 'open SW12
Delay (0,5,Sec)

'measuren on Sm200
VoltSe (Sm200_2,1,mV2500,1,True,0,_50Hz,1,0)
VoltSe (Sm200_3,1,mV2500,2,True,0,_50Hz,1,0)
VoltSe (Sm200_4,1,mV2500,3,True,0,_50Hz,1,0)

'The water content is calculated by converting mV to %
Call (Sm200Vol)
'measure on Thetaprobes
VoltDiff (Theta_1,1,mV5000,3,True ,0,_50Hz,1,0)
VoltDiff (Theta_2,1,mV5000,4,True ,0,_50Hz,1,0)
VoltDiff (Theta_3,1,mV5000,5,True ,0,_50Hz,1,0)
VoltDiff (Theta_4,1,mV5000,6,True ,0,_50Hz,1,0)
Call (ThetaVol)
SW12 (0)  'close SW12
CallTable(Water)


NextScan
EndProg
```

Appendix 2:

Wiring of sensors for Bryggen, revised 17-03-2011

CR1000-datalogger
CFM100 Compact Flash Memory Module S/N: 5119
Multiplexer AM16/32B

Wiring of CR1000

Upper panel:

1H	(none)		
1L	white	SM200_3	SM200
AG	ground	SM200_3	SM200
2H	white	SM200_4	SM200
2L	(none)		
AG	ground	SM200_4	
3H	yellow	Theta_1	ThetaProbe ML2X-321/051
3L	green	Theta_1	ThetaProbe ML2X-321/051
AG	ground	Theta_1	
4H	yellow	Theta_2	ThetaProbe ML2X-321/051
4L	green	Theta_2	ThetaProbe ML2X-321/051
AG	ground	Theta_2	
VX1			
AG			
P1			
AG			
P2			
AG			

Middle panel

5H	yellow	Theta_3	ThetaProbe ML2X-321/051
5L	green	Theta_3	ThetaProbe ML2X-321/051
AG	ground	Theta_3	
6H	yellow	Theta_4	ThetaProbe ML2X-321/051
6L	green	Theta_4	ThetaProbe ML2X-321/051
AG	ground	Theta_4	
7H	Red	AM16/32 ODD L	
7L	Red	AM16/32 Even H	
AG	Blue	AM16/32 AG	
8H	Red	AM16/32 EVEN L	
8L			
AG			
VX2	Red/black	AM16/32 EVEN H	
AG	white	10 107T Tsoil()	
VX3			
AG			

Lower panel:

G		
5V		
G	blue	Theta_1,Theta_2, Theta_3 & Theta_4
SW-12V	red	SM200(3-4) & Theta(1-4)
G	thick black	AM16/32 G
12V	(defect)	
12 V	red	AM16/32 12V
G	black	SEA G (second from right)
C1	green	AM16/32 CLK
C2	Blue	AM16/32 RES
C3		
C4		
G	white& black	AM16/32 GND
C5		
C6		
C7		
C8		
G		

Wiring of Relay Analogue Multiplexer AM16/32A S/N: E5052
AM16/32 RES = Blue = CR1000 C2
AM16/32 CLK = Green = CR1000 C1
AM16/32 GND = White/Black = CR1000 G
AM16/32 12V = Red = CR1000 12V
AM16/32 ODD H = Black = CR1000 Vx2
AM16/32 ODD L = Red = CR1000 7H
AM16/32 AG = Blue = CR1000 AG
AM16/32 EVEN H = Red = CR1000 8L
AM16/32 EVEN L = Red = CR1000 8H

WIRING OF SENSORS ON AM16/32 RELAY MULTIPLEXER

1H	Black	T107(1-3)
1L	Red	T107_1
G	Screen	T107_1
2H	Red	T107_2
2L	Red	T107_3
G	Screen	T107(2+3)
3H	Black	T107(4-6)
3L	Red	T107_4
G	Screen	T107_4
4H	Red	T107_5
4L	Red	T107_6
G	Screen	T107(5+6)
5H	Black	T107(7-9)
5L	Red	T107_7
G	Screen	T107_7
6H	Red	T107_8
6L	Red	T107_9
G	Screen	T107(8+9)

7 to 32 are empty