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Subsidence of dredged organic sediments in cultivated peatlands.

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Abstract. Many low-lying peatlands in delta areas undergo significant subsidence due to drainage for agricultural purposes. Subsidence may be attributed to shrinkage, consolidation or oxidation. At the same time the canals and ditches are regularly dredged to maintain water quality and drainage capacity. Often these dredged sediments are placed on land, which may help to slow down subsidence. In this study subsidence of organic sediments was monitored for a period of three years. The sediments were dredged from lakes and canals in the peatlands of Wormer- en Jisperveld, in the Netherlands and placed in an on-land constructed depot. Samples were collected at regular time intervals to measure water content and organic content. Additionally, laboratory tests were performed to characterize the organic sediments and determine the compression, consolidation, shrinkage and water retention characteristics under various oxidizing conditions. The laboratory tests showed that oxidation can significantly affect the compression, consolidation, water retention and shrinkage characteristics of organic soils. However, monitoring results in the field showed that the major part of the subsidence, which occurred within the three years of this study, could be attributed to shrinkage of the dredged sediments and the remainder to consolidation of the underlying peat layers, while the organic matter content did not change significantly.

1 Introduction

Peatlands in low-lying delta areas suffer from continuous subsidence induced by groundwater drainage, which is applied to prevent flooding or to cultivate these peatlands to allow its use for agriculture or recreation [1-9]. Drainage induced subsidence can be attributed to three mechanisms: shrinkage, consolidation and oxidation. Shrinkage of the peat material itself can occur as a result of evaporation. Evaporation causes an upward flux of water, which can be accelerated by evapotranspiration in case of plant growth and generates capillary suction in the pores causing the soil to shrink. Consolidation of the underlying soft soils may occur due to an increase in overburden pressure. The increase in overburden pressure may be the result of groundwater lowering, which reduces the buoyancy effect. Decomposition of organic matter in peatlands is mostly considered to be the result of aerobic oxidation, which occurs when oxygen penetrates the soil during periods of low groundwater level.

Although a lot of studies have been performed to quantify subsidence and oxidation in peatlands, there is still no consensus about which of these three mechanisms is dominant. Some researchers state that land subsidence in these types of peatlands is mainly due to shrinkage caused by drainage and evaporation leading to loss of volume as water is removed and particles rearrange. Other researchers state that consolidation and shrinkage typically occur relatively fast, while oxidation is the dominant mechanism causing subsidence at the long term.

This paper summarizes the results of a study which aimed to unravel the different mechanisms causing subsidence (i.e. shrinkage, consolidation and oxidation of organic matter) in peatlands and organic soils. An on-land depot was constructed and filled in two-stages with organic sediments, which were dredged from the lakes and ditches in the peatland area of Wormer & Jisperveld in The Netherlands. The depot was monitored for 3 years. At regular time intervals the shrinkage of the organic sediments and settlement of the underlying soils were monitored, while samples were taken to determine profiles of water content, organic matter content, type of organic matter, and nutrients. Secondly material was collected for geotechnical characterization and laboratory experiments to assess the consolidation and shrinkage characteristics under various oxidizing and loading conditions. Results of these studies have been reported in more detail in [10-13].

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2 Field study

An on-land depot was constructed to store dredged sediments from the lakes and canals in the cultivated peatland of Wormer-Jisperveld. The peatland is situated in the Northwestern part of the Netherlands located near the town of Wormerveer and surrounded by reclaimed polder areas, which were former lakes that were drained in the 17th century.

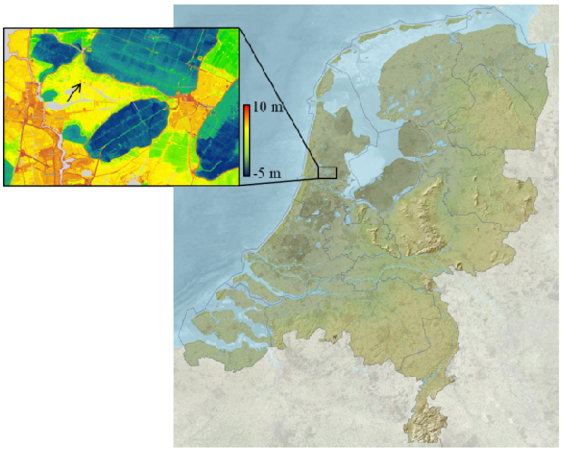

Fig. 1. The location and surface elevation of the peatlands of Wormer-Jisperveld and surrounding towns and polders extracted from the "AHN Viewer". Arrow indicates location of the constructed depot containing dredged sediments.

The surface elevation in these peatlands used to be about 2 m above sealevel, but due to drainage and cultivation of these peatlands, which initiated in the 15th century, the surface level has subsided and is currently about 1 to 1.5 m below sea level (figure 1). The current soil profile at the site consists of 30 to 40 cm of topsoil (mostly decomposed peat), followed by 2.5 to 3 m of fibrous peat, on top of clays, silts and fine grained sandy materials. The depot was constructed by removing 30 cm of topsoil, which was used to construct embankments surrounding the depot. The depot was filled with dredged material in two phases: A first phase between January and March 2014 and a second phase from July to October 2014. From April to June there were no dredging activities in the area due to the breeding season of migrating birds. Sediments were filled from the North side of the depot. During the initial weeks after filling some settling took place and excess surface water was drained of from the side. Level gauges were placed in the depot to monitor subsidence. The local water board Hoogheemraadschap Hollands Noorder-kwartier (HHNK) monitored the subsidence of the bottom of the deposit by determining the elevation of the level gauges in relation to a geodetic reference level. At the southern side of the deposit, a wooden platform was installed to allow sampling of the dredged sediments. (Figure 2) At regular time intervals the surface elevation samples were taken using a 25 mm gauge auger (Eijkelkamp). Each time, three column samples were taken over the entire depth of the dredged material, and subsampled in 10 cm intervals. Subsamples from the same depth were mixed to get average representative profiles of material characteristics. Water content and organic matter content were determined according to local geotechnical standards (ISO/TS 17892-1:2014). Gravimetric water content was obtained by drying the samples in the oven for 24 h at 105 °C. The organic content (loss on ignition) was obtained by heating the dried material for 4 h at 550 °C. In addition, some chemical analysis was performed to identify changes in the total amount of Nitrogen, Phosphorus and Sulfur and the type of organic matter as described by Oliveira et al [14].

Fig. 2. Depot in June 2014 showing the sampling platform and level gauge (top) and in September 2015, illustrating to the rapid growth and potential dewatering effect of reed (bottom).

Figure 3 shows the sediment level in the depot. A decrease in the sediment level in the pond is due to shrinkage or oxidation of the dredged sediments. Figure 4 shows the settlement of the bottom of the pond, which can be attributed to consolidation, shrinkage (or oxidation) of the underlying soils. It is clear that the major amount of volume change can be attributed to the shrinkage of the sediments themselves. After the first filling stage the sediment level dropped about 50 cm from 1.7 to 1.2 m in three months, corresponding to about 30% reduction in volume. After the second filling stage, during winter of 2015 the sediment level remained fairly constant, but from spring 2015 until autumn 2016 significant shrinkage of the sediments occurred, as the sediment level dropped 1.2 m from 1.9 to 0.7 m in 2 years, corresponding to a volume change of 63%.

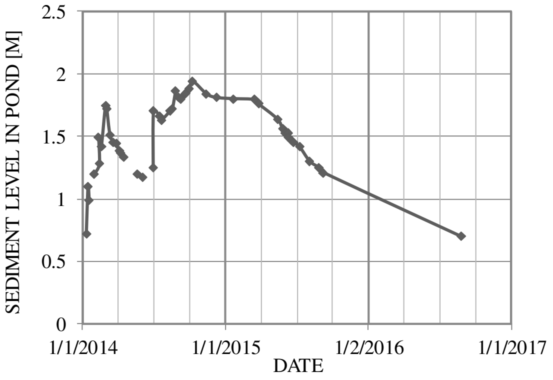

Fig. 3. Measured sediment level in the pond

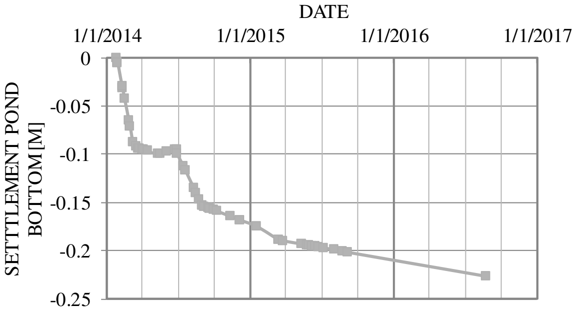

Fig. 4. Measured sediment level in the pond

Filling the depot also caused the bottom of the pond to settle. Immediate settlement was observed during both filling stages. Between the first and second filling phase no additional settlement was observed, while after the second filling stage a continuous settlement of the bottom of the pond was observed, reaching a total settlement of about 0.23 m.

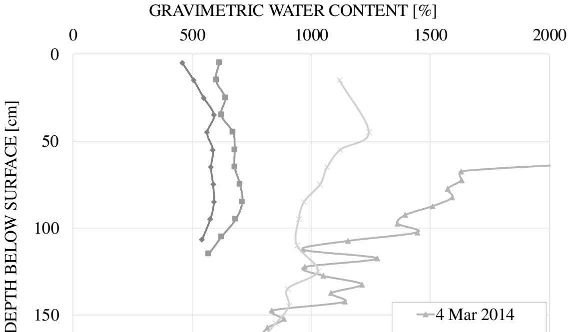

Fig. 5. Water content in the dredged sediments

The observed shrinkage of the dredged sediments was also evident from the change in gravimetric water content (Figure 5), which during the filling stage in March 2014 exceeded 1500%, but had reduced to about 520% by August 2016. The organic content did not show any significant changes during the 3 years of monitoring (Figure 6). Still, Oliveira et al. [14] showed some minor changes in the chemical composition (nitrogen, phosphor and sulphur) and type of organic matter, which indicated that some degradation of organic matter took place. Although the loss of organic matter appears to be insignificant, oxidation may still affect the physical and mechanical properties of organic soil by changing the integrity of the structural fabric of the soil.

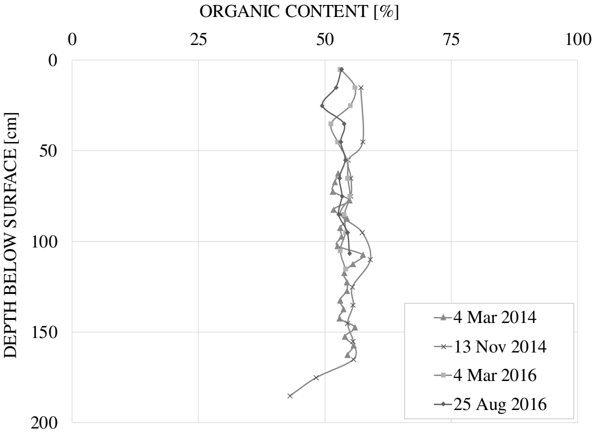

Fig.6. Organic content of the dredged sediments

These field observations suggested that the surface subsidence at the depot was mainly due to shrinkage of the dredged sediments and for the remaining part due to consolidation of underlying peat layers, while oxidation of organic matter did not seem to be an important factor causing subsidence. Shrinkage could be caused by downward drainage or upward drainage and dessication through evaporation or evapotranspiration. The growth of reed (and at a later successive stages also willow, Figure 2) indicate that vegetation may have played a significant role in the rate of evapotranspiration and resulting dewatering and shrinkage of the dredged sediments.

3 Laboratory experiments

To characterize the organic sediments and determine its compression, consolidation, shrinkage and water retention characteristics additional laboratory experiments were performed. The sediments used in all experiments were collected during the sampling campaign of 4 March 2014, one month after the first filling stage. The samples were stored in large air tight containers and placed in a 10^{o}C. climate room. A number of tests were performed to characterize the dredged sediments, including particle size distribution, X-ray Diffraction (XRD) and X-ray fluorescence (XRF) for the mineralogy and chemical composition, environmental scanning electron microscope (ESEM) including energy-dispersive X-ray analysis (EDX), Atterberg limits, water content, fibre content and Loss on Ignition (LOI) for the organic content. In order to investigate the effect of oxidation on the material characteristics, the sediments chemically oxidized using hydrogen peroxide (H_2O_2). The amount of H_2O_2 required to chemically oxidize all the organic matter could be calculated from the organic content assuming

A typical result from the ESEM-EDX analysis, shown in Figure 7, illustrated that the dredged sediments consisted mainly of partly degraded organic fibers, the inorganic fraction contained skeletons of siliceous diatoms, pyrite framboids (iron sulphides) and some silt sized clay minerals (aluminium potassium silicates).

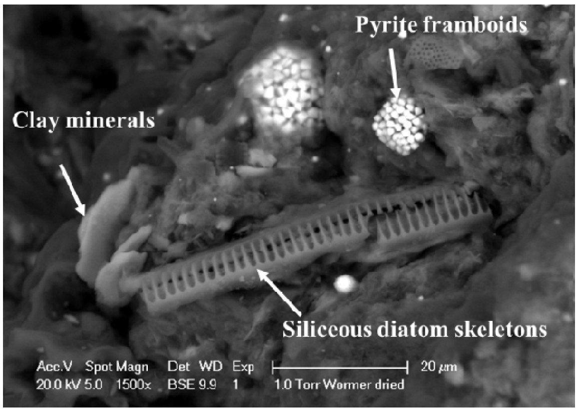

Fig.7.ESEM image showing the different components in the dredged sediments

Selected material properties of the non-oxidized and oxidized sediments are summarized in Table 1.

Table 1. Selected properties for soil classification

Properties	**Unit**	**Non-oxidized**	**Chemically Oxidized**
Fines content	%	91	n.d.
Organic content (LOI)	%	51	28
Mineral content	%	49	72
Fibre content	%	15	7
Specific gravity	-	1.8-1.82	1.86-2.03
Liquid limit (wt / vol)	%	546 / 988	271 / 532
Plastic limit (wt / vol)	%	205 / 371	127 / 246
Plasticity index (wt / vol)	%	341 / 617	143 / 277

The results shown in Table 1 illustrate the effect of organic matter on the material properties and how these are affected by chemical oxidation. Note that liquid limit, plastic limit and plasticity index is either be expressed as gravimetric water content (m_w/m_s) or weight (wt) percentage or as a volumetric water content (V_w/V_s) or volume (vol) percentage. On is converted to the other through specific gravity. It was found that chemical oxidation using hydrogen peroxide did not completely remove all organic matter, considering the organic content derived by loss on ignition remained significant. Chemical oxidation resulted in 36 – 52% of dry mass loss, while combined chemical oxidation and ignition resulted in a total mass loss of 59 -68%. The use of H_2O_2 for chemical oxidation has been debated as besides incomplete removal of organic matter it may also alter the amount and properties of inorganic constituents [15]. Chemical oxidation significantly reduced liquid and plastic limit of organic soils and consequent related engineering behaviour.

The effect of oxidation on the compression behavior of organic soil was investigated by performing one dimensional consolidation tests. Tests were performed using standard oedometers. Chemical oxidation was induced with H_2O_2 either prior to loading (ex situ) or during loading inside the oedometer cell (in-situ) at different overburden stress, 5 and 20 kPa. In situ oxidation was induced 24 hours after the load was applied by replacing the water in the oedometer cell with a 10wt% H_2O_2 solution. While the in-situ oxidized sample was exposed to oxidizing conditions, the load on all samples was kept constant for a period of 9 days. An example of the resulting compression curves is shown in Figure 8.

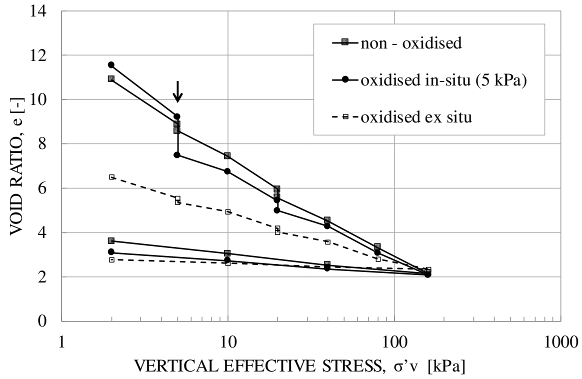

Fig. 8. Compression curves for non-oxidized and chemically oxidized organic dredged sediments

The results showed that oxidized soils have a smaller initial void ratio and lower compression and recompression indices. In-situ oxidation at 5 kPa effective overburden pressure (indicated by the arrow) induced significant additional settlement. The void ratio of the in-situ oxidised samples did not reach the virgin compression curve of the ex situ oxidized soil. With subsequent loading, a stiff response is observed, until the virgin compression line of the non-oxidized soil was reached again, after which it followed the compression response of the non-oxidized soil. Upon unloading, the in situ oxidized soil showed a reduced swelling capacity similar to the ex situ oxidized soil. The loss in dry mass due to in-situ oxidation was around 2-3% on average, indicating that the in situ oxidation was far from complete and that the volume change due to in situ oxidation was more likely due to weakening and partial collapse of the soil fabric and rearrangement of the soil particles or loss in water retention capacity and not due to loss in solid mass alone, which corresponds to other findings in literature [16-21].

The effect of chemical oxidation on the soil water retention capacity (SWRC) and shrinkage characteristics (SC) of the organic sediments were analysed using a modified Hyprop set-up (Metergroup) and X-ray-CT scanning. The Hyprop set-up allows to continuously measure the water tension and soil weight as the sample dries. Modification of the set-up involved replacing the standard steel ring, by a higher PVC ring, which allowed testing larger samples, which showed significant

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shrinkage and placing the set up in an X-ray CT scanner (Figure 9).

Fig. 9. Image processing of X-ray CT-results to separate soil volume (grey) from gas bubbles (blue) and scanning artefacts (red).

Samples were poured into the rings as a slurry, with initial volumetric water contents of 2700% and 590% for the non-oxidized and chemically oxidized slurries, respectively. At regular time intervals, the Hyprop system was disconnected from the computer and placed inside an X-ray-CT scanner, to determine the volume of the shrinking slurry and identify shrinkage cracks or occluded air pockets during drying. The results showed that oxidation of organic matter significantly reduces the soil water retention capacity of the dredged organic sediments (Figure 10).

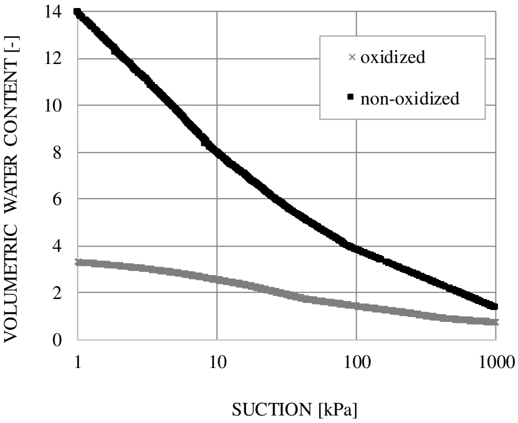

Fig. 10. SWRCs for non-oxidized and chemically oxidized organic dredged sediments starting as a slurry.

The soil water retention curves (SWRC) in Figure 10 have similar slopes as the compression curves in Figure 8. Considering the suction stresses during drying and shrinkage are closer to isotropic stress conditions the SWRC was expected to be slightly below the virgin compression curves derived from the oedometer tests. Both the oxidized and non-oxidized samples showed significant shrinkage upon drying, but the non-oxidized sample showed much more volume change than the oxidized soil. When starting the drying process with a slurry, a large part of the volume change occurred before suction could be measured. A correction procedure was suggested to extend the measuring range to very low suction values and correct for the loss in hydraulic head during soil shrinkage [11, 21]. The CT-scans of which an example is shown in Figure 10 were processed to remove scanning artefacts, such as beam hardening) and estimate the volume of the soil matrix and the occluded gas pockets (Figure 11).

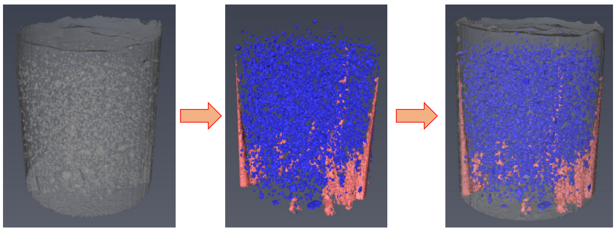

Fig. 11. Image processing of X-ray CT-results to separate soil volume (grey) from gas bubbles (blue) and scanning artefacts (red).

The CT-scans showed that some gas bubbles were present from the start or appeared during drying at very low suction pressure below 1 kPa, particularly in the non-oxidized soil (Figure 12). Formation of gas bubbles was expected as the pore water in partly decomposed organic soils is likely saturated in carbon dioxide and methane. Following Henry's law an increase in suction will reduce the solubility of the gas and cause ebullition of gas bubbles. Upon further shrinkage no additional formation of occluded gas was observed and the volume of gas gradually reduced.

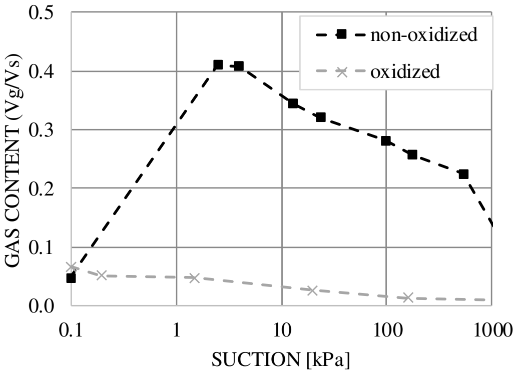

Fig. 12. Volume of occluded gas for non-oxidized and chemically oxidized organic dredged sediments during drying.

Besides these gas bubbles and some shrinkage cracks, which occurred at a later stage in the drying process, both soils remained close to full saturation during the major part of the drying process (Figure 13), which could be expected as significant desaturation typically only occurs when the soil approaches shrinkage limit. Other factors which were investigated in this study, but not covered in this paper were the effect of adding compost or manure on the ripening behaviour of the dredged sediments and the effect of initial water content, the drying rate and the thickness of the desiccation and cracking behaviour of clayey slurries [23-25].

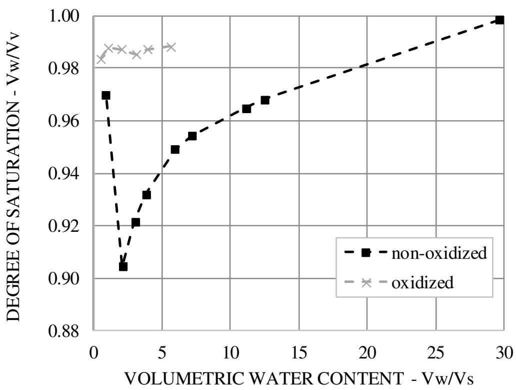

Fig. 13. Degree of saturation as a function of volumetric water content for non-oxidized and chemically oxidized organic dredged sediments during drying.

4 Conclusions

Field observations investigating the surface subsidence and volume change of organic dredged sediments in an on-land depot in the peatland of Wormer & Jisperveld in the Netherlands over a period of 3 years have shown that subsidence is mainly due to the shrinkage of the sediments themselves and partly due to consolidation of the underlying peat layers. Oxidation of organic matter and its contribution to surface subsidence appeared to be insignificant. Laboratory tests in which oxidation of organic matter was accelerated using hydrogen peroxide, showed that chemical oxidation may not oxidize all organic matter and may also alter the inorganic composition of the soil. Chemical oxidation of organic matter significantly affected the material behaviour, reducing liquid and plastic limit, compression and recompression index, initial void ratio, and water retention capacity. In situ oxidation causes weakening and collapse of the soil structure, and loss of water retention and swelling capacity, resulting in settlement.

Acknowledgements

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