The viscous behaviour of peat: what can we learn from clay?

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Abstract

Land subsidence is a serious threat for soft soil areas as consequences include damaged buildings and infrastructure and increased flooding potential. Viscous compression of soft deposits, the reorientation of soil particles in the subsurface, significantly contributes to land subsidence, and remains not fully understood. This means that it is hard or not possible to mitigate viscous compression. In the case of clay, the driving processes leading to viscous compression have been identified, but this is not the case for peat. This study analyses the driving processes of viscous compression of clay based on literature review and evaluated whether these processes can also be actively driving viscous compression of peat. The literature review shows that expulsion of micropore water, changes in the adsorbed water layer and changes in interparticle forces are all driving viscous compression processes in both clay and peat. However, it is evident that the relative contribution of these processes to viscous compression in clay and peat is different. Most likely, viscous compression of peat cannot be explained fully using these processes. Therefore bio-chemical decomposition is proposed as an additional driving process of viscous compression of peat. Furthermore, the clay and fibre content of peat have been explored for a possible relation with the viscous deformation of peat. The clay content did not show a clear relation with viscous deformation. The preliminary results of the fibre content analysis show less viscous compression with higher large fibre content.

Introduction

A large part of the subsurface of especially the near-coastal part of deltaic areas consists of soft, unconsolidated clay and peat. The soils in these areas are usually suitable for agriculture, which is why land use is often intensive (Evans, 2012) and the population density is relatively high. However, using these soils for agriculture and construction also carries risks. Land subsidence can lead to damaged buildings and infrastructure, and to increased flooding intensity, frequency and duration by rivers or the sea, which are even larger in combination with sea-level rise and increased peak discharges. Two of the most impactful factors for a large potential for subsidence are high porosity and compressibility, which soft soils generally have. Subsidence is composed of three main processes: tectonic subsidence, isostatic subsidence and compaction, of which the latter is a decrease in soil volume. The compaction process is driven by air exposure, drying and loading of the soil. An increase in loading leads to the following phases: instantaneous compression, the immediate reduction of volume by expulsion of air and possibly compression of solids, consolidation, the time-dependent expulsion of overpressured pore water and viscous compression. Here, we focus on viscous compression, the slow reorientation of soil particles, like clay flocs and peat fibres, under constant load, which is often referred to as creep (Chai et al., 2012; Le et al., 2012, Zhao et al., 2020).

Viscous compression of clay has been studied thoroughly to be able to model compaction over time given planned loading conditions (i.e. Bjerrum, 1967; Den Haan & Edil, 1994; Kooi et al., 2018). Drivers have been identified for viscous compression of clay (Le et al., 2012), but it is unknown whether all these drivers are active in peat as well and if so, whether viscous compression of peat can be fully explained by these drivers. This is the case as studies on the viscous behaviour of peat are limited. Especially the driving factors of the reorientation of the fibres thought to cause the viscous compression of peat are not understood yet. As peat is very heterogeneous in structure and hydrological aspects (Landva, 2007; Mesri et al., 2007), it is unknown if viscous compression can be related to clay admixture and fibrousness. These parameters are key to understand differences in behaviour between clay and peat as they set apart peat from clay and describe possible large variations in peat structure and/or geotechnical behaviour. Therefore, viscous behaviour analysis on these parameters as well as tensile strength and amorphity is needed. It is hypothesised that the identification of the relations between parameters and viscous behaviour can lead to quantifying viscous behaviour potential from field measurements.

Therefore, this research aims to assess which processes identified to drive viscous compression in clay also drive viscous compression in peat, their relative contribution, and if additional processes must be included to fully explain the viscous compression of peat. Furthermore, the aim is to explore relations between descriptive parameters of peat and viscous compression.

Methods

To assess if the drivers of viscous compression in clay also drive viscous compression in peat, the drivers are analysed using existing literature on micropore water expulsion, changes in the adsorbed water layer, and changing particle interactions. This is combined with previously published laboratory and field measurements, and microscopic imagery on similarities and differences in structure of clay and peat. Attention is given to i.e. the pore structure, hydraulic conductivity, surface charge, internal clay structure and plant structure. To explore relations between clay content and fibrousness, and viscous compression, existing and new incremental oedometer test data is used. Peat samples were taken in the western and northern part of the Dutch coastal plain. These samples are analysed based on variations in water content and unit weight using R.

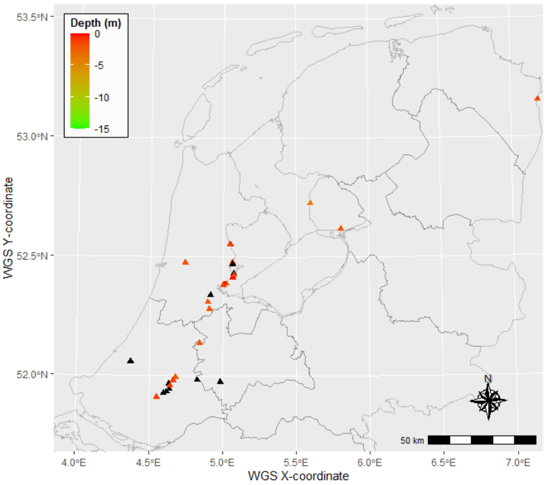

Figure 1   Sample locations and depths below mean surface level in the western and northern peat area of the Netherlands.

Results

The processes indicated by Le et al. (2012) to drive viscous behaviour in clay have been divided into micropore water expulsion, changes in the adsorbed water layer, and inter-particle processes.

Micropore water expulsion

To compare porewater expulsion in clay and peat, first, the pore structure has to be defined. The general division of pore sizes in clay and peat differs in values for pore size class boundaries, but values also differ between studies depending on the used experimental technique (Beven and Germann, 1982). Some studies define pores in clay with a diameter of <1 µm as micropores (Le et al., 2012), whereas the smallest pore class in peat is usually referred to as intra-plant pores, which typically have a diameter between 10 and 30 µm (Weber et al., 2017; McCarter et al., 2020). Also important to consider is whether these small pores are connected to the pore network and in what way. Water in dead-end pores and partially or fully closed pores is considered to be inactive (Quinton et al., 2009; Rezanezhad et al., 2012) and does not contribute to the throughflow of water. In the case of partially or fully closed pores, expelling porewater is more difficult or even impossible. Activating these types of pores would require a change in the clay or peat structure, opening up the pores. Additionally, peat is known to show a strong decrease in hydraulic conductivity with decreasing total pore volume, which means connectivity between pores in the peat decreases and expulsion of micropore water becomes more difficult.

The relation between water expulsion from the smallest pore class and viscous behaviour is most likely different for clay and peat quantitatively, because the smallest pore class of peat is larger in diameter than that of clay. However, retardation of water expulsion from the smallest pores in peat is still possible. Furthermore, the strong decrease in hydraulic conductivity with void ratio following from consolidation of the macropores could add to the retardation of micropore water expulsion due to increased tortuosity of the flow channels and decreased diameter of the pore throats. This also explains the larger hydraulic conductivity of sand compared to peat despite sand having a lower porosity in general.

Adsorbed water layer changes

The adsorbed water layer (AWL) describes the water that is bonded to the negatively charged surfaces of clay particles and peat fibres. Three zones can be recognized in the AWL (Fig. 2). The first zone is closest to the particle surface and is composed of ice-like layers of water and hydroxyl molecules, which are strongly adsorbed to the surface and therefore immobile (Asay and Kim, 2005; Osipov, 2011). Further away from the surface, the second zone is formed by a single or several transitional layers of water molecules, while the third zone closely resembles the free pore water as the water layers are increasingly governed by thermal motion (Tang et al., 2016). Generally, the total thickness of the AWL is in the order of 1 nanometer. The influence of the AWL on viscous compression primarily is related to the decrease in effective diameter of pores, but more importantly the pore throats. Water flow is obstructed as it has to pass a smaller opening, limiting the compaction potential. Besides, the AWL alters the contact and friction between particles (Le et al., 2012).

It is most likely that the AWL is of less importance in peat than in clay due to the smaller negative charge of peat fibre surfaces and the relatively larger pore diameters in peat. Changes in the AWL thickness can come from several factors. The most important of them are the pH, temperature, and salinity. The surface charge of clay can change with lower pH conditions, which can increase AWL thickness at the ends of the clay particles. In peat, the production of humic acids during decomposition can actively contribute to this. The AWL formation happens differently for different temperatures, which is described by isotherms. A higher temperature leads to a thinner AWL (Martin, 1962; Renard and Ortoleva, 1997). Lastly, the increasing salinity provides more charged ions in the pore water. The AWL will decrease in thickness to limit the contact area with these ions.

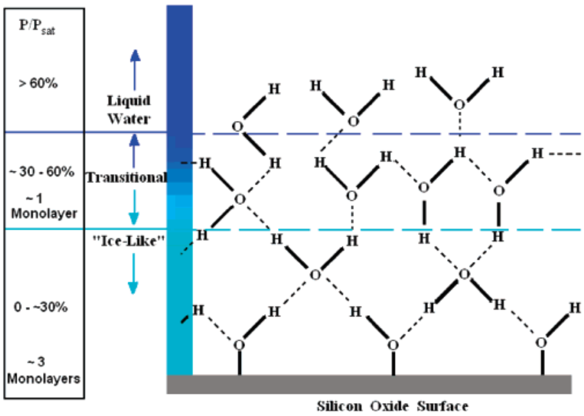

Figure 2 Schematic illustration of the structural evolution of water molecules as the adsorbed water layer thickness increases with relative humidity (Asay & Kim, 2005).

Particle interactions

Interaction between clay particles occurs very differently from interaction between peat fibres. For clay, the mineralogy is important for the structure in which clay platelets are connected. The most common polytypes and their respective groups are kaolinite (1:1), illite and smectite (2:1), and chlorite (2:1:1) (Bergaya and Lagaly, 2013). These structures are stable but can be disconnected via dispersion. Especially when Li+ or Na+ are present that can function as exchangeable cations, dispersion can occur for all mineral groups. When dissolved salt or organic cations are present in the porewater, coagulation and flocculation, the opposites of dispersion, can occur as well. The structure of peat is initially largely determined by the type of plant material it is composed of. This also makes peat very heterogeneous in structure as the composition of plant material can differ strongly over short distances. Another aspect that is unique to peat is that the fibres are often interlocked and resist being pulled apart, which is depicted by the tensile strength. Both aspects are affected by prolonged decomposition because it can break down this initial plant structure that determines the strength of the peat. Also, because fibres are degraded into smaller sizes, the contact area decreases and the resistance to movement is lowered (Erkens et al., 2013). For viscous compression the particle interaction of both clay and peat is important, but due to the large differences in the character of the interaction aspects it is difficult to compare the two. Compaction can bring clay platelets closer together, tightening the bonds and increasing the possibility of internal movement leading to viscous compression. Contradictory, increasing stress can break interparticle bonds leading to possible reorientation (Taylor and Merchant, 1940; Mesri and Godlewski, 1977). Similar effects are seen for the jumping of bonds related to ionic displacement, although this process is governed by temperature. For peat, decomposition plays a large role in changing the contact between fibres. Both the initial plant structure and the interlocking of fibres is affected by it, which might lead to more reorientation.

Parameter analysis

The dry bulk unit weight is compared to measured values of the secondary compression coefficient ($C\alpha$) parameter. Higher dry weight indicates a higher percentage of clastic content as the dry bulk density of clay is higher than that of peat (Al Khafaji & Andersland, 1981). A clear trend can be derived for the sand and clay samples, showing an increasing $C\alpha$ with decreasing dry bulk unit weight. The peat samples did not show a trend, which could not be directly related to the indicated field classes for the clastic content, following the classification of SBB5.1 (Bosch, 2000), as the dry bulk unit weights overlapped too much. It can be related to the independency of organic matter density above 20% organic matter content in samples (Erkens et al., 2016).

Discussion

Literature shows the drivers of viscous behaviour of clay as explained previously are active in peat as well. However, it has also been indicated that these drivers work differently in clay than they work in peat, because of difference in material and structural aspects. It is therefore likely that the drivers cannot fully explain the viscous behaviour of peat. For peat, decomposition has been mentioned often as a factor that can possibly affect micropore water expulsion, the AWL, and particle interactions. That in itself could be enough to consider decomposition as another driver of viscous compression. Additionally, decomposition has a direct impact on compaction, because the breakdown of organic matter reduces the volume of solids in the peat and leads to a lower potential final volume. If the by-product of the decomposition is gaseous, it is possible to escape due to the buoyancy leading to direct volume reduction. However, gas bubbles are known to be trapped in saturated conditions (O'Kelly & Pichan, 2013). The suggestion to consider decomposition a driving process of viscous compression of peat is supported by studies of O'Kelly and Pichan (2013) and Zain (2019) who respectively show that decomposition and oxidation influence the compaction potential of peat.

The fact that no trend could be seen in the clay content of peat in relation to the Cα parameter suggests that when peat is the dominant component of the soil, factors like fibrousness and botanical origin of the plant material become more pronounced in governing the Cα parameter.

Conclusion

Literature review has shown the four groups of processes influencing viscous deformation of peat. Three of these groups are also indicated to drive viscous compression of clay (Le et al., 2012): micropore water expulsion, changes in the adsorbed water layer, and changes in particle interactions. It is, however, evident that these processes are unlikely to have similar relative contributions to viscous compression in both clay and peat, because of the differences in typical pore sizes, electric charge of the particle surfaces, and attractive and repulsive forces between particles. For this reason, decomposition is proposed as an additional process driving viscous compression in peat specifically. It is expected that decomposition accelerates viscous compression of peat. Although this hypothesis is supported by a preliminary scan of existing testing data, behaviour under anoxic conditions needs to be confirmed with additional testing dedicated to this research question.

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