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Regular paper

On estimating the thickness of the Saalian ice sheet from a vertical profile of preconsolidation loads of a lacustro-glacial clay

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Abstract

The consolidation history of cohesive soils can be estimated on the basis of the one-dimensional consolidation theory of Terzaghi.

An effective stress profile, which existed during the steady state of the Saalian ice sheet, has been reconstructed from the results of a series of oedometer consolidation tests on a vertical sequence of Pot Clay (Marum, Province of Groningen, The Netherlands). From this effective stress profile and from geotechnical and structural properties, a fossil overburden pressure of 2100 kN/m^2 could be estimated, which would have required an ice cover of at least 195 m thick.

A comparison of the results of this study with geotechnical data from other locations in the northern Netherlands and a comparable research in northern Germany confirmed the regional significance of the study described in this paper.

Introduction

Geotechnical and structural properties of lacustro-glacial 'Pot Clay' near Marum, Province of Groningen, have been determined which led to the construction of a model for sub-glacial sediment deformation under the Saalian ice sheet (Schokking 1990, this issue).

Another objective of the project was to estimate the thickness of the Saalian ice sheet by studying the load-settlement curves of oedometer consolidation tests. One-dimensional consolidation tests were therefore performed on nine samples, in order to estimate the preconsolidation load. Similar investigations have been performed by Harrison (1958) for the Wisconsin continental ice sheet, by Bernhard (1963) for the Saalian ice sheet in Northern Germany, by Kazi & Knill (1969) for the Lowestoft ice sheet on the East coast of England, and by Lapadre (1982) for the Fraser, Vashon Stade, ice sheet in the State of Washington on the west coast of the United States of America. The paleo-effective stresses, estimated in this paper, are based on a continuous vertical profile of geotechnical properties and preconsolidation loads, while in the earlier investigations only samples from generally one depth level but from a number of different locations have been tested. The advantage of the present research is that a picture can be obtained of the pore water pressures and the effective stresses active during the steady state of the ice sheet, throughout the full depth of the clay body and that thus the minimum thickness of the ice sheet can be inferred.

Information on the geology of the Pot Clay at Marum and on geotechnical and structural proper-

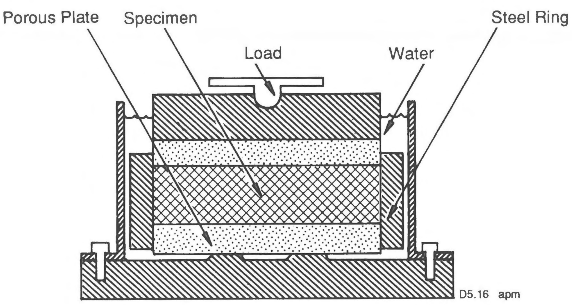

Fig. 1. Oedometer cell for one-dimensional consolidation testing (revised after Capper & Cassie, 1974).

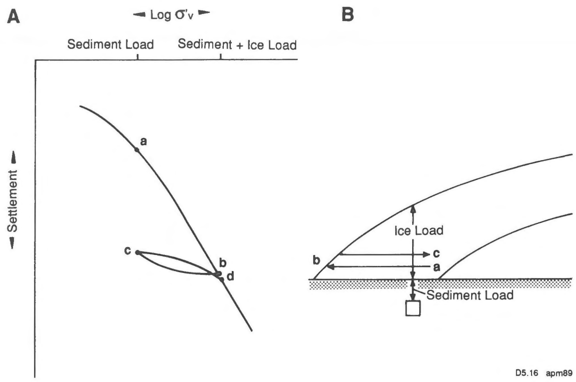

Fig. 2. A. Load-settlement curve of consolidation test with loading, unloading and reloading of clay sample.
B. Advance and retreat of an ice sheet, which is simulated in consolidation test A.

ties from undisturbed samples from the Marum borehole, as used in this paper, is described in Schokking (1990, this issue).

Preconsolidation history of clays

Clays when loaded, show consolidation behaviour, which causes a volume decrease with time, resulting in settlement. This process was studied for civil engineering purposes by several authors, to investigate the influence of constructions placed on compressible soil layers, of which some of the first were Terzaghi & Fröhlich (1936). They developed a one-dimensional consolidation theory, which in general is still applicable today.

Immediately after loading of a clay layer the increase in stress is taken up as an increase in pore water pressure. With time the excess pore pressure will reduce to zero, the pore water pressure will then again have the original value and the clay will have been consolidated to the new stress level. During consolidation pore water drains from the clay layers until pressures are equalized. This causes a volume decrease and hence a settlement of the clay layers.

This process can be simulated in the laboratory in a one dimensional consolidation or oedometer test (Fig. 1). A sample is loaded in steps and is allowed to consolidate after each step (Fig. 2A, points a to b). The resulting log σ_v' vs. settlement curve,[1] after some initial loading, approximates a straight line. When the load is removed rebound is only partial and a permanent settlement remains (Fig. 2A, points b to c). If again a load is applied in steps, and increased past the point from where the load was released, the obtained settlement curve will join the consolidation line at point d (Fig. 2A) and will continue along that line with continued loading.

Loading the clay layer (a–b) and later removing the load (b–c), can be considered to simulate the deposition of a sediment pile followed by erosion or the advance and retreat of a land ice sheet (Fig. 2B).

The pre-consolidation load (σ_{vm}'), that is the maximum effective stress to which a clay has been exposed in the past, can be determined in the laboratory from the consolidation curve obtained in an oedometer test on an undisturbed sample. With the Cassagrande (1936) construction (Fig. 3) the position of point d of Fig. 2A can then be estimated. From the preconsolidation load, the thickness of an eroded sedimentary sequence or the thickness of a land ice sheet can then be estimated.

This method for estimating the thickness of a land ice sheet, from preconsolidation data, has also been used by Harrison (1958), Bernhard (1963), Kazi & Knill (1969) and Laprade (1982). The improvement in the approach of the study described in this paper over previous work, is that here a complete vertical profile of preconsolidation loads has been used, instead of just one or two measurements at one location. Thus a better understanding of the pore pressure distribution within the clay body during the consolidation process is obtained, giving a more realistic picture of the distribution of the effective stresses and hence, a more complete solution to the problem.

Consolidation tests

Consolidation tests were performed on nine samples taken at various depths regularly distributed over the vertical profile. The oedometer cells were of the conventional type, in which a maximum effective stress of 8800 kN/m^2 can be applied on samples with a diameter of 50 mm. The results of the consolidation tests are presented in Table 1. Typical load-settlement curves, showing the determination of the approximate preconsolidation load are presented in Fig. 4.

As a check on the Cassagrande method the load-release lines were determined in two tests. For the interpretation to be correct, this line should approximately parallel the bisectrix which intersects the virgin compression curve in the pressure range of the preconsolidation load. In both tests the load-release lines show a shallower slope at the lower stress level, than at the higher stress level. For the upper stress level the load release lines parallel the bisectrix of the angle between the horizontal and the tangent through the point of maximum curvature, as used in the Cassagrande construction. This confirms that the estimates in the Cassagrande construction are reasonable.

The consolidation curves from tests on samples taken from depths[2] above approximately 30 m show a slight deviation of the load-settlement

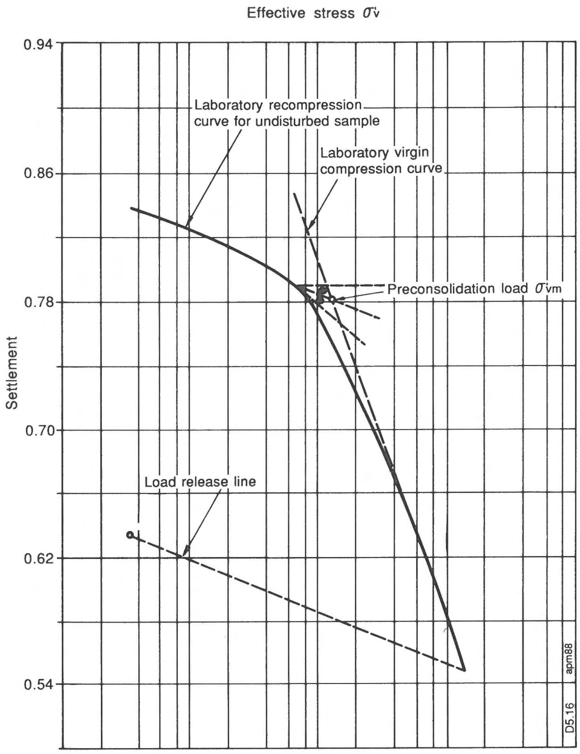

Fig. 3. The Cassagrande construction for the determination of the preconsolidation load.

curve, a bit further left of the laboratory virgin compression curve than those of samples below 30 m. The former curves also have less well defined points of maximum curvature. This effect may be a consequence of the presence of fissures. Similarly, in the lower stress range the curves have a much shallower slope – in some cases the curves are even

Table 1. Results of consolidation tests

Depth m	Preconsolidation load, σ_{vm}' kN/m^2	Amount of load increments	Swelling line determined	Max. effective stress kN/m^2
8.05	800	14		8800
10.55	900	9	+	8800
17.35	1100	12		8800
19.35	1600	5		4020
22.44	1800	12		8800
26.66	1500	12		8800
28.90	2100	6		8800
32.15	1500	9	+	8800
36.57	1400	12		8800

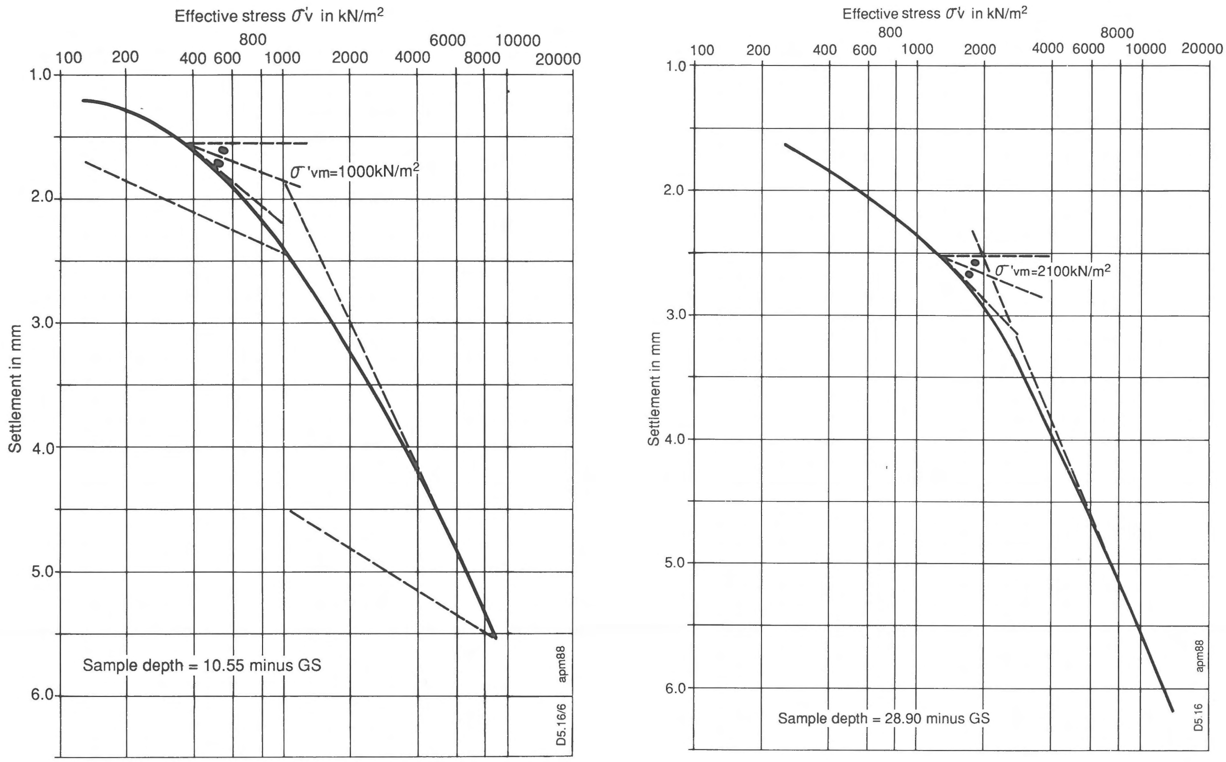

Fig. 4. Typical load-settlement curves with the determination of the preconsolidation load for samples from depths 10.55 and 28.90 m.

tangential to the horizontal – than those from the samples below 30 m. Higher than normal settlements have therefore occurred as a result of the closure of the fissures, at the start of the test.

Other causes, which also lead to overconsolidation, such as dessication, drained creep (aging) and physico-chemical changes, or the suction of pore water out of the clay as a result of freezing of the surrounding ground, can all, in end effect, show a well defined point of maximum curvature on the load settlement curve. To estimate the thickness of the Saalian ice cover, it is necessary to establish that hydrodynamic settlement has been the cause of the overconsolidation.

For that purpose a sample of Pot Clay taken at a depth of 24.5 m has been examined under the Scanning Electron Microscope. Figure 5 shows that the clay particles are strongly aligned parallel and that only very small elongated pores remain. The figure also shows how clay particles are broken and bent around a silt grain. These phenomena indicate hydrodynamic consolidation and even mechanical deformation of soil particles. Delage & Lefebre (1984) show similar features in SEM images, produced of clay samples, which had been consolidated hydrodynamically in the laboratory to an effective stress of 1452 kN/m^2.

Estimation of the minimum thickness of the Saalian ice sheet

In the graph of Fig. 6, the estimated preconsolidation loads are plotted against depth. An evaluation of the results focusses on the following points:

(i) Estimated preconsolidation loads increase with depth down to a depth of approximately 30 m. A maximum preconsolidation load $\sigma_{vm}' = 2100$ kN/m^2 has been estimated at this depth.

(ii) Below this level the preconsolidation loads decrease with depth.

(iii) The minimum ice thickness that has been present at Marum during the Pleistocene can be

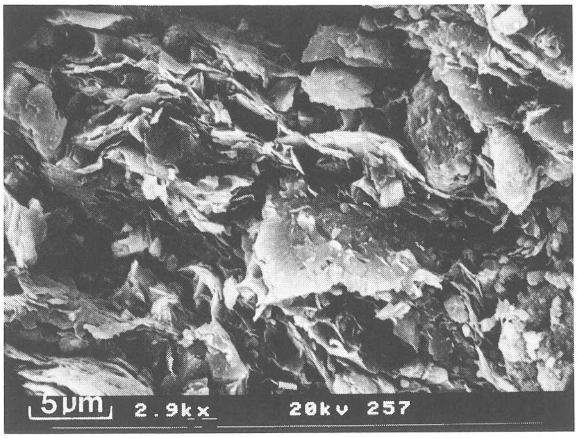

Fig. 5. SEM Image of Pot Clay fabric at 24.5 m. Note silt grain with deformed clay particles. Before exposure sample coated with evaporated gold. Image obtained with ISI SS 40 SEM, with secondary electron detector.

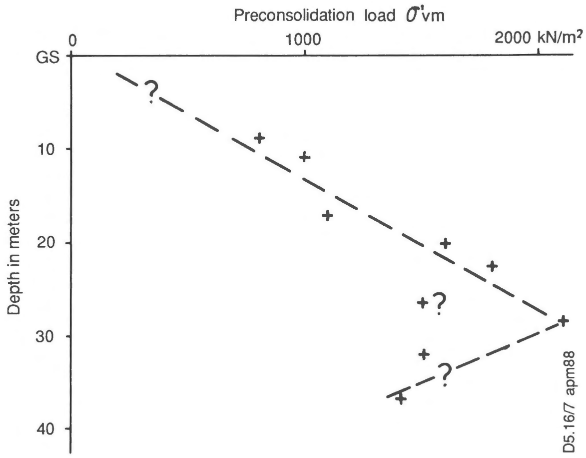

Fig. 6. Estimated preconsolidation loads vs. depth.

calculated from the estimated maximum preconsolidation load.

Assuming, a glacial till thickness of approximately 5 m, the effective overburden stress (σ_{ov}' at 30 m, at the time of the existence of the land ice sheet can be estimated with:

$$\sigma_{ov}' = \sum_{n}^{1} H_n \gamma_{sn} - u \qquad (1)$$

in which σ_{ov}' = effective overburden stress, n = number of layers, H_n = layer thickness, γ_{sn} = saturated unit weight, u = water pressure.

This gives $\sigma_{ov}' = 300\,kN/m^2$. Therefore, the minimum land ice thickness was:

$$h = (\sigma_{vm}' - \sigma_{ov}')/\gamma_i \qquad (2)$$

in which h = minimum land ice thickness, σ_{vm}' = preconsolidation load, γ_i = unit weight of ice = 9.17 kN/m². So the minimum thickness of the ice is approximately 195 m.

The assumption about the maximum thickness of glacial till has been based on the fact that the glacial till in this area has never been found to be more than 5 m thick (Ter Wee, pers. comm.). That the glacial till at Marum presently has a lesser thickness can be due to erosion at the end of the Saalian and during the Weichselian (Jelgersma & Breeuwer 1975). The value of unit weight of ice γ_i = 9.17 kN/m² assumes, that no sediment load has been present in the ice sheet. Relicts of a possible sediment load in the ice during the Saalian are only rarely found (Ter Wee, pers. comm.). Movements of the ice sheet appear to have occurred mainly at or near the ice-soil interface.

With regard to the questions whether the estimated minimum ice load is a minimum and not the actual load and what the reason is for the increase, and later decrease of the estimated preconsolidation loads with depth there are two important factors, which can have influenced the estimated preconsolidation loads. First to consider is the distribution of pore water pressures and hence the effective stresses during the consolidation process. Secondly, the phase of the pore water, frozen, unfrozen, or partly frozen, has to be taken into account.

From the estimated preconsolidation loads vs. depth graph of Fig. 6 and the calculated minimum ice load, the diagram in Fig. 7 can be constructed. The increase in preconsolidation load with depth was a result of the decrease in excess pore pressures, which existed in the low strength, low density zone with intense shearing at the top of the Pot Clay sequence during the existence of the ice sheet (Schokking 1990, this issue). This zone consisted partly of glacial till and partly of Pot Clay with sandy intercalations, down to a depth of approximately 10 m. Within this zone the effective stresses may have ranged from a minimum of 0 to a maximum of approximately 500 kN/m².

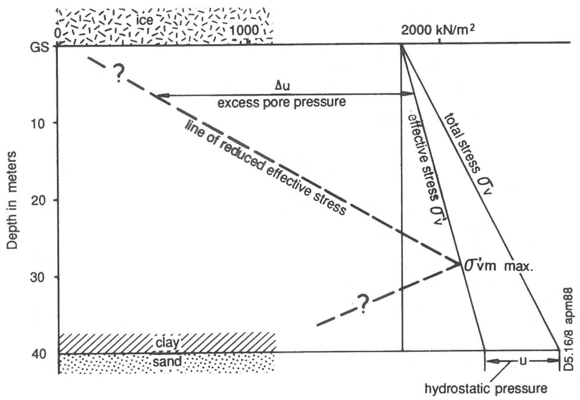

Fig. 7. Diagram representing relationships between ice load, excess pore pressures, hydrostatic pressure and paleo-total and effective overburden stresses.

In the simplest case, as shown in the diagram (Fig. 7), the clay body will have been surrounded by ground water at hydrostatic pressures, assuming that the ground water table stood near the ground surface. Melt water produced by frictional heat at the glacier sole will drain mainly vertically through the clay and partially horizontally to the aquifer that surrounds the clay. Consolidation would have taken place in the centre of the clay body, with in general, a one-way drainage of pore water together with melt water flowing downward towards the aquifer below. Around the level, where the maximum preconsolidation load has been determined, the excess pore pressure was reduced to zero. The estimated maximum preconsolidation load therefore corresponds with the actual ice load, assuming that the ground water level was near the ground surface. If the whole aquifer would have been pressurized, as would have been with ground water trapped under the ice mass, when drainage is partly or entirely blocked, the whole system of Fig. 7 can move to the right with a consequently higher ice load, without changing the estimated preconsolidation loads. Such a situation could have existed if the aquifers around the clay body had been closed off partly or entirely, for instance when the aquifer outlet were frozen as a result of permafrost at the terminus of the ice sheet. It is difficult to explain, however, that during the retreat of the ice sheet, a blockage could have remained, as the time required for total consolidation is only in the order of tens of years.

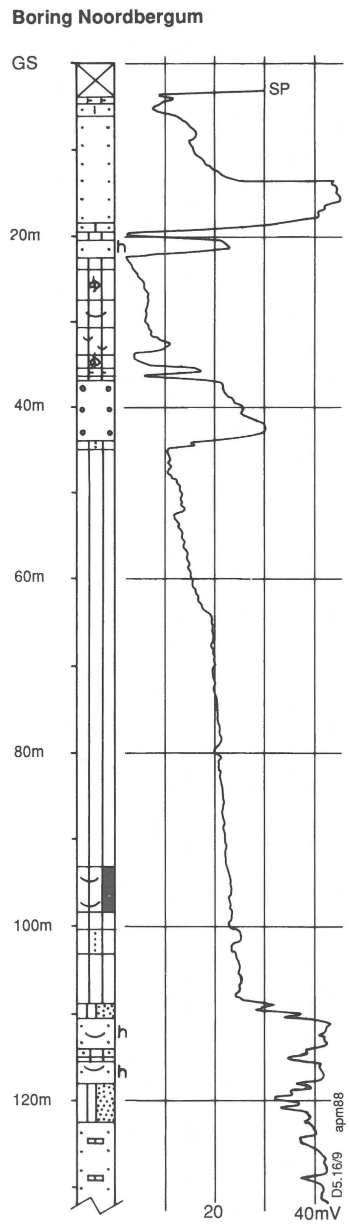

Fig. 8. Lithological and Spontaneous Potential logs of borehole in Pot Clay near Noordbergum.

Should such circumstances have persisted during consolidation of the clays, it would not be possible to determine the ice load with the present method. A possible way to determine whether a pressurized aquifer could have existed is by modelling the ground water flow under the Saalian ice sheet in the Netherlands. Such a two dimensional model along a flow line should incorporate the melt water influx into the aquifer, various ice front positions and various aquifer outlet dimensions.

The coincidence of the excess pore pressure line with the hydrostatic pressure line at approximately 30 m is a result of the fact that the Pot Clay becomes much more sandy and hence more permeable at around 28 m. The Pot Clay below that level is much less homogeneous and may occur in lenses. In that case, part of the ice load could have been taken up by grain to grain contact within the granular material. The gradual decrease in the estimated preconsolidation loads is indicative of this transition to the granular aquifer.

An alternative explanation for an apparent increase in the preconsolidation loads with depth could be due to freezing of the clay. In such a case, the clay body must have been thawed out from below, by geothermal heating, after a rise in the outside temperature. Moving up in the vertical profile, less and less pore water would have been mobile, and more and more ice would fill the pores. The higher permeability and hence the higher heat conductivity below a depth of 30 m may have played a role for there would have been less pore ice present in this zone. The reversal point could then have been at the same level (30 m) and the maximum preconsolidation load would have approximated the ice load. A pressurized aquifer may have existed particularly under such conditions, and this would impair the determination of ice loads with the present method.

Regional significance

There are data available on the state of overconsolidation from other Pot Clay occurrences in the northern Netherlands, which give a valuable comparison with the results obtained in this study. They appear to indicate that the conditions as observed at Marum occur on a regional scale.

Near Scharnegoutum in the Province of Friesland, approximately 45 km West of Marum, a cone penetration test has been made in the Pot Clay, with its top there at a depth of 44 m – NAP. Overlying the Pot Clay is a 14 m thick sequence of Holsteinian fluvial sediments which is in turn overlain by an approximately 5 m thick layer of glacial till. The fluvial sediments consist of coarse granular sands that are interlayered with clay. Cone resistances in the Pot Clay were in the order of 6 to 7 MN/m^2, i.e., 1.5 times higher than at Marum. To make a justifiable comparison with the values found at Marum, it must be stated, that the cone penetration test there had to be stopped just above the layers with the highest estimated preconsolidation loads, because the maximum capacity of the machine had been reached due to the increasing high friction on the rods. An estimate of the undrained shear strength of the Pot Clay at Marum can be obtained using the empirical formula $s_u = q_c/15$ (Begemann 1977). This gives a s_u-value of approximately 270 kN/m^2, which corresponds to the highest values measured with the laboratory vane in the area where fissures still occur. The q_c value found at Scharnegoutum, can be translated into a s_u-value of 400 kN/m^2, which is only slightly higher than the highest fall cone value measured. The cone resistance value occurs immediately below the sand-clay interface. This means, that excess pore pressures, such as encountered at Marum, would have been dissipated at this location. The presence of a considerable thickness of granular fluvial sediments at this location may have played a role in that no ground water pressure gradient developed in the clay.

An other location, where Pot Clay occurs and which can be compared with Marum, is found near Noordbergum in the Province of Friesland, approximately 20 km northwest of Marum. In a borehole a 75 m thick sequence of Pot Clay has been encountered. The clay here is covered – as at Scharnegoutum – with glacial till of approximately 5 m thick, below which lies a sequence of fluvial sands and clays of Holsteinian age. The Spontaneous Potential curve, which is related to the unit weight of the clays (Fig. 8), shows – as at Marum – a steeper increase from the top of the clay down to a level of approximately 20 m, than below that level. Of interest is that this trend continues into the overlying Holsteinian clays. This favours the possibility, that the increase in preconsolidation loads with depth to which the clay has been exposed in the past, is indeed gouverned by pore pressures, which existed under the ice sheet.

The results of the research by Bernhard (1963) on clays in northern Germany are partly similar to those found at Marum. The only reliable figures for the estimated ice thickness appear to be those which were based on preconsolidation loads obtained from four oedometer tests on samples of Pleistocene clays. The majority of the results are based on tests on Miocene, Oligocene and Cretaceous clays, which may have undergone considerable consolidation, hydrodynamically or otherwise, after deposition.

The figures for the thicknesses of the Saalian ice sheet, as estimated from test results on the Lauenburger clay, the northern German equivalent of the Pot Clay, are in the range of 50 to 60 m ($\sigma_{vm}' =$ 500–600 kN/m^2), for samples from near the ground surface. Only one sample from 11 m below the ground surface was tested, and produced a σ_{vm}' value of 2400 kN/m^2, which again is comparable to the figures found at Marum.

The tests on the older clays give higher preconsolidation pressures. The difference in thickness of the ice sheet as derived from tests on the Lauenburger clay and those from tests on the older clays is attributed by Bernhard, to be caused by different stages of the Saale glaciation (Warthe cq. Rehburger stage). This seems illogical, as in the later Rehburger stage, the ice reached further South than in the Warthe stage, which means that the Rheburger stage has caused higher effective stresses, which must have overprinted the earlier, lower ones.

Conclusions

The Pot Clay in the northern Netherlands has been overconsolidated hydrodynamically by the load of the Saalian ice.

An increase in preconsolidation pressures with depth ranging from approximately 500 to 2100 kN/m^2 has been observed. The increase is a result of the decrease in paleo-pore water pressures with depth, which existed during the presence of the ice sheet.

From the maximum preconsolidation load of 2100 kN/m^2, a minimum thickness of the Saalian ice sheet of approximately 195 m could be calculated.

There are strong indications, that the measured preconsolidation loads at Marum, and hence the estimated minimum ice thickness, occur on a regional scale in the northern Netherlands and northern Germany.

Notes

1. A glossary of geotechnical terms and symbols used is given in a previous paper: Schokking (1990, this issue).
2. All depths mentioned in this paper refer to levels below ground surface, unless indicated otherwise.

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