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ON THE ADHESION OF PORE WATER IN FINNISH ARGILLACEOUS SEDIMENTS OF DIFFERENT AGE

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In this investigation the conduct of pellicular water influenced by adhesion forces in fine grain soils of different age and at different degrees of consolidation is demonstrated. Because of sparse observational data the results rather indicate a general trend and do not claim to represent absolute values. It is the hope of the author that this work will gradually lead to a better insight into that part of hydrology which until recently has not been much investigated and that it will be of help to the hydrologists making inventory of the areal water regime in the country.

The object of this investigation was the study of surface desiccation of cohesive soils, i. e. dry crust formation.

In this paper the subject is limited solely to the aspect of geo-hydrology, a study in detail of the conduct of pellicular water in clay soils, as this differs considerably from the conduct in coarser soils. The binding characteristics of free pore water have been empirically related to the age of the sediment. Water content and age of the sediment are correlated to the natural consolidation.

The investigation was carried out in the Finnish Hydrological Office in the year 1968.

THE CLAY SERIES OF FINLAND

The formation of the clay series of Finland is essentially a consequence of the history of evolution of the Baltic Sea with its discrete phases. As clay sediments form by stratification in water each separate phase has given rise to a corresponding layer of clay.

In connection with the melting of the Fennoscandian ice cover the varved glacial clay sedimented whereas the homogeneous clay matter coagulated in saline water during the postglacial periods.

According to the inventory of soil material carried out by the National Board of Public Roads and Water Ways, clay and fine silt represent 17 per cent on the map sheets of Finland. Most abundantly the clay soils are found in south and south-west Finland. Also in the easily flooded areas of Bothnia they are rather abundant. North and east Finland belong to the supra-aquatic areas where marine stratifications is absent. Fig. 1 presents the complete series as related to the examination sites.

THE SELECTION OF EXAMINATION SITES

In outlining the work the first problem was to locate a line with four representative sites which satisfied the requirements of the investigation in the best possible manner. The most important condition was that the areas had main-

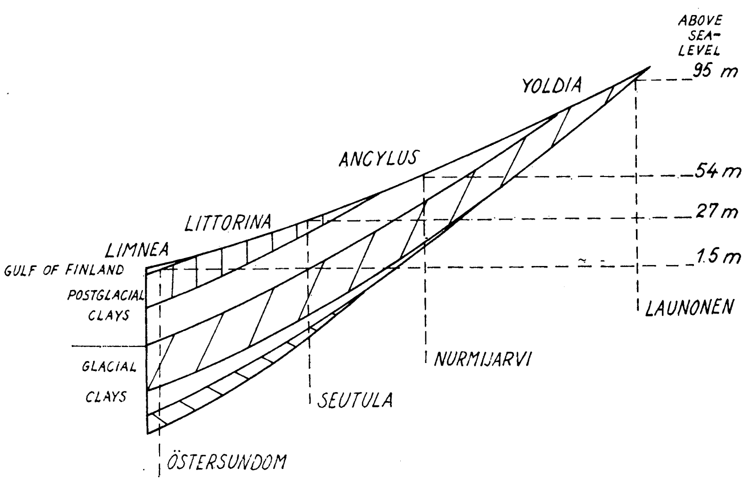


Fig. 1.
Complete clay series of south Finland with the situation of examination sites in relation to altitude.

tained their primary natural state and had not undergone desiccation by agriculture. Forested areas were avoided, too. The reason for this condition is that the investigation aimed at illustrating the influence of evapotranspirative desiccation on water content conditions in parts of the soil surface. Hence one should try to find dry crust formations of different age and water content. The survey line was chosen to proceed at right angles to the isobases of land uplift beginning near the present sea-level and rising all the way to the uppermost clayey soil deposit. In Fig. 2 the location of the examination sites is shown on the map, as well as their present elevation. The age of the sediments was determined by pollen analysis, the age indicating the time when the sediment became isolated from the water.

In general the age of the surface sediment is not a linear function of altitude, as shown in Fig. 1. The figure is meant to demonstrate at which altitude levels the sediments corresponding to the phases of the Baltic Sea may be expected to be found. At some time intervals the primary state may have been disturbed by local current scour in which case certain sediments are absent in part or altogether. Also the area may have been covered by inland waters until late, in which case the sedimentation process has developed further and the corresponding desiccation process has been initiated later.

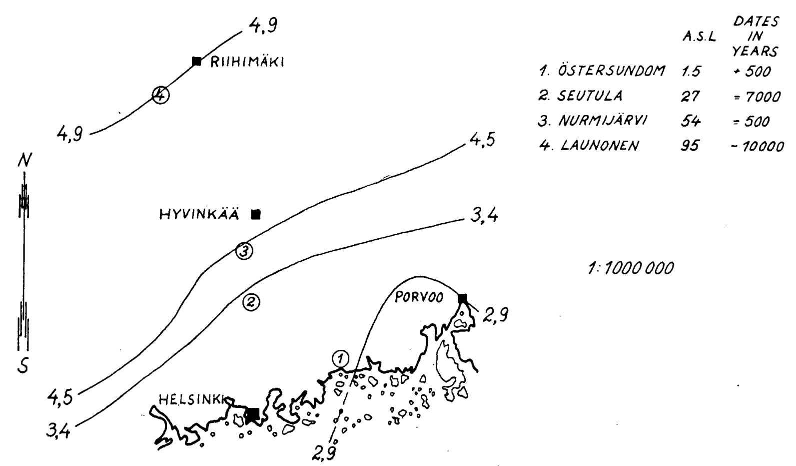


Fig. 2.
Location of examination sites in relation to the isobases of land uplift. Rates are given in mm/year.

METHODS

For this investigation 5 or 6 undisturbed samples were taken at certain intervals at each site for the pressing tests which numbered 22 in all. The determinations were made by compression apparatus by which it was possible to indicate the extrusion of pore water and the change of void ratio as well as the degree of consolidation of the natural state.

In short the experimental method was the following. The pressing system consisted of a cylinder 2 cm high and with a bottom area of 19.63 cm^2. The undisturbed sample was placed between porous disks. The sample was subjected to pressure in a vertical direction by loading with different loads and the compressibility of the sample could be followed continuously by the dial indicator. The initial volume of the sample was always constant i. e. 39.26 cm^3. In addition water casing was used to protect the sample against drying by evaporation during the experiment.

Before the actual experiment a preliminary compaction with a load of 0.125 kg/cm^2 was carried out for the purpose of returning the sample to the natural state. This was necessary because the samples always swelled somewhat after being released from the pressure of the masses above.

During experiments the samples were subjected to loads of 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0 kg/cm^2. For proper performance of the process each load was left on for 24 hours. Thus the measurement of one sample together with the decompression-recompression experiment required 12 days and nights.

The extrusion of pore water

Pore water occurs in soil either for reasons of gravity or adheres to granular particles because of various forces. The purpose of this work is not to separate the forces of adhesion into different classes but to show their combined effect as a function of the age of the sediments. In the experiment use was made of samples the pores of which were not completely saturated by water, but filled partly by air, partly by water. Main attention was paid to the conduct of pellicular water bound more firmly. The samples were taken from the intermediate zone in the water profile of the soil where the water balance is more or less static, and where even the precipitation and evaporation phenomena of different seasons do not have any influence worth mentioning. This is accounted for by the low specific permeability to water of the soil types in question.

The water content of the sample in percentage of the dry weight was determined before and after each experiment. In Fig. 3 the difference of water content ΔW is the ordinate and the initial water content W of the sample the ab-

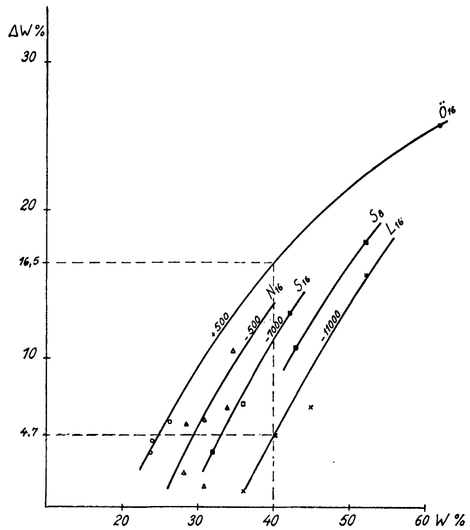


Fig. 3.
Extrusion of pore water from clay samples from sediments of different age.

scissa. The parametric variable in the Fig. 3 is the age of the sediment. Letter symbols indicate the first letter of the name of the site and the index the final load in kg/cm².

The experiments show how the pore water is more firmly bound in older clay soils than in younger ones.

When examining samples of similar water content, for instance, with water content 40 per cent, about 16.5 per cent of the water is squeezed out according to curve $Ö_{16}$, whereas from the corresponding oldest sample only 4.7 per cent is released according to curve L_{16}. As the curves converge one may further conclude that when the initial water content, i. e. the degree of saturation increases, the adhesion characteristics become identical at some point, presumably the saturation point, which according to Fig. 3 would be somewhere in the region of a water content of 60 to 80 per cent, ΔW being about 30 per cent.

The explanation of the phenomenon is purely physical and chemical. The samples were not totally saturated by water, but contained varying amounts of air. In such a state complicated redox reactions may occur between the gas, the liquid, and the solid phase, which would account for the change of adhesion characteristics in course of time.

However, the process is not quite as unambiguous as that. The adhesion characteristics are in addition influenced by electrostatic and magnetic forces between the particles as well as by the content of electrolytes of the pore water. However, the change of redox potential seems to be the principal cause. The intensity of adhesion is dependent also on the relative content of colloid matter in the soil. The greater the specific area of the particles, the more it promotes the adsorption reactions at the boundary.

For the extreme curves Ö_{16} and L_{16} in Fig. 3 equations were computed by regression analysis. As the observations were rather few, this theoretic examination should be considered rather as a hypothetic than as an exact presentation. For the curves parabola-shaped equations were computed

$$\text{Ö}_{16}\Delta W = -0.0056\,W^2 + 1.06\,W - 18.1$$
$$L_{16}\Delta W = 0.034\,W^2 - 2.10\,W + 34.0$$

The point of intersection of these curves was computed and it fell on water content value $W \equiv 56.4$ per cent. This value was to indicate the hypothetical point where the pores are totally saturated by water. However, this value of W is too small, as the regression analysis makes L_{16} curve upwards. Using only 3 observation points the curve drawn in Fig. 3 is obtained.

The determination of decompression-recompression hysteresis and compression index

In connection with the experiment of extrusion of pore water, at the same time the alteration of pore space filled with water and air during different loads was followed. The experiments were modified to the extent that the normal routine was interrupted at the load 4.0 kg/cm² after which the load was reduced first to 1.0 kg/cm² and then to 0.125 kg/cm². After 48 hours the experiment was again continued with the original loads 2.0, 4.0, 8.0, and 16.0 kg/cm².

Fig. 4 shows a semilogarithmic representation of such a compression-decompression experiment in relation to the void ratio. The experiments indicate the plastic deformation typical for clay soils in its hysteresis pattern.

The void ratio is computed using the following equations

$$e_o = \frac{\vartheta_s \cdot V_o}{W_s} - 1 \text{ and } e_p = \frac{h_w - \Sigma\Delta h}{h_s}$$

and the consolidation degree (cf. Fig. 4)

$$C_{c\,\max} = \tan\alpha \text{ or } C_{c\,\max} = \frac{e_1 - e_2}{\log\, p_2/p_1}$$

In the equations the following symbols were used

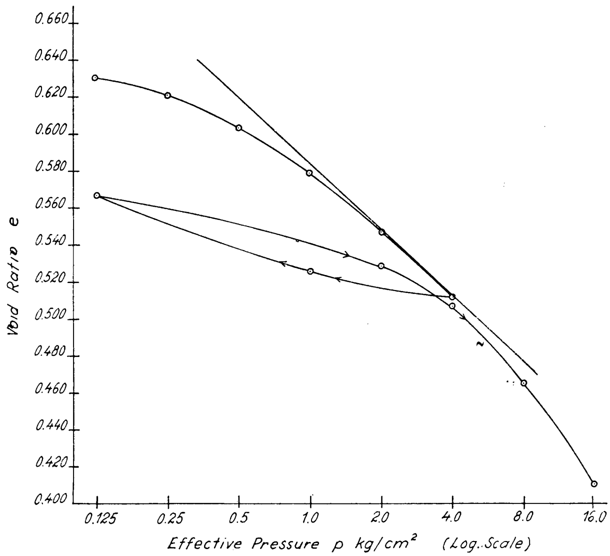


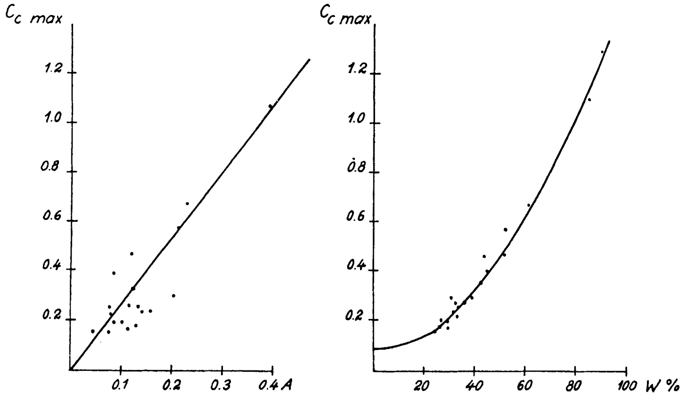
Fig. 4.
Decompression-recompression hysteresis loop in relation to void ratio, the tangent to the curve indicating the compression index.

$e_o \equiv$ initial void ratio of sample before the experiment
$e_p \equiv$ void ratio of sample at different loads
$\vartheta_s \equiv$ specific gravity of sample
$V_o \equiv$ initial volume of sample at the beginning of the experiment
$W_s \equiv$ dry weight of sample
$h_w \equiv 2 - h_s$

$$h_s \equiv \frac{2}{1 + e_o}$$

$\Sigma\Delta h \equiv$ compression sum of different loads
$e_1 \equiv$ void ratio corresponding to load p_1
$e_2 \equiv$ void ratio corresponding to load p_2

The compression index is determined without difficulty by drawing a tangent to the curve in Fig. 4. As a matter of fact, this variable index is the quantity repeatedly appearing in this investigation, as it indicates the consolidation of the area in the natural state in the best possible manner. This compression index has been related in Fig. 5 and 6, to decompression-recompression hyste-



Figs. 5 and 6.
Compression index in relation to area and water content.

resis loop area A, a dimensionless quality showing the hysteresis energy as well as the water content W.

The linear relation in Fig. 5 was computed by regression analysis from the observation points using the method of least squares and its equation is

$$C_{c\,\max} \equiv 2.503\,A - 0.016$$

with the correlation coefficient $R \equiv 0.884$ and the standard deviation of residuals $\delta \equiv 0.104$.

An equation was computed also for the curve in Fig. 6. In the computation two patterns were used, one a straight line, the other parabolic. For the straight line the following equation was obtained

$$C_{c\,\max} = 0.0163\,W - 0.282$$

with $R \equiv 0.986$ and $\delta \equiv 0.0497$. The parabola obtained the following form

$$C_{c\,\max} \equiv 0.000145\,W^2 + 0.0967$$

with $R \equiv 0.992$ and $\delta \equiv 0.0371$. One sees from the equations above that the parabola represents the character of the distribution of the experimental points better than the straight line.

Water content as a function of the age of the sediment and the compression index

In Fig. 7 the samples from each site are arranged in order of sampling depth.

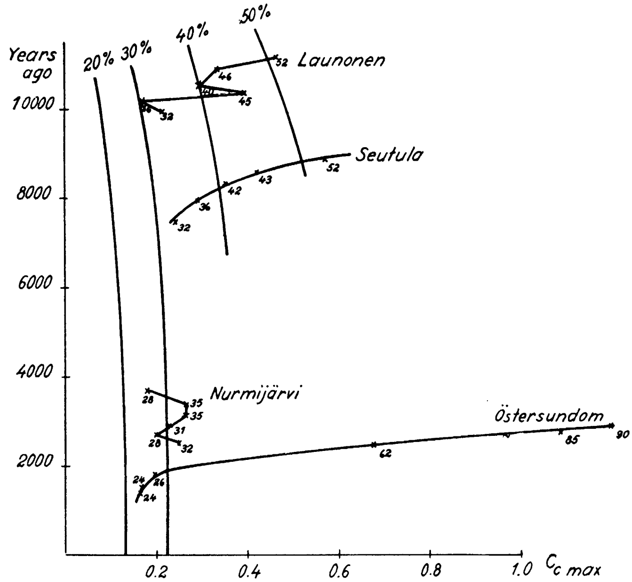


Fig. 7.
Relation between age and compression index and curves of equal water content.

The coordinates are $C_{c\ \max}$ and the age of the sediment. The water content of each sample is shown in the Figure. According to these water content values, the water content isobases are drawn. Also this Figure indicates the same fact as the previous one, i. e. how the adhesion of pellicular water in older samples of similar consolidation is stronger and how this kind af sample retains comparatively more water.

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