On the Weathering of Young Marine Clay

Le Vicillissement des Argiles Maritimes de Formation Récente

by J. Moum and I. Th. Rosenqvist, Norwegian Geotechnical Institute, Blindern, Oslo, Norway

Summary

The formation of the stiff upper crust of young Scandinavian clays is discussed. It is proved that the main factor in the formation is not a drying out process, but a weathering of rock-forming minerals into clay minerals. The liquid limit and plasticity index is markedly increased. Phenomena analogous to the formation of the upper stiff crust are found around deep root holes from weeds and herbs. These holes act as leads for oxygen bearing water.

Sommaire

La formation de la croûte solide supérieure des jeunes argiles scandinaves est discutée. Il a été prouvé que le facteur principal de cette formation n'est pas un processus de dessiccation, mais une décomposition des minéraux rocheux en minéraux argileux. La limite de liquidité et l'indice de plasticité sont considérablement accrus. Des phénomènes analogues à la formation de la croûte supérieure solide s'observent autour des trous profonds des racines des végétaux. Ces trous servent de conduites à de l'eau coutenant de l'oxygène dessous.

Introduction

The Scandinavian young pleistocene marine clays are characterized by very low shear strength values and abnormally high sensitivity values. In exceptional cases the clays may have sensitivity values which are completely unknown outside the sub-polar regions, which were covered by the ice sheet during the last ice-age. These clays are the so-called quick clays.

In the upper parts of the clay deposits the shear strength values are generally found to be much higher than in the deeper part of the same deposits. It is these firm crusts which make it possible to build houses and live on the soft clay. This stiff crust is commonly called the 'drying crust', as it has been supposed that the higher shear strength values are due to a drying out phenomenon. As indicated by the present authors in 1953, the stiff crust is mainly a result of weathering processes and not due to a mere decrease in the water content.

The Stiff Crust

The great geotechnical importance of the stiff crust makes it an interesting subject of investigation. Fig. 1 shows the geotechnical properties of a normal profile through a marine clay with an upper firm crust. It is characteristic that the liquid limit, and also to a certain degree the plastic limit, is higher in the firm crust than in the deeper part of the same deposits. The grain size distribution is, however, more or less uniform all through the profile, so there is nothing to support the hypothesis that the last period of sedimentation gave more fine grained sediment, covering coarser materials. By mineralogical analysis we have found that the stiff clay may, to a certain extent, contain montmorillonite, whereas the deeper parts of the same deposits may be purely illitic and chloritic. The base exchange capacity is accordingly higher in the stiff crust than in the deeper laying clays. All these observations indicate that there has been a secondary change in the mineralogy of the top layers of the clay, but it could not be proved with 100 per cent certainty that the top layers were not primarily different from the deeper laying clays. We have, however, later found analogous weathering phenomena in relatively deeper laying parts of clay deposits.

Some weeds and herbs may have roots going down to about 15 ft. in the clay, and when the plants die these roots may form channels through which surface water may penetrate deeply into the clay deposits. During construction works in Oslo, and also in other parts of eastern Norway, we have followed root holes down to depths below the normal stiff crust. From Fig. 2 it will be seen that the root holes are surrounded by stiff clay material, forming concentric layers with a radius up to some few centimetres. Fig. 3 shows the water content and the shear strength of the clay round the root hole. In other cases we have found fissures going nearly vertically down into the normal soft clays, and it is also found in these cases that the fissures may have a stiff crust on both sides. We have thus

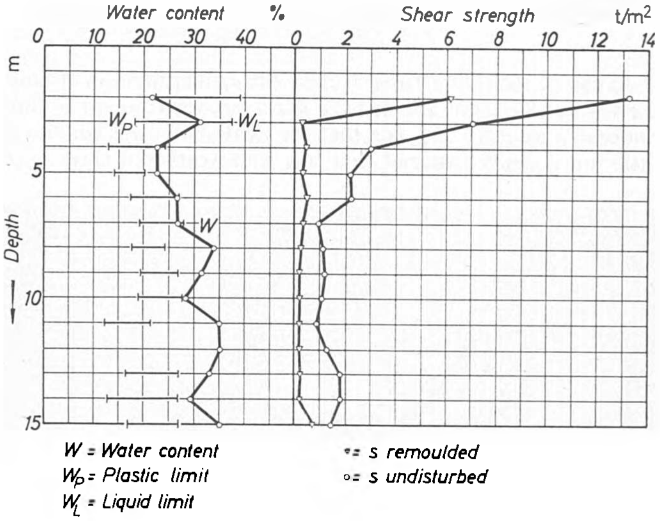

Fig. 1 Characteristic profile through the upper part of a silty marine clay

Coupe caractéristique à travers la partie supérieure de l'argile boueuse marine.

found fissures at a depth of more than 12 ft. in a certain excavation in Oslo. These fissures had a stiff crust on both sides with a thickness from 10 to 20 cm.

In the cases mentioned there have been no land slides or other processes which could disturb the original layering. If we, therefore, take a series of horizontal sections from the fissures or from the root hole of herbs we have clay which originally must have been completely identical. The variations now found must hence be of secondary nature and the processes which have caused these variations must have been the same or very similar to those which have formed the stiff crust on top of all our clay deposits. From an excavation in Uelandsgaten in Oslo we have cross-examined the clays of the stiff crust along the fissures, and also at a greater distance from the fissure, but in the same horizontal layer. The investigations have been carried out both by chemical and mechanical methods, and we have found the following results:

Table 1

Clays from Uelandsgaten in Oslo, 13 ft. below surface

	Chemical investigations			
	Soluble salts in pore water NaCl	*Soluble* K/Na *ratio*	*Adsorbed* K/Na *ratio*	*Bivalent metallic oxides*
Weathered	1·48 g/l	0·89	0·83	42·5 mg/100 g
Unweathered	2·80	0·50	0·31	33·6 mg/100 g
	Mechanical investigations			
	W	*WL*	*WP*	*PI* *S*
Weathered	33·7%	46·1%	25·8%	20·3% 13 t/m²
Unweathered	32·8%	38·4%	22·8%	15·6% 4 t/m²
	Grain size distribution			
	> 0·2 mm	0·2–0·02 mm	0·02–0·002 mm	< 0·002 mm
Weathered	4%	19%	29·5%	47·5%
Unweathered	2%	19·5%	29%	49·5%

As can be seen from Table 1, the weathering processes around the fissures have not affected the grain size distribution to any noticeable extent. The fact that the weathered clays contain a little more sandy material than the non-weathered clays may be due to formation of rust aggregates during weathering, so that some of the fine material is welded together in particles of sand size.

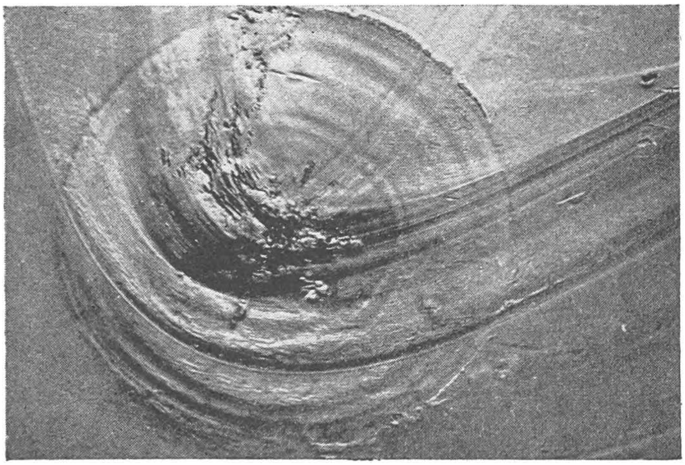

Fig. 2 A root hole surrounded by stiff clay material, forming concentric layers

Le trou d'une racine entouré de matière argileuse raide formant des couches concentriques

The mechanical investigations show striking changes due to the weathering. Most obvious is the shear strength of the weathered clay which is more than three times higher than the shear strength of the non-weathered clay. The water content, however, is the same. Further, we can see that the plasticity has increased markedly. This rise in the plasticity index is followed by a corresponding rise in the base exchange capacity.

As mentioned, the weathered clays may contain noticeable amounts of montmorillonites, supposed to have originated during the weathering. Most probably, this montmorillonite and the corresponding soluble weathering products are responsible for the rise in plasticity and shear strength.

The chemical investigations show that the leaching of the original marine salts proceeds still further in the weathered zones than in the non-weathered. At the same time the potassium/sodium ratio is increased both in the water phase and in the adsorbed cation phase. This increase in potassium can only be explained by assuming that potassium bearing minerals are decomposed and have given off free potassium ions, which have replaced parts of the adsorbed sodium.

In a previous paper (1955) it was mentioned that normally the stiff crust of the Scandinavian marine clays had a thickness of about 4 to 6 m, and it was pointed out that this thickness corresponded to the depths where the summer temperature is still noticeable. It was suggested that the weathering could be highly dependent upon the temperature, so that a short time with temperature above average more than counterbalanced the time when the clay had a temperature lower than average. Such a hypothesis cannot be maintained after the discovery of the weathered zones along the fissures and the root holes. It cannot possibly have been a very different temperature in the weathered zone and in the adjacent clays. The most natural explanation must be that the weathering is a function of the oxygen content of the pore water. Most clay deposits have layers with increased permeability in horizontal direction. A root hole or a fissure will, therefore, in many cases behave as leader of oxygen bearing water down to the silty layers and they must act as strings of high oxidizing capacity. From the fissures or the root holes, oxygen may diffuse into the surrounding water phase.

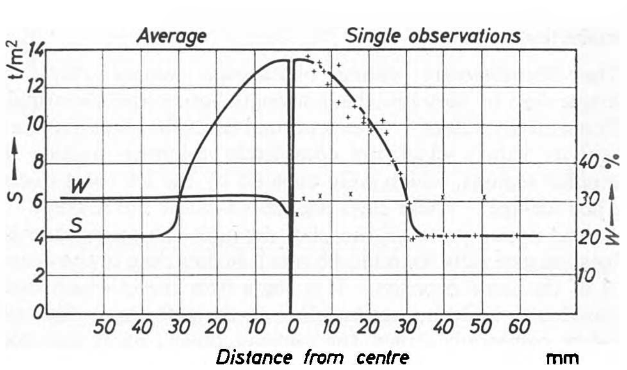

Fig. 3 Determinations of water content, *w*, and shear strength, *s*, from weathered clays around a root hole 15 ft. depth, Uelands gate, Oslo

Détermination de la teneur d'eau, *w*, et de la résistance au cisaillement, *s*, des argiles altérées autout d'un trou de racine de 15 pieds de profondeur dans le rue Uelands gate à Oslo.

The Influence of Oxygen

In order to investigate the influence of temperature and oxygen upon the Atterberg limits of Norwegian clay, we examined a certain clay from the Drammen area. These clays are relatively fine grained, but only slightly weathered. The clay sample was treated in the following manner:

After dispersion in distilled water, one part of the clay was placed in a glass, and air was bubbled through the slurry for 14 days at room temperature. Subsequently, the slurry was carefully dried down by means of dry air, which passed over the surface of the slurry. Another sample of the same slurry was covered by a thick layer of oil and placed air tight in an oven at 60° C. The clay was left here for the same 14 days as the other part was treated by air. Subsequently, the oil layer was removed and the slurry dried down to clay consistency by means of dry air. After sufficient drying, the Atterberg limits of the two samples were determined. The values found are given in Table 2.

Table 2

Natural		14 *days* 60° C. *no air*		14 *days* 20° C. *with air*	
W_L	62·5	W_L	61·0	W_L	73·3
W_P	25·4	W_P	24·6	W_P	28·6
PI	37·1	PI	37·4	PI	44·7

These few experiments show clearly that the plasticity of a clay which is not markedly weathered may increase considerably by a few days of treatment with air. This may seem curious to those who are not mindful of the origin of Scandinavian clay deposits. It must be remembered that the marine clays are mostly of glacial origin and formed from melt water streams pouring out directly in the salt sea water. Under such conditions only insignificant changes in mineralogy take place. The normal weathering of rock forming dioctahedral mica to hydromica may be represented by the following equation:

$$\underset{\text{Muscovite}}{(OH)_4K_2Si_6Al_6O_{20}} + 2H_2O \rightarrow \underset{\text{Hydromuscovite (Illite)}}{(OH)_4K(H_3O)Si_6Al_6O_{20}} + KOH$$

Most illite minerals seem to be dioctahedral micas. The rock-forming micas, however, mostly belong to the trioctahedral group. A weathering of a trioctahedral mica mineral to a dioctahedral illite mineral must obviously be an oxidation process and cannot take place without addition of oxygen and water. Such a formation of hydromica minerals will liberate potassium ions and will mostly also form limonite.

The formation of montmorillonite minerals from mica minerals is a typical oxidation process, which cannot take place in the absence of oxygen. Oxygen is the controlling component and such a process can be illustrated by the following formula:

$$\underset{\text{Mica}}{(OH)_4K_2X_6{}^{IV}X_2{}^{III}O_{20}} + 5H_2O + 1/2O_2 \rightarrow \underset{\text{Montmorillonite}}{(OH)_{12}X_8{}^{IV}Y^{III}{}_4O_{16}} + 2KOH$$

Such and similar processes are continuously going on in all illitic clays in temperate climates.

Geotechnical Significance of the Weathering

The shear strength of a clay is dependent upon the liquidity index and the effective overburden. In the upper part of a normally consolidated non-weathered clay sediment the water content is normally higher than the liquid limit and, thus, the liquidity index is greater than unity. As the effective overburden is low, the consequence is that the shear strength is low. By weathering processes analogous to those mentioned previously, the liquid limit is raised considerably, whereas the water content is kept nearly unchanged. This leads to a decrease in the liquidity index, so that this figure may be considerably below unity. As long as the effective overburden is not changed, such an increase in the liquid limit will lead to a marked increase in the shear strength. It is, therefore, natural that the top layers of the young marine clays must have shear strength higher than layers deeper down. This corresponds to what we find in nature. In the uppermost part of the firm crust other factors are active, adding to the strength of the soils.

These factors may be found in the movement of the water phase under the action of frost. When an ice crystal is formed in a clay at a temperature lower than the freezing point, a transportation of water will take place from the unfrozen parts towards the ice crystal and, thus, create a suction in the water phase, which again means an increased effective consolidation pressure. The evaporation from the upper parts has a similar effect, so that the formation of the stiff crust is a complex phenomenon and even without weathering processes an increased shear strength should be expected. It is, however, not possible to understand the whole formation of the stiff crust without taking into account the weathering processes. At this point, it is worth mentioning that weathering and oxidation processes are not bound to the surface layers only, but may take place even in deeper parts of the clay profile.

In many parts of the Scandinavian countries clays are found situated in slopes where the higher permeability in a horizontal direction may lead oxygen bearing water to penetrate approximately parallel to the surface and down to considerable depths. By means of chemical analysis it has been possible to show large variations in the oxygen contents of clay sediments, even to great depths. We have also found oxygen bearing ground water 30 m below the surface. Consequently, there must take place a 'weathering' not only from the surface, but to some extent all through the clay profile. This will lead to a secondary increase in the shear strength of the clays, even in the deeper parts, so that a line through the shear strength values will not give zero value for the strength at zero consolidation pressure, but some positive value.

References

Moum, J. and Rosenqvist, I. Th. (1955). *Kjemisk bergartsforvitring belyst ved endel leirprofiler. Norsk Geologisk Tidsskrift*

Rosenqvist, I. Th. (1955). Bidrag til Östlandsleirenes petrografi. *Norsk Geologisk Tidsskrift*, b.35