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Saturated Hydraulic Conductivity of Clayey Tills and the Role of Fractures

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The background for the present knowledge about hydraulic conductivity of clayey till in Denmark is summarized. The data show a difference of 1-2 orders of magnitude in the vertical hydraulic conductivity between values from laboratory measurements and field measurements. This difference is discussed and based on new data, field observations and comparison with North American studies, it is concluded to be primarily due to fractures in the till.

Introduction

The scope of this paper is to give a review of the state of knowledge about saturated hydraulic conductivity of clayey till (boulder clay) in Denmark. The hydraulic properties of Swedish and Norwegian tills, which in texture are very different from Danish tills, have been treated by Lind and Lundin (this volume). The presented Danish data are compared to investigations from glaciated areas in North America, which in many respects have a similar geological setting. The influence of structures on the hydraulic conductivity in till is well documented in North America in contrast to the situation in Denmark. This gives a basis for discussion and evaluation of the Danish data in relation to the possible significance of till structures, as fractures and intercalated sandlamina. Till structure is in this context used as a designation for all visible structures of sedimentary or diagenetic origin in till sediments. Independent geological evidence and preliminary data from field experiments are used to explain the variation in the Danish data.

In Denmark 50% of the groundwater is extracted from Quaternary deposits (Kelstrup *et.al.* 1982), mostly glaciofluvial sand and gravel. Another 35% of groundwater comes from limestone aquifers. Clayey till forms in many areas aquitards above, between and below the sand/gravel aquifers and above the limestone aquifers. The hydraulic conductivity of the aquitards must be considered, when estimating the groundwater resource. This has been done rather indirectly by estimating leakage and average recharge to the aquifers. Ødum (1935) found infiltration velocity to be 10-20 m/year, but this was based on a misunderstanding of the process. First by the Suså-project (Dyhr-Nielsen 1981) field data in form of tritium profiles from till made more direct estimates possible.

Early in the 20th century agrogeology gave important contributions to our knowledge of the hydraulic conductivity of till soils and the effect of soil structure (Westermann 1909, Rørdam 1910). Westermann (1909) measured soil permeability and ascribed the rather high hydraulic conductivity of clayey till soil to its structural properties, which agrees with the observation that remoulded wet soils had much lower hydraulic conductivities than intact or remoulded dry soils. The importance of this work is further elucidated from the pracitcal experience from drainage systems in clayey till soil, which indicated rather high soil conductivities (Feilberg and Feilberg 1955). While the importance of soil structure under saturated condition is accepted, no attention has been given to the importance of the till structure below the uppermost soil zone. Information on till structure can be found in the description to the early geological maps, noting bedding, lamination, sand lenses and fissility (Madsen 1897, Rørdam and Milthers 1900, Jessen 1907), but most often till was, and is, described as homogeneous. The structure was never related to hydraulic properties, even in the most recent studies on till structure (Marcussen 1975, Krüger and Marcussen 1976, Krüger 1979), except Haldorsen and Krüger (1990). The knowledge of the hydraulic conductivity and its dependence on soil- and till structure has become very important, because clayey till is considered as a barrier against migration of pollution to till covered aquifers. A number of cases where pollution has migrated through clayey till aquitards (*e.g.* Andersen and Mikkelsen 1989), support this statement.

Laboratory Measurements

As outlined in the introduction the hydraulic properties of clayey till have only been subject to few investigations. Above all geotechnicians have contributed to our knowledge, since hydraulic conductivity can be calculated from time-consolidation measurements done by oedometer as described in textbooks in soil mechanics. Most values of hydraulic conductivity previously quoted in such books are based on laboratory measurements (probably oedometer), but the methods of determination are seldom noticed. Early works are reviewed by Mertz (1949). An overview of published Danish values of hydraulic conductivities in tills is given in Fig. 1.

The values given by Feilberg and Feilberg (1955) (Fig. 1) are emperical, with no reference to methods. Based on these values calculation of drainage pipe distance in clayey soil often gives too short a drain pipe spacing. This is due to lack of representativity of the data resulting in an underestimation of hydraulic conductivity (Feilberg and Feilberg 1955). The values from agrogeologic studies only represent the soil horizon including the uppermost part of the C-horizon.

The values of hydraulic conductivity presented by DIF (Danish Engineering Society) (1946) are based on oedometer measurements (Fig. 1).

Jacobsen (1970) made a study of deformation characteristics of clayey till including hydraulic conductivity measurement by oedometer and triaxial test. He found that oedometer test in general gave values, which were too low compared to values obtained by triaxial test. This was because, the samples in the oedometer test often were not fully saturated. Jacobsen presented a method for correction of the oedometer values involving a factor of 3-4. The corrected values were in accordance with the triaxial test, which gave values of 6-80 $\times 10^{-10}$ m/s (Figs. 1 and 2). The largest values were from weathered till, and the examined till samples were presumed to be unfractured.

Values presented by Pedersen and Lind (1976) from a 17 m deep well, show large variation due to fractures with stained surfaces. An indication of their hydraulic activity was the small content of nitrate throughout the profile. Values of hydraulic conductivity of 4.3×10^{-10}-9.8×10^{-5} m/s were obtained (Fig. 2).

From landfill site investigations some values of hydraulic conductivity are reported, but description of measurement methods is often missing, making evaluation of data difficult. Values below 10^{-9} m/s are measured by falling head permeameter (Cowiconsult A/S pers. com.). Comparison of data from intact and remoulded samples with equivalent porevolumes from the same investigation, gives one order of magnitude difference in hydraulic conductivity (Cowiconsult A/S 1986). This is in agreement with results of experiments assessing the possibility of using clayey till as clay liner below landfill sites (Vandkvalitetsinstitutet 1986).

When evaluating the laboratory data possible sources of error must be considered. All data in Fig. 1 were measured on intact, undisturbed samples. Data from packed columns are excluded from the compilation.

Daniels *et. al.* (1985) and D'Astous *et.al.* (1988) give a review of advantages, disadvantages and sources of error for different laboratory methods for determination of hydraulic conductivity. Sidewall leakage seems to be the major problem for fix-wall permeameters. Also the stress condition under which the samples are tested might affect the results. Too low values can arise, if the samples are not completely saturated. These sources of error might be relevant to the data of Cowiconsult A/S (1986). Jacobsen (1970) carefully took most sources of error into

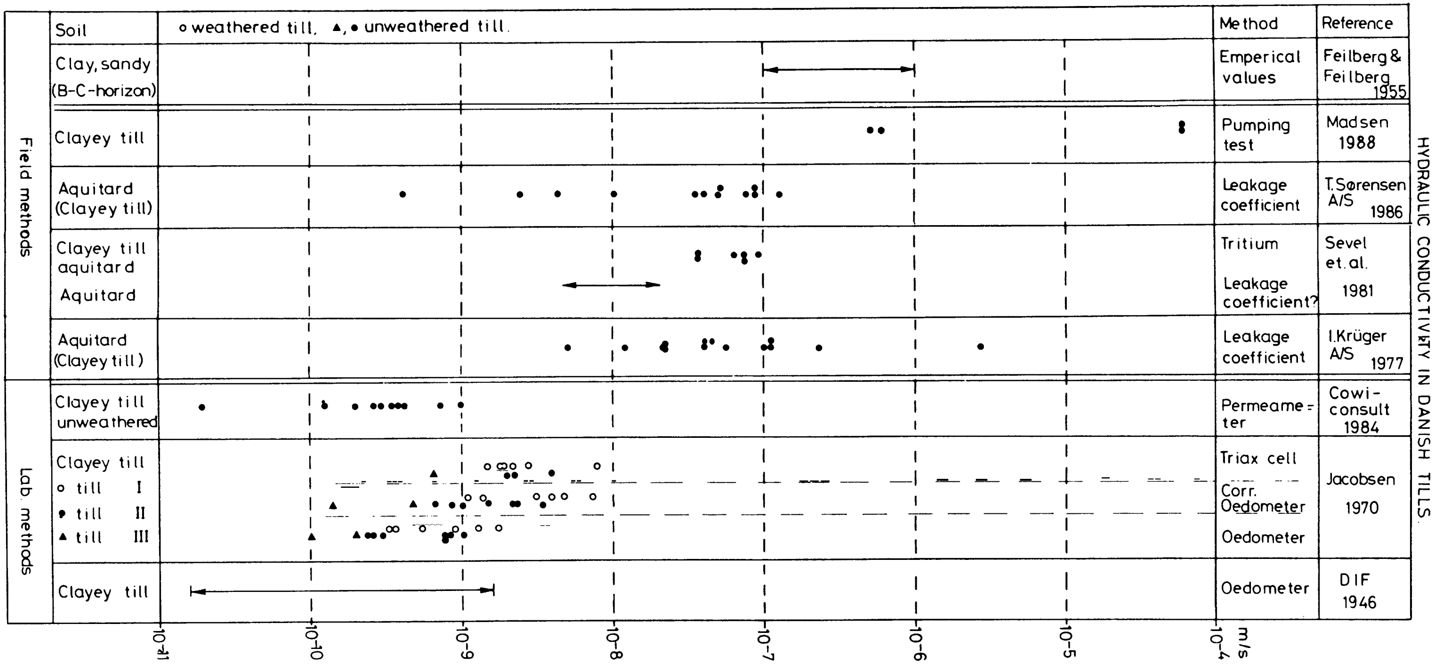

Fig. 1. Hydraulic conductivity of Danish tills determined by different methods. A clear difference between field and laboratory values are seen. Data plotted in semi-logarithmic scale.

consideration such as saturation, varying stress condition and sample size and sample preparation. He found that Darcy's law was valid for flow through the till, and that corrected oedometer values gave comparable values to triaxial cell values. When increasing gradient was used in the test, the threshold gradient was very small, but to avoid this effect a gradient of 20-30 was used. Varying confining stresses affected the hydraulic conductivity with less than a factor two in the presumed non-fractured samples. It must then be concluded that the data in Fig. 1 primarily show the natural variation in hydraulic conductivity in laboratory samples. The critical point in this conclusion is the question about fractures in the samples, because, as shown in a number of British papers *e.g.* Kazi and Knill (1973), the confining pressure will up to a certain level change the measured hydraulic conductivity from fractured samples. However, the samples, tested by Jacobsen (1970), were not observed to be fractured.

Field Investigations

Field studies concerning direct measurements of the hydraulic conductivity in the C-horizon in Danish clayey till are to the author's knowledge not reported. The values obtained from geotechnical measurements were earlier used by hydrogeologists, supporting the general view of clayey till as an impervious sediment (Milthers 1903, 1919, Sorgenfrei and Bertelsen 1954). Since the introduction of pumping tests in Denmark twenty years ago (Andersen and Hamann 1970) indirectly determined hydraulic properties of aquitards have been presented.

A compilation of data determined by different methods is given in Fig. 1. In a study on infiltration by Sevel *et. al.* (1981) bomb tritium analyses of pore water from intact samples from drilled holes were used together with the measured gradient to calculate vertical hydraulic conductivity through till. Values of 4-9 $\times 10^{-8}$ m/s were found assuming that the till acts as a porous media with an effective porosity of 30 % (Figs. 1 and 2). Sevel *et. al.* (1981) concluded that these data were comparable with general obtained values of the magnitude of 10^{-8} m/s (Fig. 1). This statement was probably based on leakage parameters. A compilation of leakage coefficients – or hydraulic conductivities based on these – does not exist. Data from two investigations, one on water ressources (T. Sørensen A/S 1986) and one on infiltration/pollution studies (I. Krüger A/S 1977), are compiled in Fig. 1. The reported values were found using the type curve method from Walton (1962), not taking the storage properties of the aquitard into consideration. The vertical hydraulic conductivities from the first investigation are calculated by the author, using estimated aquitard thicknesses based on well information. During pumping tests, piezometers are normally only monitored in the aquifer, and the assumptions for the theory on which leakage coefficients are found are seldom fulfilled. Drawdown curves can also be misinterpreted to indicate leakage, when delay in draw-

Hydraulic Conductivity in clayey till

Locality	Soil	Grain size Clay, silt, sand.	Kfield= Kbulk $K \times 10^{-10}$ meter/sec	Klab ≡ Kmatrix $K \times 10^{-10}$ meter/sec.	Number	Method of determination	Variation $K \times 10^{-10}$ meter/sec	Reason for K-variations	Reference
Denmark (DK)	Till	20-25 25-50 40-60		20	10	Permeameter	6.5-30	Highest values in weathered till	Jacobsen 1970
Suse Å (DK)	Till	20,40,40*	620		4	Tritium	400-900		Sevel et al. 1981
Skælskør (DK)	Till	20,20,60		4.3 - 980.000	5	Permeameter ?	4.3 - 980.000	Fractures	Pedersen & Lind, 1976
Alberta Canada	Till	sandy loam 20,40,40*		6.6[a]	3	Oedometer	3.4-9.8	small fractures	Hendry, 1982
				<20	7	Permeameter		large fractures	
				3700	4	Permeameter		large fractures	
			50		41	Slug test[d]			
			1700			Slug test[c]			
"Prærie" Canada	Till	clay loam[f]		0.5[g]	85	Oedometer	± 0.4	Fractures	Grisak et al., 1976[c]
		sandy loam	10		?	slug test		Fractures	
		clay	70		?				
			0.1-1000		?				
			100-1000		?				
	Till (weathered)	15-20 45-50 30-40	2000		4	Slug test	100-70000	Fractures[h]	Schwartz ref. af Grisak et al., 1976

Locality	Soil	Grain size Clay, silt, sand.	Kfield= Kbulk $K \times 10^{-10}$ meter/sec	Klab = Kmatrix $K \times 10^{-10}$ meter/sec.	Number	Method of determination	Variation $K \times 10^{-10}$ meter/sec	Reason for K-variations	Reference
Saskatchewan Canada	Till (unweathered)	40,40,20		0.35	3	Oedometer	0.1-0.76	Densely spaced fractures	Keller et al., 1986
			100		20	Slug test	10-2000		
Ontario Canada	Till (Glacio-lacustrin)	50,35,10		4.5	1	Oedometer		Fractures	Desaulniers at al.,1979
			4.0		1	Slug test			
			100-1000		1	Slug test^j			D'Astous et al., 1989
			100-8400		1	Tracer			

* Estimated from sample description

a Estimated average

c Piezometers with long screened intervals

d Piezometers with short screened intervals

e Supplementary k-values in ref, but lithology unspecific

f Lithology not specified on fraction

g Generel value for the area

h Fractures according to Grisak et.al. 1976

j Slug test in large diameter well

Fig. 2. Comparison of Danish and North American published values of hydraulic conductivity of tills. The large difference between laboratory and field values in North America are explained by the occurrence of fractures. A similar explanation is most probably also valid for Danish tills.

down is due to other effects (Freeze and Cherry 1979). In the case of leakage it must also be remembered that leakage comes both from layers above and below the aquifer. Reliable values of hydraulic conductivities can only be obtained if pumping tests are carried out with a reasonable number of piezometers in the over- and underlying aquitards (for discussion see Freeze and Cherry 1979, Neumann and Gardner 1989). This kind of test was carried out by Madsen (1988) on a two layered 15 m thick till sequence interlayered by 1 m of meltwater sand and clay and underlain by limestone. A model of the test gives the best results with the acceptance of the till unit as fractured with a vertical hydraulic conductivity of 6×10^{-5} m/s and a horizontal conductivity of 6×10^{-7} m/s (Fig. 1).

Comparison with North American Data

Comparison of field and laboratory data in Fig. 1 shows that for most data there is a difference of at least a factor of 30 in the vertical hydraulic conductivity. Similar differences are found in many investigations from former glaciated areas in U.S.A. and Canada. In most of these investigations the differences are explained by fractures, which were observed in pits and drilled cores. Some of the results are shown in Fig. 2, together with the methods for determination of the hydraulic conductivity. The data show a consequent difference between laboratory and field data, even though the tills investigated vary in lithology and genesis. Only some of the till types are comparable in lithology to clayey Danish tills. The fractures seem to be of two sizes. Small fractures (spacing 10 mm) increase the conductivity by one order of magnitude, whereas large fractures (spacing 20-630 mm) give up to two more orders of magnitude higher values for field measurements (Fig. 2) (Hendry 1982). The data in Fig. 2 can be supplemented by other investigations which support the view that fractures exist and determine the hydraulic conductivity, *e.g.* Sharp (1984), Hendry (1988), Ruland *et. al.* (1989), Keller *et. al.* (1988). Keller *et. al.* (1988) documented that in unfractured till, field values (slug test) and laboratory tests (oedometer) give values of the same order of magnitude. The main discussion in the North American papers is whether the fractures solely belong to the weathered zone as concluded by Hendry (1988), or whether they occur to a considerable depth as indicated by Ruland *et. al.* (1989) and Keller *et. al.* (1988). A discussion and review is given by Cherry (1989).

Fractures in Danish Tills

Studies of fracture systems in Danish tills are very sparse. Fractures in the soil horizons has been described by Fobian (1982). As outlined by Haldorsen and Krüger (1990) three different fracture systems are likely to exist at deeper levels.

The most densely spaced are horizontal fractures giving the till a fissility. The spacing of the other two types is considerably larger. Current research by the author shows that fractures can be found to a depth of at least 6 m in Danish till. The deep penetrating vertical and the horisontal fractures in the C-horizon have spacings in the order of 30-60 cm in one of the examined localities (Fredericia 1987). On another locality spacing in a depth of 2 m is approximate 1 metre between vertical fractures. The genesis of the fractures can be explained by different processes, and since there is some coincidence between fracture orientation and ice movement direction, a genetic relation is inferred (Fredericia 1987).

Fractures in till have not been reported in Danish groundwater research, except in the paper by Pedersen and Lind (1976). Sevel *et al.* (1981) argues against the possibility of hydraulically active fractures because of the smooth tritium profiles they obtained. The author's investigation (a double trench experiment) of the upper 5 m of a till sequence, which shows pronounced fracturing but also contains a thin sandveneer, does give bulk values of horizontal hydraulic conductivity above 10^{-7} m/s. The hydraulic conductivity and the fracture intensity decrease considerably with depth, but fractures can be identified to at least 5 m depth, which is the bottom of the trenches. Results from slug test in the weathered and most fractured part of the till give values between 3×10^{-6} and 7×10^{-8} m/s. This can be compared with laboratory measurements. The hydraulic conductivity was measured in a triaxial cell giving values of $3\text{-}6 \times 10^{-10}$ m/s in the unweathered till and $1\text{-}2 \times 10^{-9}$ m/s in the weathered till.

Discussion

From the evaluation of the hydraulic conductivities obtained in the laboratory it is clear that the variance mostly is due to the natural variation in tills. In order to compare laboratory and field data, the representativity of the laboratory samples, or other small scale measurements, must be considered. According to Haldorsen and Krüger (1990) it is likely that different fracture systems exist, but the hydraulic significance of each system is unknown. However the observed fractures in tills do have spacings of 30-100 cm. It is thus very unlikely that this kind of fractures should be incorporated in laboratory samples. This means that the laboratory measurements only represent the hydraulic conductivity of the material between this kind of fractures, *e.g.* the matrix. For determination of the bulk hydraulic conductivity the representative sampling size should, according to McKinlay *et. al.* (1978), be 20 times the minimum fracture (fissure) spacing.

Based on the reported data it is evident that there exists a large difference between data on hydraulic conductivity obtained from laboratory and field measurements. Since this difference cannot be attributed to the methods of determination, it must be due to some high permeable zones in the till, which are normally not present in laboratory samples. This indicates that hydraulic active fractures are the most reasonable explanation, which coincides with the observed occurrence of fractures in the field and hydraulic conductivities from some preliminary field test.

The effects of fractures on infiltration are well documented as they contribute to macropore flow in the unsaturated zone. A review is given by Beven and Germain (1982). In the saturated zone percolation through aquitards to aquifers will also be influenced by fractures, but the effect depends on whether fractures connect high permeable surface layers with the aquifer or whether they terminate in the aquitard. Also fracture density and effective aperture will play an important role. No such study has yet been published for Danish tills.

The hydraulic conductivities given in Fig. 1 are all vertical conductivities (except the lower values by Madsen 1988), whereas the slug test data in Fig. 2 are based on the assumption of a homogeneous, isotropic and infinite medium. Slug test data do not give an indication of the anisotropy. However, the paper by Keller *et. al.* (1988) demonstrates that both the vertical and horizontal conductivities in the field are considerably higher than the laboratory values. The anisotropy of hydraulic conductivity in clay is normally small (Freese and Cherry 1979), but in fractured clay it might be depending on the fracture system, as indicated by the large difference in the values given by Madsen (1986). However, a sensitivity analysis must be made before this anisotropy can be regarded as reliable.

Also the extent and depth of fracturing must be considered. One important problem is the recognition of fractures which do not have stained surfaces. In rare cases stained fracture surfaces can be seen to continue downwards and become unstained. Another problem is to obtain hydrogeologic evidence of fractured/non-fractured sequences. The vertical hydraulic conductivities from the investigation of T. Sørensen A/S (1986) were used in a groundwater-surfacewater model, with two aquifers separated by an aquitard. During calibration it was necessary to reduce the hydraulic conductivity of the aquitard considerably. Similarly the data from Sevel *et. al.* (1981) were 10 times larger than the parameter used in the model (The Suså model) covering the investigation area (Refsgaard and Stang 1981). The values in the model (5×10^{-9} m/s) were used to calculate infiltration through the aquitard and were sufficiently large to recharge the aquifer. Pumping tests from the same area did not show any sign of leakage, thus giving some support to rather low values of hydraulic conductivities (Andersen and Nielsen 1976). As the geological situation, transmissivities, and potentionmetric surface for the primary aquifer are well known, the recharge, and thereby the bulk hydraulic conductivity of the aquitard, cannot be far from correct. It is thus possible that in some places a fractured upper section overlies an unfractured lower section in a till sequence, and that in other places there may be direct contact between fractured till and an underlying aquifer.

Another parameter which should be considered is the effective porosity. This is often supposed to be 30% (Sevel *et. al.* 1981, I. Krüger A/S 1977), whereas T.

Sørensen A/S (1986) uses a value of only 1 %. If the effective porosity is small – as would be the case in a fracture-matrix system – rather small bulk hydraulic conductivities can be combined with long travel distances of pollution or tracers. When tracers are considered in such a system diffusion from fracture to matrix might be an important process and the tracer can be retarded considerably (Cherry 1989).

Conclusion

There are both hydrological and geological indications of the occurrence of hydraulic active fractures in Danish clayey tills, as also indicated by the author's investigation. The difference in values from field and laboratory measurements cannot be attributed to the methods of determination except the scale effect, and must thus be the result of structures in the till, which are not present in laboratory samples.

The number of published hydraulic conductivities are still small, and more knowledge is needed, especially about the fracture systems in till. These systems can be revealed by geological mapping including fracture distribution, spacing, depth of occurrence etc. Controlled tracer tests can throw light on the actual transport velocities and the importance of diffusion, and isotope studies can give the age of the porewater. In thick clayey till, bomb tritium possesses possibilities as a fracture indicator, because of diffusion, tritium will create at least a 2 m broad zone around an active fracture in 35 years (Ruland *et. al.* 1989). It might also be important to evaluate new and earlier isotope studies with an advection-diffusion flow concept, because if the till has low matrix conductivities, below approximate 10^{-9} m/s (Cherry 1983), diffusion could play an important role. Hydraulic tests with direct measurements in the aquitard, *e.g.* slug tests with different screen length and pumping tests with observation points in the till as done by Madsen (1988), can give bulk hydraulic conductivities of different sizes of volume. Methods should also take the anisotropy into consideration. Data obtained from investigation of the above proposed methods are necessary for an understanding of how effective a barrier clayey till is against migration of pollution.

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